FIELD MANUAL FOR RESEARCH IN AGRICULTURAL HYDROLOGY
FIELD MANUAL FOR RESEARCH IN AGRICULTURAL HYDROLOGY

Agriculture Handbook No. 224

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Science and Education Administration
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ABSTRACT


This publication was prepared to provide a complete set of techniques needed for the initiation and maintenance of hydrologic research projects. These techniques were obtained by soliciting information from experts and adapting material described in current literature. While this publication cannot replace individual instruction by an experienced person, it should serve as a reference for such instruction and, if followed, place the data in a form that will be suitable for potential analyses. Chapters 1, 2, and 3 deal with precipitation, runoff, and climate. Chapters 4, 5, and 6 discuss sedimentation, geology, and watershed characteristics and soil moisture. Each subject is divided into (1) installations, (2) field observations, (3) data reduction, and (4) data processing.

Key words: precipitation, runoff, climate, sedimentation, geology, soil conditions, watersheds, data reduction, data processing, field observations, field maintenance, site requirements, installations.
FOREWORD

The original Field Manual for Research in Agricultural Hydrology, U.S. Department of Agriculture, Agriculture Handbook 224, was issued in 1962. This revised version, an extension and update of the original manual, incorporates the most recent techniques and procedures that have been found useful in watershed research by the Science and Education Administration.

This publication is prepared primarily to aid field personnel conducting watershed research. Chapters 1, 2, and 3 cover precipitation, runoff, and climate. Chapters 4, 5, and 6 discuss sedimentation, geology, and soil conditions and watershed characteristics.

We have presented the most recent technology and will issue supplements and revisions as needed. For information concerning revisions and supplements, contact:

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Assistant Administrator
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INTRODUCTION

This publication was prepared to provide a complete set of techniques needed for the initiation and maintenance of hydrologic research projects. These techniques were obtained by soliciting information from experts and adapting material described in current literature. While this publication cannot replace individual instruction by an experienced person, it should serve as a reference for such instruction and, if followed, place the data in a form that will be suitable for potential analyses. Forms used here are illustrations only of how best to organize and record the data.

Chapters 1, 2, and 3 deal with precipitation, runoff, and climate. Chapters 4, 5, and 6 deal with sedimentation, geology, and watershed characteristics and soil moisture. Each subject is divided into (1) installations, (2) field observations, (3) data reduction, and (4) data processing.

Most hydrologic analyses and computations dealing with precipitation are expressed in surface inches. For streamflow and storage, however, quantities and rates often are expressed in units of feet, acres, and miles for easy conversion to structural dimensions.

The hydrologist continually is converting back and forth from surface inches and surface inches per hour to such volumetric units as cubic feet, acre-feet, and cubic feet per second-hours or to such units of rate as cubic feet per second and cubic feet per second per unit area. Table 1 lists common conversions in English units, and table 2 lists common conversions from English units to the International System (SI) units.
Table 1.—*English conversion factors for water hydrology*

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¹ Latent heat consumption in evaporating 1 g of water.

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INTRODUCTION

Precipitation includes any moisture falling from the atmosphere in liquid or frozen form. The total amount of precipitation that reaches the ground in a stated period is expressed as the depth to which it would cover a horizontal projection of the earth’s surface if there were no loss by evaporation or runoff, or if any part of the precipitation falling as snow or ice were melted. Snowfall also is measured by the depth of fresh snow covering an even, horizontal surface. The chief aim of any method of measuring precipitation should be to get a representative sample of the fall over the area to which the measurement refers. This is an important requirement for measuring precipitation in the absolute sense. The choice of site, the form and exposure of the measuring gage, the prevention of loss by evaporation, and the effects of wind and splashing are all important.

In its simplest form, a precipitation gage is an open-mouthed can with straight sides. Gages are installed with the open end upward and the sides vertical. Improved gages measure small amounts and record the time and intensity of precipitation. Rain gages are used in (1) climatology, in which nonrecording gages often are used; (2) hydrology, in which forecasting of runoff requires self-recording gages and totalizers; and (3) hydrometeorological studies, in which a rain gage must show rates and amounts of rainfall.

For most climatological studies, today’s rain gages are adequate. For hydrological purposes, such as runoff forecasting, the recording gages are satisfactory although measurement of precipitation is limited by such factors as gage sensitivity and network density. For hydrometeorological studies in which rates of rainfall and amounts must be shown accurately for short intervals, today’s networks of recording gages are frequently inadequate.

A wide variety of gages has been developed to measure precipitation; some gages were developed for a special purpose. Two types of gages (nonrecording and recording) are used primarily in the United States. The nonrecording gage retains the total precipitation between observations; the recording gage gives the time of precipitation so that intensities can be computed.

Some crude quantitative determinations of rainfall can be made by use of radar, but errors are appreciable (8). The principal value of radar is to help determine location, areal extent, orientation, and movement of rainstorms (41).

INSTALLATIONS

Installation should be geared to conditions of operation and maintenance. Climatic factors, physical conditions of the site, and the anticipated type of observer should be considered. Usually simplicity of operation is the best guarantee of satisfactory performance. Simplicity of procedure insures adequate observations. Where procedures are complicated, the duties of the observer should be reduced to a step procedure. Provision in the installation design often can facilitate such reduction. Gage sites should be selected, designed, and located to provide unconfounded records.

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111 Numbers in parentheses refer to References at the end of each chapter.
General Considerations

Site Selection

The location of the gage is the primary consideration for obtaining accurate precipitation measurements. An ideal exposure would eliminate all turbulence and eddy currents near the gage. Individual trees, buildings, fences, or other small groups of isolated objects near the gage may set up serious eddy currents, especially when their height above the gage is appreciable. As a general rule, an isolated obstruction should not be closer to the gage than twice (preferably four times) its height above the gage (37). Obstructing objects usually provide a more accurate catch when they are so numerous and extensive that prevailing windspeed in the vicinity of the gage has been reduced and, consequently, the turbulence and eddy currents also have been reduced. The best exposures often are found, therefore, in orchards, in openings in a grove of trees or bushes, or where fences and other objects form an effective windbreak.

Sites on a slope or on ground sloping sharply away in one direction should be avoided especially if this direction is the same as that of the prevailing wind. The surrounding ground can be covered with short grass or be of gravel or shingle; but a hard, flat surface, such as concrete, causes excessive splashing and abnormally high surface temperatures.

The growth of vegetation, trees, and shrubbery, and manmade alterations to the surroundings may make an excellent exposure unsatisfactory in a relatively short time. The angle from the gage orifice to the top of any nearby object should not exceed 30°, thus allowing for growth of vegetation. Under no circumstances should an obstruction be nearer to the gage than its own height (45°). Wilson (40) felt, however, that a small clearing in uniform forests, having a diameter about equal to the height of the trees, was best because the measurement would gain more from the reduction of wind than it would lose from interception.

To place a gage in a forest opening of 60-foot (18.3 m) trees, a clearing of about ¼ acre (1,012 m²) is required (23). If no such openings exist on a watershed or on control watersheds where no cutting is allowed, measuring rainfall at the surface of the tree crown should be considered (30).

At exposed sites, lack of natural protection can be compensated for by shielding or by using pit gages. The Nipher shield is recommended if the precipitation is primarily rain. The Alter shield is recommended if a substantial portion of the precipitation is snow.

Height of Receiver Funnel

Height of the mouth of the gage above ground should be as low as possible (because wind velocity increased with height) but high enough to prevent insplashing from the ground. In areas that have little snow and few puddles, a 12-inch (30 cm) receiver funnel may be used. In other areas, a standard height or 30 inches (75 cm) is recommended.

All gages in a watershed should be the same height above ground. The 8-inch (20 cm) standard or nonrecording gage, which is only 26 inches (66 cm) high, will require construction of a stand to raise the funnel up to 30 inches (76 cm), which is about the minimum height possible for the weighing-type universal recording gage.

In very exposed places where natural shelter is unavailable, results will be better if the gage is exposed in the middle of a circular turf wall about 10 feet (3 m) across. The inner surface of the wall should be vertical, and the outer surface should slope at an angle of about 15° to the horizontal. The top should be level with the mouth of the gage, and provision should be made for drainage. The main disadvantage of this arrangement is that the space enclosed by the wall may fill with snow in the winter. In areas where heavy snowfall occurs, gages are mounted on supports (towers) at a height well above the average level to which snow accumulates (fig. 1.1). This exposure will be better, however, if the tower is located among trees of comparable height.

Size of Orifice

Small-orifice gages have been developed recently to increase economically the density of rain-gage networks (26). Huff (19) compared small-orifice gages with the National Weather
Service 8-inch (20 cm) standard gage. The 3-inch (7.6 cm) circular gage and the plastic wedge-shaped gage (orifice 2.3 x 2.5 in or 5.8 x 6.4 cm) compared favorably with the standard gage. Small-orifice gages must be read shortly after precipitation has stopped because of high evaporation loss from the gages. These gages are unsuitable for measuring snow, and manufacturers do not recommend plastic gages for use in freezing weather.

Gages with different orifice diameters measure rainfall with about the same degree of accuracy. Codman (6) found that rain gages with orifices 2 to 24 inches (5.1 to 61 cm) in diameter varied less than 1 percent in accuracy of measurement over 3 years. Stow (36) and Mill (27), using gages ranging in size from 3 to 24 inches (7.6 to 61 cm) and 4 to 24 inches (10 to 61 cm), respectively, found that catch did not vary by more than 1 or 2 percent.

To lower the cost of making measurements, economical gages can be developed if guidelines for physical characteristics of gages are followed. Gages made from No. 10 cans have been tested by Rogerson (33). For 63 storms (0.01 to 4.80 in) or (0.3 to 12 cm), two-thirds of the can readings were within 0.01 inch (0.03 cm) of readings from a standard National Weather Service standard 8-inch (20 cm) gage. Costs of large rain-gage networks can be reduced by eliminating the funnel and inner brass cylinder from the 8-inch (20 cm) standard gage and by measuring the catch in graduates. Evaporation from a gage without the funnel can be controlled by adding transformer oil (12).

Gage Supports

Rain-gage supports should be economical, easy to build, and rigid enough so that the pen trace will not be affected seriously by high winds. Several types of gage supports are discussed under section 330.21 of the U.S. Weather Bureau Substation Inspection Guide (37). Choice of type should be influenced by the most economical unit, ease of getting and transporting materials, ease of installation, and durability. A permanent installation support and a temporary installation support are discussed in this publication. Provisions should be made for adjustments so that the rim of the gage will be level.

Installations for longtime records should have concrete bases extending to a depth of 3 feet (0.9 m) or below the average maximum frost penetration. Construct a form for any part of the base that will extend above ground. After the concrete is poured and before it sets, place three bolts in the top with heads buried, using the anchor or rain-gage base as a template. After the concrete has taken its initial set, remove the template and trowel the top to

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1, 2 The U.S. Weather Bureau became the National Weather Service in October 1970.
a smooth finish. After final set of the concrete, place the rain gage base and level, using shims if necessary.

Where records are to be collected for 5 years or less, or in locations generally inaccessible, construct the base by driving three pointed 2 by 4's, about 30 inches (76 cm) long, into the ground and nailing other pieces of 2 by 4's on top, to which the rain-gage base or stand is bolted. In some heavy soil areas that are subjected periodically to high temperatures or drought long steel pins may be necessary to replace the driven 2 by 4's.

Stands for the standard 8-inch (20 cm) nonrecording gage can be built locally from ½ by 1-inch (0.32 by 2.54 cm) strap iron with two rings around the can, three or four legs, and a base or platform to hold the bottom of the standard can 10 inches (2.54 cm) above ground (fig. 1.2).

For correct measurement of precipitation, the open end of the gage (the receiver) must be in a horizontal plane. This can be checked by laying a carpenter's level across the open top of the gage in two directions, one crossing the other at right angles. If the top is not level in both directions, this condition should be corrected. A note should be added to the observation form giving the date the defect was discovered and the date it was corrected.

**Enclosures**

Since rainfall stations frequently are on private lands, they should be located so that their interference with normal land use is minimal. Figure 1.3 shows the suggested size and shape of enclosures for a rain gage in a permanent pasture, in a fence line, and in a fence corner. Since some posts for these enclosures are only 3½ feet (1.07 m) from the gage, they should not extend more than 1 foot (30.5 cm) above the receiver funnel.

**Windshields**

Several windshields have been developed to correct for errors due to wind turbulence. The most notable are the Nipher (28) and Alter (2) shields. Windshields divert the flow of air down and around the rain gage. By eliminating updraft around the orifice, the gage is placed in an undisturbed flow of air (fig. 1.4).

An ideal shield should:
- Ensure a parallel flow of air over the aperture of the gage;
- Avoid any local acceleration of the wind above the aperture;
- Reduce speed of the wind striking the sides of the receiver as much as possible;
- Prevent splashing towards the aperture of the receiver, which makes the height of the gage mouth above ground less important; and
The relative effectiveness of the Alter and Nipher shields (table 1.1) has been investigated on a total catch basis by Larkin (22) and Allis and others (1). The general consensus is that the Nipher shield seems superior for reducing wind errors. Since snow may build up on the horizontal rim, the Alter shield is the best compromise for unattended gages in areas of appreciable snowfall (24).

Weiss and Wilson (39) have summarized the effectiveness of many shields in reducing catchment error of rain gages under exposed conditions. A recording weighing-type precipitation gage with windshield installed is shown in figure 1.5. A good site provides natural protection for the precipitation gages. The use of a windshield will then result in little or no improvement in rain-gage catch.

**Table 1.1—Relative effectiveness of Alter and Nipher shields on rain-gage catch**

<table>
<thead>
<tr>
<th>Shield</th>
<th>Unshielded gage catch</th>
<th>Data source</th>
<th>Duration of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rain</td>
<td>Snow</td>
<td></td>
</tr>
<tr>
<td>Alter</td>
<td>103.9</td>
<td>171.2</td>
<td>Larkin (22)</td>
</tr>
<tr>
<td>Nipher</td>
<td>107.4</td>
<td>181.0</td>
<td>Larkin (22)</td>
</tr>
<tr>
<td>Alter</td>
<td>101.5</td>
<td>134.4</td>
<td>Allis and others (1)</td>
</tr>
<tr>
<td>Nipher</td>
<td>103.5</td>
<td>147.4</td>
<td>Allis and others (1)</td>
</tr>
</tbody>
</table>

**Number and Distribution of Gages**

The number of gages necessary to determine the depth of precipitation on an area depends on (1) size of the area, (2) prevailing storm type, (3) form of precipitation, (4) topography, (5)

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**Figure 1.3.—Suggested rain gage fence enclosures.**

**Figure 1.4.—Deflection of air by rain gages without shield and with shield.**
aspect, and (6) season. Where prevailing storms are cyclonic (generally rainfall of low intensities over large areas), a rather sparse network may be adequate (14). A more dense network will be required where storms are predominately convective and are characterized by thunderstorms with high intensities and uneven distribution (29). Mountainous areas that create orographic-type storms may require more gages than flatter areas. Some areas may be subject to different types of storms, depending on the season. For example, since convective storms rarely occur in the northern sections of the United States during the winter, more gages may be needed during one season than another. Generally, more gages are needed where precipitation is variable.

The objectives of a network are also important in determining the number of gages required. For example, a network designed to relate total watershed precipitation to seasonal or annual water yield might be inadequate for the study of specific precipitation characteristics on a storm-by-storm basis. More gages also will be required for studies in which the results will be extrapolated to other areas than for studies confined to a given area. This is caused by the need for quantitative data for extrapolation, whereas qualitative or index values are adequate for a restricted area. The following tabulation shows the number of gages required for different areas:

<table>
<thead>
<tr>
<th>Size of area</th>
<th>Number of gages</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 acres</td>
<td>2</td>
</tr>
<tr>
<td>100 acres</td>
<td>3</td>
</tr>
<tr>
<td>600 acres</td>
<td>4</td>
</tr>
<tr>
<td>5 mi²</td>
<td>10</td>
</tr>
<tr>
<td>10 mi²</td>
<td>15</td>
</tr>
<tr>
<td>20 mi²</td>
<td>20</td>
</tr>
<tr>
<td>50 mi²</td>
<td>30</td>
</tr>
<tr>
<td>100 mi²</td>
<td>50</td>
</tr>
<tr>
<td>300 mi²</td>
<td>100</td>
</tr>
<tr>
<td>1,000 mi²</td>
<td>300</td>
</tr>
</tbody>
</table>

This tabulation is based only on size of area. Final determinations of the number of gages must depend on additional considerations.

Distribution of rain gages should not be random. Fixed characteristics of areas can be sampled randomly, but random events must be sampled by systematic arrangements of sampling points.

In practice, however, systematic gage distribution is difficult to arrange because access to locations frequently is difficult or disturbs the watershed. Gage networks usually are planned on paper. Gages are placed as close as possible to locations where access will be convenient and normal use of the area will not be disturbed. Gages also must be located so that their exposure is not influenced by nearby buildings, trees, or other obstructions that might cause undesirable wind currents.

Gages should be distributed so that isohyetal maps can be drawn. Some gages must be located near and outside the watershed boundary so that isohyets can be drawn to cover the watershed area completely.

When a network is designated for broad use, such as on a regional or national basis, a few gages may be needed. These should be well distributed and carefully maintained before the complete network is installed. They will provide general information on precipitation characteristics for the area. In research, however, minimum and optimum networks are the same. An optimum network contains the minimum number of gages required for precise data. Additional gages will be extraneous, and fewer
gages will negate the experimental results because the precipitation data will be below the specified accuracy (15).

Although all stations should have weighing-recording gages, satisfactory results sometimes can be obtained on larger watersheds when a third to half the gages are 8-inch (20 cm) standard gages. Small-orifice plastic gages can be used in place of standard 8-inch (20 cm) standard gages, especially where that part of the rain-gage network will be discontinued during the winter. The use of nonrecording gages depends on the objectives of the project.

Factors Affecting Accuracy

Rain gages measure the amount of precipitation that reaches the ground. Accuracy depends on inherent inaccuracies in the gage itself, wind velocity at the orifice of the gage, and form of precipitation. Inherent errors can result from bent, damaged, or deformed knife edge and orifice; leak in storage container; inaccurate calibration of measuring container or dip stick; tilted orifice due to settling or improper installation; or evaporation between the end of precipitation and when the gage is read.

The most common errors result from evaporation, adhesion, color, inclination of the gage, splash, wind, faulty technique in measuring catch, and physical damage to the gage. Kurtyka (21) estimated the percentage of errors for the following factors:

<table>
<thead>
<tr>
<th></th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporation</td>
<td>-1.0</td>
</tr>
<tr>
<td>Adhesion</td>
<td>-0.5</td>
</tr>
<tr>
<td>Color</td>
<td>-0.5</td>
</tr>
<tr>
<td>Inclination</td>
<td>-0.5</td>
</tr>
<tr>
<td>Splash</td>
<td>+1.0</td>
</tr>
<tr>
<td>Subtotal</td>
<td>-1.5</td>
</tr>
<tr>
<td>Wind</td>
<td>-5.0 to -80.0</td>
</tr>
</tbody>
</table>

The greatest amount of error in rain-gage catch results from wind. Under exposed conditions, rain-gage catch generally is deficient (39). This error is related to windspeed and to the type of precipitation. The decrease in catch increases as wind velocity increases and is greater for snow and light rain than for heavy rain. Wind increases pressure on the windward side of the gage, decreases pressure over the gage, and sets up eddy currents over and within the orifice (4). Since windspeed increases with height above a surface, the higher the gage orifice is above ground, the greater will be catchment errors due to exposure.

Some inherent errors are caused by the gage being out of calibration; binding or sticking parts in the weighing mechanism; bent, damaged, or malformed orifice ring; or other mechanical damage to the gage. The cause of these errors, except gage calibration, can be detected by brief inspection during routine visits to the station. The observer should watch constantly for errors and correct them as soon as possible to maintain high-quality records.

Sizable errors may occur in recording total catch. They may or may not be compensating and often change sign amount at the pen reversals. Therefore, the total catch in the bucket should be measured at the end of the storm.

A properly installed pit gage accurately measures rainfall at a point. When the rain gage is placed in a pit with its orifice at ground level, the gage no longer obstructs air movement and the effects of turbulent wind around the orifice are diminished. Conventionally exposed gages, even when shielded, catch less rainfall than pit gages (31, 35). Pit gages are inadequate for snow measurements, however, because of problems with drifting snow under windy conditions. Trash and sediment also tend to collect in pit gages. For extensive rain-gage networks, increased accuracy usually does not warrant the increased cost of installing and maintaining pit gages.

The possibility of inaccurate measurements resulting from vertically placed rain gages in watersheds of steep and complex topography was pointed out by several investigators (9,10, 17, 25). Errors were assumed to be due to the incidence of different volumes of precipitation on sloping surfaces of several areas and exposures where wind prevented the rain from falling vertically. It was recommended that gages be placed with their orifice parallel to the slope of the land. Rain-gage catch was divided by the cosine of the gage inclination so that the volume would be on a horizontal area.

Hayes (13) and Leonard and Reinhart (23) said that tilted gages were less accurate than vertical gages in well-sheltered sites, such as
small openings in heavily forested locations where reduced wind velocities cause precipitation to fall vertically into the gage. In general, rain gages should be installed vertically.

If reasonable care is taken in the readings, errors in measuring the catch once it has been collected in the gage are small compared with the uncertainty due to exposure of the instrument. Daily gages should be read to the nearest 0.01 inch (0.025 cm) where possible; weekly or monthly gages should be read to the nearest 0.10 inch (0.25 cm).

The main sources of error will be inaccurate measures or dip rods, spilling of some water when transferring it to the measure, and inability to transfer all water from the receiver to the measure.

Losses by evaporation also can occur. Evaporation errors are most serious in dry climates and in areas where gages are visited infrequently. Losses can be reduced by placing oil in the receiver (this forms a film over the water) or by designing the gage so that (1) only a small surface is exposed, (2) the ventilation is small, and (3) the internal temperature of the gage does not become excessive. The receiving surface of the gage must be smooth so that the raindrops do not adhere to it. It never should be painted.

In winter, rains often are followed immediately by freezing weather. Damage to the receiver and subsequent loss by leakage can be prevented by adding an antifreeze solution, especially when gages are visited infrequently. Allowance for the solution added must be made when measuring the results. All gages should be tested regularly for possible leaks.

The relative accuracy of rainfall measurements, as sampled by different gages, has been investigated extensively. Allis and others (1) reported that over a 16-year period the difference in rainfall catch between a standard 8-inch (20 cm) nonrecording gage and a weighing-recording gage was less than 0.05 percent. Using standard gages spaced 6 feet (1.8 m) apart at nine locations, Huff (19) and Huff and Niell (20) found that the average differences were insignificant for shower-type storms with precipitation up to 0.50 inch (1.27 cm). Renard and Osborn (32) found that maximum intensities were greater for convective storms determined from 6-hour rain-gage records than intensities determined from 24-hour rain gage records for intervals up to 10 minutes.

Court (7) reported that if the 8-inch-diameter (20 cm) universal weighing rain gage is properly exposed, calibrated, and evaluated, it will yield hourly precipitation values with standard error of about 0.01 inch (0.03 cm). Reliability within 0.02 inch (0.05 cm) may be assumed.

Correct timing of the recorded precipitation trace and the ability to estimate any errors in the record are important. Three causes of error that can affect timing of the record are backlash, clock rate, and change in chart dimension.

Backlash between the chart drum and the clock spindle delays the start of the record and causes a constant error once the record has started. Backlash in the timing gears can be taken up by turning the drum until the indicated time is about 3 hours fast and then turning it back to the correct time.

Another error may be caused by the clock rate or the use of an unsuitable time scale on the chart. If the difference is small, the rate of drum revolution can be adjusted with the clock regulator. All errors of this type probably cannot be removed by adjusting the regulator because clock rate will vary according to temperature and humidity.

Errors due to change in chart dimensions are caused by variation in humidity. Charts expand and contract as relative humidity increases and decreases, and most chart papers will change more in one direction than in another. Whether changes due to humidity are greater in the time scale or the depth scale depends on how the paper is cut. These changes easily can exceed 1 percent and can amount to 15- or 20-minute error in the time scale or several hundredths of an inch in the depth scale. Charts also creep up the drum because of expansion and contraction. Therefore, the bottom of the chart may be above the bottom flange of the drum in an amount equal to the creep.

All errors can be recognized and corrected if accurate time marks and zero checks are made when the charts are put on and taken off the drum, and at intermediate times when convenient.
Nonrecording Gages

Nonrecording rain gages usually consist of a collector above a funnel leading into a receiver. In the United States these gages have been standardized to the shape of a right circular cylinder with an 8-inch (20 cm) collector orifice diameter. Important requirements of nonrecording gages are:

• The rim of the collector should fall away vertically inside and be steeply beveled outside. The gage for measuring snow should be designed to minimize errors due to constriction of the aperture. Constriction is caused by the accumulation of wet snow above the rim.

• The area of the orifice should be known to the nearest 0.5 percent, and it should remain constant.

• The collector should prevent rain from splashing in or out. This can be done by having the vertical wall sufficiently deep and the slope of the funnel sufficiently steep (at least 45°).

• The receiver should have a narrow neck and should be protected sufficiently from radiation to minimize loss of water by evaporation. Rain gages used in places where daily readings are impracticable should be similar to gages used daily but should have a receiver of larger capacity.

Precipitation in nonrecording rain gages usually is measured by pouring from the gage into a calibrated container or by using a calibrated dip stick, or both. (See section on field measurement of nonrecording gages, p. 37.)

The calibrated container should be made of clear glass with a low coefficient of expansion and should be marked clearly with the size of gage with which it will be used. Its diameter should not be more than about one-third the diameter of the rim of the gage and can be made less than this. The graduations should be finely engraved; generally, they should be marked at 0.01, 0.05, and 0.10 inch (0.025, 0.127, and 0.254 cm). For accuracy, the maximum error of the graduations should not exceed 0.005 inch (0.013 cm).

To achieve this accuracy with small amounts of rainfall, the inside of the measuring cylinder should be tapered off at its base. In all measurements, the bottom of the water meniscus should be taken as the defining line. The measurement must remain vertical, and parallax errors must be avoided. It is helpful if the main graduation lines are repeated on the back of the measure.

Dip rods should be made of cedar wood or other material that absorbs little water and reduces capillarity. Wooden dip rods are unsuitable if oil has been added to the collector to suppress evaporation of the catch. Therefore, use rods of metal or other material from which oil can be cleaned. These rods should have a brass foot to avoid wear and should be graduated according to the cross section of the gage orifice and the receiving can, allowing for displacement due to the rod itself. Marks should be shown for at least every 0.02 inch (0.051 cm). The maximum error in the dip-rod graduation should not exceed +.005 inch (0.012 cm) at any point.

National Weather Service Standard 8-Inch (20 cm) Gage

The National Weather Service standard 8-inch (20 cm) gage, figure 1.6, consists of an overflow can, measuring tube, rainfall funnel, measuring stick, and wooden or metal support. The top portion of the funnel has an 8-inch (20 cm) inside diameter and a funnel-shaped bottom that conducts any liquid precipitation caught in the receiver into the tall, cylindrical measuring tube. To measure rainfall depth easily to hundredths of an inch, the measuring tube has a cross-section area that is one-tenth the cross-section area of the funnel. Therefore, when 1 inch (2.54 cm) of rain falls into the funnel, the measuring tube is filled to a depth of 10 inches (25.4 cm). Accordingly, the scale of the measuring stick used with the tube is expanded 10 times. Since the scale is graduated to hundredths of an inch, the correct depth of water in the tube is read directly to hundredths from the stick. The measuring stick is 20 inches (50.8 cm) tall and holds 2.00 inches (5.08 cm) rainfall. Additional rainfall will overflow into the outer can. Since rainfall depths in the overflow can are not increased 10 times, this measuring stick should not be used in the can. Instead, water from the can should be poured into an empty measuring tube for direct measurement with the stick. With the rainfall re-
ceiver and the measuring tube removed, the overflow can serves as a snow gage and is used in the winter for collecting all forms of precipitation. It also is used to cut snow samples to determine their water equivalent.

**Operation and Maintenance**

To maintain accuracy of the rainfall catch, protect the measuring tube and rim of the receiver from dents or other damage that might alter their shape. Correct immediately any evidence that the tube or overflow can is leaking or that the receiver is not level.

When freezing temperatures or snow are likely, remove and store the rainfall receiver and measuring tube. The overflow can will be exposed to catch any precipitation. Freezing water may split or expand the measuring tube, rendering it useless.

In winter, the precipitation gage is not equipped with a windshield. Place snow boards (depth markers) on the surface of the snow for

*FIGURE 1.6.—National Weather Service standard 8-inch (20 cm) gage. This nonrecording precipitation gage consists of (1) receiver, (2) measuring tube, (3) measuring stick, (4) overflow can, and (5) metal support.*
better sampling of snowfall. Place markers where the depth of snowfall represents the average depth over the area surrounding the gage and where drifting is minimal. Where the depth is frequently nonuniform, use several markers, if practicable, to get a representative measurement. Note on the observation form when the gage catch differs significantly from the water equivalent of samples cut from the surface. Differences of more than about 5 percent are significant. Record the larger amount as the snowfall for the observation period. Note the smaller amount and indicate whether it is from the gage or sample.

**Storage Gages**

Storage gages are used in remote areas where inspections are infrequent. They are used commonly in isolated mountain areas to measure winter snowfall, and their size depends on the expected precipitation. The Sacramento totalizer is a popular storage gage in the United States (fig. 1.7). It has a truncated right circular cone mounted on a tower above the maximum expected depth of snow and surrounded by a windshield to reduce the effects of wind on catch. The Sacramento gage with an 8-inch (20.3 cm) orifice may be capped by snow if the snow is frequently wet and sticky. In such locations, gages with 12-inch (30.5 cm) orifices are recommended to prevent capping.

**Operation and Maintenance**

In operation, charge the storage gages with an oil-antifreeze solution. This will melt the snow, prevent the solution from freezing, and preserve the catch by retarding evaporation. Use an automotive antifreeze such as ethylene glycol or alcohol. A solution of 30 percent calcium chloride and 70 percent water by weight will result in an antifreeze with a freezing point of \(-60^\circ F\) \((-51^\circ C)\). If calcium chloride solution is used, add 2 pounds (907 g) of potassium chromate and \(\frac{3}{4}\) pound (340 g) of hydrated lime to reduce corrosion.

To suppress evaporation, use an oil that allows easy passage of the precipitation and at the same time completely covers the solution. A light motor oil with specific gravity of 0.8 to 0.9 can be used, or new or used electrical transformer oil can be obtained from a local electric company.

The quantity of oil-antifreeze solution required is based on the expected maximum precipitation between observations. Generally, the initial charge should equal 1.5 times the normal precipitation but should not exceed one-third the capacity of the gage. The most reliable method of measuring precipitation in storage gages is to weight the catch, subtract the weight of the initial charge, and convert the results to inches of water. Taps in the bottom of the gage permit quick draining.

During winter the solution may freeze in the upper layers due to stratification of the anti-
freeze. Occasional stirring during routine visits will usually forestall such action. If the problem becomes serious, the U.S. Department of Agriculture Forest Service has developed a system whereby the solution is in a constant state of agitation by allowing nitrogen bubbles to rise through the solution from the bottom of the gage.

Other Nonrecording Gages

Nonrecording gages of other shapes and dimensions (fig. 1.8) sometimes are used either as primary gages or secondary gages to fill in gaps in a network of standard or recording gages. These gages usually have a support that can be mounted on metal or wooden posts. In a network, all gages should be installed with the orifice level and at the same height above the ground. Because most plastic gages will suffer from freezing and thawing, their use generally is restricted to rainfall measurements. Metal gages can be used in winter just as the National Weather Service standard 8-inch (20 cm) gage is used. Gages with orifices 3 inches (7.6 cm) or more in diameter are usually accurate enough for supplementary use in an intensive network. Gages with small orifices are less accurate primarily because they are read directly and do not have the magnified scale of larger gages.

Recording Gages

Three types of recording precipitation gages in general use are weighing, tipping bucket, and float. The only satisfactory instrument for measuring both liquid and solid precipitation is the weighing-type gage.

Several rainfall intensity recorders have been designed and used for special purposes. They are not recommended for general networks, however, because of their complexity. A satisfactory record of rainfall intensity can be determined from a float- or weighing-type recorder by providing the proper time scale.

Whether the rainfall recorder operates by weighing the rise of a float, the tipping of a bucket, or other method, these movements must be converted into a form that can be stored and analyzed later. The simplest method of recording is to move a time chart by a spring or electrically driven clock past a pen that moves as the float or weighing device moves. Two main types of charts are:

![Figure 1.8.—Nonrecording rain gages: (A) 4-inch (10.2 cm) self-reading, three-piece plastic gage; (B) 7½-inch (19.4 cm) three-piece metal gage with dip stick; (C) 2½-inch (6.4 cm) by 2¼-inch (5.7 cm) wedge-shaped self-reading plastic gage; (D) ¾-inch (1.9 cm) self-reading glass gage with support; (E) 3½-inch (8.9 cm) four-piece, metal and plastic, Canadian standard gage; and (F) 3-inch (7.6 cm) three-piece metal gage with dip stick.](image-url)
The drum chart, which is secured around a drum that should revolve once a day (exactly), once a week, or another period as desired;

2. The strip chart, which is driven on rollers past the pen arm. By altering chart speed, the recorder can operate from 1 week to a month, or even longer. The time scale on this chart can be large enough to calculate intensity easily.

The movement of a float, bucket, or weighing mechanism also can be converted into an electric signal. This signal can be transmitted by radio or wire to a distant receiver where records can be made from several rain recorders on data-logging equipment.

Most clocks for rain gages can be geared to provide one drum revolution in 6, 12, 24, or 192 hours. The time scale selected will depend on the storm characteristics being studied, the shortest interval to be read from the charts, and the frequency or ease of servicing gages. Table 1.2 is a guide for deciding which time scale to use. Generally, the shorter the interval, the more difficult it is to extract data from the charts because of the crossing and recrossing of trace lines between chart changes. For ease in chart reading, use the longest interval that is compatible with the study objectives.

**Universal Weighing-Type Gage**

The Universal weighing-type gages in common use consist of a collecting bucket resting on a weighing platform and frame, which are suspended from an isoelastic spring. Precipitation collected in the bucket increases the load on the spring, which lowers the platform and frame. This deflection is proportional to the amount of precipitation collected. The movement of the frame is transmitted through a system of links and levers to the pen, which marks a graduated revolving chart. The ratio of the frame movement to the pen movement is controlled by the position of the pinions relative to the pen-arm system pivot. Calibration is accomplished by adjusting these pinions. The gage normally has no provision for emptying itself, but a system of levers can make the pen traverse the chart any number of times.

Falling precipitation is directed into the bucket through a collecting ring and funnel. The diameter of the collecting ring is 8 inches (20 cm), providing a catchment area of 50.26 in$^2$ (324 cm$^2$). The weight of this volume of water is usually about 1.8 pounds (816 g).

The universal weighting-type gage has been designed to prevent excessive evaporation losses, which may be reduced further by adding oil or other evaporation suppressant to the container. Difficulties due to oscillation of the balance in strong winds can be reduced by fitting a damping mechanism. The main usefulness of the weighting-type gage is in the direct recording of both solid and liquid precipitation. Solid precipitation does not need to be melted before it can be recorded.

Most universal weighting-type gages are the dual traverse type with a 12-inch (30.5 cm) capacity. Many single-traverse gages have a capacity of 6 inches (15.2 cm), however, and a few triple-traverse gages have a capacity of 3 inches (7.6 cm) per traverse and a capacity of 9 inches (22.9 cm) in use. All these gages have basically the same design. The only difference is in the lever system used to transmit platform deflection to the pen arm.

**Operation and Maintenance**

Clocks should be cleaned, oiled, and adjusted by a qualified jeweler once a year or during the year when necessary. At locations where several recording gages are in operation, have several spare clocks on hand. Replacement clocks permit continuous operation of a gage when a clock needs to be removed for servicing or repair.

The ideal trace should be as thin as possible without becoming illegible or without the pen scratching the paper. To achieve and maintain such a trace, treat the pens carefully. Clean them regularly, using warm water, commercial

<table>
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<th>Time for 1 revolution of drum (hours)</th>
<th>Shortest interval between chart time lines</th>
<th>Shortest interval on chart</th>
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<tr>
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<td>30</td>
</tr>
</tbody>
</table>
pen cleaner, carbon tetrachloride, and so forth. Pens used on most weighting-recording rain gages are simple triangular reservoirs attached to a short holder that slides over the end of the pen arm. When the pen fails to feed ink, start the flow by drawing a piece of thin, strong paper, such as cellophane or bond, between the nibs of the point to clean and wet the inner faces. The nibs must not be permanently bent or separated. Insert the paper into the slot only about half the slot depth. Hold the pen away from the chart with the pen bar during the operation. The paper should be drawn through the nibs with a motion directed away from the ink reservoir and toward the point.

A trace that is too wide sometimes can be improved by pinching the nibs together with the finger to produce a finer trace. Carry spare pens to replace pens that have been damaged or produce too wide a trace. Damaged pens may be restored by cleaning the points and then sharpening them by honing on a hard Arkansas stone. A magnifying glass of about 7 power is necessary to make certain the nibs are square, true, and sharp.

Ink that is exposed to air absorbs water and becomes diluted, especially in damp weather. When the trace on the chart becomes faint or otherwise unsatisfactory, remove the ink from the pen reservoir with blotting paper and refill the pen. Keep the ink bottle tightly closed when it is not in use.

When freezing temperatures or snow are likely to occur, the gage must be placed at a height greater than the expected snow accumulation. The weighing mechanism should be cleaned, and, if lubricated at all, a dry graphite should be used. The bucket should be charged with an oil-antifreeze solution to melt the snow by chemical action, prevent the solution from freezing, and preserve the catch by retarding evaporation. Add ethyl glycol antifreeze (approximately 400 ml (0.1 g)) to the bucket until the pen rests on the \( \frac{1}{2} \)-inch (1.3 cm) line. Add a lightweight oil until the pen is raised to the \( \frac{3}{4} \)-inch (1.9 cm) line. Use motor oil with a specific gravity of 0.8 to 0.9, or, use new or used electric transformer oil from the local electric service company. To prevent freezing because of stratification, stir the solution lightly during each visit. The bucket should be emptied and recharged when the pen reaches the 3-inch (7.6 cm) line because the solution will be diluted and may freeze. If more than 2½ inches (6.4 cm) of precipitation is expected between visits, increase the initial charge of antifreeze proportionally but never allow it to exceed one-third the capacity of the gage.

Once a year on a clear, warm day, wash all moving parts of the weighing mechanism and spring with a grease-dissolving solvent such as gasoline, benzine, or carbon tetrachloride. Carefully observe all safety requirements. Reliability can be attained without using any lubricants on the moving parts if all parts are disassembled before gage installation; all shafts and bushings are cleaned with fine steel wool and polished with crocus cloth; and all parts are washed in solvent, rinsed in hot water, blown dry, and carefully reassembled. Do not use lubricants when the gage is in a dusty environment or when it is operated during extremely cold weather. Use a nongumming oil or graphite if lubrication is desired.

Assemble the following items to be taken to the field:

- A chart for each instrument, a clipboard, and a fieldbook.
- An assortment of screwdrivers, and both fixed and adjustable open-end wrenches.
- A few cleaned and sharpened recorder pens and a pen cleaner.
- A bottle of grease-dissolving solvent; a small syringe or oil can for washing the mechanism with cleaning solution; and, if lubrication is desired, a bottle of nongumming oil or graphite with a small camel’s hair brush for applying it.
- A piece of fine steel wool and a piece of crocus cloth or a honing stone.
- A set of calibration weights each equal to 1.8 pounds (816 g) per inch of precipitation.
- A 2-H pencil and blotter.
- Extra spindles.
- Clock spindle washers of various thicknesses, such as 0.060, 0.075, 0.090, 0.105, 0.120, and 0.140 inch (0.15, 0.19, 0.23, 0.27, 0.31, and 0.36 cm).
- Thin, noncorrosive metal bands for placing on the pen arm to lengthen the distance from pen-arm shaft to pen.
• A three-sided windbreak to shield the gage during field calibration.

Before attempting field calibration, carefully study all field notes and chart notations of gages to be calibrated to find errors or discrepancies noted by the observer during weekly servicing. Spare clocks should be available to replace those showing consistent time errors on the charts. Wherever possible, spare gages should be available to replace network gages that are to be brought into the shop for major maintenance or repairs. To maintain a network at peak efficiency, each gage should be brought into the shop at regular intervals of about 2 years. It should be completely disassembled, cleaned, polished, reassembled, and carefully calibrated. High-quality records can be assured only by regular maintenance.

The techniques of servicing single-, dual-, and triple-traverse gages are essentially the same. Since the dual-traverse gage is the most popular, detailed instructions for servicing and calibrating it will be given with a short description of the differences between dual-traverse and single-traverse gages.

**Dual-Traverse Gage**

The dual-traverse gage (fig. 1.9) has a capacity of 12 inches (30.48 cm) precipitation. The first 6 inches (15.24 cm) are recorded on the rising traverse, and the second 6 inches (15.24 cm) are recorded on the falling traverse. The identifying numbers in figure 1.9 refer to specific parts of the gage mechanism involved in the calibration. The specific calibration steps are as follows:

1. Upon arriving at the rainfall station, set up the windbreak. Remove the collector ring by giving it a slight clockwise turn and lifting it from the case. Raise the inspection door and remove the pen from the chart. Remove the bucket and the weighing platform. Remove the screws that hold the case to the base and lift the case from the base. Replace the weighing platform and the bucket. The entire weighing mechanism is now exposed for primary adjustments and calibration. Wash the spring and all moving parts with the cleaning solution, lubricate if desired, and work the mechanism by moving the bucket platform up and down.

2. If the gage has a dashpot, lift its cover and check to see if the fluid level is high enough to cover the piston at its highest position. A small amount of fluid can be added without removing the dashpot. If it is necessary to remove the dashpot, remove the two thumbscrews holding it, lift the cover, and slide the dashpot forward while swinging the damper piston forward. At most locations gages should be operated with dashpots empty to provide more accurate records of the intensity of short rainfall bursts. However, dashpots should be
3. Place the calibration chart (fig. 1.10) on the clock cylinder and install it on the clock. Be sure the chart fits snugly and rests on the flange of the drum throughout the circumference. Place a clean pen on the pen arm and fill it about half full of ink. Place a small weight in the bucket and place the bucket on the platform with the handle opposite the overflow pipe. A displacement of the center of gravity of the weight in a direction perpendicular to the rotational axis of the casting does not affect the accuracy greatly. If the bucket does not have an overflow pipe, the axis of the bucket handle should be parallel to the rotational axis of the casting and the handle should always be in the same position. Test the pen by rotating the drum to make a trace about 1 inch (2.54 cm) long. If the trace is too thick or ragged, clean, pinch, and hone the pen until a clear, fine trace is obtained. If more than one trial is necessary, place a larger weight in the bucket to raise the pen above the first trace.

4. After a satisfactory trace is obtained, check the gage for binding by slightly depressing the platform by hand and then slightly raising it. Allow the pen to return to its normal position in each case by gently releasing the force. Rotate the drum after each operation to give two pen traces. A vertical distance between these two lines of more than $\frac{1}{50}$ inch (0.051 cm) indicates binding, which should be corrected before proceeding. If the source of the binding cannot be found easily in the field, replace the gage with a spare gage and take the binding gage into the shop for a major overhaul. Check the base with a small level and adjust, if necessary, to make sure it is horizontal.

5. To see if the pen trace follows the time line, place the pen on the chart and depress the platform to make a 1-inch (2.54 cm) line near the bottom of the chart. Depress the platform further to mark a 1-inch (2.54 cm) line near the top of the chart. (Shift the pen from the chart when moving from one position to another.) The two lines should be made within 1 minute of each other. Failure of these lines to agree within $\frac{1}{50}$ inch (0.051 cm) may indicate a bent spindle. Remove the clock, replace the spindle, and repeat the check. If the arc described by the pen is the same for two or more spindles but still does not follow a time line, it indicates improper thickness of the washer between the base and the gear. When the arc falls to the

**Figure 1.10.—Chart record of a dual-traverse rain gage calibration.**
right of the time line at the top of the chart, the clock spindle washer is too thick and vice versa. Change the washer as indicated and check until agreement with the time line is good.

6. Remove the small weights used in step 3 from the bucket and adjust the pen to the zero line of the chart with the adjusting nut (10) of figure 1.9. Place weights, each equivalent to 1 inch (821 g) of precipitation, in the center of the bucket one at a time and record the pen reading for each in the fieldbook (fig. 1.11). Determine the adjustment needed by plotting the pen error against the total amount of the weights and connect the points with a smooth curve, (fig. 1.12). If the plotted points define a smooth curve, make the first adjustment according to step 7. If the points for each traverse fall on a straight line, proceed as in step 8.

7. This step covers the primary adjustment of levers and linkages and usually will be necessary only for repaired or reassembled gages in the shop. Add weights equal to half the gage capacity (normally 6 in. (15.2 cm)). The milled surface of the casting [12] should now be horizontal. (This may be checked by using a small level or by measuring up from the base to the top surface of the casting at two extreme positions, using a thin piece of stiff cardboard or a small scale.) Change the spring tension with the large knurled nut [23] until the casting is horizontal. With weights equal to one-fourth the gage capacity in the bucket (normally 3 in. (7.62 cm)), loosen the setscrew [5] on the rear link [8] and adjust the slide [6] so that the axis of the pinion and the rotational axis of the rear 6-inch (15.2 cm) range lever [20] are in a horizontal plane. Loosen the setscrew on the

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**WATERSHED AND HYDROLOGIC STUDIES**

**FIELD NOTES**

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**Calibration of Rain Gage 1298 (Dual Traverse)**

**Initial Check**

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*Figure 1.11.—Field notes for a dual-traverse rain gage calibration.*
pen-arm holder until the pen arm is parallel to the bracket [16]. Loosen the bracket setscrew [14] and rotate the pen and bracket until the pen is on the 3-inch (7.62 cm) chart line. Tighten the bracket setscrew. Loosen the setscrew on the front 12-inch (30.5 cm) range lever [4], hold the pen at the 3-inch (7.62 cm) line and rotate and set the range lever in a horizontal plane. (To set the range levers in a horizontal plane, set the axis of the pinions at the elevation of the pen-arm axis shaft by measuring up from the base.) When setting the front and rear range levers, be sure the links [7 and 8] remain in a plane perpendicular to the pen-arm axis shaft.

Adjust the stopscrews [11 and 22] so that when the bucket is removed, the pen will set halfway between the zero line and the bottom

**FIGURE 1.12.—Graphs to determine type and extent of adjustment necessary for dual-traverse rain gage.**
flange of the clock cylinder. Adjust the high range stopscrew [24] so that the pen will set halfway between the 12-inch (30.5 cm) line and the bottom flange when the capacity of the gage is exceeded. If necessary, these stops should be checked and reset during calibration to prevent damage to the pen arm.

8. Place weights equal to half the gage capacity in the bucket. Lower screw [1] on the bottom of link [7] until it almost falls out. Loosen screw [2] on the side of the link and let the slide [3] fall to its lowest position. Loosen screw [5] on the rear link [8] and set the slide so that the pen is at the 6-inch (15.24 cm) line. Minor adjustments may be made with the knurled knob [10]. Remove all weights and note the pen registration. If the pen is above the zero line, lengthen the lever arm of the rear calibration lever [21]. If the pen is below the zero line, shorten the lever arm of the rear calibration lever. Again, add six weights, adjust the slide on the rear link [8] and repeat the calibration check at 6 inches (15.24 cm) and 0 until the pen registers correctly at both points.

9. The calibration lever [21] has been moved as far as possible and the gage cannot be calibrated at 0 and 6 inches (15.24 cm), change the number of active spring coils and repeat step 7. If the calibration lever [21] has been shortened as much as possible, decrease the number of spring coils. If the calibration level [21] has been lengthened as much as possible, increase the number of spring coils. If the calibration lever [21] has been lengthened as much as possible, increase the number of spring coils. Place weights in the bucket, one at a time, and record the pen reading for each increment from 0 to 6 inches (15.24 cm). Plot the pen error as in step 6. If step 7 has been performed carefully, the error should be negligible. If error exists, correct it by placing three weights in the bucket and recording the pen reading. If the error at 3 inches (7.62 cm) is 0.03 inch (0.076 cm) and positive, rotate the pen clockwise and set at 3.0 minus 0.6, or 2.4 inches (7.62 minus 1.52, or 6.1 cm). The pen should then be reset at 3 inches (7.62 cm) by adjusting the stop [6] on the rear link [8]. Check the 0- to 6-inch (15.24 cm) calibration with weights and repeat step 8 until the maximum error is acceptable. A total error range of 0.02 inch (0.05 cm) in the 0- to 6-inch (15.24 cm) range is not difficult to achieve.

10. Place six weights in the bucket. The pen should now be at the 6-inch (15.3 cm) line. Turn the adjusting screw [1] until the stop [3] just touches the pinion of the front 12-inch (30.48 cm) range lever [4]. Tighten the setscrew [2]. The pen should now reverse at the 6-inch (15.24 cm) line as the slightest amount of weight is added to the bucket. If necessary, file down the end of the slide [3] on link [7] to meet the requirements of primary adjustments and to have the reversal occur at the correct location. Add weights equal to 6 inches (30.48 cm). If the pen falls short of the 12-inch (30.48 cm) line, shorten the front lever arm [13]; if it goes beyond the 12-inch (30.48 cm) line, lengthen the lever arm. Repeat this procedure until the gage registers correctly at 6 and 12 inches (15.24 and 30.48 cm). Each time the lever arm [13] is adjusted, it changes the reversal point, therefore, slide [3] also must be readjusted. Check the gage registration between 6 and 12 inches (15.24 and 30.48 cm). A negative error can be corrected by rotating the front 12-inch (30.48 cm) range lever counterclockwise on the pen-arm shaft. Make the reversal adjustment each time the range lever is rotated. Make adjustments until the maximum error is acceptable.

11. Carefully check the collector ring for damage or malformation since gage chart measurements are based on the assumption that the orifice is a circle, 8 inches (20.3 cm) in diameter. The knife edge should be sharp, and the ring should be a true circle. Minor irregularities can be corrected by light filing and polishing. An orifice slightly out of round sometimes can be corrected by pressing on the outside of the collector ring or by rolling the ring, under hand pressure, across a hard object.
such as a board. If these methods fail to correct the situation, the collector ring must be replaced.

12. Remove the bucket and weighing platform, place the case over the weighing mechanism, and screw it to the base. Replace the weighing platform and the bucket, and replace the collector ring by putting it on the case and giving it a slight counterclockwise turn. Check the collector ring with a level to make sure it is in a horizontal plane.

**Single-Traverse Gage**

Calibrating the single-traverse gage is essentially the same as calibrating the dual-traverse gage. Follow steps 1, 2, 3, 4, and 5 of the previous section. In calibrating the single-traverse gage, refer to figure 1.13. If evidence of binding is found in step 3, check the link between members [I] and [W], the shaft that supports [W] and the pen arm, and the shaft and castings [B]. Proceed as follows:

1. With the bucket empty, set the pen at zero by using the adjusting screw [G]. Adjustment of [G] will not affect the calibration of the gage. Adjust stops [B] and [C] so that the pen will travel slightly below the zero line without touching the drum flange when the bucket is lifted, and slightly above the printed part of the chart without getting off the chart when the bucket is full or weighted beyond the capacity of the gage. When adjusting stops [B] and [C], shift the pen from the chart when moving it from one stop to another. Check the zero setting and reset if it was disturbed in adjusting the stops.

2. Place weights in the center of the pail, one at a time, and record the pen reading for each weight. On regular graph paper, plot the pen error as the abscissa and the correct reading as the ordinate (see fig. 1.14). If the error plots as a straight line, proceed as in step 4; if it plots as a smooth curve, proceed as in step 3.

3. If the pen error plots as a curved line, place calibration weights equal to half the capacity of the gage in the center of the bucket. At this pen reading, the link [W] should be horizontal. This can be checked and adjusted by sighting. Place yourself about 3 feet (0.91 m) from the gage and line the top of the pen-arm shaft into the chart reading 0.05 inch (0.127 cm) above the centerline of the chart (on 6-in (15.24 cm) gage, this would be 3.05 in. (7.75 cm) or center the shaft onto the chart centerline. Keeping the eye at this level, bring the rectangular link [W] into a horizontal position by adjusting screw [G]. This adjustment will cause the pen to read something other than half capacity. Correct this by loosening the setscrew that holds the pen arm on its shaft and rotating the pen arm until the pen rests on the horizontal centerline of the chart. Maintaining this parallelism of pen arm and link [W] insures simultaneous movement through the same central angle.
4. If the pen error is not curvilinear, remove the weights from the bucket, reset stops [B] and [C], and check the zero setting. Place weights in the bucket to within 1 inch of the gage capacity. Place the pen on the chart and rotate the clock cylinder to mark a trace about \( \frac{1}{4} \) inch (0.64 cm) long. If the chart reading is in error by more than 0.02 inch (0.05 cm), adjust the length of link [I] and repeat the step. If the chart readings are too small, link [I] must be moved out. If the short readings are too large, link [I] must be moved in. Repeat step 2 until the error throughout the range of the gage is acceptable.

5. Replace the gage cover and collector ring, check the collector ring with a level to be certain it is horizontal, and place the gage in operation.

**Tipping Bucket Rain Gage**

The tipping bucket rain gage consists of a collector orifice, 12 inches (30.48 cm) in diameter, that funnels rainfall to a small outlet directly over a tipping bucket mechanism (fig. 1.15). The tipping bucket is divided into two equal compartments, each holding exactly 0.01 inch (0.025 cm) of rainfall. When one compartment fills, the bucket tips (momentarily closing a mercury-in-glass contact) and empties into the overflow reservoir. Simultaneously, the opposite compartment is positioned below the nozzle to receive the incoming rainfall. Electrical impulses are transmitted to a recorder or indicator, each impulse representing 0.01 inch (0.025 cm) of rainfall.

When the bucket tips, its contents fall into a
funnel beneath the bucket. At the base of the funnel is a cock that, in its open position, permits the rain to collect in the measuring cylinder below the funnel, where it can be measured with the measuring stick. Accuracy is about 2 percent for rainfall at a rate less than 1 in/hr (2.54 cm/hr), 4 percent for 3 in/hr (7.62 cm/hr), and 6 percent for 6 in/hr (15.24 cm/hr). A cylinder and measuring stick are supplied to check measurements. The gage normally is operated on 6 volts d.c. and will not function satisfactorily in below-freezing weather unless a heating unit is provided. Its diameter is 12 inches (30.48 cm) and its height is 37\(\frac{1}{2}\) inches (95.25 cm). The diameter of the tripod mounting is 24\(\frac{1}{2}\) inches (62.23 cm).

A single-channel event recorder and digital indicator operate with the tipping-bucket rain gage. A permanent record of each 0.01 inch (0.025 cm) of rainfall is made on a chart marker for each minute and hour so that duration and total accumulation rate (up to 2 in/hr (5.08 cm/hr)) can be determined. At normal chart speed of 4 inches per hour (10.16 cm/hr), a single chart roll of 250 feet (76.2 m) will record without attention for 30 days.

The recorder is designed with reset-type, built-in digital counter to show cumulative rainfall. It has a chart drive mechanism requiring 115-volt a.c., built-in transformer and silicon diode rectifier supplying 6 volts d.c. for operation of mercury switch in tipping-bucket rain gage. The recorder has a flat bottom for table or shelf mounting, and a slotted hole on back permits wall mounting. A motor-operated chart rewind attaches to the bottom of the recorder case.

The main advantage of the tipping-bucket gage is that it can record at a distance or simultaneously record rainfall and river stage on a water-stage recorder. Its disadvantages are:

- The bucket takes a small but finite time to tip over. During the first half of its motion, the rain is led into the compartment already containing the calculated amount of rainfall. This error is appreciable only during intense rainfall.
- Since the water surface exposed in a typical bucket is relatively large, evaporation losses can occur, especially in hot regions. Losses are highest in light rains.
- Due to the discontinuous nature of the record, the gage is unsatisfactory in light drizzle or rain. The time of beginning and ending cannot be determined accurately.
- Due to its small diameter, the opening that drains the collecting funnel often becomes clogged with such debris as leaves, nuts, bird droppings, and large insects. Water frequently will build up on the collector, resulting in a loss of record as to the time distribution of the storm. The total rainfall is shown in the measuring cylinder.

**Maintenance**

The tipping bucket assembly and measuring cylinder should be inspected for corrosion or
deterioration. The bucket should move freely in its casting, and the mercury switch should be inspected to be sure it is intact.

The tipping-bucket gage is built simply and seldom requires overhauling. Check regularly to see that:
- The tipping bucket has 0.015 end play at its pivots.
- The mercury switch is functioning.
- The magnet has not lost its strength.
- The drain cock is clean and not dripping.

Digital Precipitation Gage

The digital precipitation gage (Fischer and Porter) shown in figure 1.16 is a weighing-type gage that records the weight of accumulated precipitation (rain or snow, or both) on punched paper tape at selected intervals in digital code.

A dial readout is provided for manual reading. The main advantage of this recorder is that the precipitation data can be put rapidly and accurately into a form suitable for computer analysis. For this reason, the digital recording gage has been adopted by the National Weather Service for its primary recording rain-gage network. Other Government agencies involved in hydrology data collection also use this instrument because of its automatic data-processing capability.

The digital gage recorder consists of (1) the orifice, (2) the weighing mechanism, (3) the drive shaft and gearing assembly, and (4) the punch programing cycle system. The orifice, which is 8 inches (20.3 cm) in diameter, defines the area over which the precipitation is measured. The input weighing mechanism has a collector for receiving and storing the precipitation and a cross flexure spring scale for measuring the varying weight of accumulated precipitation. Motion of the scale is converted to an angular position of an input shaft assembly by a pulley arrangement. The shaft's position is converted to successive positions of a code disk.

At predetermined intervals the code position of the disk is punched on paper tape, thereby recording the amount of accumulated precipitation to the nearest 0.10 inch (0.25 cm). The total capacity of the rain gage is 19.5 inches (49.5 cm).

The recorder can be programed to automatically punch the readings at preselected intervals of 5, 6, 15, 30, or 60 minutes, or 12 hours, as desired. The interval is selected by installing the proper cam in the mechanical timer unit or by choosing the electronic timer with the correct cycle. The recorder is designed to operate with minimal care by persons with little technical training. It is designed for permanent installation in remote areas. Power may be provided by either a 7½-volt dry cell battery or standard 117-volt, a.c. service. A battery-powered unit can operate unattended for more than 3 months while recording at a readout rate every 5 minutes.

Recording is done in a standard binary decimal code on a 16-channel paper tape that is suitable for computer processing after automatic translation of the data onto punchcards.
or magnetic tape. The paper tape shown in figure 1.17 permits visual reading with minimal effort. A horizontal row of punched holes represents the total amount of accumulated precipitation in digital form at the time of punching. Each row is divided into sections representing the tenth's, unit's, and 10's digit of the number. Each section is binary coded 1–2–4–8, and a summation of the holes punched will establish the digital value. A hole punched in the 8 column at the extreme left of the tape is made by the rain trace indicator whenever rainfall occurs (if the gage is equipped with the indicator). On instruments without the rain trace indicator, a hole is punched in the 80 column at the extreme left of the tape. Absence of this hole indicates the end of the tape to an automatic translator.

With auxiliary equipment, a combination of electrical contacts may be operated simultaneously to present an output for telemetering. This capacity permits remote reading by interrogation through radio or telephone. A binary-decimal transmitter serves this function as adjunct equipment.

**Maintenance and Service:**

Check and calibrate each instrument thoroughly before placing it on station. The following procedure is recommended as the basic check to assure carefree and reliable service.

Place the base assembly on a bench for ease in service preparation. Remove the latch cover (taped to the case), rotate the outer cover counterclockwise to release it from its latches, and carefully lift the cover up from the weighing and recording mechanism. Remove all shipping lashings and inspect immediately for damage. Pay careful attention to the thin metal flexures on which the cantilever beam pivots.

These flexures are damaged easily by improper handling and will cause gage insensitivity. An undamaged flexure will have no creases or kinks and will bend smoothly. A damaged flexure must be replaced to assure proper sensitivity although the recorder will seem to work correctly.

Carefully follow instructions on tags attached to the instrument. Note the tag attached to the shipping screw protruding from the base casting of the scale support assembly. Loosen this screw, turning out until the end is flush with the casting surface. Retain the screw for re-shipment by tightening the lock nut securely.

Insert the force post into the weighing scale just ahead of the zero adjust knob and place the collector on the force post. Place the sensor for the trace indicator (if included) on the post inside the collector. Secure the purple wire to the force post with the rubber rings provided and loosen the wiring to allow the weighing mechanism to move freely.

The weighing assembly of the instrument is shipped in a locked position. Rotate the zero adjust knob (on top of the weighing assembly) counterclockwise until the code disk moves freely. Turn the adjusting knob until the code disk zero is aligned with the pointer.

Contrary to the manufacturer’s instructions, the dashpot cylinder should not be filled initially with oil during the checkout period. If damping oil is placed in the dashpot, binding in the dashpot assembly cannot be determined. Instructions for installing the paper tape supply roll will vary, depending on the type of supply spool and paper tension assembly.

Detailed instructions for operating and maintaining the digital gage are given in the Fischer-Porter instruction manual (fig. 1.18). Routine service depends on physical conditions of the area.

**Float-Type Gage**

In these gages (fig. 1.19), rain passes into a chamber containing a light float. Vertical movement of the float as the level of the water rises is then transmitted, by a suitable mechanism, into the movement of the pen on the chart. By adjusting the dimensions of the receiving funnel, float, and float chamber, any desired scale value on the chart can be obtained.

To provide a record over a useful period (at least 24 hr is normally required), the float chamber must be very large (showing a compressed scale on the chart) or automatic means must be provided for emptying the float chamber quickly whenever it becomes full. The pen will return to the bottom of the chart by one of several siphoning arrangements.

If freezing is possible, a heating device should be installed inside the gage to prevent damage to the float chamber. A minimal amount of
Time (24-Hr Clock)

Translator Alignment Holes

Punch Code Reading

Time | Amt.
--- | ---
0440 | 13.1
0445 | 08.1

Figure 1.17.—Paper tape for digital recorder.
heat should be supplied to prevent freezing. The heat will affect the accuracy of the observations by changing vertical movements of air above the gage and by increasing losses from evaporation.

Snowfall

Snowfall is the amount of new snow deposited over a given period. Because of the variability of snowfall, the redistribution of snow on the ground, and the water stored in the snowpack, accurate measurement of snow is difficult. Snowfall should be measured at enough places to represent cover, conditions, slopes, and aspects within the basin. In snow hydrology, the measurement of snowfall is vital.

Direct Measurement

Direct measurements of fresh snow in open areas are made with a graduated scale. Special precaution should be taken not to measure any old snow. This can be accomplished by placing a "snowboard" of suitable material (such as
rough-surfaced wood, painted white) on top of the previous snow. After each snowfall, the depth down to the snowboard is measured. The board is removed, cleaned, and replaced on the surface of the snow. The difference between two consecutive measurements of total depth cannot be used as snowfall because of the continuous settling of the snowpack.

Where drifting exists, enough measurements must be taken to obtain an average of representative depth. The snowfall also may be measured in a fixed container of uniform cross section. The container should be placed above the maximum expected snow depth so that it is not exposed to drifting snow. The receiver should be at least 8 inches (20 cm) in diameter and deep enough, or divided into quadrants, to prevent the catch from being blown out. The container should be used cautiously because an unshielded receiver is unreliable in high winds. However, a shield may catch drifting snow and cause errors.

The water equivalent of snowfall should be determined by:
- Taking samples of the snowpack with a suitable sampler and weighing or melting them.
- Using ordinary rain gages equipped for winter operation.
- Using snow pillows.
- Using gamma radiation to measure density from which the water equivalent can be calculated.

Several measurements should be taken over an area to give a representative sample.

**Recording Snow Gages**

The most common recording snow gages are the weighing-type rain gage and the snow pillow.

**Weighing-type Rain Gages:**

Recording rain gages, such as those discussed, can measure the water equivalent of snowfall. The gage must be serviced before it is used. The funnel in the receiver should be removed so that the snow can fall directly into the bucket. Two to 4 inches (5 to 10 cm) of a solution of CaCl₂ and water should be placed in the receiver bucket. This solution melts any solid precipitation that falls in the gage and prevents errors due to snow blowing out of the gage. The gage should be placed so that the top of the receiver is well above the maximum expected depth of snow.

**Snow Pillows:**

The snow pillow is a large flat rubber pillow, generally 12 feet (3.66 m) in diameter and 9 inches (23 cm) thick (fig. 1.20). The pillow is filled with 4.66 ft³ (1.32 kiloliters) of a 1:1 mixture of methyl alcohol and water. The snow pillow is connected to an instrument that records the pressure.

The snow pillow should be installed on a firm,
level, and permeable base to reduce the effect of frost heaving and to prevent burrowing rodents from damaging the pillow. A packed and leveled area of sand makes a good base. The surface of the base should be even with the surrounding ground. The top of the pillow should be painted white. Use a good paint that is recommended for rubber. The pillow is placed on the base and filled with the alcohol-water mixture. Avoid leaving air pockets in the filled pillow. Connect the filled pillow by pipe to a stilling well equipped with a liquid level recorder or a pressure transducer for recording changes in the pressure of the liquid caused by changes in the weight of snow on the pillow. Figure 1.20 shows the installation of a pillow by using a stilling well and liquid level recorder. The liquid level recorder should have a sensitivity of 0.06 inch (1.5 mm). The size of the stilling well will depend on the diameter of the float required with the recorder. A chart speed of 2.54 in/hr (1 cm/hr) is adequate.

Only the liquid level recorder needs servicing. The density of the alcohol solution must be determined for the range of temperatures encountered in operating the pillow. The density is used to convert changes in pressure on the pillow to increments of snow water equivalent.

During the snow season when the pillow is covered, no maintenance can be performed without disturbing the snowpack. Avoid puncturing the pillow with snow tubes, stakes, or probes. The area should be fenced to reduce the possibility of animals, vehicles, or people damaging the pillow. Each year before installation, carefully check the pillow and repair any leaks. If the white surface of the pillow becomes marked or discolored, repaint it before installation.

The response of the snow pillow is rapid. Changes in water content of 0.04 inch (1 mm) can be measured with properly designed equipment. The greatest source of error results from ice bridging in the snowpack. When thick ice layers are in the snowpack, the readings from the snow pillow may be unreliable. Frost can change the position of the pillow and cause errors in the readings. Air pockets in the pillow also will introduce errors into the readings.

Snowpack

Snow Surveys

The accumulation of snow in a basin is a natural storage reservoir from which most of the water supply for an area may be derived. At the same time, a rapidly melting snowpack may result in costly flooding. Forecasting of flows from snowmelt for water supply and flood control is important to many people and agencies concerned with these problems. Understanding and predicting the rates of snowmelt are also important for many hydrologists.

Selection of Snow Courses:

A snow course is a permanently marked area where snow surveys are taken each year. The snow courses should provide an estimate of the snowpack conditions in environments within the basin and the average watershed condition. Some requirements for selecting snow-course sites are:

- The site should be open and large enough so that it is not affected by interception.
- The site should be protected from high winds.
• The site should be on a well-drained area.
• The site should be accessible so that continuous measurements can be made throughout the season.
• The site should represent the snow conditions at a given exposure, cover, and elevation complex.

The number of snow courses will depend on the diversity of topographic and meteorological conditions and local environmental features, such as aspect and ground slope. Planned use and required accuracy of the data also should be considered in determining the number of snow courses.

Several snow courses should be selected in a basin. Short courses are preferable to a few long courses. The courses should give an adequate sampling of cover, aspect, and elevation differences within the basin. The number of courses depends on planned use of the data, the variability of basin relief and cover, and the basin size.

Sites should be mowed and cleared in the fall. The course should be marked conspicuously with markers that extend above the deepest snow. The sites should be fenced, when practical, to prevent the course from being disturbed by snowmobiles, skiers, or animals.

**Layout of Snow Courses:**

Snow courses need not be on a straight line. Snow courses vary in length from about 49 feet (15 m) to more than 3,281 feet (1 km) with sampling points spaced from 10 to 164 feet (3 to 50 cm) apart. More samples will be required in areas where snow drifts because of wind. Once the prevailing length and direction of drifting are determined, the number of measurement points might be reduced. Each sampling point should be located by measuring the distance from fixed reference points.

**Snow-Sampling Equipment:**

The equipment used to sample snow consists of a metal or fiberglass tube with a snow cutter fixed to the lower end and a scale marked or stamped on the surface of the tube; a scale with a wire cradle to support the tube while weighing to determine the water equivalent of the snow cores; and tools for operating the snow sampler. Two typical sets of equipment are shown in figure 1.21. The cutter must be designed to penetrate the snow through crusted and ice layers and sometimes solid ice layers at the ground surface. The cutter must not compact the snow so that too much is forced into the sampler.

The cutter must size the core base so that the core will not fall out when the sampler is withdrawn. Small-diameter cutters retain the sample better, but larger samples increase the accuracy of weighing. The cutter may be smooth or serrated and should be as thin as practical. Its diameter should be slightly larger than the outside diameter of the snow tube. The sampling tube should have an inside diameter slightly larger than the inside diameter of the cutter. The core can go up the tube with minimal wall friction. The inside walls of the tube should be as smooth as possible; but wet, coarse-grained spring snow will still stick to the tube.

The standard method of getting the water equivalent of the snow samples is to weigh the core taken by the sampler (fig. 1.22). The weight of the core is obtained by subtracting the known sampler weight from the weight of the sampler and core. Some scales are calibrated so that the core weight is read directly by putting in a tare for the weight of the sampler. The weighing is done with a spring scale or a special balance. The scale balances are more accurate but very difficult to use in wind.

Water equivalent also can be obtained by storing samples in plastic containers or bags and returning them to a station where they may be weighed or melted, and measured. Unfortunately, data can be lost because of errors not recognized in the field where readings can be repeated. When designing or selecting a sampler, remember that measurements frequently are taken under difficult physical conditions.

**Gamma-Ray Method**

The measurement of snow density with radioactive isotopes depends on the attenuation of gamma rays when traversing a medium. The attenuation is a function of the energy from the source and the density and thickness of the
substance traversed. Since a high-energy source of gamma radiation is required, cobalt-60 and cesium-137 are used frequently. Three methods used in placing the sources for measuring snow are:

- The source is placed at ground level, and the detector is placed above the snow surface.
- The detector is placed below the ground surface, and the source and shielding are placed above the maximum expected snow depth.
- The gamma-ray source and the detector are moved synchronously through parallel tubes placed vertically in the snowpack. This method gives a density profile of the snowpack in addition to the average or composite density.

The installation and operation of the gamma-ray gages are not standard. Most systems are specially made and not commercially available. Installation requirements and operational procedures for representative installations are discussed here.

The gamma-ray gage consists of a detector using a Geiger-Muller tube and cobalt-60 source in a lead shield mounted flush with the ground surface. The cobalt-60 emits high-energy radiation that is essentially monochromatic. The gamma photons cause pulses of electricity to flow in the Geiger-Muller tube. These pulses are proportional to the intensity of the radiation. They can be radio telemetered or sent directly into scaling equipment, where they are recorded. Figure 1.23 is a sketch of a typical gage. The instrument must be calibrated to give count rate versus water content. The radioactive source must be shielded with lead because of the health hazard from gamma radiation. This type of installation has been used to measure snowpacks containing over 50 inches (127 cm) of water. The error depends on the count rate or the water content of the snow; namely, the higher the water content, the lower the count and the greater the percentage of error.

This system has the same principle of operation as the system with the source and detector reversed and requires the same health hazard precautions. The advantage over the reverse system is that the Geiger-Muller tube is tem-
perature sensitive. By placing it under the snow, the temperature fluctuations are reduced (16). Most instruments used in this method are not commercially available. The method is described in detail by Houghton and Howe (18).

A watertight sheet-metal box buried in the ground contains the motors, racks, pinions, and other apparatus associated with the drive mechanism. Fastened to the top of the box are two polyvinyl-chloride tubes sealed at the top and spaced 1.9 feet (57.9 cm) apart. A tube with a 3/4-inch (1.9 cm) diameter contains the 5-millicurie source, and a tube with a 3-inch (7.6 cm) diameter contains the photon detector. Both are mounted on racks driven by synchronous motors in the control box. The rack motors are operated by a control panel located away from the instrument. A calibration bar of known density is installed permanently between the tubes below ground for calibrating the instrument before each run.

To get a snow profile the operator sends source and detector in search of the calibration bar. Both stop automatically when directly opposite the bar with the source exactly opposite the 1/2-inch (1.27 cm) window of the detector. A count is taken as the energy flows through the calibration bar of known density, the instrument is adjusted, and actual profiling is ready to begin. The source and detector move synchronously up the tubes at the rate of 1 ft/ min (26.9 cm/min).

The signal from the photon detector flows to a pulse-height analyzer (PHA) that filters out all random "noise." From the PHA, the selected signal flows through a processor to a recorder that produces a profile of snow depth versus density. Repeatability with this system is excellent. Some detail of the density variations is lost because of time averaging within the signal processor. Small errors can be made in measuring depths.

Descriptions of similar instruments and discussions of the accuracy and sources of error are given in references 11 and 34.

Precipitation Quality

With the increasing emphasis on water quality in agriculture and the considerations being given to the chemical balance of a watershed in addition to the hydrologic balance, the researcher must be able to estimate the chemical input to his system by precipitation so that its relative importance can be evaluated. Considerations must be given to the collection of precipitation for chemical analysis that need not be given to collection for the determination of precipitation quantity.

A rain gage collects a sample of the amount of precipitation falling during an event. A precipitation quality collector shows the chemical quality of this precipitation. Because of the relatively small amounts of chemicals usually found in a precipitation sample, care must be taken in the construction, location, and operation of a precipitation quality collector so as not to contaminate the sample gathered by the collector.

The container in which the precipitation is collected, and any part of the collector that the precipitation touches before it reaches the con-
container, should be of a material that would not interfere with the chemical analyses being run on the precipitation sample. Polyethylene is a good choice where inorganic chemicals are being analyzed, while glass would be required for organic analysis.

The collector must be covered when there is no precipitation to eliminate contamination of the container by dust, birds, and so forth. The cover can be removed manually at the start of precipitation and can be replaced once precipitation ends. If the collector is in a field, this process can be automated. The cover must be removed at the first sign of precipitation since the initial precipitation usually contains most of the total contaminants deposited by the storm.

Researchers have used many collectors, ranging from a simple glass funnel and bottle to completely automated collectors. Since automated collectors are more practical for field applications (and since simple collectors are easy to visualize and construct), two automated collectors will be discussed here.

One automated collector that works well is available from Wong Laboratories in Cincinnati, Ohio. This collector was used by the Public Health Service in its nationwide precipitation quality network, by the National Center for Atmospheric Research, and by independent researchers. It consists of an 11-inch-diameter polyethylene bucket mounted in a supporting frame. The entire frame and bucket are covered when no precipitation occurs. A grid moisture sensor is activated by the first precipitation falling, which activates a small motor that swings the cover from over the bucket. As long as precipitation occurs, the cover stays in its

![Figure 1.23.—Sketch of a gamma-ray snow density gage showing the principal components.](image-url)
retracted position. Once precipitation stops, a heater in the moisture sensor evaporates the remaining moisture bridging the grid and the cover closes. Both the temperature and sensitivity of the moisture-sensing grid are adjustable. This installation requires 110-volt, 60-cycle power.

The North Appalachian Experimental Watershed at Coshocton, Ohio, has designed and constructed a precipitation-quality collector (fig. 1.24). This collector is similar to the Wong collector, but the temperature and sensitivity of the moisture grid are not adjustable. The bucket is made of stainless steel and is the same size as the National Weather Service 8-inch (20 cm) nonrecording rain gage. Its installation also required 110-volt, 60-cycle power.

**Operation and Maintenance:**

A precipitation quality collector should be installed with a standard rain gage. The amount of precipitation should not be measured from the catch of the quality collector because of contamination problems, differing catch efficiencies of the precipitation quality collectors, and so forth. The collector should be located where no local condition, such as an incinerator or smokestack, could contaminate the sample and make it nonrepresentative of conditions at the site.

The collector should be chemically cleaned before each sampling period with a cleaner that will not interfere with the chemical analyses being done on the sample. After precipitation, empty the collector as soon as possible. The sample should be stored or preserved, or both, as the chemical analyses dictate. Avoid contamination in transferring the sample.

The collecting container must be kept free of contamination. It must be cleaned after each sample, and the bucket should be checked periodically during extended periods of no precipitation. If the bucket gets dirty between sampling, it should be cleaned.

The moisture-sensing grid also must be kept clean to insure instant response to the start of precipitation. Continued evaporation from the surface of the grid can cause a buildup that makes the grid increasingly insensitive to precipitation. Periodic cleaning of the grid face with a mild abrasive helps alleviate this problem.

Maintenance of the mechanical parts of the collector depends on the construction of the instrument. Check periodically to make sure all mechanical parts of the gage are working. If the gage is equipped with a mechanically operated cover, the cover must be free to move when the motor is activated by the moisture sensor. It must be maintained in as tight a position as possible when no precipitation is occurring to minimize contamination.

Winter operation of a precipitation quality collector poses the same problems as winter operation of a standard rain gage. These problems are in catch efficiency caused by wind and freezing of the mechanisms. The collector can be enclosed with a plywood base that has a thermostatically operated heat bulb within the base. The amount of snow in the gage increases because the snow melts when it reaches the bucket. It has less tendency to bridge the opening and consequently eliminate further catch. Higher operating temperatures of this enclosure also help preclude additional cold-caused problems with the gage mechanism.

Limitations of this type of data are basically the same as those of precipitation quantity data. Both the sample's representativeness of precipitation at that point and its ability to be extrapolated over an area are questionable. As long as the collector catches a sample constantly proportional to what is falling, the
sample will be representative and concentrations in all or part of the sample will be constant.

Subsequent extrapolation of this point measurement to an area, remains subjective, however, and must be based on experience and local conditions. The question is whether the concentration or the total (concentration times amount of precipitation) chemical contaminant sampled should be extrapolated. If there is a point during precipitation after which additional precipitation brings no appreciable contaminants, the total amount should be extrapolated. The total amount applied also should be considered where precipitation amounts differ significantly over the area in question. Where precipitation lasts a short time or where it is relatively uniform over the area in question, the chemical concentration sampled should be extrapolated.

The most probable source of error in the data is contamination of the sample by the collector or by sample-handling procedures before analysis. Because small amounts of contaminant usually are found in these samples, this aspect of the problem requires careful consideration to make the data meaningful.

FIELD MEASUREMENTS

Field observations are made to record accurately events for complete data tabulation, analysis, and interpretation. Many conditions or phenomena must be noted personally. Records from instruments that did not function properly often provide usable data if adequate notes are taken concerning the nature and cause of the failure. Observers should realize that many notes are needed.

Observers should be prepared to make systematic field notes by using standard forms or a fieldbook with columnar pages. Before leaving for the field, the observer should assemble a notebook, charts for the recording gages, a bottle of recorder ink and blotter, a pencil, and an accurate watch that is checked with a radio time signal before departure. It is convenient to have a small toolkit consisting of pliers, two or three screwdrivers, a small adjustable wrench, and two or three open-end wrenches for routine adjustments or minor repairs in the field.

General Reporting Procedures

Instructions to Observers

Clearly written instructions for all observers should include:

- Brief description of instruments, with diagrams.
- Routine care and maintenance of instruments and action to be taken if serious breakage or malfunctioning occurs.
- Procedure for taking observations.
- Times of routine observations.
- Criteria for beginning, end, and frequency of special nonroutine observations (that is, river-stage observations while water level is above a predetermined height).
- Procedure for making time checks and putting observations on charts at stations with recording instruments.
- Completion of fieldbook or station journal.
- Completion of report forms including methods of calculating means and totals and examples.
- Sending report forms to central office.

These instructions should be supplemented by verbal instruction to the observer by the inspector at the time of installation of instruments and at regular intervals thereafter.

These instructions should emphasize the importance of regular observations with perhaps a brief account of how the observed data are used in water resource development, river forecasting, or flood-control studies. Observations during special periods, such as floods, or any special reports that are to be filed, should be specifically outlined. Observers must fill in station names, date, and observer's signature. Instrument failure or significant modification of the observing site should be reported immediately.
These instructions apply to observers at stations with continuous 24-hour-per-day observational programs to observers who measure only precipitation or stage once a day. The instructions must be more detailed in the 24-hour observational programs than in the once-a-day observational programs.

Observers at stations equipped with automatic recording instruments must be provided with instructions on the method of changing charts and taking check observations. At stations with full-time personnel, the staff should be sufficiently well trained to abstract data from charts of recording rain gages. Carefully worded instructions on the method of abstracting data from the charts and the completion of report forms must be provided. At stations where observers may not be thoroughly trained, observers should not be required to abstract data from charts. Charts should be forwarded to a central office for abstraction of data.

At some locations, gages are being introduced for water-level and precipitation requirements that produce the required data on punched paper tape or other digital output, instead of on graphical charts. Instructions to observers need only contain information on routine maintenance, taking check observations, and method of forwarding the tape or card output to the central office for machine processing.

**Inspection of Stations**

To maintain good observations, stations must be inspected periodically. Principal climatological stations should be inspected at least once every 2 years. Ordinary climatological stations should be inspected at least once every 4 years. At some locations inspectors from offices visit at least once a year, with less frequent visits being made by inspectors from the central office.

The inspector must:
- Note and record any change in observation site (a sketch map and photographs are useful).
- Make local arrangements for improving or restoring the observing site (that is, removal of trees affecting rain-gage catch).
- Check the instruments and make necessary repairs and adjustments.
- Inspect the observer's fieldbook.
- Instruct the observer on procedures and routine instrument maintenance.
- Emphasize the importance of filing promptly complete and accurate returns.
- Brief the observer on special observations that may be required (that is, more frequent readings during storm periods).
- See that the observer has sufficient forms, mailing envelopes, and other supplies to perform his duties.

The inspector must be advised of errors made by observers, especially recurring errors made by a particular observer. Such advice should be forwarded regularly to the inspector by the officers responsible for preliminary checking and error detection.

**Special Data Collection**

Data on severe storms and floods are important in determining design criteria for many hydraulic structures. Regular observation networks generally do not give enough detailed information on storm rainfall distribution. Therefore, valuable information can be obtained by a field survey crew after a severe storm. Data from instruments such as weather radar are often valuable in hydrological studies.

Rain can be measured in receptacles, such as pails, troughs, and barrels, that were empty before the storm. Rainfall data can be augmented from the regular observing network. Eyewitness reports can be obtained of times of beginning and ending of rain and of periods of very heavy rain. Data from bucket surveys must be interpreted carefully. Where discrepancies exist between data from a bucket survey and the regular observation network, greater weight usually should be given to the latter.

**Nonrecording Gages**

Observers should have fieldbooks or station journals, or both, in which to enter their observations. Forms also should be provided for daily, weekly, biweekly, or monthly observations. The fieldbook or station journal should be retained by the observer in case a report form is lost in transit.

The report forms should permit easy copying of results from the fieldbook or station journal.
A good arrangement is to have the report form identical to a page in the fieldbook or journal. The elements should be in the same columns or rows to minimize copying errors. The journal and the report form should have space for any conversions or corrections from the original readings.

Alternatively, an observation fieldbook with carbon paper between successive sheets will permit easy preparation of an original form for the central office and a copy for the local station record. This may be impractical if the observer's office or home is far from the observation site and the fieldbook would be subject to frequent inclement weather.

**National Weather Service Standard 8-Inch (20 cm) Gage and Storage Gage**

Before measuring rainfall in the 8-inch (20 cm) nonrecording gage, remove the receiver. If the measuring tube is partially full, place the rainfall measuring stick vertically in the tube with the zero end resting on the bottom. After 2 or 3 seconds, remove the stick and read the depth of rainfall to the nearest hundredth of an inch (0.025 cm), as indicated by the wetted portion of the stick. Empty the measuring tube, allow it to drain, and replace it.

If the tube is overflowing, carefully remove it without spilling water into the overflow can. Empty the tube and allow it to drain for several seconds. Each full tube represents exactly 2.00 inches (5.08 cm) of rainfall. To avoid any serious loss of record if rainfall is spilled when emptying the overflow can, take a stick measurement of the depth of water in the overflow can before it is emptied. The stick reading from the overflow can will be approximately one-tenth that of the measuring tube. Carefully fill the measuring tube, when necessary, with the water remaining in the overflow can. When the water in the overflow can partially fills the tube, take a stick reading, add individual measurements (fig. 1.25), and enter the date and time of observation in the fieldbook.

The water equivalent of samples of frozen precipitation is determined by melting each sample and measuring its liquid content, or by weighing the frozen sample. Weighing the sample is the fastest and usually the most accurate method if scales are available that read directly in ounces or in inches of precipitation from 8-inch (20 cm) gages.

In winter, the receiver and measuring tubes are removed, and the overflow can be used as the gage. Snow samples are obtained from catch in the gage or by inverting the overflow can and using the rim to cut a cylindrical vertical sample to the required depth. A piece of sheet metal is slipped beneath the mouth of the can to hold the sample as the can is withdrawn. Whenever the depth of snow to be sampled is deeper than the can, cut the sample and remove a portion at a time until the required depth has been sampled. The sample is taken where it will most nearly represent the average fall and where the snow cover seems least affected by drifting.

Measure a quantity of warm water (to the nearest hundredth of an inch) in the measuring tube and pour it into the overflow can, or other container, with the sample of snow and ice. Put melted contents back into the measuring tube and measure it like rainfall. Subtract the amount of warm water from the total, and the remainder will be the water equivalent of the sample.

Attach an empty dry container to the scale and read the weight to the nearest hundredth of an inch precipitation or to the nearest ounce. Place the sample in the container and read the scale again. Subtract the first reading from the second to arrive at the amount or weight of water in the sample. If the scale is calibrated in ounces, convert the difference to inches precipitation by multiplying by 0.0358 since 1 ounce (30 ml) of water in an 8-inch (20 cm) gage equals 0.0358 inch (0.9 cm) precipitation. When the sample exceeds the capacity of the container, get the water equivalent of each portion of the sample as stated previously. Add the values for the portions to get the value of the total sample.

**Other Nonrecording Gages**

Nonrecording gages are available in so many shapes and sizes that specific instructions cannot be listed for each. Carefully follow the manufacturer's literature for each type of gage. Do not use plastic and glass gages in winter because they are damaged easily by freezing.
and thawing. If water equivalent is determined by weighing, use a scale calibrated for the orifice size. If catch is measured in ounces, use the correct factor to convert to inches of precipitation. To convert ounces weight to inches precipitation, multiply the weight in ounces by the factor, \( F = \frac{2.29}{D^2} \)

where \( D \) is the orifice diameter in inches.

**Recording Gages**

The design of report forms for summarizing information from continuously recording gages measuring precipitation is a special problem. Relative values must be assessed of the ways in which the data could be abstracted and tabulated.

One difficulty is that the hourly rainfall data usually are calculated for calendar days and local standard time. The nonrecording rain gage is read and the recording gage chart changed according to a precipitation day, which is often 0800 EST to 0800 EST the next day. Consequently, the maximum amounts for durations are tabulated for the "precipitation day" instead of the calendar day. A simpler form and easier data tabulation would be possible if the recording gage data were not corrected to be compatible with the standard gage observations.

While many forms can be used for summariz-

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**FIGURE 1.25.—Field notes for a standard rain gage.**

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Depth- of Meas.</th>
<th>Depth in Inches</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>8:30 a</td>
<td>0.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>11:15 a</td>
<td>2.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.30</td>
<td>0.14</td>
<td>Very hard rain during early morning, strong winds, some hail.</td>
</tr>
<tr>
<td>13</td>
<td>11:30 a</td>
<td>1.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>8:30 a</td>
<td>0.24</td>
<td></td>
<td>Drizzle all day.</td>
</tr>
<tr>
<td>23</td>
<td>8:20 a</td>
<td>1.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>4:00 p</td>
<td>0.77</td>
<td></td>
<td>Light intermittent showers 24th, 26th, 27th.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monthly total</td>
<td>7.77</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**JANUARY, 1944**

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Depth- of Meas.</th>
<th>Depth in Inches</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>9:00 a</td>
<td>0.42</td>
<td>0.35</td>
<td>--Total in measuring tube</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.35</td>
<td>--Warm water added</td>
</tr>
<tr>
<td>24</td>
<td>9:30 a</td>
<td>0.67</td>
<td>0.07</td>
<td>--Net precipitation or water equivalent.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>10:00 a</td>
<td>2.45</td>
<td>-1.50</td>
<td>Sum of two measurements.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monthly total</td>
<td>1.19</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
ing data from recording charts, summaries of the most frequently used data should be abstracted from the charts. The abstraction should begin immediately after the chart is removed from the instrument to check on the functioning of the instrument and to verify unusual events indicated on the recorder as soon as possible. It is easier to spend a few minutes abstracting the chart data each day, week, or month, than to deal with a large backlog of data abstraction at one time.

**Universal-Type Recording Gage**

Visit each recording gage as often as practicable to see if the clock is running and if the pen is making a trace. At each inspection, mark a time check on the chart by gently touching the weighing mechanism to make a ½-inch (0.64 cm) vertical mark on the trace. If the clock is not running, mark the trace by turning the cylinder slightly to the left and right to produce a short horizontal line across the trace. This will identify the top of the trace although vibration may have caused the pen to rise above this level on the chart. If the pen is not making a trace, place a circle on the chart to mark the position of the pen. For all time checks, note the date, time, and initials of the inspector on the chart and in the fieldbook.

Before a chart is placed on the cylinder, it should have the proper station designation, chart number, date and time of placement, name or initials of observer, and any other information required. Military time is recommended, and the chart should note whether standard or daylight saving time is used. Standard time usually will be used for continuity although the surrounding area may be on daylight saving time during part of the year.

Charts on weighing-type rain gages should be changed weekly or as soon as possible after precipitation. To change the chart, remove the receiver and open the inspection door or remove the outer shield of gages not equipped with a door. Make a time check and remove the pen from the chart by shifting the pen bar. Record the date and time of removal in the fieldbook (fig. 1.26). Empty and replace the bucket, except during the winter when the bucket is charged with antifreeze. Remove the cylinder by gently grasping the top and lifting it over the spindle. Release the clip holding the chart but avoid touching the trace or storing the chart so as to smear the trace. Note the time of removal and initials of the observer on the chart (fig. 1.27). Wind the clock and wrap a new chart around the cylinder.

The new chart should have the correct station designation, date and time of placement, and initials or name of the observer. The chart should fit smoothly and snugly, with its base uniformly in contact with the flange of the cylinder. Replace the cylinder by lowering it gently over the spindle until the gears are fully meshed. Fill the pen to slightly less than level so that it will not overflow as the ink absorbs moisture from the atmosphere. If the trace becomes faint, remove the ink with a blotter and replace it. With the pen almost touching the chart, errors in time are corrected by turning the cylinder until the indicated time is about 3 hours fast, then turning the cylinder back to the correct time. This will take up any backlash in the timing gears. Place the pen on the chart and make a time check. Record the placement time and date on the chart and in the fieldbook. Replace the outer shield if it has been removed, close the inspection door, and replace the receiver. Note the form of precipitation, clock failures, or any malfunctioning of the gage in the fieldbook.

If recording gages are equipped with battery-operated, electrically driven, or electrically wound clocks, use a portable voltmeter. Note the battery voltage at each inspection while the clock motor is running in case the voltage drops during operation.

After a chart has been removed, enter the time and date of removal at the end of the chart. Verify the time and record discrepancies between the chart time and watch time. Add other notes that will explain unusual or missing parts of the trace.

When visiting the station in the winter, do not empty the bucket until the pen reaches the 3.00-inch (7.6 cm) line. When the accumulated precipitation in the gage reaches this point, oil-antifreeze-water solution may freeze. Therefore, empty the bucket and recharge it.
### FIGURE 1.26.—Field notes for a recording rain gage.

<table>
<thead>
<tr>
<th>Chart No.</th>
<th>Date</th>
<th>Time</th>
<th>Remarks</th>
<th>Date</th>
<th>W.T.</th>
<th>Measured Prec.</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>353</td>
<td>7/29</td>
<td>12:30 p</td>
<td></td>
<td>8/2</td>
<td></td>
<td></td>
<td>Clock slow, adjusted</td>
</tr>
<tr>
<td>354</td>
<td>8/2</td>
<td>9:13 a</td>
<td>Windy, low</td>
<td>8/9</td>
<td></td>
<td>9:10 a</td>
<td></td>
</tr>
<tr>
<td>355</td>
<td>8/9</td>
<td>9:15 a</td>
<td>humidity</td>
<td>8/12</td>
<td></td>
<td>11:59 a</td>
<td>1.92 1.61</td>
</tr>
<tr>
<td>356</td>
<td>8/12</td>
<td>12:05 p</td>
<td></td>
<td>8/13</td>
<td></td>
<td>11:04 a</td>
<td>1.90</td>
</tr>
<tr>
<td>357</td>
<td>8/13</td>
<td>11:10 a</td>
<td></td>
<td>8/16</td>
<td></td>
<td>9:10 a</td>
<td>.37</td>
</tr>
<tr>
<td>358</td>
<td>8/16</td>
<td>9:10 a</td>
<td></td>
<td>8/23</td>
<td></td>
<td>8:52 a</td>
<td>1.28</td>
</tr>
<tr>
<td>359</td>
<td>8/23</td>
<td>9:00 a</td>
<td></td>
<td>8/27</td>
<td></td>
<td>4:28 p</td>
<td>1.00</td>
</tr>
<tr>
<td>360</td>
<td>8/27</td>
<td>4:35 p</td>
<td></td>
<td>8/30</td>
<td></td>
<td>9:40 a</td>
<td>0</td>
</tr>
<tr>
<td>361</td>
<td>8/30</td>
<td>9:45 a</td>
<td></td>
<td>9/6</td>
<td></td>
<td>11:14 a</td>
<td>.86</td>
</tr>
</tbody>
</table>

1/ Central daylight saving time

### Tipping-Bucket Rain Gage

Inspect each tipping-bucket rain gage and remote recording system as often as practical to see if the recorder is working and if the pen is making a trace. At each inspection, make a time check with a ballpoint pen or other permanent marker. If the pen is not making a trace or the recorder is out of time synchronization, place a circle on the chart to mark the position of the pen. Replace the pen if it is not working and adjust the recorder tape to the proper time synchronization. For all time checks, note the date, time, and initials of the observer on the tape and in the fieldbook. Check the tipping bucket assembly and measuring cylinder for corrosion and deterioration.

The tipping bucket should move freely on its pivots, and the mercury switch should be intact and operational. If the funnel hole has become clogged and is backing up rain water in the collector, remove the obstruction to allow the water to drain through the gage assembly and into the reservoir at the base of the gage. Note any malfunction in the fieldbook.

While the bucket tips during an intensive rainfall, the rainfall will continue to flow from the collector into the reservoir. Slightly more water will be in the reservoir than the tape record indicates. Thus, the total amount of precipitation in the reservoir should be measured. This measurement should be taken shortly after the rain to minimize evaporation loss from the reservoir.
Before a tape is placed in the recorder, make sure it has the proper station designation, chart number, date and time of placement, name or initials of observer, and any other information required. Military time is recommended, and the chart should note whether standard or daylight saving time is used. Standard time usually is used for continuity throughout the year although the surrounding area may be on daylight saving time during part of the year.

Remove the recording tape on the tipping bucket recorder each week, and install a new tape if the supply is insufficient for the period between servicing. Remove the record as soon as possible after precipitation.

At the beginning and removal of each paper tape spool, record the following directly on the chart in ink.

- Gage number (serial no.).
- Gage location number.
- Time and date.
- Value of precipitation indicated by measuring tube and dip stick.
- Person servicing gage.
- Watershed location.
- Tape time (EST only).
- Watch time (EST only).
- Record information, as needed.

**Digital-Recording Gage**

Inspect the digital rain gage at regular intervals to determine that the recording mechanism is operating and the tape is at proper time. A schedule of checking and servicing the gage will give accurate records for each instrument and will reduce the periods of missing or incomplete records. This servicing should be for 1 month or less and should include:

- Checking battery voltage (greater than 6½ volts).
- Checking amount of tape on spool.
- Checking time synchronization.
- Draining collector when greater than 10 inches.
- Checking to see that trace indicator contacts are clean.
- Spraying motor switch contacts with contact cleaner.

The gage should be inspected for other malfunctions, and adjustments should be made when necessary.

A checklist (fig. 1.28) will aid the observer in servicing the equipment and in recording gage operation. This checklist will be valuable in maintaining a network of rain gages with minimal malfunction and loss of records.
**FIGURE 1.28.—Field checklist for precipitation gage.**

<table>
<thead>
<tr>
<th>Instrument No:</th>
<th>Timer No:</th>
<th>Watershed:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location No:</td>
<td>Date to be Serviced</td>
<td>Date Actually Serviced</td>
</tr>
</tbody>
</table>

### Synchronization
- Correct E.S.T.
- Tape time
- Time correction
- Tape day No.

### Tape Supply
- Supply tape released
- Tape No.
- Days remaining on tape
- Record removed
- Notation on tape

### Instrument Reading
- Dial reading
- Tape reading
- Punchout in line
- Punchout clean
- Sensitivity checked
- Range adjusted
- Zero adjusted
- Collector emptied
- Calibration made

### Battery Supply
- Battery Replaced
- Voltage across battery
- Voltage across motor
- ma drain of timer
- ma drain of punchout

### Operation
- Evap. suppression oil
- Dashpot fluid added
- Contacts cleaned
- Material in collector
- Mechanical malfunction

### Seasonal Operation
- Trace (in or out)
- Trace battery voltage
- Funnel (in or out)
- Antifreeze installed

### Gage Serviced By

(Make additional comments on back.)
Snowfall

Direct Measurement

Measure snowfall at all precipitation rain gage stations. These measurements complement the regular precipitation measurements.

The water equivalent of new snow may be determined from recording rain gages. The snow pillow will record additions of water to the snowpack. Snow tube sampling and gamma-ray methods can be used to determine the water equivalent of new snow. Use of the snow tube or gamma-ray method to determine the density of new snow assumes that snow did not melt between measurements. If any melting occurs, the determinations may be in error by significant amounts.

Recording Gages

How to handle the measurement of snow with a weighing-type rain gage was discussed on page 29.

When using recording gages, inspect the snow pillow site to ensure that snow on the pillow has not been disturbed. If possible, check the area for leaks in the pillow. Check the liquid level recorder for proper operation when the record is changed. Check the stilling well and connection lines for leaks whenever possible.

When the record (chart) is put on or taken off, note the date and time. Note the amount of precipitation during the period of record. Any unusual behavior, such as jumps in the record, should be noted and explained, if possible.

Snowpack

Snow Courses

Snow courses provide data on depth, density, and water equivalent of the snowpack. They also provide information on the spatial variation of the snowpack over a drainage basin. Such data as ground condition, type of snow (including granular snow, ice layers, or corn), and stream conditions are also part of the snow-course data.

Before going to the field to take snow-course data, check the equipment thoroughly. Test the scales, check the snow tube, and make sure the cutter is sharp and firmly attached to the snow tube. Identify the stations before going to the field so that only the recorded data have to be entered during the sampling. This procedure saves time and helps reduce errors in making observations.

The snow course sampling points should be marked carefully or located precisely by measuring from a given reference mark. Unless samples are taken at the proper location, the data will be inconsistent and basin averages or other calculations using the data will have errors. To cut a core with the snow tube, force the sampler downward (cutter end first) through the snowpack until it reaches the ground. If conditions permit, the core should be taken with a steady downward thrust of the tube. A minimum amount of turning should be made to reduce sampling error. When turning is necessary, rotate the tube clockwise to help the cutter penetrate ice layers within the snowpack.

The cutter normally should penetrate to the ground. A trace of ground litter on the end of the cutter indicates that none of the core has been lost. The weight of the core is the water content of the snowpack at that point. The depth of the snow is read at the surface of the snow on the outside of the tube before the core is lifted. When the cutter has penetrated below ground, the depth of penetration is determined. The snow depth is obtained by subtracting this depth from the depth reading at the surface of the snow with the tube in the snowpack. The weight of the soil plug must be subtracted from the weight of the core to determine the water content. When the snow is melting and the snowpack is "wet," take a soil plug with each sample to hold the core in the tube. The sample should be weighed as quickly as possible to prevent water from draining out of the core. The density of the snow is computed by dividing the water equivalent of the snow by the depth of snow. The density of snow should be reasonably constant over a course. Because a large deviation from the average usually indicates an error, the snow should be resampled.

Gamma-Ray Method

This method provides a point measure of the snow density of the snowpack. The water con-
tent of the snowpack can be determined from the density measurements when the depth is known. The requirements for this method depend on the system used and how the data will be used. Some general requirements are outlined regarding the instruments and the installation of the system. The components of the detection system should be stable, easy to calibrate, and easy to maintain. The radioactive source should have sufficient strength to measure the maximum expected snowfall. It should not saturate the detection system under shallow snowpack conditions. Strict precautions will prevent unnecessary exposure of operation personnel, hunters, or other persons to the radiation from these installations. Installation of gamma-ray density gages requires expensive and complex instrumentation.

Data from radioisotope snow gages generally are recorded as a count rate (counts per minute, CPM) on a strip chart or as a number of counts taken over an interval as read from a scaler. Regardless of the recording method used (chart or scaler), the signal pulses must be processed in some manner. Two signal processing systems and method of recording the data from each will be discussed in this section. These systems are similar to the gamma-ray method except that each reading represents the entire water content of the snowpack at the time of the reading. The recording scheme and requirements are the same as those of the gamma-ray method.

The instrument described on page 31 records data in chart form. The chart moves at a given speed through the recorder, that is 5 in/s (12.7 cm/s). One centimeter represents 6.1 centimeters of snow depth. The density is recorded on a scale graduated from 0 to 1 gram per cubic centimeter. The chart output thus shows a profile of density versus depth for the snowpack. The signal-processing equipment gives an immediate reading of average density on a display. The average density, the date and time, and the depth of snow should be noted on the chart. The soil-snow and snow-air interfaces should be indicated on the density curve from the system. Figure 1.29 shows an annotated chart from this system. Similar systems that produce only a chart record of count rate from the detector, PHA, and rate meter units are used in the United States. This record requires similar notation on the chart and a calibration curve for converting count rates to densities in centimeters per cubic grams.

**FIGURE 1.29.—Chart from a gamma-ray snow density gage.**

**DATA REDUCTION**

Many field observations become useful only when properly transcribed. Field data are no better than office tabulation and reduction. Accurate final results require care through all processing steps.

Data should be compiled under the premise
that only documented evidence will be available for subsequent analysis. Malfunctions of equipment, interpretive data, pertinent conditions, location, date and time, and other information that might influence analyses or conclusions should be written formally and properly referenced. Identity and qualifications of each record should be retained throughout the compilation of data. Although data may be unnecessary for some analyses, they will help in selecting the analytical procedure.

Memory is a poor substitute for notes. The best of notes, however, rely somewhat upon memory to fill in the gaps. Data should be compiled, therefore, when still fresh in the observer's mind. This may not always be practicable, however.

In this section, data reduction is considered in annotations, tabulations, and calculations. All three parts should be completed as soon as possible after the event. Each part provides information for subsequent steps so that if the first part, annotations, is completed soon after the event, confusion will be minimal.

**Manual Methods**

Records and supporting field notes should be processed as soon as they are received in the office. Processing frequently will be done in separate operations by different individuals. The first step is to transfer all field notes to the chart and add any notes required for compilation of data. Then tabulate the data from the records and compute depths and intensities. Each step will be outlined.

There is no substitute for good records. All possible precautions should be taken to prevent instrument failure and faulty records. Estimates should be made as soon as possible. Designate all estimated values with the letter "e."

Estimates of storm or daily totals at an inoperative gage may be obtained by the isohyetal method if reliable data from a surrounding rain gage network are available. The value for the station with the missing record is estimated from the isohyetal map of the storm period.

Clock stoppage or a sluggish mechanism (indicated by irregular steps and jumps in the pen trace) usually results in an unsatisfactory intensity record. The total catch, however, is measured by pouring it into the tube of the standard gage when the chart is changed. Time distribution of the total catch at the malfunctioning gage is estimated by proportioning the record from an adjacent gage in the ratio of their total catches; that is, the quotient of the total catch in gage No. 1 divided by the total catch in gage No. 2, when applied as a multiplier to observed values of gage No. 2, provides estimates of corresponding values for gage No. 1.

**Annotating Charts**

Begin processing as soon as the charts and supporting field notes are received in the office. To reduce data, follow these steps:

- Visually edit charts and field notes to determine that the period of record is continuous and no charts are missing.
- Compare charts from adjacent gages and note obvious discrepancies between either time or amount of precipitation events. Resolve discrepancies by discussion with field personnel if necessary.
- Make annotations by transferring field notes directly to the charts and by adding other notes to facilitate data tabulation. Examples of notes are:
  - Date and watch time of chart placement, inspections, and removal.
  - Time correction if the watch time does not correspond to the chart time. These corrections are made by assuming a linear variation between placement or inspection and removal. For example, if the chart was on for 4 days, had a total time error of 8 minutes at removal, and the rain began 2½ days after placement, the time correction for the storm would be $2.5 \div 4 \times 8$, or 5 minutes.
- Beginning, ending, and total accumulated amounts for each precipitation amount on the chart.
- Form of precipitation, such as rain, hail, sleet, or snow.
- Station designation and name or initials of the observer on the right marginal tab. (This should have been done before the chart was placed in the field.)
• Time zone and whether standard or daylight saving time was used.
• Other notes showing malfunction of the instrument or clock, or anything that will help explain apparent anomalies.

For those charts covering periods of no rainfall, show only the chart number and the dates in the upper righthand corner. Since these charts show continuity of records, other notes are unnecessary.

Figure 1.30 shows weekly and 12-hour rain-gage charts following editing and annotating. Use of rubber stamps will help simplify and standardize chart notations.

The tipping-bucket rain gage has a recording system that uses a continuous paper tape record. Since this record is reduced manually by the preceding procedures, make notes directly on the paper tape, where necessary. Note the total precipitation catch measured with the collecting tube and dip stick on the paper tape next to the record of the event.

Figure 1.30.—Rain gage charts prepared for tabulation.
Once the charts are corrected, tabulate the records on forms (fig. 1.31). Complete the forms as follows:

- Fill in the heading. Most items need no explanation. The file number includes the station designation, year, and the storm number, if used on the project. The dates should cover those in the tabulation although no rainfall occurred on many days.

- Since the tabulations are to show continuity of records, note the date of the first storm of the current year and the date of the last storm of the previous year on the first sheet. Thus, if the last storm of the previous year occurred on December 26 and the first storm of the current year was on January 4, write “No precipitation December 27 to January 4.” Then skip one line and tabulate the January 4 storm. All subsequent periods are shown with no precipitation.

- Note break points on the recorder chart. Disregard minor changes, especially during periods of low rainfall intensity.

- If space permits, tabulate several small storms on the same sheet, unless storm intensities are to be computed. Tabulate storms for which intensities are to be computed on individual sheets.

- In column 2, tabulate the beginning, break points, regular time intervals (if needed), midnight (where the storm involves more than 1 day), and end of storm.

- In column 3, enter the difference in minutes between successive time entries of column 2.

- In column 4, enter the correct depth for each time tabulated in column 2. Leave a space after the end of the storm and enter the amount measured in the bucket. For snow, show values for beginning, midnight, and end since hourly amounts or intensities are meaningless.

**Snow Pillows**

Data from the snow pillow are taken from the recorder charts in a manner similar to that used for runoff data. Points are taken from the chart when the slope of the recorded line changes. The depth and time of each point are recorded. Figure 1.32 shows a typical snow pillow recorder chart. Figure 1.33 shows data tabulated from the chart readings. Readings from the chart of date, time, and gage height are entered in columns 1, 2, and 3. The gage change (column 4) is computed by subtracting the previous gage reading from the present gage reading, a plus sign indicating an increase in water and a minus sign indicating a decrease.

Column 5 is the ratio of the density of water to the density of the antifreeze solution in the pillow. It generally remains constant throughout the season. Large temperature variation or other factors that influence the density should be considered. Column 6 is the time interval between readings. Columns 7 and 9 are computed similarly, depending on whether the water content or snowpack increases or decreases. Columns 7 and 9 are computed by multiplying column 4 by column 5, by 12. Columns 8 and 10 are computed by dividing columns 7 or 9 by column 6 and multiplying by 60. (Note: Multiplying by 60 converts the answer from in/min to in/hr) Column 11 is computed by adding column 7 or subtracting column 9 from the previous column 11. Column 12 is used for remarks about the raw data or the calculations. If the quantity of data is sufficiently large, the calculations may be done by a computer.

**Snow Courses**

Reducing the data is simple if samples are taken carefully. The density of each sample is computed by dividing the water content by the depth of snow. Note that the weight of the empty tube exceeded 0 (in samples 9 and 10) due to a soil plug in the end of the tube (fig. 1.34). This weight must be subtracted from the tube and core weight to get the water content. The average snow depth and water content are computed by adding the depth and water content of each sample and dividing by the number of samples. The average density is obtained by dividing the average water content by the average depth. Samples that are believed to be incorrect should not be used in the averages.

**Tabulating Data**

The use of electronic digital computers has revolutionized the processing of hydrologic data by reducing computational time and improving
## RECORD OF RAINFALL INTENSITY

Rain gage: Type 6" Non-reversing (Fries)
1 inch on chart = 1.00 inches of precipitation.
1 inch on chart = 62 minutes of time.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Time Interval</th>
<th>Accumulated Depth</th>
<th>Depth for Each time interval</th>
<th>Intensity for Each time interval</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hours</td>
<td>Minutes</td>
<td>Inches</td>
<td>Inches</td>
<td>Inches per hour</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan. 4</td>
<td>10:40</td>
<td>a</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2:50</td>
<td>p</td>
<td>.21</td>
<td>.21</td>
<td>.21</td>
<td>Snow began</td>
</tr>
<tr>
<td>Jan. 5</td>
<td>1:40</td>
<td>a</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Rain began</td>
</tr>
<tr>
<td></td>
<td>2:15</td>
<td></td>
<td>.02</td>
<td>.02</td>
<td>.03</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3:10</td>
<td></td>
<td>.12</td>
<td>.10</td>
<td>.11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4:10</td>
<td></td>
<td>.21</td>
<td>.09</td>
<td>.09</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6:40</td>
<td></td>
<td>.37</td>
<td>.16</td>
<td>.06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7:50</td>
<td></td>
<td>.54</td>
<td>.17</td>
<td>.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10:00</td>
<td></td>
<td>.65</td>
<td>.11</td>
<td>.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.35</td>
<td></td>
<td>.72</td>
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<tr>
<td></td>
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<tr>
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### MAXIMUM DEPTH AND INTENSITY FOR SELECTED TIME INTERVALS

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</tr>
</tbody>
</table>

Tabulated by G.R. Lloyd 2/6/46
Computed by G.R. Lloyd 2/6/46
Checked by N.E. Minshall 5/13/46

Figure 1.31.—Record of low-intensity storms at Fennimore, Wis.
the accuracy of results. With high-speed printing and reading equipment, large volumes of data can be handled rapidly. Analytical techniques have been avoided because of the laborious and time-consuming computation procedures. These techniques can now be done quickly and easily, thus enhancing the use of a computer as a research tool. To make the best use of computer systems, however, carefully prepare tabulations of data.

Tabulation of data for computer analysis demands as much attention as data processed manually. For data to retain their usefulness, chart records and field notes should be documented systematically when transferring data to computer input.

Basic to the tabulation of data for computer analysis is an adequate knowledge of the computer system to be used and its capabilities and limitations. Different systems may require different methods of tabulation. Most computer systems have card input and output as their minimum basic requirement. More advanced systems have card, magnetic tape, and magnetic disk input-output devices. The minimum tabulation equipment requirement for most computers is a keypunch.

Daily rainfall values tabulated manually can be converted to punchcards, as shown in figure 1.35. As shown in figure 1.35, each card contains the watershed number, gage number, day, and a daily rainfall amount for the day for each month. Using this system, a year's worth of daily rainfall values will be contained on 31 cards. These data can be processed by computer to obtain watershed average rainfall, using the Thiessen or arithmetic methods.

The use of automatic chart readers has reduced the time for and improved the accuracy of tabulating rainfall data. Values of time and gage height are read automatically from rainfall charts and are punched onto cards. Figure 1.36 is an example of data tabulated by this method. The card deck shows complete tabulation of break point data for a storm. The code is used to indicate type of precipitation, estimation, type of reduction, and so forth. This method of tabulation is complete enough to
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<th>Date</th>
<th>Time (min)</th>
<th>Gage Reading (ft)</th>
<th>Gage Change (ft)</th>
<th>Liquid Density (%)</th>
<th>A Time (min)</th>
<th>Increase</th>
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No. of tube sections used... Comp. by... Checked by...
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<th>Apr</th>
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</table>

**Figure 1.35.** Manually tabulated data converted to punchcards.

**Figure 1.36.** Tabulation of rainfall data from chart reader.
allow reconstruction of the chart trace by replotting the punchcards. Computer computation follows the procedure used in manual computation.

Computer systems now in use have magnetic disk storage capabilities. Magnetic disks have the advantage of random access, which reduces processing time by increasing input-output speed. Data can be selected randomly from any section of the disk data file. Tabulation of data from cards to disk is advisable in analysis requiring sorting of data or continuous input-output operations. Data reduction can be read onto disk storage and used in a variety of analysis.

Tabulation of data on magnetic tape can be done in many formats. The most important factor, however, is the type of computer and tape drive available. Common magnetic tape drives used are 7 and 9 track. On some computers these drives are incompatible. Consult the computer manuals for limitation of formatting and tape-drive characteristics.

**Digital Methods**

With the advent of high-speed computers, the precipitation data processing routine has been revamped to take advantage of data-processing equipment. The punched paper tape record from the digital recording rain gage is designed for data reduction by automatic paper tape-to-magnetic tape or paper tape-to-punchcard translators. This translated record of the 16-channel punched paper tape is compatible with computer input equipment.

Automatic data processing necessarily imposes some standardization. For example, a given computer program is designed to accept input data in a particular format, and even the slightest deviation from this format will produce erroneous results. Equally important but not so apparent is that the efficiency of automatic data processing depends on adapting associated procedures to take advantage of the system. The digital recorder system is a new system and does not necessarily follow the procedures developed for manual methods. As new procedures are devised for translating and computing the records in a central location, procedures also should be developed in the field for using these changes.

Two features of the digital recording rain gage present special problems in data processing. First, the lack of a visual trace hampers the manual editing of the record for abnormalities. Thus, computer checks and visual editing of data listings at intermediate steps must be relied on more than was necessary for chart records. Second, the short interval of readout required to define precipitation patterns during a storm produces many more records than are necessary during nonstorm periods. Processing unnecessary data is expensive. Therefore, points not required should be deleted during tape translation or during the condense and edit program step. The original number of records required can be reduced by 95 to 99 percent and still maintain the original form of the data without any preconceived data analysis.

**Handling and Storage of Magnetic Tape**

Since increased quantities of hydrologic data are being stored on magnetic computer tape, the permanence and recoverability of this vital data are important. If data stored on magnetic tape are unrecoverable because of improper procedures or improper storage, the result could range from temporary inconvenience to complete failure of a research program.

Modern magnetic tape coatings can retain the information placed on them during the recording process for an infinity. The recorded information does not fade or weaken with age. It is essentially permanent and will remain unchanged until altered by an external magnetic field. The tape may be erased intentionally so that it can be used for another recording, or it can be erased accidentally by operator error or poor storage procedures.

The following sections outline basic considerations for prolonging tape life and assuring permanence and recoverability of stored information.

The area in which the tape is used should approach, as closely as is practicable, a "clean-room" environment, which does not have airborne dust and lint. Air-conditioning filtration systems are available for this cleaning.
The work area should be designed to control temperature and humidity. Variations of temperature should remain within ± 5°F (-21°C to -15°C) of a preselected value, and the relative humidity should remain within ± 10 percent. Generally, an environment that is comfortable for personnel is also suitable for tape. A temperature of about 70°F (21°C) and a relative humidity of about 40 percent are suitable.

Smoking should not be allowed because ashes can contaminate the tape. Food and drink should be prohibited. Minute food particles can be transmitted easily to the tape and tape transports from the operator's hands.

Shelves and floors of the computer area should be cleaned periodically. Floors should not be waxed because normal traffic abrades the wax, causing fine dust that could contaminate the room. When vacuum equipment is used for cleaning, the exhaust must be located outside the room.

Tape Storage

Temperature and humidity of the storage area should approach those of the work area. The smaller the environmental change experienced by the tape, the better will be its operation and reliability.

A tape is easily protected from accidental erasure in the storage area because fields strong enough to cause erasure normally are not found in an "office" atmosphere; a space as small as 3 inches also will protect a tape.

The hub is the strongest, most stable part of the reel. Reels always should be handled by their hubs, and in storage they should be supported by their hubs. Therefore, the reel should be returned to its canister before being stored. The canister is designed so that the reel actually hangs by the hub with no weight on the flanges. The canister also gives protection from dust.

Closed containers should be stored on edge so that their reels are upright. While they may be stored lying flat, the canisters never should be stacked so high that the bottom container can be distorted. This can damage the edge of the reel of tape in the bottom canister. For long-term storage, additional protection from dust and moisture can be gained by sealing the canister in a plastic bag.

To store more tape in a given area (reducing storage cost per unit), a plastic ring or collar may be used that wraps around the outer diameter of the reel. This allows the reel to be hung in the storage facility without the use of a standard canister.

While this device will suffice in many applications, its use is a tradeoff. Additional space is gained for storage, but the reel is supported by the flanges rather than the hub. The plastic ring or collar may seal well enough to prevent dust from settling on the tape during storage, but the outer surface of both flanges may accumulate dust.

Care in preparing tapes for storage is just as important as the excellence of the storage area. How the tape is wound on the reel is important because poor winding can distort the tape's backing.

Relatively low wind tension should be used. Six to 8 ounces per half inch of tape width (177 to 207 ml per 1.5 cm) will insure a firm, stable wind. This tension will not cause high pressures that could permanently distort the polyester backing within the roll. Backing distortion caused by extreme pressures within the tape pack may result if a roll of tape wound too tightly is subjected to an increase in temperature.

If the tension of the tape is too loose, slippage can occur between the layers on the reel. This can distort the tape by causing a series of creases or folds in the area that has slipped. When the roll is unwound, the surface will be wrinkled, which disrupts the necessary intimate contact between the tape and the head, resulting in continuous errors. If the tape is rewound properly immediately after cinching, the information may be saved.

Quality of wind is also important. The successive layers of tape should be placed on the reel so that they form a smooth wind with no individual tape strands exposed. A smooth wind offers built-in edge protection. A scattered wind allows individual tape edges to protrude above the others. Since these exposed edges have no support, they may be damaged.

Tapes in storage should be rewound at specific intervals, such as every 6 to 12 months, to
relieve internal pressures. Modern tapes with polyester backings and advanced binders, may not require periodic rewinding.

A good practice is to select a random sample of reels from the tape library for visual inspection. Examine these reels for loose winds and dust accumulations. Check for rippled edges and other signs of physical distortion. If anything indicates a problem, inspect additional samples to ascertain the percentage of the library that may be affected.

### Tape Handling

The tape should be protected while being transported. The outer shipping container into which the canisters are placed must have enough strength and rigidity to protect the tapes from damage caused by dropping or crushing. A container must be resistant to water. The free end of the tape reel should be secured by both a holddown sponge and a vinyl strip.

Since the tape carries magnetic information, the reels must be protected from accidental erasure. Tests have determined that magnetic field strengths of 50 oersteds or less within the tape cause no discernible erasure. Tape in shipment can be subjected to sources of magnetic energy such as motors, generators, and transformers. These devices are designed to contain their magnetic fields to accomplish some type of work. Thus, field strengths of more than 1,500 oersteds would not be encountered in ordinary shipping.

Because field intensity decreases rapidly with distance from the source, a magnetic strength of 50 oersteds (mentioned previously as not affecting the tape) is reached at a distance of 2.7 inches (6.9 cm) from a 1,500-oersted source. Thus, the easiest and least costly method of protecting tapes from erasure is by insuring some physical spacing from the magnetic source.

Tape prepared for shipment should be packed with bulk spacing material such as wood or cardboard between the canisters and the outer shipping container. Normally, 3 inches (7.6 cm) of bulk spacing will protect the tape from erasure. This magnetically protective spacing also protects the tape from physical damage.

Tape in transit may be subjected to extremes in temperatures as low as −40°F (−40°C) which might be encountered in the cargo hold of aircraft. A temperature of 120°F (48°C) easily could be encountered in a motor vehicle in the summer sun. All incoming tape should be allowed to reach environmental equilibrium before being used.

The tape canister is probably the cleanest area in the computer center. Thus, tapes should remain in their canisters until they are placed on the tape drive and should be returned to their canisters immediately after use. To maintain a clean canister, its cover should be replaced when the tape has been removed. The canister should not be opened outside of the clean-room environment.

Tape contamination caused by fingerprints can be reduced by touching the tape only when necessary. Contamination can be eliminated by using lint-free gloves. Frequent cleaning of the tape drive will reduce the chance of spreading contamination from one reel of tape to another. A lint-free pad moistened with Genesolve-D (an Allied Chemical trademark), Freon TF (a DuPont trademark), or a similar cleaner is recommended for cleaning all elements of the tape path on the handler. If other cleaning agents are used, make certain the tape drive is thoroughly dry before loading the tape. This will prevent the cleaner from damaging the tape.

Empty reels should be inspected and cleaned thoroughly before tape is wound on them for storage. Reels with dirty hubs or with hub damage, such as a plastic burr, can cause tape distortion.

When this tape starts and stops, the individual tape layers can shift, causing severe cinching. Cinching also can happen if a carton of very cold tape is dropped or handled roughly. Incoming tape must stabilize for 24 hours before it is used. Do not use artificial means to hasten this period.

One of the most serious and more common forms of tape failure is categorized as edge damage. Damaged edges can be caused by the reel, tape drive, or operator. A broken or badly distorted reel can quickly damage a tape. The effect of a broken or cracked flange is noticed easily because the tape will have nicks or mutilated areas along one edge. The cause can
be detected easily because of the obvious defect in the reel.

A warped or distorted reel also can damage one or both edges as the tape rubs against the flange when used. Similar damage will occur if the transport is misaligned. Either of these faults can destroy a roll of tape. The edge track will be lost, and the debris from the edge damage can be redeposited onto the surface of the tape. Edges of the tape will show an accumulation of loose polyester fibers and oxide.

Operators should inspect the transport around the guides and heads for excessive buildup of oxide or backing debris. This deposit is generally the first clue that something is wrong. Excessive errors on an edge track also may indicate an alignment problem.

A temperature greater than 130°F (54°C) and a relative humidity above 85 percent may cause layer-to-layer adhesion and some physical distortion.

To prevent fire, store the tape in a noncombustible area and make sure that no combustible materials are stored in the vicinity. A noncombustible area would be a room with metal shelves and sheet-metal walls. For maximum fire security, store magnetic tape in a fireproof vault that can maintain a desirable internal temperature and relative humidity for a reasonable time.

**DATA PROCESSING**

Hydrologic performance of a watershed is the integrated result of phenomena at locations within the watershed. Therefore, data processing is necessary to evaluate or show orientation of the records. For example, watershed rainfall, areal distribution, and storm travel are evaluated from records at several measuring sites properly oriented in time and space.

This section is concerned with the preparation of basic summaries for analyses. Some procedures provide running summaries to keep personnel abreast of their subject. Others are adopted standards for certain publications of hydrologic data. This section is incomplete in its coverage; new and improved techniques and procedures are already in evidence. The material presented demonstrates the advantages of maintaining current summaries of all phenomena related to the subject.

Data reduction gives methods for taking data from the charts and field notes and for computing intensities and daily totals. Data must be further processed for hydrologic analyses. Processing should permit statistical analysis of "point rainfall" characteristics, such as hourly, daily, monthly, and annual totals, and maximum intensities for selected intervals. Since complete records are essential for certain analyses, missing records must be substituted by the most reliable estimate possible.

**Selected Rain Gages**

When several small watersheds are grouped closely, rainfall often can be measured by one recording rain gage. On larger areas containing several recording and nonrecording gages, cursory analyses may be desirable to select one recording gage that will approximate the average measurement on the area. When only one gage is on or near the watershed or a strategically located gage represents the precipitation on the area, a complete record of this station is necessary. If the record is incomplete, the missing part should be estimated through comparison with an adjacent gage or gages. Figure 1.37 illustrates how hourly, daily, and monthly precipitation can be tabulated. The quantity is tabulated at the end of each hour; that is, the total between 4 o'clock and 5 o'clock would be shown under 5 o'clock. Summation of the hourly values shown on the right side of the sheet gives the daily total. Daily totals for each month are transferred to a sheet similar to figure 1.38, which shows the monthly and annual rainfall distribution totals.

Daily totals of precipitation from figure 1.38 are plotted in figure 1.39. Seasonal distribution of precipitation and runoff, and the type of precipitation (snow, sleet, and rain) also are shown in figure 1.39. This graph and informa-
### CLIMATIC DATA

**STATION** R-6, Fennimore, Wisconsin

#### Hourly Precipitation August, 1943

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#### Figure 1.37
Data sheet for hourly precipitation totals for a month at Fennimore, Wis.

Data on cover and tillage will indicate the condition on the watershed at any period. The vertical scale should be as large as possible, yet should anticipate ample capacity for any year of record without the necessity of using a folded scale. Awkward scales, such as 30, 60, or 75 parts to the inch, should be avoided in favor of 5, 10, 20, 50, or 100 parts to the inch.

In addition to these summaries, several outstanding storms each year should be shown in sufficient detail to permit evaluation of such factors as detention, retention, and infiltration of precipitation.

Table 1.3 is an example of daily rainfall tabulations. A computer was used to check, print, and compute monthly and annual totals, as well as the daily rainfall amounts.

Table 1.4 is an example of computer-compiled average rainfall for watershed 121, Chickasha, Okla. Average rainfall for the watershed was calculated and printed. These forms and the corresponding mean daily flow from the watershed were posted.

The mass curve of precipitation for the selected gage is a plotting of depths versus time, either directly from the recording rain-gage chart or tabulated data. Plotting for the storm of August 12, 1943, station R-6, on watershed W-2, Fennimore, Wis., is shown in figure 1.40. The slope of the mass curve at any point will give the rainfall intensity at that particular time. The mass curve is a straight line in some sections and curvilinear in others. Intensities for the curvilinear part are represented by a
pluviograph, and the straight line section is represented by a histogram.

**Spatial Distribution**

Isohyetal mapping is the most basic method of representing spatial distribution of precipitation.

Figure 1.41 shows computer methods of summarizing watershed rainfall data. Daily rainfall amounts are given for each of the 168 rain-gage networks at Chickasha, Okla. A table of watershed rainfall analyses in the upper right-hand corner helps interpretation of the map. It provides a quick and easy method for visualizing the area distribution of daily rainfall. Other variables of rainfall can be plotted similarly.

On larger watersheds, rainfall during thunderstorms often is distributed unequally. If rainfall records are available at several stations, the average precipitation may be determined by several methods. Methods are the same whether the average is required for complete storms, partial storms, or daily totals. The storm of August 12, 1943, on watershed W-1, Fennimore, Wis., is used to illustrate these methods (fig. 1.42).

For a prolonged storm with more than one period of high intensity, the average rainfall may need to be determined for part or for all of...
FIGURE 1.39.—Chart showing daily and seasonal distribution of precipitation and runoff, Fennimore, Wis.

Precipitation & Runoff
Storm of August 12, 1943
Watershed W-2
Fennimore, Wisconsin

Antecedent Precipitation & Runoff

<table>
<thead>
<tr>
<th>Date</th>
<th>Precipitation Inches</th>
<th>Runoff Inches</th>
<th>% of Area</th>
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<tbody>
<tr>
<td>August 9</td>
<td>0.16</td>
<td>0.0</td>
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<td>2</td>
<td>0.12</td>
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Crop Cover

- Corn 7
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Runoff Hydrograph

Mass Runoff

Mass Rainfall Station R-6

FIGURE 1.40.—Chart and computations of the precipitation and runoff from a storm at Fennimore, Wis.
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the storm. This is also true when the period
causing runoff can be separated from the rest
of the storm.

**Isohyetal Method**

The isohyetal method is the most laborious of
the three methods, but it is generally more
accurate than either of the other two methods,
especially where distribution of rain gages is
not uniform. For the isolyetal method, the
procedure is:

- On a base map of the area (fig. 1.42), locate
  all rainfall stations and record the amount of
  precipitation at each station. Draw isohyets
  (lines of equal rainfall) by proportioning the
distances between the adjacent gages according
to the differences in catch. Stations near or
outside of the watershed boundary facilitate
drawing the isohyets.

**Table 1.4—Watershed average rainfall calculated by computer methods**

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</table>

**Total**

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<td></td>
<td>2.00</td>
<td>1.00</td>
<td>0.94</td>
<td>3.26</td>
<td>5.69</td>
<td>3.19</td>
<td>3.80</td>
<td>4.07</td>
<td>4.10</td>
<td>1.75</td>
<td>5.00</td>
<td>1.53</td>
</tr>
</tbody>
</table>

**Notes**

Yearly precipitation 36.33 inches. Precipitation values are a Thiessen-weighted average of 32 gages on the watershed.
• Prepare a table similar to table 1.5 and enter the depth represented by the isohyetal on each side of a strip in columns 1 and 2. Enter the average depth between isohyetals in column 3.

• Measure the areas between the isohyetals within the watershed boundaries with a planimeter and record these measurements in column 4. Convert these measurements to acres and enter them in column 5.

• Multiply the average depth by the area column 3 times column 5 and enter the products in column 6.

• Add columns 5 and 6.

FIGURE 1.41.—Daily rainfall values mapped by a computer and overlayed with an outline of the watershed.
• Divide the total depth-area product of column 6 by the total area of column 5 to get the average depth of precipitation.

**Thiessen Method**

The Thiessen method involves determining an area of influence for each station rather than assuming a straight-line variation between stations, as was done for the isohyetal method. Although the Thiessen method usually is not as accurate as the isohyetal method, it is easier. When several average depths are to be computed for areas in which the number and location of rainfall stations remain unchanged, proceed as follows:

- Locate the rainfall stations on a base map of the area (fig. 1.43).
- Connect each station by straight lines with the several nearest stations to form a series of triangles. Erect perpendicular bisectors on each of these lines and extend them to intersect with other bisectors, thus forming a series of irregular polygons around each station.
- Measure the area of each polygon with a planimeter and record the areas as in table 1.6.
- Divide the area in each polygon by the total area in the watershed to obtain the fraction of the total watershed area lying within each polygon. These fractions are constants to be applied to the catch at the respective station in computing the weighted average rainfall over the watershed for the period considered.

- In table 1.7, columns 1 and 2, record the station numbers and the Thiessen constants.
- Enter in columns 3, 5, 7, and so forth the amounts of rainfall at each station for the parts of the storm for which average rainfall is to be computed.
- Multiply the depths listed in columns 3, 5,

![Figure 1.43.—Map showing Thiessen method of computing polygons.](image-url)
TABLE 1.7—Average rainfall computed by the Thiessen method for a watershed at Fennimore, Wis.

Fennimore, Wis., Watershed W-1
August 12, 1943

<table>
<thead>
<tr>
<th>Rainfall station No.</th>
<th>Thiessen constant</th>
<th>Prior to 4:48</th>
<th>4:48 to 5:15</th>
<th>Entire storm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inches</td>
<td>Inches</td>
<td>Inches</td>
<td>Inches</td>
</tr>
<tr>
<td>R-1</td>
<td>.0144</td>
<td>.105</td>
<td>.218</td>
<td>.350</td>
</tr>
<tr>
<td>R-2</td>
<td>.110</td>
<td>.105</td>
<td>.196</td>
<td>.216</td>
</tr>
<tr>
<td>R-3</td>
<td>.104</td>
<td>.104</td>
<td>.213</td>
<td>.222</td>
</tr>
<tr>
<td>R-4</td>
<td>.133</td>
<td>.109</td>
<td>.203</td>
<td>.270</td>
</tr>
<tr>
<td>R-5</td>
<td>.132</td>
<td>.110</td>
<td>.145</td>
<td>.284</td>
</tr>
<tr>
<td>R-6</td>
<td>.113</td>
<td>.105</td>
<td>.119</td>
<td>.238</td>
</tr>
<tr>
<td>R-7</td>
<td>.064</td>
<td>.106</td>
<td>.106</td>
<td>.138</td>
</tr>
<tr>
<td>R-8</td>
<td>.055</td>
<td>.105</td>
<td>.110</td>
<td>.245</td>
</tr>
<tr>
<td>R-9</td>
<td>.095</td>
<td>.115</td>
<td>.109</td>
<td>.217</td>
</tr>
<tr>
<td>Total</td>
<td>1.00</td>
<td>9.50</td>
<td>10.53</td>
<td>19.32</td>
</tr>
<tr>
<td>Average</td>
<td>.056</td>
<td>.2147</td>
<td>.3502</td>
<td>.3495</td>
</tr>
</tbody>
</table>

7, and so forth by the Thiessen constant of column 2 and enter these data in columns 4, 6, 8, and so forth.

- Add columns 4, 6, 8, and so forth to get the average precipitation for the various periods.

**Arithmetic Average Method**

This is the simplest method for estimating the average rainfall on a watershed, but accuracy requires a fairly uniform distribution of the rainfall stations. Add the values for all stations and divide by the number of stations. Averages thus obtained also are shown in table 1.7. Close agreement between the three methods for the particular storm selected is probably the result of the relatively uniform spacing of rainfall stations on this area and the small percentage difference between the maximum and minimum measured amounts for the storm. When the rainfall stations are distributed uniformly and no orographic influences are present, as in the example given, the extra work involved in the Thiessen or isohyetal method generally is unnecessary.

**Storm Studies**

Popular methods of analysis require that watershed rainfall be represented as an area average for comparison with the runoff record. This may be an average curve of rainfall accumulation, an average catch for a specified period, or an average intensity.

**Mass Curve**

The simplest method of getting an average mass curve, and one that often will be sufficiently accurate, is to select the station that most nearly represents the average catch at several times within the storm. Table 1.8 shows that for the storm of August 12, 1943, the catch at station 7 agrees closely with the average catch for the total and the two intermediate points. Therefore, data from station 7 represent watershed rainfall for most analyses of this storm.

Since the distribution of precipitation may not be uniform or the rainfall pattern may vary widely between gages, there may be no gage
that represents the average pattern. Therefore, an average curve must be drawn, taking all gages into account. The suggested method is to list the times for one gage then pick depths at each of the other gages for each of these times. Average the times arithmetically for a good distribution of gages or use the Thiessen method where the spacing of gages is uneven. The storm of August 12, 1943, was tabulated in detail for station R-4 on figure 1.44. Periods of low intensity during this storm probably do not warrant as much detail as was used in this figure because all the runoff came from rainfall that occurred between 4:48 and 5:15. Data are shown in figure 1.44. It will be seen that R-7 closely agrees with the average values obtained. More work would be required to apply the Thiessen method. A good distribution of stations saves time in preparing the data for analysis.

**Isohyets**

If the storm has more than one period of high intensity, each of which caused an independent rise in the hydrograph, or if one period produced runoff from only a part of the area so that the amount of runoff resulting from each such period can be readily computed, construction of isohyetal maps usually is advantageous for these storm increments. For example, in the storm of August 12, 1943, all runoff occurred as the result of the rain from 4:48 to 5:15. Therefore, an isohyetal map is desirable for this part of the storm.

---

**TABLE 1.8—Time distribution of rainfall at different gages and average distribution of all gages for a storm at Fennimore, Wis.**

<table>
<thead>
<tr>
<th>Time</th>
<th>R-1</th>
<th>R-2</th>
<th>R-3</th>
<th>R-4</th>
<th>R-5</th>
<th>R-6</th>
<th>R-7</th>
<th>R-8</th>
<th>R-9</th>
<th>Arithmetic average</th>
</tr>
</thead>
<tbody>
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<td>0</td>
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<td>3.00</td>
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<td>3.50</td>
<td>3.70</td>
<td>3.73</td>
<td>3.50</td>
</tr>
</tbody>
</table>
Frequencies

Frequency of rainfall is an important climatic characteristic. References for rainfall frequencies include Beard (3), Chow (5), and U.S. Weather Bureau Technical Paper 40 (38).

Intensities

Incremental intensity data from rain-gage charts can be tabulated and calculated by manual and computer methods. These methods are quite similar, but they differ in the machine technique used for calculation. If the same input data are used, however, both methods should give the same results. The suggested method for calculating incremental intensities is:

- Enter in column 3 of the forms illustrated in figures 1.31 and 1.44 the difference in minutes between successive time entries in column 2.
- Enter in column 5 the difference between successive entries in column 4.
- Show hourly totals in column 6 for those stations reporting amounts for regular intervals.
- Enter in column 7 the intensity for each time interval, which is obtained by dividing the values in column 5 by the time interval of column 3 and multiplying by 60. A slide rule will give sufficient accuracy for this computation and table of intensities (table 1.9) may simplify the computation. In using this table to determine intensities where depths exceed 0.10 inch (0.25 cm), add the values of two or more columns such as the 10-minute intensity for depths of 0.60 inch (1.52 cm) and 0.03 inch (0.08 cm) or 3.60 + 0.18 = 3.78 in/hr (9.6 cm/hr).
- Fill in the maximum depth and intensity at the bottom of the forms for those storms that have intensities given in column 7. This is done by checking column 7 to find maximum depths for the highest intensities for the various durations. Interpolation may be necessary between the times and depths actually tabulated. For example, in table 1.4 (p. 62) the duration of the three maximum intensities in column 7 is only 9 minutes from 4:51 to 5:00. Total depth during this period is 1.07 inches (2.72 cm), to which the 1 minute amount from 5:00 to 5:01 must be added, or one-fifth of 0.41, giving a total of 1.15 inches (2.92 cm). From table 1.9 the maximum 10-minute intensity obtained is 6.00 + 0.60 + 0.30 = 6.90 inches per hour (17.53 cm/hr).
- Enter "snow" or "rain began" or "ended" in column 9, opposite the proper time in column 2. Column 9 also is used to record the total daily precipitation and descriptive information such as "hail" or "sleet."
- Enter the name of the person making the computations and the date at the bottom of the form.

Using the tabulated data shown in figure 1.35 (p. 52) for the storm of April 9, 1967, on watershed 311, Chickasha, Okla., incremental intensity and selected clock hour interval data for gage number 60 can be calculated by electronic computer. The resulting computer printout of the output card data is shown in figure 1.45. Calculation by this program follows the suggested manual method with a few exceptions. Select time interval intensities are computed for 15- and 30-minute clock intervals. The
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last column shows the output card code. A code 6 represents the breakpoint intensities. Code 7 designates the clock hour interval intensity.

Figure 1.46 shows an abbreviated flow chart of the computer methods of calculation. Storms can be stacked one after another and processed by this method. The output cards can be sorted for further analysis requirements or tabulated on forms similar to that illustrated in figure 1.31, p. 49.

**Snow Course**

Snow-course data may be analyzed for several purposes. Processing requirements must fit the specific need. Some common uses are discussed in this section.

Spacial variations in the snowpack over a basin are important in computing the water storage and the potential runoff from snowmelt. Snow-course data can be used to study the effects of elevation, cover, slope, and aspect on the distribution of snowfall. Data also may show how the redistribution of snow on the ground is affected by the same factors. The effects of these factors vary from one location to another. A good understanding of these effects may be helpful in understanding the hydrology of an area.

Snow-course data are often invaluable in studying snowmelt. Snowmelt is analogous to rainfall in supplying water for infiltration and all runoff except the additional storage and lag of the snowmelt by the snowpack. When no precipitation is involved, differences in a series of measurements of water equivalent to the snowpack are analogous to increments of rainfall. Only in rare cases are these measurements a satisfactory measure of snowmelt. The snow-course data may be used to give relative magnitude of snowmelt under various combinations of elevation, cover, slope, and aspect. The timing of snowmelt, as it is influenced by these factors, also can be determined from snow-course data. The effects of these factors will depend on the sources of snowmelt energy. For example, when snowmelt is absorbed by solar radiation, the influence of slope, aspect, and

![Figure 1.45.—A printout of computer-processed rainfall increments and intensities.](image-url)
cover will be important. When most energy is supplied by condensation, these factors probably will be unimportant.

For winter records, all phenomena affecting the relation between depth and water content of the snow blanket and the rate of snowmelt can be placed on one graph (fig. 1.47). On this graph maximum and minimum air temperatures are given, rather than the mean daily temperature, since the average can be less than 32° F (0° C) and still cause thawing during part of the day. Scales on these graphs should show all important fluctuations and give ample capacity for the expected range in any future record. In addition to the data shown in figure 1.47, solar radiation and evaporation should be included if these data are available.
Figure 1.47.—Charts of related hydrologic phenomena for Spirit River station above Spirit Falls, Wis.
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INTRODUCTION

The objectives of a study influence selection of a runoff measuring device. For example, if a water budget is studied in an area where runoff accounts for only about 5 percent of the water budget, 95 percent of the funds should not be spent on measurement of runoff. More funds should be directed to other parts of the hydrologic cycle. If the objective of a study, on the other hand, is to measure the effect of land treatment on the water supply derived from a watershed, a precalibrated runoff measuring device would be required. Less funds and time should be directed to other parts of the hydrologic cycle.

This chapter provides guidance on selecting devices for measuring runoff. It also provides guidance on types of recorders, field installation and maintenance of a station, and how to process data.

INSTALLATIONS

Selection of a device for measuring runoff depends on such factors as the peak runoff rate; distribution of runoff volume by categories of flow rate; absence or presence of sediment or woody trash, or both, in the flow; whether backwater submergence will affect flow through the device; icing conditions; foundation conditions; material availability; and economics.

The term "runoff" normally is used to distinguish surface flows from ground-water contributions to a streamflow. This distinction generally is derived through analysis of hydrographs since independent measurement is not feasible. The terms "runoff" and "streamflow" are used interchangeably here. They refer to all the flow, regardless of origin, that passes through the control at the point of measurement.

Selection of Gaging Station Control

In open channels, a control is a cross section or length of reach above which the water level is a stable index of the discharge rate. All sections have equal capacity to pass a flow. In natural streams the control may shift from one point to another with changes in stage. For use as a runoff station, a control must be selected, altered, or constructed to provide a stable head-discharge relationship.

Many conditions influence selection of a control for flow measurements. The ultimate objective is to provide a stable relationship between the depth of water and the rate of flow. Since the rate of flow equals the product of average velocity and the cross-sectional area, controls should be selected for stability of cross section and such factors as slope; configuration; channel roughness; and absence of tailwater, which affects velocity.

Quantitative evaluation of flow is easier if the flow passes from subcritical to supercritical around the control section. Precalibrated devices use this advantage. Natural controls that maintain critical flow at all stages are unusual. They are selected, therefore, to provide subcritical velocities at all depths since changes in depth are approximately equal to changes in specific energy. Measurement of flow at critical depth should be avoided since it presents so many difficulties. This sometimes can be accomplished by converting to subcritical flow through impoundment or manipulation of the channel gradient. The flow subsequently can pass through critical downstream of the point of head measurement.

For some purposes the control must be located so that gaged streamflow represents the entire flow from the watershed—none escapes beneath or around the control. Cutoff walls extending vertically in impervious strata and
laterally in floodplains may be needed to prevent flow from bypassing the gaging station. Bypassing flow may be unimportant for some studies and at some locations.

Other considerations in selecting a control include capacity needed for major flows; silt, ice, and debris content of expected flows; and structural requirements such as footings and protection against frost heaving. Controls are classified herein as (1) precalibrated devices, (2) existing structures adapted to calibration, and (3) natural controls, such as cross sections or channel reaches with suitable hydraulic characteristics for calibration. Procedures for each class will be given.

A flow chart to assist in selecting a runoff measuring device is shown in figure 2.1. Although other criteria besides size may be used in selection, the use of size is convenient. Thus, the primary key to the flow chart is the maximum discharge rate to be selected. The flow chart provides paths based on the absence or presence of debris, type of flow in the approach channel, whether ponding is allowed, whether backwater problems are anticipated, and, finally, the type of stream and flow characteristics (perennial streams have relatively long, constant requirements for measuring base flow). Although a flow chart is a quick reference, the following material should be checked carefully to ensure selection of the best measuring device for the flow conditions encountered.

Precalibrated Devices for Measuring Runoff

Devices for measuring runoff usually are selected to meet specific needs at each location. Runoff should be measured as accurately as possible at low, medium, and high rates of discharge. Flow occurs on some watersheds only as the result of occasional storms of high intensity. Other watersheds have continuous flow.

Wherever possible, precalibrated devices should be used to gage the entire flow. For large watersheds, precalibrated devices large enough to gage high rates of flow may not be feasible. Instead, a precalibrated device may be needed to measure low flows and current-meter measurements may be needed to establish the high part of the stage-discharge relationship.

Weirs

A weir is a low dam or overflow structure built across an open channel. It has a specific size and shape with a unique free-flow, head-discharge relationship. The edge or surface over which the water flows is called the crest. Discharge rates are determined by measuring the vertical distance from the crest to the water surface in the pool upstream from the crest. When the water level in the downstream channel is sufficiently below the crest to allow free aeration of the nappe (the thin sheet of water falling over the crest), the flow is said to be free. If the nappe is partially under water, the weir is said to be submerged and the head-discharge relationship may not be unique. If submergence is permitted, special head-discharge computations may be necessary and accuracy of measuring the flow may be reduced. Do not install weirs for measuring runoff sites where concentrations of sediment exceed low values.

Many formulas and shapes and sizes of weirs are used to compute the discharge rate. Some commonly used weirs will be described here.

Sharp-Edged Weirs

Kindsvater and others (22) developed a method for computing rates of flow over rectangular, sharp-edged weirs. Their method includes both suppressed and unsuppressed free-discharge weirs with correction factors for approach velocity. These factors change with the ratio of crest length to approach channel width and with the ratio of head-to-crest height above the bottom of the approach channel or weir box.

V-notched Weirs

Triangular or V-notched weirs measure low discharges more accurately than horizontal weirs. The V-notch is usually a 90° opening with the sides of the notch inclined 45° with the vertical. The approach velocity can be neglected if the minimum distance from the weir to the channel banks is at least twice the head and if the minimum distance from the channel bottom to the crest is at least twice the head.
FIGURE 2.1.—Selection guide for measuring runoff.
FIGURE 2.1.—Selection guide for measuring runoff.
**Broad-Crested V-Notched Weirs**

Sharp-crested V-notched weirs are difficult to maintain if they are used to obtain discharge records for long periods. They may become dull due to impact from ice or drift (11). Broad-crested V-notched weirs, over which ice and debris pass without damage, are desirable for measuring runoff over long periods. These are called triangular weirs.

Triangular weirs with 2-to-1, 3-to-1, 5-to-1, and 10-to-1 crests measure flows larger than 1,000 ft³/s (7.9 l/s). A 3-to-1 triangular weir installation is shown in figure 2.2. The recorder for water stages is located on a stilling well 10 feet (3 m) upstream from the weir. A reasonably straight channel that is level for 50 feet (15 m) above the weir is essential for accuracy. The notch must be 6 inches (15.2 cm) above the bottom of the channel.

Cross-sectional dimensions are given in figure 2.3. A weir of this size needs a substantial apron of concrete for about 12 feet (3.7 m) downstream from the weir, 2 feet (0.61 m) below the notch, and 20 feet (61 m) across the channel. A 3-foot (0.91 m) (plus) end cutoff wall also is needed to prevent the weir from being undermined. The middle 10-foot (3 m) width of this apron is level, and the two 5-foot (1.5 m) sides are sloped slightly more than the weir crest.

Calibration of these weirs, as given in table 2.1, is affected by the approach velocity. The cross-sectional area of the approach channel 10 feet (3 m) upstream from the weir at the point of recording gage heights, is a measure of the approach velocity. Table 2.1 supplies discharge figures at each foot of head from 1 to 6 feet (0.3 to 1.8 m) for several areas of cross section. For example, the discharge for a 3-to-1 weir at 2-foot (0.61 m) head and a section area of 40 ft² (3.7 m²) is 48.7 ft³/s (380 cm³/s). For an area of 62 ft² (5.76 m²) the discharge is 47.5 ft³/s (379 cm³/s).
The basic expression for discharge through a V-notch neglecting velocity of approach is:

\[ Q = C' \tan \frac{\theta}{2} H^{2.5} \]  \hspace{1cm} (2-1)

\[ = C' \frac{8}{15} \sqrt{2g} \tan \frac{\theta}{2} H^{2.5} \]

where

- \( Q \) = discharge (ft\(^3\)/s);
- \( C' \) = coefficient correcting for energy loss and contraction of the jet;
- \( C' = \frac{8}{15} \sqrt{2g} C \);
- \( \theta \) = total angle of V-notch opening (for 90°, \( \tan \theta/2 = 1.0 \));
- \( H \) = head above the lowest point of the V-notch (ft); and
- \( g \) = gravitational acceleration (ft/s\(^2\)).

Most engineers consider the experimental work of Cone (11) very reliable. His formula for the 90° V-notch weir is:

\[ Q = 2.49 H^{2.48} \]  \hspace{1cm} (2-2)

where

- \( Q \) = discharge (ft\(^3\)/s); and
- \( H \) = head above lowest point of V-notch (ft).

Equation 2.2 can be generalized for values of \( \theta \) between 60° and 90° by adding the \( \tan \frac{\theta}{2} \) term.
Q = 2.49 \tan \frac{\theta}{2} H^{2.48} \quad (2-3)

for heads between 0.2 and 2.0 feet. The same equation in metric units would be:

\[ Q_m = 1.342 \tan \frac{\theta}{2} H_m^{2.48} \quad (2-4) \]

where

\[ Q_m = \text{discharge (cubic meters per second)}; \]
\[ H_m = \text{head above the lowest point in the V-notch (meters)}. \]

Likewise, this equation is accurate (1 percent) for \( \theta \) between 60° and 90° with heads between 0.06 and 0.6 meter.

For angles smaller than 60°, the experimental results reported by Lenz \(24^e\) should be used. The water-discharge equation without any correction for temperature is:

\[ Q_I = \left( 2.395 + \frac{N}{H} \right) \tan \frac{\theta}{2} H^{2.5} \quad (2-5) \]

For a water temperature of 70°:

\[ N = 0.035 + 0.033 \left( \tan \frac{\theta}{2} \right)^{-0.8} \quad \text{and} \]
\[ e = 0.2475 \left( \tan \frac{\theta}{2} \right)^{0.09} + 0.340 \left( \tan \frac{\theta}{2} \right)^{-0.05} \]

This formula is recommended for 0 angles between 28° and 90°. The value of \( N/H \) always should be equal to or less than 0.09. If the weir is installed with complete contraction, the approach velocity will be low and can be neglected in the head-discharge relationship.

The value of discharge, \( Q \), equation 2-5, expressed in cubic meters per second would be:

\[ Q_m = \left( 1.322 + \frac{0.522 N}{3.281 H_m} \right) \tan \frac{\theta}{2} H_m^{2.5} \quad (2-6) \]

where

\[ H_m = \text{head in meters}; \]
\[ N = 0.035 + 0.033 \left( \tan \frac{\theta}{2} \right)^{-0.8} \quad \text{and} \]
\[ e = 0.2475 \left( \tan \frac{\theta}{2} \right)^{0.09} + 0.340 \left( \tan \frac{\theta}{2} \right)^{-0.05} \]

The term 0.522 \( N/(3.281 H_m) \) always should have a value equal to or less than 0.05.

The stage-discharge relation is approximated by use of the equations in figure 2.3. Whenever practical, make current-meter measurements to check this calibration. Any large cutting or filling changes in the approach cross section may require a revision of the calibration.

Rating values for heads between 0.2 and 0.8 foot may be obtained by

\[ Q = \left[ 2.51 + 0.0066 \tan \frac{\theta}{2} \right. \]
\[ + \left. \left[ 0.3292 + 0.5074/tan \frac{\theta}{2} \right] \log_{10} H \right] \tan \frac{\theta}{2} H^{2.5} \quad (2-7) \]

where

\[ Q = \text{discharge, cubic feet per second (ft}^3/\text{s}); \]
\[ \theta = \text{Total angle of V notch (tan} \frac{\theta}{2} = S \text{ in fig. 2.3}); \]
\[ H = \text{head above the point of zero flow on the V-notch, feet}. \]

This equation is based on full-scale tests with negligible approach velocity. These tests were run in the SEA hydraulic laboratory at Stillwater, Okla. Tan \( \frac{\theta}{2} \) varied between 2 and 10.

The same equation for discharge in cubic meters per second for \( H_m \) between 0.06 and 0.3 meter is:

\[ Q_m = 1.4795 + 0.003644 \tan \frac{\theta}{2} + \frac{0.1445}{\tan \frac{\theta}{2}} \]
\[ + \left( 0.18175 + \frac{0.28013}{\tan \frac{\theta}{2}} \right) \log_{10} H \tan \frac{\theta}{2} H_m^{2.5} \quad (2-8) \]

**Drop-Box Weirs**

The drop-box weir was modeled at Washington State University. Use of this weir to improve the accuracy of measuring water under heavy sediment load and varying conditions of approach was reported by Copp and Tinney
### Table 2.1—Discharge values corresponding to various cross-sectional areas of the channel of approach 10 feet upstream from center of crest for triangular weirs

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#### 3:1 Triangular Weirs

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### Footnotes

1. The values are approximate and should be used for design purposes only.

### Additional Notes

- The discharge values are calculated using the formula $Q = 0.0104A^{1.5}$.9
- The area values are in square feet ($F_t$).
- The discharge values are in cubic feet per second ($F_t^{1/3}$).

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### References

### TABLE 2.1—Discharge values corresponding to various cross-sectional areas of the channel of approach 10 feet upstream from center of crest for triangular weirs

3:1 TRIANGULAR WEIRS—Con.

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5:1 TRIANGULAR WEIRS

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Based on hydraulic laboratory tests made by the Soil Conservation Service at Cornell University, Ithaca, N.Y.

\( Q/D^{2.5} = 1.67 \sqrt[3]{gH_i/D}^{3.00} \) \hspace{1cm} (2-9)

or:

\[ Q = \frac{1.67 \sqrt{gH_i/D}}{\sqrt[3]{D}} \] \hspace{1cm} (2-10)

where

- \( Q \) = discharge, (ft\(^3\)/s);
- \( g \) = acceleration due to gravity (ft/s);
- \( H_i \) = head measured at gage 4 (fig. 2.3), feet; and
- \( D \) = depth of 1-to-1 V-section, feet.

Equation 2-10 has a range of \( H_i/D \) values between 0.25 and 0.7. Precalibration tests are unnecessary for flow within this range. Field

(13) Johnson, Copp, and Tinney (21) reported on field experience with the drop-box weir in the Reynolds Creek Experimental Watershed. This weir is shown in figure 2.4.

The depth of the 1-to-1 V-notch weir was used to provide dimensionless proportion of the weir. The depth in the drop-box weir was 8 feet (2.4 m) or 1 D. The following dimensionless equation of discharge is recommended:

\[ Q/D^{2.5} = 1.67 \sqrt[3]{gH_i/D}^{3.00} \] \hspace{1cm} (2-9)

or:

\[ Q = \frac{1.67 \sqrt{gH_i/D}}{\sqrt[3]{D}} \] \hspace{1cm} (2-10)
Figure 2.4.—Dimensions of the Salmon Creek weir of the Reynolds Creek Watershed, Idaho.
calibration tests are necessary for flows with \( H/D \) values less than 0.25.

Ratings above \( H/D \) value of 0.7 have the following limitations:

- Placement of the weir creates an approach angle (with the weir centerline) of 5° or less.
- The approach bed slope must be less than about 5 percent.
- Accuracy of the discharge rating must be within 5 percent.

The formula for gage 1 for \( H/D \) values between 0.7 and 1.3 is:

\[
Q = 1.73 \sqrt[3]{g} \left( \frac{H_1}{D} \right)^{1.1} D^{2.5} = 1.73 \sqrt[3]{g} \frac{H_1^{1.1}}{0.6}. \quad (2-11)
\]

The formula for gage 2 for \( H_2/D \) values between 0.8° and 1.7 is:

\[
Q = 1.20 \sqrt[3]{g} \left( \frac{H_2}{D} \right)^{1.9} D^{2.5} = 1.20 \sqrt[3]{g} H_2^{1.9} D^{0.8}. \quad (2-12)
\]

Periodic maintenance will be required to keep the cage openings free from sediment and to keep the box sidewall orifice from becoming blocked with debris.

The estimated capacity of Salmon Creek was 7,000 ft\(^3\)/s (19.8 m\(^3\)/s). No model data were reported, however, in this range of discharge. The value of \( D \) can be determined for designing by using the maximum discharge in the following formula:

\[
D = \frac{[Q]^{0.4}}{6.82 \sqrt[3]{g}}.
\]

This equation was obtained using the capacity of Salmon Creek, which is 7,000 ft\(^3\)/s (19.8 m\(^3\)/s). The dimensions of the weir then may be determined using the Salmon Creek dimensions (fig. 2.3) divided by 8 feet (2.4 m) and multiplied by \( D \).

Flumes

There are many types of precalibrated flumes. Most flumes use the principle of minimum energy or critical depth. Critical-depth flumes fall into two categories: (1) Flumes where critical depth occurs in region of curvilinear flow and (2) flumes for which the length dimension is such that critical flow occurs in a region where the flow lines are parallel or nearly parallel. Flumes that have little obstruction to the transport of these solids should be used to measure runoff where suspended and bedload solids are present in the flow. Where flow contains heavy suspended or bedload solids and velocity is reduced in the measuring section of the flume, material may deposit and interfere with performance of the flow. If reduction in velocity and deposit of sediment occur before the flow enters the flume, the flume will perform correctly.

Since \( HS \) flumes are designed to measure very small flows with a high degree of accuracy, construct them in strict accordance with the drawings and the following provisions. The slanting opening must be bound by straight edges and have precisely the dimensions shown on the drawings. The opening must lie in a plane with an inclination of the exact degree shown on the drawings. Prepare detailed drawings, using proportional dimensions shown in figure 2.5, with care taken to maintain the dimensional tolerance. Construction details are given with the discussion on \( H \) flumes.

Use the discharge equations for \( HS \) flumes in figures 2.6 and 2.7. These equations contain the basic dimensions that define the control section of the flume. Table 2.2 gives ratings for \( HS \) flumes of various sizes.

\( H \) Flumes:

Measure runoff from watersheds where the maximum runoff ranges from 0.3 to 30 ft\(^3\)/s (0.009 to 0.85 m\(^3\)/s). An \( H \) flume 0.5 foot deep will gage a maximum flow of 0.3 ft\(^3\)/s (0.009 m\(^3\)/s). Table 2.3 gives ratings for \( H \) flumes of various sizes. \( H \)-type flume dimensions and flow capacities are shown in figure 2.8. To measure flows with the required accuracy, construct the flume in strict accordance with the drawing and the following provisions of these specifications. The slanting opening must be bound by straight edges and have precisely the dimensions shown on the drawing.
Construction specifications for the H-type rate-measuring flumes are:
- Prepare detailed drawings, using the proportional dimensions shown in figure 2.8.
- Use only new materials of the best commercial quality in constructing H flume. These materials must be free from defects.
- Use sheet metal of galvanized open-hearth iron or copper-bearing steel.
- Make all structural angles of high-grade structural steel and galvanize them. These angles must be straight, and the surface of the legs must be flat.
- Fabricate the flume by following the best commercial practice in all details of construction. Make all joints and seams watertight and strong.
- Cut all plate edges straight and sharp. Do not warp the plates or distort them by cutting.
- Make the vertical sides of the flume from one sheet. The bottom plate must not contain more than one joint, and no portion of this joint should lie within 12 inches (30.5 cm) of the outlet opening. Any necessary joint in the bottom plate must be transverse to the longitudinal axis of the flume and must be made so that the joint is substantially flush. Make all dimensions for which tolerances are not indicated on the drawings within 1/4 inch (0.64 cm) of those given on the drawings.
- Form the slanting outlet opening so that its dimensions are precisely those shown on the drawing. The slopes on this drawing must be rigidly adhered to. Edges of the opening must be straight and smooth.
- Clamp the plates rigidly in position and get the proper dimensions and slopes before making the final connections. Make the side plates perpendicular to the bottom of the flume. All cross sections of the flume must be symmetrical about the longitudinal axis. All plates must be flat and show no appreciable warp, dent, or other distortion. No projections should occur on the inside of the flume. All joints must be solid and watertight.
- Carry out all operations affecting the dimensions of the outlet opening and the straightness of its edges. Follow good machine shop practices in all operations. The completed flume should not have deep tool marks, dents, or other blemishes.
- Before using, inspect the flume to confirm its compliance with the plans and specifications.
- Flumes 4.5 feet (1.37 m) deep can be constructed in the field if the proportional dimensions in figure 2.8 are used. The flow capacity of this flume is 84 ft³/s (2.35 m³/s). Reinforced concrete floor resting on two reinforced concrete footings—one across the upper face of the flume and the other about 1 foot (30.5 cm) in from the downstream edge—provides a substantial base for the flume walls. These walls
Figure 2.6.—Effect of submergence on the calibration of an H flume.

\[
H = \frac{d_1}{1 + 0.00175(e^{d_2/d_1})^{5.44}}
\]
\[ Q = \left( C_0 + C_1 \log_{10}\frac{H}{T_c} \right) \sqrt{g} \tan\frac{\theta}{2} \left( H + \alpha \frac{v^2}{2g} \right)^{2.5} \]

\[ \alpha = 1.33 \]

\[ v = \text{average velocity in cross section 10 feet (3.048 m) upstream from center of crest} \]

\[ H = \text{head (water surface elevation - zero head) 10 feet (3.048 m) upstream from center of crest} \]

\[ T_c = \text{crest thickness (16 in or 0.4064 m)} \]

<table>
<thead>
<tr>
<th>Tan $\frac{\theta}{2}$</th>
<th>Range $\frac{H}{T_c}$</th>
<th>$C_0$</th>
<th>$C_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.750 - 1.627</td>
<td>0.4798</td>
<td>0.06793</td>
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<tr>
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<td>1.628 - 3.716</td>
<td>0.4906</td>
<td>0.01689</td>
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<tr>
<td>2</td>
<td>3.717 - 4.500</td>
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<tr>
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<td>2.380 - 3.755</td>
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<tr>
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<tr>
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<tr>
<td>5</td>
<td>3.770 - 4.500</td>
<td>0.5669</td>
<td>-0.12692</td>
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</table>

Figure 2.7.—Discharge equations for triangular weirs.
may be either concrete or wood treated with preservative. In either case, angle iron forms the sloping edge of the flume. Sometimes the wood walls are lined with sheet metal. The wood should be 2-inch (5 cm) shiplap or tongue-and-grooved siding with watertight joints.

- **H** flumes using 1-on-8 sloping false floor are calibrated in table 2.3. Discharge equations for **H** flumes are listed in figure 2.6 and figure 2.7. These equations contain the basic dimensions that define the control section of the flume.

**HL Flume:**

The **HL** flume was designed to handle flow rates up to 117 ft³/s (3.28 m³/s). As shown in

---

**TABLE 2.2—Rating tables for HS flumes**

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<tr>
<th>FLUME 0.4 FOOT DEEP</th>
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1 Rating derived from tests made by the U.S. Department of Agriculture's Soil Conservation Service at Washington, D.C., and Minneapolis, Minn. Table prepared April 1941.
2 Trace.

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### TABLE 2.3—Rating tables for H flume

[Discharge in cubic feet per second]

#### FLUME 0.5 FOOT DEEP

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<th>0.03</th>
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<th>0.07</th>
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See footnotes at end of table.
### TABLE 2.3—Rating Tables for H Flume—Continued

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TABLE 2.3—Rating tables for \( H \) flume—Continued

(Discharge in cubic feet per second)

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See footnotes at end of table.
TABLE 2.3—Rating tables for H flume—Continued

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1 Rating derived from tests made by the Soil Conservation Service at the Hydraulic Laboratory of the National Bureau of Standards using 1-on-8 sloping false floor.
2 Trace.

figure 2.9, the HL flume may be built in several sizes. Only the 4-foot (1.2 m) HL flume is recommended because smaller flows are measured more accurately by H flumes. Construction is similar to that for a 4-foot (1.2 m) H flume. Calibration appears in table 2.4.

Discharge equations for HL flumes are listed in figures 2.6 and 2.7. These equations contain the basic dimensions that define the control section of the flume.

**Venturi Flume:**

Experiments on the Venturi flume were conducted in 1915 by Cone (12) at Colorado State University. This flume is characterized by a relatively long contracted section or throat. The floor of the throat is horizontal. Venturi flumes measure the discharge in an open channel by contracting the flow either by tapering the sidewalls of the flume or by changing the elevation of the floor of the flume, or both. These flumes require a measurement of depth at the entrance and at the constricted region. Later modifications using the properties of critical flow to define the flow properties in the throat under conditions of sufficient discharge required only a measurement of depth at the entrance. Critical-depth flumes usually are used in irrigation canals where the Froude number is less than 0.6 in the approach to the flume. Where sediment must be passed and the canal must be drained periodically, flat-bottomed flumes are more practical. For sediment movement, the velocities in the approach section of the flume should not be less than about 2.5 ft/s (0.76 m/s).

Acker and Harrison (1) used critical-depth theory and proposed two methods of computing head loss in the throat to derive ratings for trapezoidal-throated flumes. Replogle (35) modified their boundary layer-thickness method to a boundary-drag-and-energy accounting method. He successfully predicted calibrations on a wide variety of throat and approach channel shapes including triangular, rectangular, and trapezoidal shapes, and combinations of these.

The head usually is measured in the entrance section to the flume (fig. 2.10). If we let $H$ equal the maximum head in this section, the length of the entrance section and the throat section should be $2H$ or more. The throat section should not exceed about 20 times the minimum head of interest. Most experimenters agree that the convergence of each wall relative to the centerline in the transition section should not exceed 1:3. The throat should have a length of $2H$ to obtain parallel flow. The exit transition of 1:6 is recommended by Skogerboe and others (39). To avoid submergence, the downstream depth should not exceed two-thirds of the head for any range of flow. Deviation from these dimensions should be calibrated before use; otherwise, the flume should be constructed exactly the same as standard calibrated flume.
Parshall Flume:

This type of Venturi flume was developed in 1922 by the late Ralph L. Parshall in the hydraulic laboratory at Colorado State University. The main advantage of the Parshall flume is its relatively low loss of head. The head loss is only about a fourth of that needed to operate a weir having the same crest length. Parshall flumes are usually more expensive than weirs, however. Dimensions for various sizes are given in figures 2.11 and 2.12.

The discharge formula for small flumes was reported by Parshall (29) to be:

\[ Q = 4 WH_d^{1.522}W^{0.026} \]  

\[ (2-14) \]
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1 Rating derived from tests made at the National Bureau of Standards using flat floor.
2 Trace.
where
\[ Q = \text{discharge, cubic feet per second}; \]
\[ W = \text{throat width or length of crest (size of flume), feet}; \]
and
\[ H_a = \text{upper gage head (2.3(W+2+4) feet back from the crest), feet}. \]

Equation 2-14 expressed in meters would be:
\[
Q_m = 4 \left[ 0.3048 \right]^2 \times 1.57 \left[ \frac{W}{m} \right]^{0.026} \left( \frac{H_a}{m} \right)^{0.026} \]
(2-15)

where
\[ Q_m = \text{discharge (m}^3/\text{s}); \]
\[ W_m = \text{throat width in meters}; \]
\[ H_{am} = \text{upper gage head in meters (2.3(W/2)+1.219) meters back from the crest}. \]

Large flumes (10 to 40 ft, or 3 to 12 m) were modified by increasing the length and decreasing the side angle of the converging section. The general discharge formula for these flumes was reported by Parshall (30) to be:
\[
Q = (3.6875W + 2.5) H_a^{1.6} \quad (2-16)
\]

where
\[ Q = \text{discharge, cubic feet per second}; \]
\[ W = \text{throat width (size of flume), feet}; \]
and
\[ H_a = \text{upper gage head (referenced to crest), feet}. \]

Equation 2-16 expressed in meters would be:
\[
Q_m = (2.29265 W_m + 0.47876) H_{am}^{1.6} \quad (2-17)
\]

where
\[ Q_m = \text{discharge (m}^3/\text{s}); \]
\[ W_m = \text{throat width in meters}; \]
and
\[ H_{am} = \text{upper gage head (2.3(W/2)+1.219) meters back from the crest}. \]
\( H_{am} \) = upper gage in meters (referenced to crest).

Flow submergence occurs when the water in the diverging section of the flume rises to a level where it retards the flow in the converging section. The tailwater level is measured near the downstream end of the throat section (in fig. 2.11 it is labeled \( H_b \)). This zero reference, \( H_b \), is the crest.

Skogerboe and others \((39)\) developed the following equation for the Parshall flume:

\[
Q = \frac{C_1(H_a - H_b)^{n_1}}{[-(\log H_b/H_a + M_2)]^{n_2}} \tag{2-18}
\]

This equation is reasonably accurate (2 to 5 percent) for submergence values up to \((H_b/H_a) = 0.96\). Transition submergence, \( S_t \), was defined as the value of submergence at which the change from free flow to submerged flow occurs. Values of submerged flow coefficients and exponents for Parshall flumes \((C_1, H_a, H_b, n_1, C_2, n_2)\) are given in table 2.5. Submerged flow coefficients for use with meters are given in table 2.6.

Davis \((17)\) used original data to develop the following comprehensive formula for the free outfall rating of a Parshall flume:

\[
\frac{H_a}{W} \left( \frac{Q}{g^{1/2} W^{3/2}} \right)^2 = \frac{1.351 \left( Q \right)^{0.645}}{Z \left( H_a/W \right) \left( 1 - 0.4 \frac{c}{W} \right)^2} \tag{2-19}
\]

where

- \( H_a \) = upper gage head, feet;
- \( W \) = throat width or length of crest, feet;
- \( Q \) = discharge, cubic feet per second;
- \( g \) = acceleration due to gravity, feet per second²; and
- \( c \) = horizontal distance parallel to the centerline between the crest and the point of observing the upper head, \( H_a \), feet.

An electric computer can be used to solve this equation.

Davis \((17)\) reported an error in equation 2-19 of less than 1 percent for the majority of points.

![Figure 2.12.—Parshall flume dimensions.](image-url)
and less than 2 percent with few exceptions. Under normal operating conditions, however, the discharge can be determined within an accuracy of 2 to 5 percent.

**Walnut Gulch Supercritical Flume:**

A flume was developed in the late 1950's to measure the ephemeral, flashy, and sand-and-gravel-laden flows conveyed by the steep streams in the Walnut Gulch Watershed near Tombstone, Ariz. This flume was constructed on Walnut Gulch and was calibrated with model studies in the ARS Water Conservation Structures Laboratory, Stillwater, Okla. (18,28).

Walnut Gulch supercritical flumes (40) have a 15-foot (4.6 m), curved entrance approach to a 20-foot (6.1 m), straight section with a shallow V-shaped floor and sidewalls with a 1-on-1 slope. Figure 2.13 shows the design of a typical flume. The width, W, ranges between 5 and 120 feet. The cross slope, S,, ranges between 7.5 and 15. The length of the straight portion should be about twice the maximum head. The curved approach has a cylindroid surface (coordinate origin shown in fig. 2.13) defined by the equation:

\[
y = 0.03x + \frac{z - 0.03x^2}{0.00267x^2 + 1} \tag{2-20}
\]

where
- \(x\) = horizontal coordinate positive in the upstream direction, feet;
- \(y\) = vertical coordinate, feet; and
- \(z\) = horizontal coordinate normal to centerline of the flume, feet.

A perspective view of this surface is shown in figure 2.14. The floor of the flumes has a slope of 0.03 in the downstream direction parallel to the centerline to insure movement of sediment.

**TABLE 2.5—Submerged flow coefficients and exponents for Parshall flumes**

<table>
<thead>
<tr>
<th>W</th>
<th>(C_1)</th>
<th>(C_2)</th>
<th>(n_1)</th>
<th>(n_2)</th>
<th>(S_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 inch</td>
<td>0.299</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.56</td>
</tr>
<tr>
<td>2 inches</td>
<td>0.812</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.61</td>
</tr>
<tr>
<td>3 inches</td>
<td>0.915</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.64</td>
</tr>
<tr>
<td>6 inches</td>
<td>1.66</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.58</td>
</tr>
<tr>
<td>9 inches</td>
<td>2.51</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.63</td>
</tr>
<tr>
<td>12 inches</td>
<td>3.11</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.62</td>
</tr>
<tr>
<td>18 inches</td>
<td>4.42</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.64</td>
</tr>
<tr>
<td>24 inches</td>
<td>5.94</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.66</td>
</tr>
<tr>
<td>30 inches</td>
<td>7.12</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.67</td>
</tr>
<tr>
<td>3 feet</td>
<td>8.60</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.68</td>
</tr>
<tr>
<td>4 feet</td>
<td>11.16</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.70</td>
</tr>
<tr>
<td>5 feet</td>
<td>13.55</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.72</td>
</tr>
<tr>
<td>6 feet</td>
<td>15.85</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.74</td>
</tr>
<tr>
<td>7 feet</td>
<td>16.15</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.76</td>
</tr>
<tr>
<td>8 feet</td>
<td>20.40</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.78</td>
</tr>
<tr>
<td>10 feet</td>
<td>24.79</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.80</td>
</tr>
<tr>
<td>12 feet</td>
<td>29.34</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.80</td>
</tr>
<tr>
<td>15 feet</td>
<td>36.17</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.80</td>
</tr>
<tr>
<td>20 feet</td>
<td>47.56</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.80</td>
</tr>
<tr>
<td>25 feet</td>
<td>58.95</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.80</td>
</tr>
<tr>
<td>30 feet</td>
<td>70.34</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.80</td>
</tr>
<tr>
<td>40 feet</td>
<td>93.11</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.80</td>
</tr>
<tr>
<td>50 feet</td>
<td>115.89</td>
<td>0.0044</td>
<td>1.15</td>
<td>1.00</td>
<td>0.80</td>
</tr>
</tbody>
</table>

**TABLE 2.6.—Submerged flow coefficients (metric) and exponents for Parshall flumes**

<table>
<thead>
<tr>
<th>(W_m) (meters)</th>
<th>(C_{wm})</th>
<th>(C_2)</th>
<th>(n_1)</th>
<th>(n_2)</th>
<th>(S_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.025</td>
<td>0.172</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.56</td>
</tr>
<tr>
<td>0.051</td>
<td>0.360</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.61</td>
</tr>
<tr>
<td>0.076</td>
<td>0.535</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.64</td>
</tr>
<tr>
<td>0.152</td>
<td>1.005</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.65</td>
</tr>
<tr>
<td>0.228</td>
<td>1.432</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.66</td>
</tr>
<tr>
<td>0.305</td>
<td>1.76</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.67</td>
</tr>
<tr>
<td>0.457</td>
<td>2.56</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.68</td>
</tr>
<tr>
<td>0.610</td>
<td>3.48</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.69</td>
</tr>
<tr>
<td>0.782</td>
<td>4.26</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.70</td>
</tr>
<tr>
<td>0.914</td>
<td>5.10</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.71</td>
</tr>
<tr>
<td>1.219</td>
<td>6.66</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.72</td>
</tr>
<tr>
<td>1.524</td>
<td>8.23</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.73</td>
</tr>
<tr>
<td>1.829</td>
<td>9.74</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.74</td>
</tr>
<tr>
<td>2.134</td>
<td>11.29</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.75</td>
</tr>
<tr>
<td>2.438</td>
<td>12.68</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.76</td>
</tr>
<tr>
<td>3.048</td>
<td>15.23</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.78</td>
</tr>
<tr>
<td>3.658</td>
<td>18.03</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.80</td>
</tr>
<tr>
<td>4.572</td>
<td>22.22</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.80</td>
</tr>
<tr>
<td>6.096</td>
<td>29.22</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.80</td>
</tr>
<tr>
<td>7.620</td>
<td>36.22</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.80</td>
</tr>
<tr>
<td>9.144</td>
<td>43.22</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.80</td>
</tr>
<tr>
<td>12.192</td>
<td>57.21</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.80</td>
</tr>
<tr>
<td>15.240</td>
<td>71.20</td>
<td>0.0044</td>
<td>1.55</td>
<td>1.00</td>
<td>0.80</td>
</tr>
</tbody>
</table>

1 Where \(Q_m = \frac{C_{wm}(H_{wm} - H_{wm})^{n_1}}{[-(\log H_{wm} H_{wm} + C_2)^2]^{n_2}}\).
through the flumes. The flume invert is placed about 2 feet above the streambed to reduce backwater on the flume. The head is measured with piezometers at the midpoint of the straight portion of the flume. Velocities are supercritical at the head measuring section.

The approximate location of critical depth upstream from the piezometers is given by the following formula:

$$L = 0.88 + 14 C_r$$  \hspace{1cm} (2-21)

where

$L$ = horizontal length between critical section and point of head measurement, feet; and

$C_r$ = contraction ratio (area of flow at point of head measurement divided by approach channel area) of flow.

Equation 2-21 is valid only for flows where the sidewalls are exerting control, that is, heads greater than the intercept of the floor with the 1-on-1 sidewalls. The contraction ratio, $C_r$, always should be less than 0.5.

A computed rating, $h_p$ versus $Q$, may be obtained using the following equation of the energy relationship:

$$h_p = h_r + \frac{A_r}{2T_r} + 0.03L - \frac{Q_r^2}{2g A_r^2}$$  \hspace{1cm} (2-22)

where

$h_p$ = head above the flume zero, feet;

$h_r$ = depth of flow above V-shaped floor at the critical section, feet;

$A_r$ = cross-sectional area of flow, square feet;

$L$ = horizontal length between critical section and point of head measurement, feet;

$g$ = acceleration due to gravity;

$Q$ = discharge, cubic feet per second;

$T_r$ = top width of flow, feet;

$p$ = subscript relating to point of head measurement; and

$c$ = subscript relating to critical section.

The values of $A_c$ and $T_c$ are computed from a selected value of $h_c$. The discharge $Q_c$ is calculated from the following equation:

$$Q_c = \left[ \frac{gA_r^3}{T_r} \right]^{0.5}$$  \hspace{1cm} (2-23)

A value of $L$ is assumed, and $h_p$ is calculated from equation 2-22. A backwater computation is made from the point of head measurement to a point approximately 100 feet (30.48 m) upstream from the flume. This estimates the
water surface for determining the cross-sectional area of the approach channel. The contraction ratio, $C_r$, is calculated and used to compute the value of $L$ in equation 2-21. If $L$ disagrees with the initially assumed value of $L$, the calculation is repeated. This iteration is continued until a balance is obtained. The computed rating is valid for flows controlled by the 1-on-1 sidewalls of the straight portion of the flume. For flows within the floor of the V section (lower head range), field determinations of the rating should be made. These lower flows combine channel and flume control.

Observations in the prototype have shown that the thalweg in the approach section is unstable and varies with flow sequences. Therefore, the flow streamlines are not always parallel to the flume centerline and cause some irregular water surface profiles at the measuring section. Such eccentricity can be corrected by inserting porous training dikes in the approach channel. These dikes provide symmetrical flow (fig. 2.15).

The metric equivalent of the curved cylindroid surface defined by equation 2-22 is:

$$g_m = 0.03r_m + \frac{z - 0.09842r_m^2}{0.0287r_m^2 + 1}$$  \hspace{1cm} (2-24)

where

- $g_m$ = vertical coordinate, meters;
- $r_m$ = horizontal coordinate positive in upstream direction, meters; and
- $z_m$ = horizontal coordinate normal to the centerline of the flume, meters.

Equation 2-21 expressed in meters would be:

$$L = 0.29 + 4.59C_r$$  \hspace{1cm} (2-25)

where

- $L$ = horizontal length between critical section and point of head measurements, meters; and
- $C_r$ = contraction ratio (area of flume divided by area of approach channel).

**Existing Structures**

Runoff can be measured by using hydraulic structures. These include culverts, conservation structures, reservoirs, spillways, and other works for water conveyance and control.

Laws governing flow through these structures are now fairly well understood because of hydraulic studies, both analytical and experimental, which have been made for guidance in design. Studies also have provided the coefficients needed to calculate discharge rates. By the use of these data, head-discharge relationships can be predicted for certain structures without the need for further calibration. Re-

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**Figure 2.15**—Walnut Gulch supercritical measuring flume with porous dike training fences for ensuring symmetrical flow (4/10).
sults are available for other hydraulic studies made specifically to calibrate structures for runoff measurement. Principles in the studies guide the hydrologist, who may consider using an existing structure to measure runoff.

Accuracy of the discharge measurement can range from a rough estimate to a determination approaching the 5-percent level. Under good conditions where the field structure is similar in form to the model used in the hydraulic studies and comparable relative velocities exist in magnitude and direction, accuracy will be ± 10 percent. With calibration studies from model studies and from current-meter measurements in the field, the accuracy level can be raised to ± 5 percent. If a nonstandard condition exists—for instance, a high approach velocity—the discharge rate may be underestimated by 30 percent.

These accuracy estimates also apply to custom-built devices for measuring runoff, but standard approach conditions can be built into the installation. Where existing structures are used to achieve an inexpensive runoff measuring station, nonstandard conditions are not corrected because of cost or inaccessibility of the approach.

Cost of the analysis should be considered carefully. It should not exceed the average annual cost of the study, which includes station installation, maintenance, operation, and data analysis. Installation of the station may be only a small part of the total cost, especially for a long study. Therefore, the use of an existing structure for the flowmeter may afford relatively small savings. If existing structures are used at the expense of data quality, the study will become expensive. Structures for runoff measurement may provide the only way to get the data at a site.

Sometimes the performance of a water control works is studied to evaluate the criteria used in its design. Part of the works—for example, a spillway—is used to measure the discharge rates. An alternative is to use a watershed that drains through an existing structure with satisfactory hydraulic properties. This watershed is found at certain places in a proposed hydrologic study. Use of this structure as a flowmeter is economical.

One flowmeter is the single-head control structure that includes weirs, spillways, culvert entrances, flume entrances, or free overfalls. Measurement of the elevation water surface upstream from this structure is sufficient to determine the flow rate through it. The hydraulic law operating for the structure can be the critical depth law, the orifice flow law, or the sluice gate law. Closed conduits flowing full and having free discharge also can be included in this category, or they can be in a category subject to friction control, which would be unsatisfactory for measurement of flow.

A head-loss structure also can be used to measure runoff. For this structure, two water surface deviations must be measured—one upstream and one immediately downstream. The difference between the two measurements is a function of the discharge rate. Head-loss structures include bridge opening, culverts under tailwater control, and closed conduit spillways with both the entrance and the exit submerged. They can be divided into two subgroups: (1) Where the head loss is caused largely by velocity head differences at the two measuring stations and (2) where the head loss is caused mainly by friction loss in the conduit. Structures in the first group may be better flowmeters than those in the second group because friction factors are easier to estimate and may change with time.

A third structure for measuring runoff is the reservoir. For this structure, an estimate of the runoff rate is the product of the rate of the reservoir water surface rise and the surface area of the reservoir at the corresponding instant. Outflow occurring at the same time must be added to the reservoir volume change used to obtain the true inflow rate of the reservoir. Although this estimate is no different than the pondage correction principle, the characteristic that establishes this category is a relatively small rate of outflow as compared to the rate of volume change. Although the spillway for the outflow is not a good flowmeter in itself, the rate of runoff can be estimated by gaging fluctuations of the water surface. Even a large percentage error in estimating the outflow rate—such as an error caused by accumulation of trash at the spillway inlet—may result in only a small percentage error in estimating the inflow rate.
Highway Box Culverts

Highway culverts can be used as runoff meters. They are usually simple and regular in form, and their hydraulic behavior is well understood because of several studies on flow through culverts (8). Six types of flow that can occur at a culvert are shown in figure 2.16. Types 1 and 5 are suitable for metering flow.

Discharge for type 1 can be calculated by the equation:

\[ Q = CA \sqrt{2g\left(h_1 - z + \frac{V_1^2}{2g} - d_e - h_{f1}\right)} \]  

(2-26)

where
- \( Q \) = discharge rate in cubic feet per second;
- \( C \) = coefficient of discharges;
- \( A \) = cross-sectional area of culvert (ft²);
- \( g \) = acceleration of gravity (ft/s²);
- \( h_1 \) = head depth of flow (ft);
- \( h_{f1} \) = head loss (ft) due to friction between sections 1 and 2;
- \( z \) = vertical distance between culvert outlet and entrance (ft);
- \( V_1 \) = velocity of section 1 (ft/s), a distance (1a) in feet upstream;
- \( d_e \) = critical depth of flow;
- \( D \) = height of culvert opening;
- \( W \) = width of culvert opening; and
- \( H \) = hydraulic head causing flow above culvert floor invert.

If \((h_1 - z)\) is replaced by \( H, V_1 \) and \( h_{f1} \) are disregarded because they are small, \( d_e \) is written as a function of \( H \), and \( A \) is written as a function of \( W \) and \( H \), the equation can be simplified to read:

\[ Q = C'W H^{3/2}. \]

(2-27)

This is the form in which the relationship between \( Q \) and \( H \) often is found. Indiscriminate use of equation 2-27 can lead to serious error. For example, if \( V_1 \) is not small, the flow will be underestimated. If \( h_{f1} \) is large and neglected, the discharge rate will be overestimated. Therefore, equation 2-27 should be used, rather than equation 2-26, to estimate the head-discharge relationship.

The coefficient of discharge is affected by geometry of the culvert entrance. Values suggested by Carter are given in figure 2.16. The discharge coefficient is determined by applying

---

**FIGURE 2.16.—Six possible types of flow at a culvert.**
corrections to the base coefficient. Do not exceed 0.08 for the net coefficient value.

Use of values given in figure 2.17 will be illustrated by the following examples:

Given, a rectangular box culvert with wingwalls at a 60° angle with the roadway line. From figure 2.17, the base coefficient for box culverts is 0.95. The cosine of 60° equals 0.50. Therefore, \( C \) is determined by multiplying the base value of 0.95 by 1.215, the correction \((k_1)\) for \( \cos \theta = 0.50 \). Thus, \( C = 0.95 \times 1.215 = 1.155 \). Since this value is higher than the maximum of 0.98, use 0.98.

Given, a concrete pipe culvert with a 24-inch diameter. This culvert is flush with vertical headwall but has a beveled-joint entrance. Depth of the groove is 2.4 inches (6.1 cm), or 0.1 \( D \). The entrance diameter of the bevel is 27.8 inches (70.6 cm). Thus, \( t \) (thickness of culvert wall) is \( \frac{1}{2} (27.8-24)=1.9 \) inches (48 cm). The tangent of the entrance bevel is \( \frac{2.4}{1.9}=1.26 \), or the angle \((\theta)\) is about 52°. \( C \) will assume a head \((h_1-z)\) equal to 1.2 feet (36.6 cm), each point on the rating curve. For example, assume a head \((h_1-z)\) equal to 1.2 feet (36.6 cm). The ratio of head to diameter is \( \frac{1.2 \text{ ft}}{2.0 \text{ ft}} = 0.6 \). Read the table to obtain 0.927 for the base coefficient. The correction factor for the entrance bevel is obtained from the appropriate table when entered with a \( t/D \) ratio of 1.9/2.4 × 0.079 and an angle of 52°. Interpolation between the 45° and 60° columns normally is necessary. The value of \( k_w \) (entrance-beveling correction) for 45° is 1.15, however. This indicates that the product of the base coefficient and \( k_w \) will exceed the maximum value of 0.98. Again, use 0.98.

If the pipe projects beyond the headwall, calculate the coefficient for a flush pipe and apply a correction factor for a projection condition. The projection correction factor \((k_p)\) computed as length of culvert projection beyond embankment headwall \((l_p)\) divided by depth of box \((D)\) is:

\[
l_p \quad \frac{K_1}{D}
\]

<table>
<thead>
<tr>
<th>( l_p )</th>
<th>( K_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>0.1</td>
<td>0.92</td>
</tr>
<tr>
<td>≥1.0</td>
<td>0.90</td>
</tr>
</tbody>
</table>

For type 5 flow, discharge may be computed from the equation:

\[
Q = CA \sqrt{2g(h_1-z)}.
\]  

(2-28)

Coefficients of discharge vary with the degree of rounding or beveling of the entrance (whether flush vertical wall or wingwalls) and type of entrance pipes projecting or mitered.

If the pipe projects beyond the headwall, use the correction factors \((k_p)\) that were given for type 1 flow. If the end of the pipe is mitered flush with a sloping embankment, multiply coefficients (table 2.7) given for the square-ended pipe by 0.92.

Assume that a watershed with a culvert at its outflow point has been selected for a runoff study. Suitability of the culvert for flow measurement must be evaluated as follows:

- Does the culvert have a simple cross-section box or pipe with a symmetrical entrance? If so, it might be suitable without a special calibration. If not, calibration will be required, but the effort may be worthwhile.

- Does the culvert have a steep barrel? If the computed value of the term, \( \frac{SD^{1.3}}{n^2} \), for a circular culvert falls to the right of the curve labeled \( S = Sc \) in figure 2.17, critical depth occurs at the culvert inlet. If the computed value of this term falls to the left of the curve, critical depth occurs at the outlet of the culvert. Figures 2.18 and 2.19 are used similarly for rectangular culverts. Mannings \( n \) values needed for this determination are:

<table>
<thead>
<tr>
<th>Material</th>
<th>Mannings ( n ) values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td></td>
</tr>
<tr>
<td>Very smooth</td>
<td>0.012</td>
</tr>
<tr>
<td>Ordinary field construction</td>
<td>0.015</td>
</tr>
<tr>
<td>Badly spalled</td>
<td>0.020</td>
</tr>
<tr>
<td>Corrugated metal</td>
<td>0.024</td>
</tr>
<tr>
<td>Cement rubble</td>
<td>0.020–0.030</td>
</tr>
<tr>
<td>Cast iron</td>
<td>0.013</td>
</tr>
<tr>
<td>Vitrified pipe</td>
<td>0.013</td>
</tr>
</tbody>
</table>

- Does the culvert have free discharge at the outfall as evidenced by a drop or scour hole at the outlet? If so, it will be suitable if the
### BASE COEFFICIENTS OF DISCHARGE

#### Pipe Culverts, Square Entrance, Flush with Vertical Headwall

<table>
<thead>
<tr>
<th>( \frac{h_1 - z}{D} )</th>
<th>C</th>
<th>( \frac{h_1 - z}{D} )</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0.927</td>
<td>1.1</td>
<td>0.870</td>
</tr>
<tr>
<td>0.7</td>
<td>0.920</td>
<td>1.2</td>
<td>0.856</td>
</tr>
<tr>
<td>0.8</td>
<td>0.908</td>
<td>1.3</td>
<td>0.841</td>
</tr>
<tr>
<td>0.9</td>
<td>0.897</td>
<td>1.4</td>
<td>0.826</td>
</tr>
<tr>
<td>1.0</td>
<td>0.884</td>
<td>1.5</td>
<td>0.811</td>
</tr>
</tbody>
</table>

#### Pipe Culverts, Mitered, Flush with Sloping Embankment

<table>
<thead>
<tr>
<th>( \frac{h_1 - z}{D} )</th>
<th>C</th>
<th>( \frac{h_1 - z}{D} )</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0.900</td>
<td>1.1</td>
<td>0.847</td>
</tr>
<tr>
<td>0.7</td>
<td>0.902</td>
<td>1.2</td>
<td>0.823</td>
</tr>
<tr>
<td>0.8</td>
<td>0.896</td>
<td>1.3</td>
<td>0.794</td>
</tr>
<tr>
<td>0.9</td>
<td>0.884</td>
<td>1.4</td>
<td>0.764</td>
</tr>
<tr>
<td>1.0</td>
<td>0.868</td>
<td>1.5</td>
<td>0.730</td>
</tr>
</tbody>
</table>

#### Box Culverts, Square Entrance, Flush with Vertical Headwall

\( C = 0.95 \) for all heads

### CORRECTIONS TO BASE COEFFICIENT

#### Correction for Entrance Rounding, \( k_r \)

\[
\begin{array}{c|c}
\frac{r}{W} \text{ or } \frac{r}{D} & k_r \\
\hline
0 & 1.00 \\
0.01 & 1.02 \\
0.02 & 1.04 \\
0.03 & 1.06 \\
0.04 & 1.08 \\
0.05 & 1.10 \\
0.06 & 1.12 \\
\end{array}
\]

#### Correction for Entrance Beveling, \( k_t \)

\[
\begin{array}{c|c|c|c}
\frac{t}{W} \text{ or } \frac{t}{D} & n = 30 & n = 45 & n = 60 \\
\hline
0 & 1.00 & 1.00 & 1.00 \\
0.02 & 1.03 & 1.065 & 1.09 \\
0.04 & 1.05 & 1.11 & 1.16 \\
0.06 & 1.07 & 1.135 & \\
0.08 & 1.08 & 1.15 & \\
0.10 & 1.09 & 1.15 & \\
\end{array}
\]

#### Correction for Wingwall Angle, \( h_w \)

\[
\begin{array}{c|c}
\cos \phi & k_c \\
\hline
1.00 & 1.00 \\
0.90 & 1.05 \\
0.80 & 1.095 \\
0.70 & 1.14 \\
0.60 & 1.18 \\
0.50 & 1.215 \\
\end{array}
\]

**Figure 2.17.**—Coefficients of discharge as affected by geometry of culvert entrance.
TABLE 2.7.—Discharge coefficients for type 5 flow for culverts
Box or Pipe Culverts Set Flush in a Vertical Headwall.

<table>
<thead>
<tr>
<th>((h_1 - z)D)</th>
<th>(0)</th>
<th>(0.2)</th>
<th>(0.04)</th>
<th>(0.06)</th>
<th>(0.08)</th>
<th>(0.10)</th>
<th>(0.14)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>0.44</td>
<td>0.46</td>
<td>0.49</td>
<td>0.50</td>
<td>0.50</td>
<td>0.51</td>
<td>0.51</td>
</tr>
<tr>
<td>1.5</td>
<td>0.46</td>
<td>0.49</td>
<td>0.52</td>
<td>0.53</td>
<td>0.53</td>
<td>0.54</td>
<td>0.54</td>
</tr>
<tr>
<td>1.6</td>
<td>0.47</td>
<td>0.51</td>
<td>0.54</td>
<td>0.55</td>
<td>0.55</td>
<td>0.56</td>
<td>0.56</td>
</tr>
<tr>
<td>1.7</td>
<td>0.48</td>
<td>0.52</td>
<td>0.55</td>
<td>0.57</td>
<td>0.57</td>
<td>0.57</td>
<td>0.57</td>
</tr>
<tr>
<td>1.8</td>
<td>0.49</td>
<td>0.54</td>
<td>0.57</td>
<td>0.58</td>
<td>0.58</td>
<td>0.58</td>
<td>0.58</td>
</tr>
<tr>
<td>1.9</td>
<td>0.50</td>
<td>0.55</td>
<td>0.58</td>
<td>0.60</td>
<td>0.60</td>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>2.0</td>
<td>0.51</td>
<td>0.56</td>
<td>0.59</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
</tr>
<tr>
<td>2.5</td>
<td>0.54</td>
<td>0.59</td>
<td>0.62</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
</tr>
<tr>
<td>3.0</td>
<td>0.55</td>
<td>0.61</td>
<td>0.64</td>
<td>0.66</td>
<td>0.67</td>
<td>0.69</td>
<td>0.70</td>
</tr>
<tr>
<td>3.5</td>
<td>0.57</td>
<td>0.62</td>
<td>0.65</td>
<td>0.67</td>
<td>0.69</td>
<td>0.70</td>
<td>0.71</td>
</tr>
<tr>
<td>4.0</td>
<td>0.58</td>
<td>0.63</td>
<td>0.66</td>
<td>0.68</td>
<td>0.70</td>
<td>0.71</td>
<td>0.72</td>
</tr>
<tr>
<td>5.0</td>
<td>0.59</td>
<td>0.64</td>
<td>0.67</td>
<td>0.69</td>
<td>0.71</td>
<td>0.72</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Box Culverts With Wingwalls

<table>
<thead>
<tr>
<th>((h_1 - z)D)</th>
<th>(30^\circ)</th>
<th>(45^\circ)</th>
<th>(60^\circ)</th>
<th>(75^\circ)</th>
<th>(90^\circ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3</td>
<td>0.44</td>
<td>0.44</td>
<td>0.43</td>
<td>0.42</td>
<td>0.39</td>
</tr>
<tr>
<td>1.4</td>
<td>0.46</td>
<td>0.46</td>
<td>0.45</td>
<td>0.43</td>
<td>0.41</td>
</tr>
<tr>
<td>1.5</td>
<td>0.47</td>
<td>0.47</td>
<td>0.46</td>
<td>0.45</td>
<td>0.42</td>
</tr>
<tr>
<td>1.6</td>
<td>0.49</td>
<td>0.49</td>
<td>0.48</td>
<td>0.46</td>
<td>0.43</td>
</tr>
<tr>
<td>1.7</td>
<td>0.50</td>
<td>0.50</td>
<td>0.48</td>
<td>0.47</td>
<td>0.44</td>
</tr>
<tr>
<td>1.8</td>
<td>0.51</td>
<td>0.51</td>
<td>0.50</td>
<td>0.48</td>
<td>0.45</td>
</tr>
<tr>
<td>1.9</td>
<td>0.52</td>
<td>0.52</td>
<td>0.51</td>
<td>0.49</td>
<td>0.46</td>
</tr>
<tr>
<td>2.0</td>
<td>0.53</td>
<td>0.53</td>
<td>0.52</td>
<td>0.49</td>
<td>0.46</td>
</tr>
<tr>
<td>2.5</td>
<td>0.56</td>
<td>0.56</td>
<td>0.54</td>
<td>0.52</td>
<td>0.49</td>
</tr>
<tr>
<td>3.0</td>
<td>0.58</td>
<td>0.58</td>
<td>0.56</td>
<td>0.54</td>
<td>0.50</td>
</tr>
<tr>
<td>3.5</td>
<td>0.60</td>
<td>0.60</td>
<td>0.58</td>
<td>0.55</td>
<td>0.52</td>
</tr>
<tr>
<td>4.0</td>
<td>0.61</td>
<td>0.61</td>
<td>0.59</td>
<td>0.56</td>
<td>0.53</td>
</tr>
<tr>
<td>5.0</td>
<td>0.62</td>
<td>0.62</td>
<td>0.60</td>
<td>0.58</td>
<td>0.54</td>
</tr>
</tbody>
</table>

The culvert barrel is steep. If no definite evidence of free outfall exists and no deposition is present on the floor of the barrel, another test can be made before eliminating the culvert from consideration. A tail-water elevation discharge curve must be developed for the channel at the point of culvert discharge. This requires a survey of the downstream channel of approximately 1,000 feet (305 m). Obtain sufficient data to compute water surface profiles, starting at the downstream point and working up to the culvert. A water surface elevation must be assumed for the starting point. When the station of the culvert is reached, this elevation can be estimated accurately if the 1,000 feet (305 m) have been broken into enough subreaches for the computation. After the tail-water elevation-discharge curve has been developed, it must be compared with the curve of the water surface elevation versus discharge for critical depth \((d_c)\) at the outlet. If the latter curve lies above the expected tail-water curve, type 1 flow can exist if the culvert barrel is steep.

- Does the culvert have sufficient capacity to pass the maximum floodflow? This can be determined by estimating the expected flow from the watershed and calculating the culvert capacity at the maximum possible head. If the
culvert does not have the capacity to pass maximum flow, other means of estimating the infrequent overflow should be considered.

- Are the approach conditions satisfactory? Steep approach channels or channel directions oblique to the centerline of the culvert are undesirable but do not necessarily disqualify the culvert. Calibration will be required for these cases.

If the culvert passes the preceding tests satisfactorily, location of the gage well should be selected. A position near the end of a wingwall is convenient, but the gage well should be kept out of the road ditch and out of the path of the approaching flow. If the approach is slightly nonsymmetrical, choose the dead-water side of the culvert entrance instead of the higher velocity flow side for the gage-well intake. Some difficulty may be experienced with sediment, but this may be as desirable as the effects of possible approach velocity on the water level of the gage well. With the position of the gage well fixed and the culvert dimensions measured, the stage-discharge curve can be computed.

The stage-discharge relationship is calculated from equations 2–26 and 2–28. These equations can be plotted on log-log paper to find the point of intersection. Flows below the intersection point will be type 1, and flows above will be type 5. The maximum head for culvert control may be governed by the low point in the road ditch at the divide rather than the low point in the road crossing the culvert.

Pondage corrections probably will be needed when culverts are used for runoff measurements. (Use the method described in the section on data processing, p. 56.)

**Culvert Modification**

Rectangular culverts are not good meters for low flows. A low flowmeter is required to accurately measure small flows. Before discussing these modifications, consider the need for such a device.

To gain sensitivity in the low-flow range, rectangular culverts are modified to confine low flows to a small opening and the low flowmeters are designed not to interfere with the maximum capacity of the culvert. Since the total available operating head remains the same, an increase in sensitivity obtained at low heads is gained at the expense of sensitivity in the high-head range. To design an effective device for measuring flow, characteristics of the flow must be studied. The meter then can be
designed so that it will obtain the greatest accuracy in the range where most runoff occurs.

A cumulative distribution graph of percentage of total runoff against runoff rate is required for a rigorous solution. For example, if total runoff from a watershed can be estimated by measuring 95 percent of the runoff, the meter must be sensitive only down to the rate above which 95 percent of the flow occurs. Such detailed knowledge is unavailable, however, for an ungaged watershed. Obtain estimates from the flow-duration characteristics of streams in the area. If low flows are sustained for many days, a large percentage of the flow will come off at low rates and a low flowmeter will be required. In regions where streams are flashy and flows are ephemeral, low flow rates contribute only a small percentage of the total runoff. For these regions, a low flowmeter is unnecessary and may be undesirable. If a low flowmeter is installed, two arrangements are possible—one within the culvert or one outside the culvert.

The Villemonte weir sill is installed within the culvert. In this position it is out of the way and does not reduce the maximum flow capacity of the culvert. Another advantage is that it stays clean and free of debris. It has the disadvantage of having some minimum head below which a measurement is impossible. Construction within the culvert entails some difficulties, especially when flow is continuous.

The Villemonte weir sill is described in a bulletin by W. O. Ree and F. R. Crow (33). Dimensions of the design are given in terms of the culvert width ($W$) (fig. 2.20). The weir consists of a pair of converging sills placed on the floor of the culvert downstream from the entrance. The shape and placing of the sills leave a small trapezoidal opening between the sills through which the low flow must pass. The contraction is great enough to control the water level at the gage intake for all but the smallest trickles. As flow increases, control gradually passes to the culvert entrance. The transition is smooth and reversible, and the combination of measuring devices acts as a single unit.

Sills are placed in the culvert to measure low flows, but they also have a lower limit below which a measurement is impossible. The culvert apron is, in effect, a low dam interposed between the point of zero head (the floor at culvert throat) and the gage well. The relative height of this barrier depends on the culvert slope, and heads less than this height cannot be measured. Even after this height is exceeded, channel flow occurs between the gage well and the sill throat until backwater produces an effective control. An empirical expression derived from test data has provided the following relationship between culvert slope and minimum measurable flow:

$$\frac{Q}{W^{5/2}} = 0.000067\sqrt{gS^{2.4}} \quad (2-29)$$

where

- $Q$ = discharge (ft³/s);
- $W$ = width of culvert (ft);
- $s$ = slope (percent);
- $g$ = gravitational acceleration (ft/s²).

The minimum measurable flow for the preceding 4- by 8-foot culvert with a 1.2 percent slope is 0.107 cubic foot per second. If flows less than this rate must be measured accurately, the head on the weir sill throat can be measured within the culvert a distance $W$ downstream from the culvert entrance and a special rating can be used. Standardized ratio-type rating tables have been prepared for culvert floor slopes of 0, 1, 2, 4, 5, and 6 percent. The information is presented in figures 2.21 to 2.26 because these tables are rather extensive.

Weir sills should be installed carefully so that the standard rating table will apply. If the sills are made of concrete, they can be precast in a trough form. Layout dimensions for a trough form are shown in figure 2.27. A steel plate at the downstream end of each sill will protect and maintain the dimension of the throat.

The Virginia V-notch weir was devised for use in locations where unfavorable features of the Villemonte weir sill would be intolerable. The V-notch is placed on the culvert apron upstream from the culvert entrance. In this location flows can be measured down to zero head. Since the V-notch is outside of the culvert barrel, it is easier to construct than weir sills located inside culverts. A disadvantage of the Virginia V-Notch weir is possible reduction of culvert capacity. The weir also has the usual
ills of ordinary V-notch weirs associated with upstream deposition.

Capacity reduction was investigated first by the use of laboratory model studies. Figure 2.28 is reproduced from these studies to illustrate the findings concerning capacity reduction by weir sills of various heights and distances from the entrance of the culvert. In the practical range, however, reduction can be held within less than 5 percent.

Head-discharge characteristics of these V-notch weirs have not been generalized except in the low flow range. When flow is confined to the V-notch opening, the standard rating will apply. The culvert is assumed to meet the criteria for entrance control so that free overfall exists at the weir in this range. When flow is increased further, control gradually passes to the culvert entrance. Throughout the range of flow the head-discharge relationship is reversible, and the combination provides a satisfactory flowmeter. Flow for entrance control can be the critical-depth type or orifice type, depending on whether the entrance is submerged. Flows in the upper range can be approximated from the hydraulic laws for the culvert opening. Calibration is still needed, however, to develop a satisfactory rating curve to cover the full range of operating head. Use of model studies, supplemented by field current meter or field volumetric measurements, is the best way to develop a rating curve.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Small Model</th>
<th>Large Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>8&quot;</td>
<td>16&quot;</td>
</tr>
<tr>
<td>( \frac{w}{16} )</td>
<td>( \frac{1}{2} )</td>
<td>1&quot;</td>
</tr>
<tr>
<td>( \frac{h}{y} )</td>
<td>( \frac{7}{8} )</td>
<td>( \frac{3}{4} )</td>
</tr>
</tbody>
</table>
| \( \frac{r}{32} \) | \( \frac{1}{4} \) | \( \frac{1}{2} \)  

**Figure 2.29.—Dimensions of weir sills and their placement within the culvert.**
FIGURE 2.21.—Head-discharge relationship obtained from tests on short rectangular culverts equipped with weir sills and with a floor slope of 0 percent.

FIGURE 2.22.—Head-discharge relationships obtained from tests on short rectangular culverts equipped with weir sills and with a floor slope of 1 percent.
FIGURE 2.23.—Head-discharge relationships obtained from tests on short rectangular culverts equipped with weir sills and with a floor slope of 2 percent.

FIGURE 2.24.—Head-discharge relationships obtained from tests on short rectangular culverts equipped with weir sills and with a floor slope of 4 percent.
Figure 2.25.—Head-discharge relationships obtained from tests on short rectangular culverts equipped with weir sills and with a floor slope of 5 percent.

Figure 2.26.—Head-discharge relationships obtained from tests on short rectangular culverts equipped with weir sills and with a floor slope of 6 percent.
Soil Conservation

Many water control structures have been built as part of a soil and water conservation program. The original hydraulic studies for design guidance can be used to estimate the head-discharge relationships of those that have been constructed.

Closed Conduit Spillways

A closed conduit spillway is a tube through a dam. This definition includes simple culverts that have been discussed. Closed conduit spillways will be analyzed according to the suitability of various devices for measuring runoff. The devices considered will be those most often found in conservation areas.

Drop Inlet

A closed conduit with a drop inlet entrance can be used for runoff measurement, but only some structures under certain conditions can yield a fair measurement. A study of the hydraulics of the drop inlet will indicate structures that can be used. Blaisdell and Donnelly (4) pointed out that several types of flow are possible for a combination-type structure. Four possible controls are: (1) weir flow, (2) entrance orifice control, (3) short tube control, and (4) pipe flow.

Under some conditions a fifth control might be possible—that of orifice control at the junction of the riser and the barrel. A structure that can exercise all these controls on the reservoir water level is unsuited for flow measurement. In figure 2.29, three discharge rates are possible for a given elevation of water surface. Since the discharge rate can fluctuate over this range, the action is unpredictable. A properly designed drop inlet will not exhibit this behavior; instead, it is proportioned so that the orifice and short tube controls are impossi-
ble. Either weir flow or pipe flow will occur, each in its own range. The head-discharge relationship will follow the same curve on either the rising or falling stage. This structure can be used to measure runoff. Thus, before a drop inlet can be considered for use as a flowmeter, its hydraulic behavior should be studied. The head-discharge relationship should be calculated for each control and should be plotted on a common graph, as was done in figure 2.29.

**Weir flow.**—This type of flow is estimated by the equation:

$$ Q = CLH^{1/2} $$  \tag{2-30}

The value of $C$ can range from about 2.5 to 5.7, varying with approach conditions, weir crest-form riser proportions, and head. Values of $C$ should be based on those obtained from studies on similar structures. The crest length ($L$) is measured on the inside edge if the drop inlet of the weir is square edged. If it is rounded, the weir length is measured around the point of tangency on the crest.

**Pipe flow.**—When the conduit is flowing completely full, the head ($H_c$) causing the flow is the difference between the level of the headwater surface and the point where the hydraulic grade line pierces the plane of the conduit exit. Discharge is calculated by the equation:

$$ Q = \frac{\pi D^2}{4} \sqrt{\frac{2gH_c}{K_e+K_n+fL^2/4R_{ri}A_{ri}} \left(1+f_{r}^1A^1\right)^2} $$  \tag{2-31}

where

- $D$ = diameter of circular barrel;
- $K_e$ = entrance coefficient;
- $K_n$ = exit loss coefficient;
- $f$ = Darcy-Weisbach friction coefficient for the barrel;
- $l$ = length of the barrel;
- $R_{ri}$ = hydraulic radius of the drop inlet;
- $A$ = area of the barrel opening; and subscript $r$ refers to the riser.

**Figure 2.28.**—Reduction of flow capacity caused by a pair of V-notch weirs on the apron of a twin-barrel culvert.
The head-discharge relationship for orifice \( H_o \) control at the entrance is calculated by the equation:

\[
Q = C_o A H_o^{1/2}.
\]  

(2-32)

Values of crest \( C_o \) suggested for rough estimating are square-edged crest = 4.0 and rounded crest = 6.0.

The equation for estimating the head-discharge relationship under short tube control is:

\[
Q = C_s A H_s^{1/2}.
\]  

(2-33)

where \( H_s \) is assumed to be the distance from water surface in the reservoir to the top of the barrel at the juncture with the riser.

For a well-rounded entrance to the barrel, the breakaway point may be a little higher than the line at the top of the barrel. Uncertainty of the short tube coefficient \( C_s \) makes the difference meaningless. The values of \( C_s \) range from 1.9 for a short riser with a large flaring entrance section to 5.3 for a 6-inch (15.2 cm) vitrified clay tile with a bellmouthed entrance.

If hydraulic characteristics of the drop inlet are suitable runoff measurements, the calculated rating curve should not be used to estimate runoff rates. Instead, the drop inlet should be calibrated by current meter. The major difficulty is accumulation of trash. Field current meter measurements on one structure have showed the discharge rate to range from 2 to 83 ft\(^3\)/s (0.06 to 2.5 m\(^3\)/s) for the same head, the variation being caused by accumulation of trash on the intake. If trash accumulates, the calculated rating curve should not be used to measure runoff.

### Straight Headwall Inlet

The straight headwall inlet is essentially a culvert. Because of its length and high operating heads, it probably will flow full over much of its operating range. The principles used to analyze the drop inlet can be applied here.

As conduits are usually circular, the rating for the weir or critical depth flow through a circular opening can be shown best graphically. Three such curves are shown on figures 2.30 and 2.31. These are dimensionless and apply to
Any diameter. The only requirement for these curves is that the pipe slope below be steep so that the entrance alone controls the rate of flow.

Pipe flow will be estimated the same as conduit flow with a drop inlet entrance except that the term for riser loss is omitted from equation 2-31. The values of entrance coefficients (K_e) also will be different: Suggested values for rounded entrance, 0.25; for square edge, 0.7; and for pipe groove, 0.3.

The discharge equation for orifice flow also will be the same as for the drop inlet. Orifice coefficient values (C_o) suggested for estimating are 4.8 for square edge and 6.0 for rounded edge. Current-meter calibration is recommended, particularly in the pipe flow range. Again, the possibility of trash fouling the intake must be considered.

**Box Inlet Drop Spillway**

Box inlet drop spillways, with entrances as shown in figure 2.32, have rather long weir lengths. As such, they are unsuitable for measuring small flow rates. Under some conditions, however, they are a satisfactory estimate of peak flows. For these conditions, information on calculating the flow rate can be found in reference (3). Three types of flume entrances are presented.

**U-type flume entrance.**—The U-type flume entrance is a box inlet with a sloping floor (fig. 2.33). The rating curve for inlet control can be approximated by the equation:

> \[
> \frac{Q}{D^{5/2}} = \frac{2}{1 + \left( \frac{h}{D} \right)^2}
> \]

**Figure 2.31.**—Effect of grooved edge and of rounded edge on the rating curve of a circular opening.

**Figure 2.30.**—Diagram of a circular opening and rating curve for weir flow or critical depth flow through the opening.
where
\[ Q = \text{discharge rate (ft}^3/\text{s)}; \]
\[ W = \text{width of the flume (ft)}; \]
\[ B = \text{length of the box, (ft)}; \]
\[ L = \text{total length of weir (ft)}; \]
\[ H = \text{head on lip of box (ft); and} \]
\[ g = \text{acceleration of gravity (ft/s)}. \]

The inlet control ceases when the discharge reaches the value indicated by the following equation:

\[ \frac{Q}{W^{2.5}} = 0.95 \sqrt[2.5]{\frac{L}{W}} \left[ \frac{H}{W} \right]^{1.7} \]  

(2-34)

Test data are available on rectangular drop spillways with a trapezoidal channel approach. Proportions are shown in figure 2.34. The discharge equation for this structure, which contains an approach velocity term, is:

\[ Q = C L \left[ H + \frac{V^2}{2g} \right]^{3/2} \]  

(2-39)

Construct a rating curve for the flume entrance by plotting the inlet control and headwall control discharge curves on a single sheet. Intersection between the two should be smoothed by placing a short section of reverse curve between them. This should approximate the rating.

**Wisconsin flume entrance.**—The Wisconsin flume entrance has a vertical curve connecting the entrance apron with the floor of the flume. It was tested with circular entrance walls and 2-to-1 tapered entrance walls. Their arrangement is shown in figure 2.33.

The rating curve for either entrance of the Wisconsin flume is expressed by the equation:

\[ \frac{Q}{W^{2.5}} = 0.617\sqrt{\frac{H + D}{W}} \]  

(2-36)

**2:1 flume entrance.**—For the 2:1 flume entrance the apron floor intersects the floor of the flume at an angle. The design is shown on figure 2.33. The approximate discharge equation for this entrance is:

\[ Q = 0.661\sqrt{g W^{0.9} H^{1.6}}. \]  

(2-38)

**Figure 2.32.—Construction of a box-inlet drop spillway.**
where

\[ \begin{align*}
C &= \text{weir coefficient for flow;} \\
L &= \text{total weir length;} \\
H &= \text{hydraulic head on weir;} \\
V &= \text{velocity of flow; and} \\
g &= \text{acceleration of gravity.}
\end{align*} \]

The coefficient varies with the dimensional proportions of the notch opening and the values given in figure 2.32.

The coefficient varies with the dimensional proportions of the notch opening and the values given in figure 2.32.

Installation of HS, H, and HL Flumes

Whenever possible, installation of these flumes should be made with approach boxes depressed below the natural ground surface, as shown in figure 2.35. Where the watershed slope is small and the flow dispersed, gutters may be necessary to collect the runoff at the bottom of the slope and channel it into the approach box (fig. 2.36). These gutters and the approach box sometimes are covered to prevent complication of runoff record by rain falling thereon. The more common approach box is shown in figure 2.37. Here, the runoff has concentrated naturally into a small stream channel upstream from the flume.

Metal flumes are bolted to the concrete approach with gaskets to make a watertight joint. The concrete cutoff wall extends below the concrete approach at the upstream face of the flume to provide substantial support and to prevent seepage below the flume. A drain tile releases water from below the flume. Leveling bolts on the downstream supporting wall are used to fasten and adjust the flume to this level.

The flume floor must be level. If silting is a problem, a 1-on-8 sloping false floor can be set in to concentrate low flows and thereby reduce silting. The difference in calibration of a flume with a flat floor and that with a sloping false floor is less than 1 percent.

The stilling well for water stage recorder floats usually is made of sheet metal attached to the flume wall. Openings to the flume supply ready exchange of water between the flume and the stilling well. Support and shelter for the water stage recorders are fastened to the flume wall. Where freezing temperatures are expected, the well should be heated or drained automatically after each runoff period.

**HS Flumes**

Instructions for setting water level recorders for HS flumes are:

- See that the water level recorder is fastened securely to its support and that the support prevents movement of the recorder relative to the measuring device. Make sure
that the chart is mounted correctly on the chart drum.

- Mount a point gage vertically over the floor near the tip of the flume. This ordinarily will be done by a temporary point-gage support.
- Use modeling clay (plasticine) or a similar material to dam the outlet end of the measuring device. If necessary, dam the inlet end to prevent loss of water. To avoid the effects of surface tension, the nearest point of the dam at the elevation of water surface should be at least a half inch away from the point gage.
- Fill the flume and float well with water until a depth of 1/2 to 1 inch (1.3 to 2.5 cm) of water is obtained over the control section.

- Obtain point gage readings for the water surface and floor of the flume. Subtract the crest reading from the water-surface reading.
- When point gage readings are made, the water level recorder will note the elevation of water surface on the chart. Subtract the difference between point gage readings from the chart reading to obtain the chart reading for zero head on the measuring device.
- Check the two preceding steps with a different amount of water in the flume.

**H and HL Flumes**

Instructions for setting the water level recorders for H and HL flumes are:
STRAIGHT HEADWALL INSTALLATION
(for use when flume is to be installed in a well defined natural channel)

DROP BOX INSTALLATION
(for use when the runoff must be concentrated by gutters or dikes)

Figure 2.35.—Plans for straight headwall and drop box installations of HS, H, or HL flumes.
Form temporary watertight pool around intakes outside of stilling well.
- Raise water level in stilling well until it is 1 or 2 inches (2.5 or 5.0 cm) above lowest intake.
- Place water level recorder on floor of shelter or on shelf; install float, counterweight, and graduated float tape in position; install tape index pointer (I.P.); insert clock; place chart paper on clock; fill pen with ink and place it in position to record.
- Observe the record for about 5 minutes to see if the setup is watertight. If the water level drops during this period, find the leak and repair it.
- With surveyor's level, take backsight (B.S.) on crest of flume or notch of weir to get elevation of the height of instrument (H.I.). All rod readings are to 0.001 foot (0.03 cm).
- Attach plumb bob to steel tape graduated in 0.01 foot (0.3 cm). Set point of plumb bob at elevation of H.I. and read tape at horizontal index line (L) marked on shelter or any other convenient object over the pool. (Estimate tape reading to 0.001 ft (0.03 cm)).
- Lower plumb bob to water surface of pool and read tape at index line. Repeat this step for a check. Read tape index pointer on float tape immediately.
- Subtract difference of tape readings at (L) of the preceding two steps from height of instrument to get elevation of water surface.
- Lower the float by the difference between the two preceding readings (if the preceding reading is less than the reading preceding it) or raise the float (if the preceding reading is greater than the reading preceding it) with respect to the float tape. Minor adjustments up to 0.05 (1.5 cm) foot can be made by adjusting the index pointer.
- Check height of instrument by rod reading on flume crest.
- Set pen on chart to read water surface elevation obtained in the last reading.
Check the preceding eight steps with water at a different level.

**Submergence Effect on H Flumes**

Flumes should be installed with free outfall or no submergence, wherever possible. The free discharge head, $H$, can be computed with the terms shown in figure 2.6 by using the following equation:

$$H = \frac{d_1}{1 + 0.00175 (cd_2/d_1)^{5.44}} \quad (2-40)$$

where

- $H$ = free flow head;
- $d_1$ = actual head with submergence;
- $d_2$ = tail-water depth above flume zero head; and
- $e = 2.71828 \ldots$ base of natural logarithms

$$0.15 < d_2/d_1 < 0.90.$$

Submergence of 30 percent has less than 1 percent effect on the free discharge head (fig. 2.6). A 50-percent submergence has less than a 3-percent effect.

**Rating Malformed Flumes and Weirs**

The crests or controlling edges of a weir or $H$ flume are the most important part of a measuring device. They should be formed carefully so that the dimensions are precise. The controlling edges should be straight and smooth. If the weir, as built, deviated appreciably from the design slope, a correction must be applied to the discharge values determined from the laboratory tests.

For triangular weirs, the slope term is $\tan \frac{\theta}{2}$, where $\theta$ is the total angle of the V-shaped crest. The angle $\theta$ is obtained from field measurement on each crest. One method of obtaining the crest measurements is to establish a horizontal control and a datum for elevation and obtain at least eight equally spaced points on each crest. These crests should be relatively straight. Therefore, an equation of a straight line can be obtained by using least-square methods for each crest and by using elevation and horizontal distance as the $X$ and $Y$ terms. Solving the two equations simultaneously for the common $Y$ will yield the zero elevation for head. The $\tan \frac{\theta}{2}$ term can be obtained by averaging the slope terms of the two equations! The $\tan \frac{\theta}{2}$ term is then used in the discharge equations 2.3 to 2.8. Discharge equations for triangular weirs are listed in figure 2.7. More than eight points may be necessary if the crests are not smooth. The texture (concrete, steel, pebble) of the crest on triangular weirs is unimportant, however, as long as the shape is well defined.

$H$ flumes may be corrected for small deviations from the design dimensions by measuring the control edges of the flume. Enough measurements should be taken to obtain the values of $B_0$ and $B_1$ in figures 2.38 and 2.39. The flume should be installed before these measurements are made to obtain the correct head, $H$, for each width of control obtained. The discharge rating then may be computed using the discharge equations in figure 2.38. These equations apply only where the velocities approaching the flume are uniform and tranquil. The sloping floor is a 1-on-8 false floor in the $H$ flume to concentrate flows along the wall with the stilling well intake. The height of the false floor is 0.2D at the intersection of the wall and entrance to the flume. This floor slopes downward 1-on-8 along the wall and also at the entrance to the flume. If drop boxes or sloping channels in the direction of flow produce high velocities in the approach channels, the flume should be calibrated under these conditions. Discharge equations in metric form are listed in figure 2.39.

**Preparation of Rating Tables**

The laboratory staff conducting the calibration tests should prepare rating tables. Using discharge coefficients to prepare the tables can eliminate small errors constructing the prototype measuring device. This is accompanied by incorporating prototype measurements in the discharge equation. Where electronic computers are used in the runoff analysis, rating tables may not be required. The hydrographer usually desires a rating table, however.

Wherever practical, current-meter or volu-
metric measurements should be made to check the calibration. Any large cutting or filling changes in the approach cross section may require a revision of the calibration. These changes may be especially large in sediment-laden streams where deposition may alter approach gradients and thereby alter the approach velocity. In such instances, a different measuring device should have been used.

**Pondage Corrections**

Installation of a flume or weir in a natural waterway may cause unnatural detention or retention of storm runoff in the pond formed by it.

### Flume Types

<table>
<thead>
<tr>
<th>Flume Type</th>
<th>Design Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_0$</td>
<td>$B_1$</td>
</tr>
<tr>
<td>HS</td>
<td>0.025 D</td>
</tr>
<tr>
<td>H</td>
<td>0.050 D</td>
</tr>
<tr>
<td>HL</td>
<td>0.100 D</td>
</tr>
</tbody>
</table>

### Low Flow

\[
Q = A_0 \left( 2B_0 + B_1 H \right) H [H - 0.01]^{1.5} + 1
\]

### Transition

\[
Q = (K_0 B_0 + K_1 B_1 H) \sqrt{2gH^{3/2}}
\]

### Medium and High Flows

\[
Q = \left[ (E_0 + E_1 D) B_0 + (F_0 + F_1 D) B_1 \right] (H + v^2/2g) \sqrt{2g(H + v^2/2g)^{3/2}}
\]

if $D > 1$ then $D = 1.0$

\[v = \text{average velocity, head measuring section}\]

<table>
<thead>
<tr>
<th>Flume</th>
<th>Floor</th>
<th>Range $H$ in Feet</th>
<th>$A_0$</th>
<th>$A_1$</th>
<th>$E_0$</th>
<th>$E_1$</th>
<th>$F_0$</th>
<th>$F_1$</th>
<th>$K_0$</th>
<th>$K_1$</th>
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<tbody>
<tr>
<td>HS</td>
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<td>0.01 - 0.10</td>
<td>3.93</td>
<td>0.526</td>
<td>0.861</td>
<td>0.112</td>
<td>0.479</td>
<td>-0.035</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
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<td></td>
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</tr>
<tr>
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<td>0.522*</td>
<td>0.7804*</td>
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<td>0.3788*</td>
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<tr>
<td>HL</td>
<td>Flat</td>
<td>0.20 - D</td>
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<td></td>
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<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

*Derived from rating table (4-foot HL)

**Transition range**, heads 0.1 to 0.2 feet.

Values of $K_0$ and $K_1$ are determined by a simultaneous solution of the value of $Q$ for $H$ equal to 0.1 foot from low flow equation and value of $Q$ for $H$ equal to 0.2 feet.

**Figure 2.38.**—Discharge equations for HS flume, H flume, and HL flume, using flume dimensions.
by this installation. Both conditions may result if the pond is large in relation to the size of the watershed. The record for this interruption in the natural streamflow may need to be corrected to derive values of watershed runoff without the pond. Pondage correction can be determined for a few storms where the rate of change in depth through the control structure is large. This test will show the size of corrections, and the hydrographer can determine if

<table>
<thead>
<tr>
<th>Flume Type</th>
<th>Design Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B&lt;sub&gt;m&lt;/sub&gt;</td>
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<td>HS</td>
<td>0.025 D&lt;sub&gt;m&lt;/sub&gt;</td>
</tr>
<tr>
<td>H</td>
<td>0.050 D&lt;sub&gt;m&lt;/sub&gt;</td>
</tr>
<tr>
<td>HL</td>
<td>0.100 D&lt;sub&gt;m&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

Low Flow

\[
Q_m = A_m (2B_m + B_1 H_m) \frac{H_m}{H_m - 0.003} \]

Transition

\[
Q_m = (K_0 B_m + K_1 B_1 H_m) \sqrt{2g H_m^{3/2}}
\]

Medium and High Flows

\[
Q_m = \left((E_0 + E_m D_m) B_m + (F_0 + F_m D_m) B_1 \frac{H_m + v^2/2g_m}{H_m + v^2/2g_m}\right) \sqrt{2g_m (H_m + v^2/2g_m)^{3/2}}
\]

if \(D_m > 0.3048\) then \(D_m = 0.3048\)

\[v = \text{average velocity, head measuring section}\]

<table>
<thead>
<tr>
<th>Flume</th>
<th>Floor</th>
<th>Range (H_m) in Meters</th>
<th>(A_m)</th>
<th>(A_1)</th>
<th>(E_0)</th>
<th>(E_m)</th>
<th>(F_0)</th>
<th>(F_m)</th>
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<th>(K_1)</th>
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<td>0.7804*</td>
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</tbody>
</table>

*Derived from rating table (4-foot HL)

**Transition range**, heads 0.03 to 0.06 meters

Values of \(K_0\) and \(K_1\) are determined by a simultaneous solution of the value of \(Q_m\) for \(H\) equal to 0.03 meter from low flow equation and value of \(Q_m\) for \(H\) equal to 0.06 meter.

FIGURE 2.39.—Discharge equations for HS, H, and HL flumes using metric flume dimensions.
such corrections are worth the effort. Pondage corrections generally increase the peak rate and shift the peak time forward.

Some pondage corrections are ignored or neglected if only the total runoff volume is of interest to the watershed study. Therefore, peak rate and hydrograph are unimportant. If the total runoff for each day from midnight to midnight is to be calculated, the difference in amount stored at the beginning and end of the day must be considered.

Pondage corrections generally are made by using computerized runoff analysis. Procedures for calculating pondage corrections are described in the section on data reduction (p. 184).

A contour map of the area of the pond is used to compute pondage rates corresponding to rates of change in stage. The maximum elevation of the contour map should be the maximum head on the outflow structure. Use the areas obtained from the contour map of the pond to compute the volume of pond for various stages. A typical calculation and curves are shown in figure 2.40.

**Natural Controls**

Streamflow is gaged at an uncalibrated runoff-measuring station by measuring discharge rates (product of the flow velocities and channel cross-section areas) of various stages of flow. Measured discharge rates are plotted against stage to provide a means of converting continuous records of stage into runoff rate and amounts. The field-calibrated gaging station may be the most practical means of measurement where the quantity of water is large and operating conditions are unfavorable for precalibrated devices.

**Low Water Controls**

Natural low water controls may be found in streams at rock outcrops or ledges in the channel. The sensitivity of low water control will depend on its contraction in the channel and the amount of fall below the control. Critical depth usually will be found upstream of the brink for low flows.

As stage increases, the low water control may become ineffective as a flow control due to tail water. This usually occurs when submergence exceeds 0.90. Sometimes, however, the submergence value can be as high as 0.95 without affecting the flow control. The zero reference used in determining the submergence ratio may be difficult to obtain on a natural control. One method is to plot the free discharge measurements on logarithmic paper, using var-

![Figure 2.40](https://example.com/figure2.40.png)

**FIGURE 2.40.**—Computations to obtain volume of pond for various stages of elevation and pondage volumes and curves, Fennimore, Wis.
ious elevation references for zero head. Then use the zero reference that will give 1.5 for the exponent of the head (slope of the line).

**High Water Controls:**

As the stage increases on a natural control, the control may shift from low water control to a bridge downstream or a bend in the channel, or even to channel control.

*Bridge openings and contracted sections.*—Bridge openings and similar contracted sections can be used to obtain estimates of peak flows. The U.S. Geological Survey devised a method for making such estimates (2, 3, 6, 16, 19, 22, 25). It is described for guidance in estimating of peak flows, but reference to the circular will be required to evaluate the coefficients needed for a solution.

This method is for computing an isolated peak discharge rate from the high watermarks it left behind. It does not provide a system for obtaining continuous measurement of flow rate through the bridge opening. The principles outlined can be adapted to obtain a continuous record, but the current-meter rating curve for a station with the bridge for a control probably would be better. The contracted-section method is satisfactory, and it is often the only way for estimating floods. This method is different from that for culverts in that the estimate is based on the relationship between the drop of the water surface level and the velocity change instead of critical flow. Thus, elevations of water surface are required at two points in the flow system rather than at one point as in the previously described methods.

Figure 2.41 shows a typical contracted section.

The two points of measurement are at sections 1 and 3. A discharge equation can be derived by writing the energy and continuity equations for the reach between these two sections. This equation is:

\[ Q = C a_1 \sqrt{2g \left[ \Delta h + \alpha_t \frac{V_1^2}{2g} - h_l \right]} \]  \hspace{1cm} (2-41)

where

- \( Q \) = discharge in cubic feet per second;
- \( C \) = coefficient of discharge;
- \( a_1 \) = gross area of section 3 in square feet (this is the minimum section parallel to the constriction between the abutments and is not necessarily at the downstream side of the bridge);
- \( \Delta h \) = difference in elevation of the water surface between sections 1 and 3, in feet;
- \( \alpha_t \frac{V_1^2}{2g} \) = weighted average velocity head in feet at section 1, where \( V_1 \) is the average velocity, \( Q \cdot A_1 \), and \( \alpha_t \) (alpha) is a coefficient that takes into account the variation in velocity in that section; and
- \( h_l \) = the head loss in feet due to friction between sections 1 and 3.

The fieldwork necessary for evaluating the terms in this equation is described in detail, but the office procedure is discussed in more gen-
erals terms. If the fieldwork is done well and completely, the flow can be computed when the needed reference material is at hand.

Define and locate sections 1 and 3. Section 1 is located at least one bridge-opening width upstream. It must be at right angles to the direction of the stream at this point and is to extend across the entire valley. Section 1 may be omitted when the degree of contraction is large and the difference in roughness between sections 1 and 3 is not great. In this instance, the upstream water-surface elevation is obtained on the embankment at a distance from the center of the opening equal to one bridge-opening width. When the approach section has much vegetation, friction loss will be a large part of the total fall and must be calculated. If surveying of section 1 is unduly difficult because of this vegetation, estimate its cross section by measurements of the nearest accessible similar cross section, say at the edge of the right-of-way. The value of Manning’s $n$ selected for the approach section should represent the upper half of the reach between section 1 and the bridge opening.

Section 3 is defined by a straight line parallel to the constriction that marks the minimum area between the two abutments of the bridge. The area, $a_0$, used in equation 2-41, is always the gross area of the section extending to the free-water surface. It does not exclude the area occupied by piles or piers in the plane of the section, nor does it include any submerged lower part of the bridge. Where large scour holes are under the bridge, the bridge geometry no longer forms the control and the available coefficients do not apply.

Use of a transit is recommended for a field survey. The following method is recommended:

- Locate and obtain the elevation of floodmarks near the constriction. Include marks along the channel edges and marks on the upstream and downstream faces of the embankments forming the constriction.
- Locate the river channel, bridge opening, and all features pertinent to the hydraulics of the site; in brief, locate a plan of the bridge and vicinity.
- Obtain ground elevation for cross sections at sections 1 and 3. If flow also occurred over the highway embankment, obtain elevations (a profile) of the centerline of the submerged portion of the highway. Obtain typical cross sections of the roadway.

- Survey and measure the bridge abutments and embankments so that plan and elevation drawings can be made. Identify all factors that influence the discharge coefficient. Physical features that affect the coefficient are (1) percentage of channel contraction; (2) ratio of abutment length to bridge opening width; (3) rounding of entrance corners; (4) wingwall angle; (5) wingwall length; (6) angularity of bridge with respect to flow line; (7) distance from free-water surface at section 3 to tops of right and left banks under the bridge; (8) embankment slope; (9) abutment slope; (10) shape of entrance when embankments and abutments slope; (11) eccentricity of bridge opening with respect to cross section of channel; (12) area of bridge piles or piers; and (13) degree of submergence of the bridge.

- Select values of Manning’s $n$ for sections 1 and 2. If $n$ cannot be decided in the field, take sufficient data in notes and photographs for later study and comparison with channels of known $n$ value.

Estimates of the flow can be made by using standard hydraulic computation procedures. The coefficient of discharge must be estimated, however, as it can range from 1.0 down to 0.50 or less for one type of bridge opening.

**Bends in Channel:**

Bends in a channel cause spiral flow or counterrotation currents that contribute to moving the bedload downstream and toward the inside of bends. Eddies develop about three-fourths of the way around the bend because of the spiral motion of the flow, causing deposition on the inside of the banks in the bend. The slack water produces some energy loss due to friction. Friction loss also occurs on the walls and bottom of the channel. All these factors produce a measure of control over the flow in the channel. Unless the banks in the bend are stabilized, the bend should not be used as a control.

**Channel control.**—Channel control is the main control for high flows in natural channels. Bridge openings and bends can produce local
disturbances. The natural channel, however, will return to normal flow depth upstream and downstream of the disturbance. Since channel roughness controls the flow depth, changes in roughness will change the depth-discharge relationship. These changes include debris, vegetation, size of bed material, scour or filling of the channel, and bed forms in the channel.

The slope-area method can be used to obtain an approximate discharge. Discharge determined by this method is only approximate, however. It consists of using the hydraulic slope in a uniform reach of channel, and the average cross-sectional area of that reach, to give a discharge rate. The channel reach should be at least 300 feet (91 m), and preferably 1,000 feet (305 m), in length. The course should be straight and should be free of rapids, abrupt falls, and sudden contractions or expansions. Discharge may be computed from Manning's formula:

$$Q = rac{1.486}{n} A R^{2/3} S^{1/2}$$  \hspace{1cm} (2-42)

where

- $Q$ = discharge, cubic feet per second;
- $A$ = area of cross section, square feet;
- $R$ = hydraulic radius (area/wetted perimeter), feet;
- $S$ = hydraulic slope (loss of energy/length of reach); and
- $n$ = roughness factor depending on character of the channel lining and depth of flow.

Slope and areas must be determined simultaneously if the water levels are changing. The terms $A R^{2/3}$ should be computed for each end of the reach and averaged for use in Manning’s formula.

**Shifting Control:**

Control of flow in a natural channel with no natural falls or supercritical velocities depends on the loss of energy within the total system. Increase or decrease in energy loss will influence the discharge rate. Therefore, the control will shift, depending on roughness of the channel.

**Effects of scour and fill.**—Scour is the erosive action of running water in streams. This action excavates and carries away earth and solid rock material from the bed and banks. Fill or aggradation is the opposite of scour. Scour occurs where local velocities are large enough to remove and transport material. Turbulence level, sediment concentration, water temperature, and size of bed material are other factors that influence scour. Aggradation usually is caused by a reduction in stream velocity. Many changes can reduce velocity. Scour and fill change the area of a channel and the loss of energy in the channel. Thus, the control is changing continually. A current-meter rating is necessary at all times during a flow event.

**Channel change above the control.**—Changes in the channel above a control will affect the velocity of approach to the constricted area of the control. These changes may result from aggradation or degradation of the main channel or changes in vegetation along the banks. Therefore, the rating (depth-discharge relationship) will shift. The amount of the shift will depend on the relative change in the channel. Such changes also may affect precalibrated measuring devices and are a continuing problem when collecting accurate runoff records.

**Return of overbank flow.**—Constriction or bridge openings force the flow to pass through a limited area. This produces lateral flow from the overbank areas to the main channel both upstream and downstream of the constriction. Control of the flow is a combination of the whole system both upstream and downstream. Submergence of the bridge occurs because of backwater from the flow downstream. Control may shift from above the bridge, to downstream, and back again. The only measure of flow at such a location is the head loss through the bridge or constriction. Discharge determined by this method is only approximate.

**Effect of ice.**—Ice can shift the control for various reasons. If the stream is wide (200 ft or 61 m) and the ice is 1 to 2 feet (30.5 to 61 cm) thick, the ice cover is sufficiently flexible to rise and fall with the stream and the stream can flow as a closed conduit. The underside of the ice can become rippled due to the fluid turbulence when the ice is formed. If the stream is narrow, bridging or airspace can occur under the ice. In the spring and fall slush, ice can form on the surface and present problems for
current metering. Ice jams in the spring can produce shifts in the depth-discharge relation and in the flow control position. Ice in streams causes a variable backwater that only can be determined by frequent discharge measurements during such periods.

**Effect of vegetal and aquatic growth.**—Aquatic growth increases the energy loss of a stream. This can produce changes in the approach velocity to a current-meter station, and it can shift the stage-discharge relationship seasonally. Increase in vegetal and aquatic growth also can shift the flow from the main channel to the overbank.

**Other Factors in Selecting Gaging Station Locations**

Field-calibrated gaging stations should be located in straight, uniform reaches of channel having smooth beds and banks of a permanent nature whenever possible. Their location should be far enough from sewage outfall, power stations, or other installations causing flow disturbances so that the relationship of gage height to discharge will not be affected. In many channels these conditions are difficult to locate, and care must be taken to obtain a satisfactory station. Daily current-meter measurements may be necessary where sand shifts occur.

Geology of the watershed must be considered in the location of a gaging station. Ground water flow and surface return flow can be important elements of the total hydrologic analysis of the flow. The use of rock formations for support of precalibrated runoff measuring devices and dissipation of the added energy created by these devices can save on installation costs and prevent failure.

Topographic features of the watershed should be considered in locating gaging stations. If ice is a problem, a measuring device may be located in a protected area that receives sunlight most of the time. Orographic features may determine the spacing of gaging stations within a watershed.

**Instrumentation**

The stage of a stream is the height of the water surface above an established datum. It usually is expressed in feet (meters) and hundredths of a foot (meters).

A control provides a stable cross section wherein the rate of flow can be determined if the stage is known. The frequency of flow determinations is dictated by the purposes and conditions of the study. Instruments are commercially available to provide continuous stage records. These instruments are particularly useful when a record of the entire hydrograph is needed on rapidly fluctuating streams. When less detail is needed or when flow fluctuation is gradual, periodic readings on a graduated staff may be adequate. When only maximum peak flow information is needed, a crest gage will protect and retain a high watermark for subsequent observation.

**Water Stage Record**

Water stage record is important in the runoff study. The rate of flow is determined by applying the depth discharge relationship to the stage reading. Therefore, reliability of the stage reading is important.

**Nonrecording Gages**

Two general types of nonrecording gages are (1) wire-weight gages, float, or point gages, which measure from a fixed point, and (2) staff or crest gages, which read stage directly.

**Wire-weight gages.**—Various wire-weight gages have been used for many years, usually as an independent reference of water levels outside the stilling well at gaging stations. The gage height indicator on the wire-weight gage is set to correspond with the recorder datum. When the bottom of the weight is at the water surface, water level is checked to assure accurate recording. Wire-weight gages are useful at bridges, weirs, and other structures over the water. These gages consist of mounting frame, turning handle, cable drum, water-level indicator, and weight wire or cable and weight (7). They can be attached securely to a wall or bridge rail for ease in lowering the weight and observing the water level.

**Staff gages.**—Staff gages are used as an easily visible reference of water level for stage recorder charts and for periodic observation of water levels where continuous records are not required. Staff gages should be porcelain, en-
ameled iron, or stainless steel. They should be fastened securely to a vertical wall, column, or other well-anchored support. For best visibility, staff gages should be separated from the high-velocity area in the stream. They should be referenced carefully to a permanent elevation marker and the recorder datum for ease in checking the gage setting after frost and ice periods, which may damage or loosen the support. Reservoir staff gages often are fastened to an inclined timber, metal, or concrete surface. This surface must be graduated carefully and placed accurately to insure correct stage readings. The location and setting of stage gages for weirs, flumes, and gaging stations should follow recommendations in appropriate handbooks (3, 47).

Crest gages.—These gages are an inexpensive means of determining maximum stage when no observer is present. They indicate the maximum stage reached between visits of the observer and provide useful information for computing peak discharge of flood events. They are located with reference to bridges, culverts, spillways, and stable streambank sections for which stage-discharge relationships can be obtained.

A commonly used crest gage consists of a well-anchored 2-inch (5 cm) galvanized pipe with a perforated cap on the bottom and a fill cap or pipe cap with vent hole on top. A length of thin-wall conduit or a wood measuring stick is placed within the pipe, as shown in figure 2.42. Extreme caution should be taken when inserting a wood stick since rapid lowering may cause a false high water measure. A supply of powdered or granulated cork in the pipe rises with the water level and adheres to the measuring rod, thus recording maximum water level. A graduated rod simplifies reading of high water levels. The cap should be locked or fastened securely for protection against vandalism. Figure 2.43 shows a typical crest gage installation.

Float-Type Recording Gages

Many float-actuated water-level recorders are available from instrument manufacturers. The recorder and accessories best suited for a specific site depend on (1) the time interval between chart changes and clock servicing, (2) expected maximum rate of stage changes, (3) available funds for site instrumentation, (4) importance of continuous records, (5) accuracy required in flow computations, and (6) compatibility with other instrumentation in the total program. Drum-type recorders are much cheaper, require weekly servicing, and are less compatible with other hydrologic instrumentation. Therefore, more expensive strip-chart recorders usually are used at remote locations where continuous records are necessary.

The water-level recorder should be equipped with a graduated float tape and index pointer to enable the observer to check the recorder pen reading against the actual water level in the stilling well and on the outside staff gage. Careful calibration of the water-level recorder before field installation will prevent inaccurate data from being recorded. Proper calibration and adjustment assure that (1) pen reversals occur at the appropriate edge of the printed chart, (2) the pen arm is the proper length and applies proper pen-inking pressure, (3) binding in the bearings or misalignment in the mechanism does not occur, (4) the pen follows the chart lines on the full traverse, (5) no recorder parts are missing or damaged, and (6) the clock is timed properly.

Field installation should follow instructions provided with the recorder. Detailed planning of the field installation should provide:

• Manufacturer's installation instructions.
• Careful packing of the recorder and accessories for safe transport.
• Proper tools to complete the installation.
• Adequate personnel to establish a precise recorder level datum.
• Necessary equipment for a field calibration.

Drum-type recorders.—Vertical or horizontal drum-type recorders are used in runoff studies on small watersheds and plots where visits are scheduled to the site weekly or more frequently. These recorders may be driven by spring-wound, falling-weight, or battery-powered clock mechanisms and usually are designed with interchangeable gear ratios for time and gage scales. The time scale varies with the anticipated maximum rate of change in stage. A 6-hour drum rotation (1 min resolution) may be needed on most plot studies. Most recorders have reversing mechanisms that do not limit
**Figure 2.42**—Details of a maximum stage gage and its location.
FIGURE 2.43.—Typical crest gage installation at a highway bridge with detailed drawing.
the range in stage. Instruments have been adapted for self-starting in special studies (15).

Strip-chart recorders.—Most strip-chart recorders will operate unattended for a month or longer, depending on the length and speed of the chart. Clock and drive mechanisms usually are powered by a falling weight, a spring drive, or a battery. For unusual installations, chart speeds are available from about 1 inch (2.54 cm) to over 700 feet (213 m) per day. The range in stage may vary from a few inches to several hundred feet. The common A-35 recorder accommodates a strip chart 25 yards (23 m) long and usually is changed 1 to 12 times per year, depending on the chart speed selected.

The pen reverses at each chart margin to record a wide fluctuation in water level. Many floats, float tapes, float pulleys, time-scale gears, stage-scale gears, and driving mechanisms are available on order.

Catalogs describing strip-chart recorders are available at many Federal and State offices concerned with hydrologic measurements. Numerous publications explain suitable locations and successful installations (7, 34).

Digital punched tape recorders.—Digital punched tape recorders are battery-operated, paper-tape recording instruments that mechanically convert angular positions of a rotating shaft into a coded digital output. The primary actuating unit permits liquid level analog measurements to be digitally converted and recorded on punched paper tape.

The basic recorder (fig. 2.44) may be used in conjunction with many primary actuating devices for measuring and recording parameters. The liquid level recorder has been designed, however, to measure liquid level by a cable, drum, and float assembly similar to that used in drum and strip-chart recorders. The measurement source may be geared to the liquid level recorder to obtain a convenient ratio

FIGURE 2.44.—Digital punched tape recorders: Left, exterior; right, interior.
between relation of the recorder input shaft and rotation of the primary actuating unit shaft. For example, when used with a liquid level transducing system having a 1.0-foot (30.5 cm) circumference float wheel on the input shaft, each revolution of the input shaft will represent a change of 1 foot (30.5 cm) in liquid level; that is, the low-order code disk (fig. 2.45) will represent the hundreds and tens digits. The high-order code disk will represent the units and tens digits. This instrument may include a push button mounted on the front plate, which initiates a punch sequence upon demand, primarily for testing.

The punched-tape recorder is operated by two interrelated systems—the input gearing-count memory system and the punch programming cycle system. The input system receives the shaft motion from an external source and converts this motion to successive positions of memory code disks. By means of a clock mechanism, the punch programming system initiates the punch and reset operations required for recording measured values on a data recording tape.

The timer unit, consisting of a clock, cam, follower, and switch assembly, derives its operating power from an external 7½-volt dry cell. The clock continuously rotates a cam arranged so that a switch is actuated every 5, 15, 30, or 60 minutes, or each 12 hours, as specified. The cam also is used for setting the time within the specified cycle.

An available optional electronic timer is recommended for improved accuracy and dependability. This timer consists of a precise quartz crystal oscillator whose frequency is counted by cascade flip-flops. The resultant count of the last stage is the time cycle. This cycle may be 5, 6, 15, 30, or 60 minutes, with the crystal excited by a 7½-volt battery. Output is through a silicon-controlled rectifier. The timer has no moving parts and is unaffected by environmental changes.

Two recorders may be actuated by one timer equipped with a special slave unit to provide an almost simultaneous (about 3 seconds difference) punchout of two bits of data. This is especially valuable in applications that obtain synchronous stages upstream and downstream of weirs, flumes, or drop structures.

At designated time intervals, the water level is punched on a paper tape (fig. 2.46). (A foil-back tape has been more satisfactory than regular paper tape.) Data are punched on tape
in the binary-coded decimal system. Four binary digits (bits), 1, 2, 4, and 8, are added together to form a single digit. The recording tape used has time printed in the center, based on a 24-hour clock. After each punchout, the tape will move one-tenth of an inch and will position itself for the next punchout. The punched columns on the tape are printed so that actual values may be read by the observer at any time.

Special translators are available to convert punched-tape data into punched cards, or magnetic tape, for rapid computer processing. This process is discussed on page 184.

Punched-tape recorders can be equipped with optional equipment to present a parallel binary-coded decimal output in electrical form. This output will have the value that appears on the data recording tape for telemetering to remote equipment.

**Bubble Gage Servo-Manometer**

The U.S. Geological Survey developed the bubble gage servo-manometer shown in figure 2.47 to obtain more reliable records of surface water level of streams subject to large variation in bed elevation. The bubble gage is also useful on reservoirs or streams subject to large variation in water level. A standard bubble gage will record a 50-foot (15.2 m) range of water level. The initial cost of a bubble gage and its installation is often less than the cost of installing a gage well. A bubble gage can be moved to another gaging site with little expense, whereas movement of a gage well may be more expensive than installing a new gage well.

**Sand point and orifice installation.**—An excellent sand point for the orifice housing can be made from a 4-inch (10 cm) I.D. galvanized pipe about 20 feet long, as shown in figure 2.48. The orifice is placed in the side of the sand point near the top. While a vented cap on the sand point minimizes sediment entry, it permits nitrogen gas to escape so pressure will not build up in the sand point. Transfer of pressure from the stream to the sand point is provided by a series of lengthwise slots. These slots are covered with screen wire to hinder sediment entry.

When driven or jetted into the streambed, the 20-foot (6.1 m) length of sand point is sufficient to assure stability of the orifice. This length also provides ample storage for the sediment that enters the sand point during several runoff events. All steel in the assembly is galvanized to inhibit corrosion. The sand point may be installed by:

- Driving it into the streambed. A crane is required for this method.
- Jetting it down in one piece. A bridge or other structure to which block and tackle can be attached is needed for this operation. Separate tackle are required for the sand point and the jet pipe because the jet pipe must be able to move independently.
- Jetting it down in sections. The first section should be 10 feet (3 m) long, and additional sections should be 5 feet (1.5 m) or less. Couplings are needed for both the sand point and the jet pipe.

The jet pipe may be constructed by 1 1/2- or 1 3/4-inch (3.8 or 3.2 cm) pipe. The pump used in jetting should have a capacity of 250 gallons per minute (950 l/min) at 15 pounds per square inch (10,547 kg/m) pressure.

The 4-inch (10.2 cm) sand point can be turned easily with a 36-inch (91.4 cm) chain wrench during installation. The saw-toothed edge at the bottom end of the sand point assists in cutting through tree limbs, other buried objects, and layers of gravel.

Elevation of the orifice is determined by the anticipated minimum elevation of the channel bed. The orifice must be set sufficiently low initially to measure the minimum anticipated stage because the pipe is difficult to lower or raise after the sand has settled around it. The vent assembly can be extended upward above the streambed, however, by simply removing the vent assembly and adding a 4-inch (10.2 cm) coupling and nipple, of the appropriate length, to the top of the sand point. The vent assembly performs best when all openings are above the streambed.

During low flows, a sand streambed meanders and may move away from the sand point, rendering the orifice inoperative. The low water channel may be stabilized laterally to prevent this meandering by installation of low water jetties that keep water flowing over the sand point. Jetties have been constructed by spurtting 10- to 14-foot (3 to 4.2 m) lengths of angle
FIGURE 2.47.—Bubble gage servo-manometer water level sensor.
NOTE: 72" x 32" Piece of 16 Gage Mesh Aluminum Screen Wrapped Over Slots for Silt Trap.

DETAIL 'C'
Scale 3" = 1' - 0"

DETAIL 'B'
Scale 6" = 1' - 0"

SECTION A-A
Scale 3" = 1' - 0"

DETAIL 'D'
Scale 3" = 1' - 0"
FIGURE 2.48.—Giant sand point with built-in silt trap and vent: Left (page 140), details C, B, and D; Above, detail A.
iron into the streambed and lacing them together with number 9 wire. Chicken wire of 1/8-inch mesh, attached to the angle iron projections, catches sufficient debris to deflect the low flow current. Tops of the low water jetties should not exceed 1 foot (30.5 cm) above the channel bottom.

**Manometer installation.**—Federal law requires that the nitrogen bottle be capped during handling to avoid accident. This bottle should be capped until it is fastened securely in the shelter. Although oil-pumped nitrogen is preferred, dry nitrogen is satisfactory.

Plastic tubing from gage to orifice should run downgrade continuously to avoid low spots where water or oil might collect and cause an erratic record. Splices in the line should be avoided. If a splice is necessary, it should be readily accessible for checking leaks. All threaded fittings in the purge system should be doped, except for the zytel fittings and connections between the nitrogen bottle and the constant pressure regulator.

Tube connections to the mercury reservoirs usually are not tightened at the factory. Tighten these connections with a small wrench before pouring the mercury into the float-switch reservoir. Slightly more mercury may be required than that which comes with the gage. Disengage the motor and turn the manometer reservoir shaft till the reservoir moves through the expected range of operation. Adjustment in the track may be required if the reservoir assembly does not move freely. A negator constant-torque spring drive or an electric drive is preferred to the weight drive because provision must be made for adequate vertical movement of the weight between servicing.

**Electronic Transducers for Measurement of Water Level:**

If alternating-current electricity is available at a measuring site, several transducers are available for measuring water elevation. These transducers have output that is compatible with high-speed digital computers. The field of electronic measurements is so dynamic that significant information for a handbook may become obsolete before the handbook becomes available.

At the Southwest Watershed Research Center in Tucson, Ariz., water depth has been measured successfully with pressure transducers located at the streambed or flume bed (must correct for water-sediment density changes); sonar transducers, which are suspended above the flow on a rigid support; and a potentiometer, which may be attached to the float wheel of a conventional float-tape-counterweight system in a stilling well. The EMF outputs from such transducers may be recorded on data loggers in digital form, using punched or magnetic tapes. They also may be recorded on a strip chart. The response time of such transducers is generally rapid, and the transducers provide better time resolution than spring-wound clock-type recorders. Although costs are decreasing for such equipment, they are still higher than the costs of mechanical equipment. Additional accuracy justifies the cost in many instances, however.

**Stilling Well**

Regardless of the type of runoff control used, the well should be located to one side of the waterway so it will not interfere with the flow pattern over the spillway. The well for a triangular concrete weir should be 10 feet (3.05 m) upstream from the centerline of the weir crest as the laboratory discharge calibrations are based on head measurements at that distance. If other structures are used for the control section, the well should be located far enough upstream to be out of the area of drawdown at the control. Tall wells required on detention reservoirs and ponds can be located near the spillway at the toe of the fill, or they can be dug into a side bank. Setting the well back in the bank will reduce the difficulty of supporting it and will allow for access by walkway rather than ladders. This location presents some problems in intake design, however. If the well is set at the toe of the slope and access to the instrument shelter is by ladder only, the station cannot be serviced during high stages, which may result in the loss of valuable records. Wells for metal flumes are fabricated as part of the flume.

The size of the well selected will depend on such factors as the required rigidity, height, type of material, necessity to get inside, and, possibly, protection from freezing. If ability to
TABLE 2.8—Suggested pipe sizes for stilling wells

<table>
<thead>
<tr>
<th>Heads up to—</th>
<th>Diameter of corrugated pipe Inches</th>
<th>Metal Gage</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 feet</td>
<td>18</td>
<td>14</td>
</tr>
<tr>
<td>5 to 10 feet</td>
<td>24</td>
<td>12</td>
</tr>
<tr>
<td>10 to 20 feet</td>
<td>30</td>
<td>12</td>
</tr>
</tbody>
</table>

It is important to get inside the well, see table 2.8 for sizes of pipes that should provide the required stability. This table contemplates a length of intake pipe of only 15 feet (4.6 m). If actual installation requires a much longer pipe, the diameter or number of pipes will need to be increased. Although the minimum requirement is one pipe, two pipes are recommended because one may become plugged. They should be installed at slightly different elevations. When installing intake pipes, make provisions for flushing out the silt.

The well should be watertight below the lowest intake. All seams and rivets must be brazed or treated both inside and out. An asphalt or tar seal should be made on the inside at the junction of the pipe with the concrete base. Two access doors should be provided: One, near the top, to allow for adjusting the tape length and for changing gears without removing the recorder; the other, just above low water, to assist in checking the setting of the recorder and to permit removal of silt without entering the well. On low-head installations, one door with its bottom slightly above the lowest intake may be sufficient. Rusting of hinges on these access doors has caused considerable difficulty. Hinges of rust-resistant metal, such as brass or bronze, should be used. If no hinges are used, the door can be held in place by wingnuts on short bolts welded to the well.

When streams containing heavy sediment loads are measured, a reservoir must be provided beneath the intakes to store the sediment dropping through the intake slots. Experience in ephemeral streams with heavy bedloads has shown that small slots and a small stilling well provide the best record. A 9/4-inch (1.9 cm) pipe has been used successfully to hydraulically connect the intake to the stilling well. The intake system is then kept with water by providing flow from an auxiliary reservoir with the intake water level held constant by a float valve. Air traps in the line between the stilling well and the intake must be eliminated to provide an accurate stage record. These small intakes have been inserted in larger systems and have eliminated problems connected with the intakes’ silting full.

Where ladders are necessary, use 1/4 by 2-inch (0.64 by 5.04 cm) iron straps as rails. Space these straps 12 inches (30.5 cm) apart and use 3/8-inch (1.9 cm) round rods, 12 inches (30.5 cm) on centers, for the rungs. Bolt or weld the ladders to the well, using angle iron clips so the rungs are 3 inches from the pipe. Complete all fabrication work in the shop before taking the well to the field. After all cutting and welding are completed, give the well a coat of metal priming paint (especially those areas where galvanizing has been destroyed during fabrication), followed by a coat of aluminum.

Place the well on a concrete base that extends below the maximum penetration of frost. The top of this base need not be more than a few inches below the lowest intake. This will not provide much space for sediment storage, but removing small accumulations frequently is easier than removing the accumulation of several years at one time. Although the concrete base may need to extend 4 feet (1.2 m) below spillway elevation, corrugated pipe does not need to extend more than 12 inches (30.5 cm) into this base. The base should extend a minimum of 6 inches (15.2 cm) beyond the corrugated pipe. Figure 2.49 shows a typical stilling well that might be used with a triangular concrete weir or other low head installation.

Large streams often have a bridge pier in the stream at the gaging station. During a rise, the bed may scour several feet around the pier. A self-cleaning gage well can be made by installing a funnel-shaped bottom in the well and attaching the well to the pier at this elevation so that the bed will scour below the bottom of the well during a rise.

**Intakes:**

Intakes can be one or more galvanized pipes, a series of rectangular slots, or several 1-inch-diameter (2.54 cm) holes. A general guide to the size and number of intakes required is that
their total cross-sectional area should be at least 1 percent of the cross-sectional area of the stilling well. Another guide is to limit the head loss in the intake for the expected maximum rate of change in stage to a given maximum amount, such as 0.02 foot (0.61 cm). For example, if the maximum rate of change in stage is assumed to be a half foot per minute, the minimum number and size of intakes for wells of different sizes are shown in Table 2.9.

If an intake channel is dug between the pond and the well, it should have concrete sides and bottom and a perforated metal cover flush with the natural bank. This cover should be hinged so as to permit easy access for periodic removal of the accumulated silt. If 1- by 6-inch (2.54 by 15.2 cm) intake slots are used, only the minimum number need be provided above the line of possible maximum silt accumulation. Except for locations where storage is considerable below the spillway crest, the lowest intake slot would be only 0.03 to 0.05 foot (0.91 to 1.5 cm) below the spillway. If a considerable volume of storage occurs before discharge through the spillway, the lowest intake must be placed near the point of zero storage to get a complete record of rates and amounts of runoff.

**Outside Staff Gage Supports:**

Supports for the outside staff gage should be located the same distance upstream from the spillway crest as the intakes to the stilling well and at a point where they will not interfere with the flow pattern. They should be independent of, rather than attached to, the stilling well.

**TABLE 2.9.—Minimum intakes for stilling wells if maximum rate of change in stage is assumed as 0.5 foot per minute**

<table>
<thead>
<tr>
<th>Diameter of well (inches)</th>
<th>Intake pipes'</th>
<th>1-by 6-inch slots</th>
<th>1-inch round holes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number Diameter</td>
<td>Inches</td>
<td>Number</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>3 1</td>
<td>5 1</td>
</tr>
<tr>
<td>18</td>
<td>1 1</td>
<td>3 1</td>
<td>7 1</td>
</tr>
<tr>
<td>24</td>
<td>1 1</td>
<td>3 1</td>
<td>11 1</td>
</tr>
<tr>
<td>30</td>
<td>2 2</td>
<td>3 2</td>
<td>15 2</td>
</tr>
</tbody>
</table>

1 Intake pipe 15 ft. long.

A satisfactory support for permanent installations is a section of 6-inch (15.2 cm) channel iron imbedded about 18 inches (45.7 cm) into a concrete base and extended above the base to the maximum height desired. The concrete base should extend well below the maximum penetration of frost expected, and the top of the lowest concrete base (if more than one is required) should be a few inches below the lowest intake to the well. A piece of 2- by 6-inch (5.2 by 15.2 cm) cypress or other durable wood is bolted to that portion of the channel iron above the concrete base. An enameled staff gage section is fastened to the wood with brass screws when the instrument is installed.

**Permanent Bench Marks:**

Locate permanent bench marks of brass on and near the control or spillway and set in concrete bases in undisturbed ground. A concrete base set in fill material will settle. The base for the staff gage support also can serve as the location for one bench mark. Set another bench mark on the control or entirely independent of any part of the station. For independent installations, extend the concrete base below the maximum penetration of frost. To assure accuracy of records, check the setting of the instrument and staff gages a minimum of three times each year—once in the winter, once in the spring immediately after the frost is out of the ground, and once in midsummer.

**Stilling Well Siphon System:**

A siphon system has been used successfully as a reservoir stilling well intake. This system is often less expensive to install than conventional intake pipes. A sample installation is shown in figure 2.50. Maximum height of the siphon summit above the surface of the water is limited to the minimum atmospheric pressure expressed in feet of water at the installation site, less the vapor pressure in feet of water.

For a successful system, entrance of air into the siphon line must be minimized. This requires care in installation of all fittings, valves, and joints. Plastic tubing is not recommended for the siphon line. If no leaks exist in the system, a 600-in³ (9,834 cm³) trap will not fill
TOP VIEW

Access doors should have a lap on all sides.

Bolt or weld brass or bronze hinges.

Weld or braze joints and rivets below intake.

Elevation lowest intake G.D. 1.20

Ground line G.D. 0.8

Extend concrete base below max frost penetration

SECTION A-A

DETAILS OF ACCESS DOOR AND INTAKE SLOTS

NOTES

That portion of the stilling well below the lowest intake must be watertight. Braze all joints and rivet heads, inside and out, below the intakes. The $\frac{3}{4} \times 3$" asphalt or tar seal should extend along the entire inside circumference to insure watertightness along this joint.

Access doors should be cut from an extra section of pipe to provide for the top and bottom laps. For larger wells the door openings can be the full 2ft height of a section and no extra length of pipe is required if the vertical seam is used as one side of the door. After the fabrication is complete, the well should be given one coat of metal priming paint and one of aluminum.

SECTION B-B

Leave down $\frac{1}{8}$ to $\frac{1}{4}$ from top.

1" x 6" intake slots or $\frac{1}{4}$ holes as required.

FIGURE 2.49.—Details of stilling well for low head installations.
with air in less than a year under normal fluctuations of water level.

Connection of the siphon line to a well point in the reservoir or stream is recommended to inhibit entrance of sediment into the system. A sufficient rate of water transfer must be provided, however, to prevent a significant lag in the gage height record. Relations between stilling well diameter and siphon line diameter for rates of change in gage height are the same as those for a conventional stilling well system.

**Instrument Shelters:**

Instrument shelters can vary from simple shelters, just large enough to cover the instrument and hinged to lift in the same direction as the instrument cover, to those commonly used on large streams that permit the observer to enter and remain inside with the door closed. If a simple shelter is used, the instrument cannot be serviced during periods of precipitation and charts and other supplies cannot be stored.

The most practical shelter for small watersheds is just large enough to cover the top of the wall and high enough to lift the recorder cover and change charts for checking the instrument even during severe weather. The door should be hinged at the top to provide protection for the observer when it is opened. Skirts can be made from pressboard or plywood and can be attached at right angles to the door near its edges, to afford additional protection to the observer in stormy weather. A double door also can be used, the upper two-thirds of the

---

![Diagram of siphon system for measuring water levels](image)

**Figure 2.50.**—Siphon system for measuring water levels.
opening being covered with a door hinged at the top and the lower third covered by a door hinged at the bottom to swing down horizontally for a small writing shelf. Any hasps or hinges should be placed so that they cannot be removed while the door is closed. A \( \frac{1}{8} \) inch (0.32 by 1.9 cm) strap iron with a small notch near one end should be hinged or pinned to each side of the door and should be run through a staple on each side of the door opening. Pulling the door out until the notch in the iron strap drops into the staple will hold the door in position while the observer checks the station.

The shelter house can be anchored to the well by bolting the floor at the four corners to the small angles welded to the top of the well. Another method is to bolt the framework to which the floor is nailed to the sides of the well at the four points of contact. The first method probably will be easier to assemble or dismantle. A hole with a 3-inch (7.6 cm.) diameter should be provided in the floor of the shelter directly below the clock so that gears, spindles, and clock spindle washers can be changed without removing the recorder. A shelter house that can be used with an 18-inch (45.7 cm) stilling well is shown in figure 2.51.

Large shelters.—A shelter that is 4 feet by 4 feet by 8 feet (1.2 by 1.2 by 2.4 m) is satisfactory for installation of a bubble gage. A shelter with walls fabricated from panels is shown in figure 2.52. A metal roof is desirable, but a plywood floor is adequate. This shelter contains adequate space for the bubble gage, strip chart recorder, and equipment for wading-discharge measurements. At locations where vandalism may occur, armor plate of rolled sheet metal \( \frac{1}{8} \) inch (0.25 cm) thick may be desirable on the walls to protect expensive instrumentation.

Walkways, ladders, and observer’s platform.—Where the well is short or set back in the bank, access to the shelter house can be provided by a walkway (fig. 2.53). Walkways should be at least 2 feet (61 cm) wide, should be above the maximum water stage expected, and should be entirely separate from the well or instrument shelter. The observer’s platform and walkway should be approximately \( \frac{3}{4} \) feet (107 cm) below the shelter floor, have a minimum width equal to the width of the shelter, and extend far enough out from the well for the observer to open the door without getting off the platform. Ample railings should be provided where the walkway or platform is more than 3 feet (91 cm) above ground. Walkways, platforms, and railings should be constructed of good 2 by 4 and 2 by 6 lumber. Sufficient footings and bracing should be provided to give reasonable rigidity to the walkway and platform. Where the walkway is used with a concrete spillway, it can be anchored securely on one end to the spillway wingwall.

Where tall wells are used and set out from the bank, the access ladder and observer’s platform should be anchored securely to the stilling well. The observer’s platform and railings should be framed out of angle iron that is \( 1\frac{1}{2} \) by \( 1\frac{1}{2} \) by \( 1\frac{1}{4} \) inches (3.8 by 3.8 by 3.2 cm). The actual platform can be a section of subway grating.

Use of the walkways permits servicing most any time, whereas access ladders on a well can be used only during low water. This might result in the loss of valuable records.

Current-Meter Gaging Equipment:

Current meters for velocity measurement of open channel flow can be classified into vertical-axis and horizontal-axis meters. The vertical-axis or cup-type meter (fig. 2.54) generally is used in the United States for the following reasons:

- The meter will operate at low velocities, and its accuracy and consistency are equal to those of horizontal-axis meters in high velocities.
- The bearings operate in air pockets that largely eliminate entrance of sediment.
- Meter cups that become dented or slightly bent may be repaired in the field without seriously affecting the meter rating.
- The bucket wheel is relatively slow moving, and a single rotor serves for the entire range of velocities ordinarily found in stream gaging.

The horizontal-axis or propeller-type meter (fig. 2.55) is superior to the vertical-axis meter in measurement of flows containing large amounts of fine debris. Grass roots in the flow may immobilize the rotor of a cup-type meter or cause unreliable performance, whereas the
Figure 2.51.—Construction details of instrument shelter for 18-inch (45.7 cm) stilling well.
same roots will not affect the performance of a horizontal-axis meter. Stream gagers generally agree that vertical-axis meters overregister and horizontal-axis meters underregister in turbulent flow.

Existing structures.—In deciding whether to use an existing bridge for stream gaging, consider the following:

- What are the hazards from traffic?
- Will great turbulence from piers or piling occur in the gaging section?
- Will piers or piling catch debris?
- Will low velocity or dead water occur in the gaging section?
- Must cable measurements be made through a bridge truss requiring frequent raising and lowering of the meter and weight?
- Does the gaging accuracy required justify the expense of a special bridge or cableway?

Traffic hazard sometimes can be solved by
constructing a catwalk on the outside of the bridge. This catwalk also makes the gaging section farther from turbulence around bridge piers. A suggested design is shown in figure 2.56. In designing gaging structures, the engineer is limited only by his imagination;
adequate protection against it around the abutments.

A steel footbridge with a clear span of 70 feet (21 m) is shown in figure 2.57. Truss connections can be made with gusset plates and bolts. Railings should be 36 to 44 inches (91.4 to 111.8 cm) above the deck.

Cableways.—Two types of cableways are used in measuring discharge. The passenger cableway has a standup or sitdown car in which the observer rides with the gaging equipment. The shore-operated cableway is handled from the shore with only the current meter assembly riding on the cable. The observer may stand or sit in an enclosure on the streambank.

Debris on the meter can be removed more quickly when using a gaging car rather than a shore-operated unit. For short spans and flow with little debris, however, the shore-operated cableway is less expensive and less hazardous to operate.

The design of passenger-type cableways is covered in reference (103). A modified cableway support is shown in figure 2.58.

An example of a shore-operated cableway, an elaborate gaging facility in Switzerland, is shown in figure 2.59. The head tower with the operating mechanism for the cableway and the tail tower on the opposite bank may be fixed installations, or the system can be portable with vehicles used as anchors on each side of the stream. A counter on the head tower reel positions the traveling block, and a counter on the reel raises and lowers the meter.

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**Figure 2.56.—Catwalk support.**
Field observations are made (1) to record accurately and completely what is happening and (2) to promote proper notes and equipment operation in obtaining complete records of what will happen. Notes on instrument operation are vital to data tabulation, especially when appreciable lag occurs between obtaining the record and tabulating data. Notes on attending conditions are vital to data analysis and interpretation. Attending conditions not recorded on instruments must be noted personally. Records obtained with instruments not functioning properly may provide usable data if adequate notes are collected concerning the nature and cause of instrument failure. Subject to specific instructions, an observer should adopt the philosophy that excess notes are merely excess material, whereas data not recorded are lost forever.

Maintenance of equipment and runoff stations is mandatory for collecting good records. Improperly maintained equipment will not provide the accuracy which the equipment is capable of. Economy in equipment maintenance often can lead to excessive office work to explain what might have happened. Most equipment used in runoff observations is provided with recommended maintenance procedures from the manufacturer. Other suggestions for maintenance are provided in this section.
Instrument and Equipment Notation and Maintenance

Nonrecording gages

Safety is important when working near streams. Whether making observations or merely inspecting a runoff station, extreme dangers exist because of inclement weather such as lightning during thunderstorms, icy or wet conditions causing unstable footing, or rapid water in the stream due to high discharges. Observers must be aware of these problems and must be taught to operate as safely as possible (4).

Wire-Weight Gages:

Notation of wire-weight gage readings should be placed on recorder charts showing exact time read as well as stage reading. The observer should be identified by including his initials with the notes. If the reading is made in conjunction with discharge measurement, it should be shown with the recorder reading and time on the measurement note.

Staff Gages:

Nonrecording or staff gages are visited by the observer at regular intervals, their frequency being determined largely by the type of data desired and by accessibility of the gage.

The observer's notes for the nonrecording (staff) gage are shown in figure 2.60. General information at the top of these notes should include the name of the stream; distance and direction from the nearest city; exact location, section, town and range, mean sea level datum (m.s.l.) of the zero height, if available; month; and name of observer. The observer should visit the station at a regularly scheduled time, either morning or evening, and should note the date, time, stage, and other pertinent information under "Remarks." Additional observations on the rising and falling stages of floods should include the stage and approximate time of the high watermark (fig. 2.60).

The staff gage should be examined carefully after every major flow to ascertain physical damage requiring correction. Accumulated debris should be removed; and, in some instances, the face should be wiped clean to permit accurate reading. Periodic surveys are required to assure accuracy of gage datum.

Crest Gages (Maximum Stage Gages):

The crest gage normally is used to determine the highest stage during the year, but it can be serviced more frequently to give the maximum stage by storm, month, or season. Notes for several stations for any year can be shown on a single sheet, or a separate sheet can be used for each station to record the data for several years. Where several stations are shown on a single sheet (fig. 2.61) the heading should show only the year. Information on the location, drainage area, and type and size of control are entered in the office before going to the field.
FIGURE 2.59.—Interior (top) and exterior (bottom) of short-operated cableway.
Enter only the date of the observation, the maximum stage since the last inspection, and comments on condition of the station. When a separate sheet is used for each station (see fig. 2.62) the title should show the location, type and size of control, and drainage area in acres or square miles. Several observations for each year, shown on figure 2.62, are convenient where it is desirable to know whether the maximum annual peaks are the result of melting snow or summer thunderstorms. Steps in servicing the maximum-stage gages are:

- Upon arrival at the station, open the lock, lift the cover, and remove the stick.
- Note and record in the fieldbook (fig. 2.62) the date and maximum stage as shown by the line of powdered cork adhering to the stick.
- Wipe the powdered cork from the stick.
- Check to be sure that the holes in the bottom cap are open.
- Remove any accumulation of silt from the inside of the pipe. (Removal of the bottom cap may be necessary.)
- Add powdered cork to the metal cup, replace the stick, and lock the cover.
- Under "Remarks," note items that might affect the accuracy of record, such as excessive accumulation of silt.

If installed properly, maximum stage gages require relatively little maintenance. Visual inspection is necessary during routine readings to determine if physical damage has occurred from flow events or vandalism. Periodic surveys should be made to verify correct gage datums.

**FIGURE 2.60.—Observer's notes of staff gage on Fennimore Branch of the Blue River.**
Recorder Chart Notation and Maintenance

All recorders should be maintained according to the manufacturer’s instructions. The observer should familiarize himself with instruction manuals provided by the manufacturer and should follow recommended maintenance and servicing procedures.

Drum Chart Recorders:

Placement of notes on charts will be simplified greatly by the use of rubber stamps (fig. 2.63). A series of stamps for runoff stations might include station designation; time zone (eastern, central, mountain, or Pacific, and standard or daylight saving); chart number; placement, inspection, and removal watch times (W.T.), and index pointer (I.P.); chart line and outside gage (O.G.); rising; falling; corrections—time and stage; notch (G.D.E.); and G.D.E. lowest intake. Charts should be numbered and dated to show that the record is continuous although no runoff occurred during the period covered by some of the charts. Use a 3.H pencil for all notes and proceed as follows:

For those charts covering periods during which no runoff occurred, show only chart number and dates in the upper righthand corner. No other notes are required as the main purpose of these charts is to show continuity of records.

For charts covering periods during which runoff occurred (fig. 2.63):

- Include the chart number and dates in the upper right-hand corner.
Maximum Stage Gage Record on Twin 4 x 4 Drop Inlet
in Sec. 34, T20N, R10W, Trempealeau County, Wisconsin
Drainage Area = 385 Acres (Steep-Fan shaped)

<table>
<thead>
<tr>
<th>Date</th>
<th>Stage</th>
<th>q</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr. 15, 1949</td>
<td>0.43</td>
<td></td>
<td>Spring peak from melting snow</td>
</tr>
<tr>
<td>June 30,</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aug. 2,</td>
<td>4.65</td>
<td>950 Flood of July 27, heavy damage to roads and bridges from this storm</td>
<td></td>
</tr>
<tr>
<td>Nov. 15,</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apr. 15, 1950</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>June 30,</td>
<td>1.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nov. 15,</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apr. 15,</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>June 30,</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nov. 15</td>
<td>1.23</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 2.62.—Observer's notes for a season on a maximum stage gage in Wisconsin.**

**FIGURE 2.63.—Annotations of a stage chart for Fennimore, Wis.**
• Show the time zone (eastern, central, mountain, or Pacific, and standard or daylight savings).
• Enter dates, watch time, index pointer, chart line, and outside gage reading at times of placement, inspection, and removal.
• Show the G.D.E. of the spillway crest and the lowest intake.
• Indicate the time scale and gage-height ratio used in the proper place on the marginal tabs.
• Check to see how placement and removal marks agree with the watch time. If they do not agree within 2 minutes, apply a time correction. To determine this correction, assume a straight line variation between placement or inspection and removal. For example, the chart time of figure 2.63 was correct at the time of placement, was 5 minutes slow at inspection, and was 10 minutes slow at removal. The total elapsed time between the last inspection and removal was 74 hours. The time from this inspection to the beginning of runoff was 64 hours. The correction to be applied would be
\[
5 + \frac{64 \times 5}{74} = 9.3 \text{ minutes.}
\]
Since time data are tabulated only to the nearest minute, a time correction of plus 9 minutes would be applied.
• Write the correct times of rise, noons, midnights subsequent to the rise, and any other points necessary to simplify the compilation of records. (In locating these times, begin at the removal time and work backward.)
• Check for discrepancies between the chart line and index pointer and for failure of the pen to reverse at the edges of the printed portion of the chart. If the pen reverses below the limits of the engraved part of the chart about the same extent at both the upper and lower reversals, apply a constant correction to each traverse. This correction for the traverse upward across the chart is plus, whereas that for the downward traverse is minus. Where the lower reversal is correct and the upper reversal falls short, a graduated correction is correct theoretically. As tabulations are to be made only to the nearest 0.01 foot (0.3 cm), a graduated correction would not be feasible and a constant correction should be applied through a given range in stage. If the upper reversal falls 0.01 foot short, the entire correction should be applied only to the upper half of the chart. If the upper reversal is 0.02 foot (0.6 cm) short, a correction of 0.01 would be applied from 0.25 to 0.75, and 0.02 would be applied from 0.75 to 1.25. Note any correction that must be applied to the stage.
• Show the corrected stage values at all peaks, troughs, and reversals of the actual record. (For weirs, the number of reversals will be even at each edge of the chart provided that where the pen travels once across the chart for each foot change in stage, the stage at removal is in the same foot range as when the runoff began.
• Add notes to show when the stage is rising or falling.

**Strip Chart Recorders:**

A step-by-step procedure should be established and followed during each visit to a gaging station equipped with a strip chart recorder. Routine inspections, made weekly, require the following operations and chart notations:

• Identify station on chart.
• Mark the chart by grasping the float pulley and rotating it in the direction required to raise the float a short distance. This causes the pen to make a short line normal to the time trace. Do not rotate the float pulley in the opposite direction (opposite to raising the float), which causes slack because the float tape may kink or slip around the float pulley wheel.
• Note the date and time directly on the chart. Use military time, preferably, or designate a.m. or p.m.
• Record gage heights as indicated by check gages, using initials to indicate type of gage (O.G., outside gage; I.G., inside gage; W.W.G., wire-weight gage; S.G., staff gage).
• Initial chart.
• Note pertinent information about the station or equipment condition on chart (repairs needed, repairs made, trash removed, intakes clogged, intakes cleared, clock stopped).
• Wind clock.
• Make sure pen is against the chart and an ample ink supply is in reservoir.
• Make sure adequate chart remains on the supply roll.
• After completing other work (such as making discharge measurements), inspect the instrument to make sure the procedure of wind-up does not cause the clock to stop or the paper to shift from its correct position.

The first six items will be repeated for every visit to the site if other operations, such as discharge measurements, sediment sampling, or repairs, are performed.

If necessary, replace the chart soon after the observer reaches the station so that the instrument operations can be checked after the work has been completed and the new chart has been running for some time. If trouble has developed, it can be corrected without loss of record.

Clocks and mechanisms are to be oiled on a regular schedule, usually annually or semi-annually. Use lubricants specified by the manufacturer. Gaging station inspection sheet and chart removal instructions (for Leupold & Stevens, Model A-35 recorder) should be posted in recorder shelters. Figures 2.64 and 2.65 are examples of instruction sheets used in the field.

**Digital Punch Recorders:**

Follow the strip chart recorder routine when servicing digital punch recorders, omitting those steps not applicable. Since little space is available for writing on punched tape, a notebook should be placed in every recorder shelter. Comments other than station identification, date, time, gage height, and observer's initials will be recorded in this notebook. A satisfactory field checklist used by technicians is shown on figure 2.66.

**Equipment Servicing**

Equipment should be serviced on a specified schedule set up to maintain continuous operation. Timing will depend on the equipment used and the clock mechanism.

**Flumes and Weirs:**

The structure and upstream pond area must be kept free of weeds and trash, and sediment must be removed as it accumulates. The approach area and pool banks should be trimmed to maintain a clean approach channel.

The level of the crest should be checked periodically with reference to the elevation of the gage zero. The structure should be inspected for leakage. Leaks must be repaired, and the structure must be rechecked carefully to see that it is level and at the correct elevation.

The crest should be examined for nicks or dents that might reduce measurement accuracy. These imperfections should be corrected carefully. Imperfections that would change the shape of the weir opening should not be removed.

Flumes must be maintained in original condition and in accordance with design specifications. Levels and slopes of installation must be checked periodically and must be corrected if necessary.

**Gage Wells:**

If constructed properly, gage wells will require little servicing. The well, intake pipes, intake pipes, and upstream pond area must be kept free of weeds and trash, and sediment must be removed as it accumulates. The approach area and pool banks should be trimmed to maintain a clean approach channel.

The level of the crest should be checked periodically with reference to the elevation of the gage zero. The structure must be rechecked carefully to see that it is level and at the correct elevation.

The crest should be examined for nicks or dents that might reduce measurement accuracy. These imperfections must be corrected carefully. Imperfections that would change the shape of the weir opening should not be removed.

Flumes must be maintained in original condition and in accordance with design specifications. Levels and slopes of installation must be checked periodically and must be corrected if necessary.

**GAGING STATION INSPECTIONS**

**Weekly**

Routine inspection
1. Mark chart.
2. Note date.
3. Number tape (I.G.)
4. Note time (A—a.m., P—p.m.)
5. Initial.
6. Wind clock.
7. Put pen down.
8. Check ink supply in pen.

**Monthly**

Routine inspection plus station identification
1. Remove one month’s chart record.

**Quarterly**

Routine inspection plus station identification
1. Remove chart.
2. Install new chart roll.

**Yearly**

Oil clock and mechanism (during April).

**Cleanup Inspections**

Routine inspection plus:
1. Check well for sandfill.
2. Check bar reading. Record on chart.
3. Wire weight or staff gage reading. Record on chart.
4. Replace sample bottles in storage box.

**FIGURE 2.64.—Gaging station inspection sheet (Model A-35 recorder).**
and silt trap (if used) should be free of silt. When the well or trap is cleared or the intake pipe is unclogged, the recorder stylus should be raised from the chart. Otherwise, surge in the well may cause excess ink on the chart to soften the paper, causing the pen to tear it. The gage should be read before and after cleaning, and gage heights and notes should be recorded on the chart.

After flow events, wells must be checked for debris accumulation that needs removal. In some channels, shifting sand may have isolated intakes, necessitating removal of a quantity of sand.

**Bubble Gage System:**

Preventive maintenance should be performed on the bubble gage as follows:

- Check tolerance between the jeweled bearings and float mast pivot. If the float does not operate properly, the pivot and bearings should be examined under a magnifying glass and should be replaced if worn or damaged. Avoid overtightening the bearings, which will damage the bearings and pivot.
- Remove corrosion accumulating on the contacts and float mast because it creates large steps in the stage record. Corrosion can be removed with crocus cloth or a small knife blade.
- Use a control with a time delay circuit because it will provide a better stage record and will prolong battery life. The time delay should be checked regularly, however, because resistors may need to be replaced.
- Wash the tubing from manometer to sand point or orifice with clean water followed with alcohol and then dried with a release of nitrogen once a year or as needed. A garden sprayer or a fire extinguisher can be adapted for this use.
- After each major flow event or a series of small events, remove the top (vent assembly) from the sand point and check the water depth in the sand point. Sufficient space within the sand point will prevent sand from covering the orifice during a major rise. Sand can be removed from the sand point with a portable pump and enough 1½-inch (3.8 cm) hose to reach the bottom of the sand point.
- When cleaning the sand point, check the manometer and tubing for high pressure leaks. Plug the orifice and allow nitrogen to slowly increase the pressure in the system to an amount greater than would be expected during any flow event. Shut off the nitrogen supply. If the indicated stage begins to decrease, a leak is in the system. Leaks can be located by applying soapy water or children’s bubble blowing solution at suspected leaky joints in the gas purge system.
- Replace the batteries when the motor speed becomes sluggish.

---

**PROCEDURE FOR REMOVING STRIP CHART**

1. Routine inspection.
2. Unlock screws on tape pulley.
3. Make pen reversal at both sides of chart.
4. Lift pen.
5. Pull lettered disk to right and turn counterclockwise to a stop.
6. Run chart forward till graph is beyond edge of writing plate.
7. Cut chart using writing plate as a guide.
8. Lift takeup roller out of bearings.
9. Remove flanged shaft and half tube clamp.
10. Replace takeup roller.

**Procedure for replacing chart**

1. Remove writing plate.
2. Lift out supply roll.
3. Remove knurled washer nut and remove old core.
4. Place new chart on supply cylinder—flush end toward flange.
5. Replace knurled nut.
6. Place supply roll on bearings with flange to the left.
7. Crease chart about ¼ inch from edge.
8. Feed chart between chart drum and friction roller.
9. Replace writing table.

(Start here monthly.)

10. Pull chart 1 inch beyond takeup.
11. Butt up left edge of chart square to flange on takeup roller.
12. Place half tube clamp over chart and takeup roller.
13. Turn takeup roller at least one turn—use knife to keep edges from doubling back under first turn of chart.
14. Make pen reversal—adjust pen if necessary.
15. Lock screws on tape pulley.
16. Mark point on chart where pen is to be set.
17. Set chart and pen to point.
18. Turn and push disk to left to restore friction drive.
19. Make routine inspection plus station identification.

**FIGURE 2.65.—Chart removal instructions (Model A-35 recorder).**
<table>
<thead>
<tr>
<th>Instrument No.</th>
<th>Station No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date to be serviced</td>
<td>Date actually serviced</td>
</tr>
</tbody>
</table>

**Synchronization**
- Correct E.S.T.
- Tape time
- Time correction

**Tape Changed**
- Off time (plus or minus)
- On time

**Tape Supply**
- New tape installed
- Days remaining on tape

**Instrument Reading**
- Punchout in line
- Punchout clean
- Dial reading
- Tape reading
- Float tape reading
- Staff gage reading
- Zero adjusted to T.B.M.

**Battery Supply**
- Voltage
- Battery replaced
- Added 1½ volt battery

**Operation**
- Contacts cleaned
- Gage movement free
- Intake flushed
- Debris in well
- Visible damage
- Repairs made
- V-notch clear

**Mechanical Malfunctions**
- Broken leaf switch
- Defective timer
- Bent or broken punches
- Tape slipping
- Tape binding

**Others**
1.
2.
3.
4.

**Gage Serviced By**

**Figure 2.66**—Field checklist for digital punch recorder.
A suggested form for recording bubble gage maintenance is shown in figure 2.67.

**Siphon Intake System:**

One advantage of the siphon intake system for measuring water levels is its relatively trouble-free performance, which requires only a semiskilled observer. The air trap must be evacuated periodically, however. This trap also must be protected from freezing by housing, wrapping, burying, or heating. An alternative solution is filling the air trap with antifreeze. The antifreeze should have the same density as water, however, to avoid unbalancing the siphon. If the siphon inlet becomes covered with sediment, the inlet must be moved up or the sediment must be removed. The 4-inch (10.2 cm) pipe sand point previously described makes an excellent attachment to the siphon inlet. Sediment can be flushed from the sand point with a portable pump.

**Stage Recorders**

Several water level recorders are available from weather instrument manufacturers. Many recorders operate on the principle of a reversing mechanism for stage that permits the recording of an unlimited range in stage on a scale, which can be read accurately to the nearest 1/100 foot.

Several horizontal drum recorders are available, some with spring-wound clocks and other with weight-driven clocks. Most drum recorders have several time and stage-scale ratios available. All record on a selected time scale, others repeat, and still others record on a continuous roll. Those recording on a continuous roll of graph paper are well adapted for use in remote locations or places that are not readily accessible under all weather conditions. They will run as long as 60 days between windings, depending somewhat on the time scale used.

The FW-1 and FW-2 recorders are the simplest. Both have a spring-driven clock supported on a vertical spindle, and they can be equipped with several gears to make one revolution each 6, 12, 24, 48, 96, or 192 hours. The smallest time division for a 6-hour chart can be either 1 or 5 minutes, and for the 192-hour chart, 2 hours. These clocks will run 8 days on one winding regardless of the time scale used. Both recorders (FW-1 and FW-2) have reversing mechanisms and can record an unlimited range in stage on a scale of 5 inches (13 cm) of chart equal to 12 inches (30.5 cm) of stage. If greater refinement is required, as might be true for detention reservoirs, a small float wheel and special tape are available for older models and special gears are available for newer models. Each special equipment device will record the stage on a scale of 10 inches (25.4 cm) of chart to 12 inches (30.5 cm) of stage.

The chief difference between the FW-1 and FW-2 recorders is that the former uses a curvilinear chart and the latter uses a rectilinear chart. The time scale selected should vary with the anticipated maximum rate of change in stage, and the scale must be open enough to give the desired accuracy to the runoff computations. Thus, if accurate discharge computations require a change in stage not to exceed 0.2 foot (6.1 cm) between successive time intervals, the chart scale should be such that the maximum rate of rise during the minimum readable time interval will not exceed this amount. A rough guide is to use a 6-hour chart for areas up to 300 acres (121.4 ha) a 12-hour chart for areas from 300 to 2,500 acres (121.4 to 1,012 ha), and a 24-hour chart for larger areas. It may be advantageous to use the time scale on the water level recorder for the recording rain gages. Where several subwatersheds are being gaged, the addition of one 192-hour recorder will reduce the work of figuring faster time-scale records.

Regardless of the type of water level recorder selected, it should be equipped with a graduated float tape that passes over the float wheel and has the ends attached by ring connectors to the float and to a counterweight. If no tape index pointer is furnished as part of the instrument, one should be attached either to the instrument case or to the floor of the shelter house. The graduated tape and index pointer enable the observer to check the pen reading against the water level in the well and that shown on the outside staff gage. Failure of these to show reasonable agreement indicates errors and need for adjustment in the station setting.
**Bubble Gage Log**

Station:

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Gage height</th>
<th>Pressure Psi</th>
<th>Bubbles per min</th>
<th>Party</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Watch</td>
<td>Pen</td>
<td>Outside counter</td>
<td>pen</td>
<td>Cylinder feed</td>
<td></td>
</tr>
<tr>
<td></td>
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</tr>
</tbody>
</table>

**rr** — remove record  
**B** — change batteries  
**T** — change tanks  
**R** — new supply roll  
**D** — discharge measurement

**FIGURE 2.67.—Bubble gage maintenance form.**
Calibration of FW-1 Recorder Before Installation:

The instructions given here are for the FW-1 recorder. They can be adapted to other types of installation also.

FW-1 recorders (fig. 2.68) are calibrated at the factory, and, when in proper adjustment, the following relationships exist:

- The total pen travel between upper and lower reversals is about 5.00 inches (12.7 cm), and both reversals occur at or near the edge of the printed portion of the chart.
- Cam follower pin \( C \) is horizontal.
- The pen arm is parallel to the cam follower arm.
- The pen arm is tilted inward just enough so the pen will not fall away from the chart near the upper reversal. (Note: A slight change in tilt of the pen arm will cause a shift in position of the reversals).
- The clock spindle washer is of the proper thickness to place the centerline of the chart and the pen shaft in the same horizontal plane.

When establishing a new or exchange recorder, its calibration should be checked in the office or laboratory. Periodic checks or calibrations of established instruments are made more often in the field. The procedure for calibration in the office or laboratory is:

- Purchase a calibration wheel from an instrument manufacturer or prepare one similar to that shown in figure 2.69, using 24-gage sheet metal.
- Cut out a circular piece about 15 inches (38.1 cm) in diameter, and from the center of this, strike off a circle using a radius of 7.2 inches (18.3 cm).
- Set dividers at 4.45 inches (10.3 cm) and mark off 10 spaces along the arc of this circle. These 10 points should be equidistant; if not, reset the dividers to obtain 10 equal spaces.
- Punch or drill \( \frac{1}{32} \)-inch (0.24 cm) holes at each of the 10 points.
- Drill an \( \frac{1}{16} \)-inch (0.08 cm) hole in the center.
- Cut away most of the material to leave a center hub, six to eight spokes, and the outside ring.
- Place the recorder on a table or stand so that the float wheel just clears the edge.
- Loosen screws \( E \) and remove the knurled brass disk and the float wheel.
- Place the calibration wheel on the shaft, replace the float wheel, replace and tighten the knurled brass disk, and tighten screws \( E \).
- Mark a line on the edge of the table or stand, directly behind the outside rim of the calibration wheel, for use as a reference point. The edge of the table top or stand also can be used for this purpose.
- Make sure the gear on the clock matches that on the recorder spindle.
- Fill in the data on the end tabs of a 1940 AB chart with india ink. Draw a horizontal line, about 2 inches (5.08 cm) long, near the right end of the chart, 5.05 inches (12.8 cm) above the lowest graduation. This represents the expanded width of the chart under conditions of high humidity (fig. 2.70).
- Wrap the chart around the clock cylinder; be sure that the chart fits snugly and smoothly and rests on the bottom flange throughout its circumference. (Note: In using the AB chart, which has a margin at both ends, the right margin is folded under, then placed over the left end with the chart clip running down through the fold.)
- Place the clock in the recorder by grasping it with the winding key and lowering it gently over the spindle until the gears are meshed. Be sure the clock rotates freely and does not bind at any point. Binding may indicate improper position of the clock mechanism with respect to the spindle, or it may indicate a bent spindle. To correct binding, remove the clock, loosen the three screws on the base, shift the gear away from the center, and tighten the screws. Further binding probably is caused by a bent spindle, which should be straightened or replaced.
- Rotate the float wheel to see that the pen arm is tilted inward just enough to prevent it falling away from the chart near the upper reversal.
- Place a small quantity of ink in the pen and check to see that the point gives a clean fine line. Check adjustment of the recorder as follows (for designated parts, see fig. 2.69).
- Note that the pen arm and the cam follower arm, which holds the counterweight \( M \) and \( C \) (fig. 2.68), are parallel.
FIGURE 2.68.—Water level recorder with float and counterweight.
- See that the cam follower pin $C$ is horizontal by sighting over the shaft that carries the pen arm and the cam follower arm.

- To see how close the pen follows the time line, place the pen on the chart, and rotate the float wheel through the upper and lower reversals. Deviation from the time line between the upper and lower reversals indicates either a bent spindle or improper thickness of clock spindle washer. Remove the clock, rotate the spindle $90^\circ$, and repeat the check. Failure of these pen traces to agree for positions of the spindle indicates that the spindle is bent and should be straightened or replaced before continuing with the check. If the arc described by the pen is the same for two or more positions of the spindle but still does not follow a time line, it indicates improper thickness of washer between the base and the gear. When the arc falls to the right of the time line at the top of
the chart (fig. 2.70), the clock spindle washer is too thick. When the arc falls to the left, the washer is too thin. Change the washer as indicated and check until agreement with the time line is good. The proper thickness of the washer for some older recorders is about 0.140 inch (0.36 cm).

- Rotate the float wheel to bring the pen within a half inch (1.3 cm) of the lower edge of the chart. Place the pen on the chart and continue rotating the float wheel until the pen reverses. If this lower reversal occurs above or below the lowest graduation, bring pen to this line by adjusting screw $K$. (The function of screw $K$ is to make the cam follower arm parallel to the pen arm.) Remove the pen from the chart.

- Hold the calibration wheel so that one of the $\frac{3}{64}$-inch (0.24 cm) holes is on the reference line. Loosen screws $E$ and turn the knurled brass disk until the pen is at the lower reversal. Tighten screws $E$. Place the pen on the chart and rotate the clock to mark a line about 1.4 inch (0.6 cm) long.

- Check for ascending and descending symmetry: Rotate the calibration wheel in a clockwise direction and, while holding each hole at the reference line, rotate the clock to make short lines showing the actual chart reading.
for each 0.1 foot (2.5 cm) until the pen has made one complete traverse up and down the chart width.

- If these short lines on the ascending traverse are higher than those on the descending traverse and the reversal occurs too early, shorten the cam follower arm. This is done by loosening the setscrew and the nut on the side toward the cam and tightening the nut on the counterweight side. If lines on the ascending traverse are lower than those on the descending traverse, lengthen the cam follower arm. After each such adjustment, check to make sure the cam follower pin \( C \) is horizontal.

- Repeat the preceding four steps until best symmetry is obtained, then tighten the setscrew. Good agreement between the ascending and descending traverses is more important than having reversals occur at the exact stage.

- Lengthen or shorten the effective length of the pen arm so the upper reversal occurs at the 5.05-inch (12.8 cm) line. The effective length can be increased by adding thin, noncorrosive metal bands to the pen arm, back of the pen. If the effective length must be decreased, file back the pen-arm shoulder against which the pen is set. Never try to change the length of the pen arm by bending it. The alternate calibration method, which follows, is probably more satisfactory than filing the pen arm. Changing the length of the pen arm will change the position of the lower reversal, which must be adjusted by screw \( A' \) before checking the upper reversal.

**Calibration of FW-1 Recorder in the Field:**

If an FW-1 recorder has not been calibrated according to recommendations in the previous section, field calibration can be used to adjust the instrument. Although field calibration is not as accurate as office calibration, it usually will leave the instrument reading within 0.005 foot (0.15 cm) of the correct value at all stages, which is sufficiently accurate for this type of work. The procedure for field calibration is:

- Set dividers at 4.45 inches (18.3 cm) and mark off 10 spaces along the arc of this circle. These 10 points should be equidistant; if not, reset the dividers to obtain 10 equal spaces.

- Punch or drill \( \frac{3}{4} \)-inch (0.24 cm) holes at each of the 10 points.

- Drill an \( \frac{11}{64} \)-inch (0.08 cm) hole in the center.

- Cut away most of the material to leave a center hub, six to eight spokes, and the outside ring.

- Place the recorder on a table or stand so that the float wheel just clears the edge.

- Loosen screws \( E \) and remove the knurled brass disk and the float wheel.

- Place the calibration wheel on the shaft, replace the float wheel, replace and tighten the knurled brass disk, and tighten screws \( E \).

- Mark a line, on the edge of the table or stand, directly behind the outside rim of the calibration wheel, for use as a reference point. The edge of the table top or stand also can be used for this purpose.

- Make sure the gear on the clock matches that on the recorder spindle.

- Fill in the data on the end tabs of a 1940 AB chart with india ink. Draw a horizontal line, about 2 inches (5.08 cm) long, near the right end of the chart, 5.05 inches (12.8 cm) above the lowest graduation. This represents the expanded width of the chart under conditions of high humidity (fig. 2.70).

- Wrap the chart around the clock cylinder; be sure that the chart fits snugly and smoothly and rests on the bottom flange throughout its circumference. (Note: In using the AB chart, which has a margin at both ends, the right margin is folded under and then placed over the left end with the chart clip running down through the fold.)

- Place the clock in the recorder by grasping it with the winding key and lowering it gently over the spindle until the gears are meshed. Be sure the clock rotates freely and does not bind at any point. Binding may indicate improper position of the clock mechanism with respect to the spindle, or it may indicate a bent spindle. To correct binding, remove the clock, loosen the three screws on the base, shift the gear away from the center, and tighten the screws. Further binding probably is caused by a bent spindle, which should be straightened or replaced.

- Rotate the float wheel to see that the pen arm is tilted inward just enough to prevent its falling away from the chart near the upper reversal.
• Place a small quantity of ink in the pen and check to see that the point gives a clear fine line. Check adjustment of the recorder as follows (for designated parts, see fig. 2.69).

• Note that the pen arm and the cam follower arm, which holds the counterweight A and C (fig. 2.68), are parallel.

• See that the cam follower pin C is horizontal by sighting over the shaft that carries the pen arm and the cam follower arm.

• To see how close the pen follows the time line, place the pen on the chart and rotate the float wheel through the upper and lower reversals. Deviation from the time line between the upper and lower reversals indicates either a bent spindle or improper thickness of clock spindle washer. Remove the clock, rotate the spindle 90°, and repeat the check. Failure of these pen traces to agree for positions of the spindle indicates that the spindle is bent and should be straightened or replaced before continuing with the check. If the arc described by the pen is the same for two or more positions of the spindle but still does not follow a time line, it indicates improper thickness of washer between the base and the gear. When the arc falls to the right of the time line at the top of the chart (fig. 2.70), the clock spindle washer is too thick. When the arc falls to the left, the washer is too thin. Change the washer as indicated and check until agreement with the time line is good. The proper thickness of the washer for some older recorders is about 0.140 inch (0.36 cm).

• Rotate the float wheel to bring the pen within 1 inch (2.54 cm) of the lower edge of the chart. Place the pen on the chart and continue rotating the float wheel until the pen reverses. If this lower reversal occurs above or below the lowest graduation, bring it to this line by adjusting screw K. Continue rotating the float wheel to make the upper reversal, which should occur near the 5.05-inch (12.8 cm) line. If the distance between upper and lower reversals does not come within 0.02 inch (0.05 cm) of the 5-inch (12.7 cm) line, change the length of the cam follower arm. If the traverse is less than 5 inches (12.7 cm), shorten the cam follower arm. If more than 5 inches (12.7 cm), lengthen the arm.

• Check for ascending and descending symmetry. Rotate the float wheel in a clockwise direction, stopping at each 0.1 foot (3.0 cm) on the tape index pointer. Rotate the clock to make a series of short lines to show the actual chart reading for each 0.1 foot (3.0 cm) until the pen has made one complete traverse up and down across the chart.

• If the lines on the ascending and descending sides do not agree, select the point of maximum discrepancy. Hold the float wheel firmly, loosen screws E, turn the knurled brass disk to correct for half the difference, and tighten screws E. Repeat until the two lines agree and repeat check for symmetry.

• Lengthen or shorten the effective length of the pen arm so the upper reversal occurs at the 5.05-inch (12.8 cm) line. The effective length can be increased by adding thin, noncorrosive metal bands to the pen arm, back of the pen. If the effective length must be decreased, file back the pen-arm shoulder against which the pen is set. Never try to change the length of the pen arm by bending it. The alternate calibration method, which follows, is probably more satisfactory than filing the pen arm. Changing the length of the pen arm will change the position of the lower reversal, which must be adjusted by screw K before checking the upper reversal.

• Place a tape clamp across the counterweight end of the tape about 1 inch (2.54 cm) below the bottom of the floor of the shelter house. This will prevent the float from dropping to a reading more than 1 inch below the bottom of the lowest intake. Recheck the tape index pointer and chart line readings, and make further adjustments, if necessary. Remove most of the excess tape at the float. Rotate the float wheel in a counterclockwise direction until the tape clamp touches the bottom of the floor of the shelter house. Place the pen on the chart and rotate the clock to mark a line about a half inch (1.3 cm) long. Remove the pen from the chart. Remove the chart from the clock cylinder and blot. Upon returning to the office, complete entries on the chart with india ink (fig. 2.70) and retain the chart and notes in the office file.

Current Meter Maintenance:

Operation of a current meter will be affected by the way in which it is used. While the
design, material, and construction of the meter also contribute to its successful operation, they will not prevent errors caused by improper care of the instrument. Each fieldman should keep his meter in the proper condition, but he should not make repairs that may affect the rating of the meter. He should check the following items before and after each measurement.

True shaft alinement.—The shaft of any meter may become bent if the meter is subjected to a sharp blow or if the bucket wheel is lifted improperly. When lifting the cups from the pivot point by the bucket-raising nut, always hold the cups stationary and turn the bucket-raising nut. Spinning the rotor while the bucket-raising nut is held stationary creates momentum that, when suddenly checked, may spring either the yoke or the shaft. The shaft assembly does not need to be dismantled to see if the shaft is in alinement. With the contact chamber in place, the cap removed, and the meter held in a vertical position, turn the bucket wheel slowly. Watch the metal frame to which the inner edges of the cups are fastened and see if the shaft is bent. Observe movement of the shaft inside the contact chamber. A wobble not caused by a worn bearing lug in the chamber indicates that the shaft is bent. As a final test, dismantle the shaft and roll it on a flat surface. Repair any meter found with a bent shaft.

Proper Condition of Pivot Point and Pivot Bearing:

After every discharge measurement, thoroughly clean both the pivot and pivot bearing and remove all water, oil, dirt, or abrasive substances that may be present. Examine the pivot with a magnifying glass to see whether the point is fractured, worn, flat, or rough at the apex. Discard any pivot that is fractured or has a rough point. To examine conveniently and to clean the pivot bearing, carefully remove the contact chamber, so as not to mar the penta gear, and tilt the shaft assembly to one side. When the pivot bearing becomes coated with an oily substance that cannot be removed with a cloth, a blunt, soft wooden pin, turned several times within the bearing, usually will clean it. If the bearing shows rust, use a few drops of oil. Examine the pivot bearing and the pivot point for possible fracture, pits, and roughness, but do not remove the bearings from the housing. Do not pack the meter or transport it with the pivot bearing resting on the pivot point. Use a raising nut (15) to raise the cup wheel off the pivot when not in use.

Cleaning, Oiling, and Inserting New Parts:

In addition to the pivot bearing just discussed, every current meter has bearing surfaces above the bucket wheel. These include cylindrical bearings, mesh bearings, and thrust bearings. Examine these bearings and oil and clean them after each discharge measurement. If a new part must be inserted in the field, always test the meter afterward for proper adjustment. Take additional precautions in replacing the contact chamber cap as all caps do not screw into the chamber to the same fixed depth. During high velocities the caps may become worn by the head of the shaft riding on the cap, and occasionally the cap must be refaced when the meter is being repaired. Before a new cap is tightened into the contact chamber, lower the pivot or release the cups by lowering the bucket-raising nut because the head of the shaft may be brought to bear against the cap with sufficient pressure to bend or throw the shaft out of alinement. For lubrication, use the highest grade of oil as tests have shown that inferior oils do not eliminate the corrosion of several parts.

Standard requirements for operation.—The so-called "spin test" is the common method for determining the condition of the meter. Correct interpretation of the results from the test will determine the condition of the meter. When a meter is subjected to a spin test, place it so that the shaft is in a vertical position and the cups are protected against all air movements. As the rotating cups near the stopping point, observe them carefully to note whether they stop abruptly or gradually. Velocities more than 0.6 ft/s (18 cm/s) give sufficient excess motive power to overcome any appreciable effect of mechanical resistance in the meter. Therefore, the principal value of the spin test for velocities above 0.6 ft/s is to indicate whether the meter is operating freely. Any meter that spins 1½ minutes is satisfactory for
measuring all velocities except those that are very low. A meter that spins 1 minute will measure velocities above 1 ft/s without appreciable error.

As the velocity decreases, motive power also decreases. For velocities less than 0.6 ft/s (18 cm/s) the difference between motive power and mechanical resistance of the meter decreases. Therefore, a meter should be well adjusted and should spin at least 2 minutes when velocities less than 0.6 ft/s (18 cm/s) are measured.

Check any meter not meeting the required spin test for pivot and bearings. Replace damaged wheel shafts and other parts.

The National Bureau of Standards in Gaithersburg, Md., calibrates the current meter at a small cost. The rating curve supplied by the National Bureau of Standards is used to prepare the rating table. Meters commonly are rated on a 0.5-inch (1.27 cm) round rod. Coefficients are available for adjusting the rod rating to standard cable suspension ratings with 15- or 30-pound (6.8 to 13.5 kg) lead weights.

Miscellaneous Gaging Equipment

Miscellaneous gaging equipment required may vary appreciably, depending on the type of measurement to be made—wading, cableway, bridge, boat, or through ice. A checklist of required items should be prepared by the engineer. All items should be inspected after each use, and repairs, adjustments, or replacements should be indicated immediately (41).

Discharge Measurement

Discharge measurements usually are computed in cubic feet per second and are plotted against gage height to define the station rating. At a shifting control station, measurements should be made frequently enough to achieve the desired accuracy in the runoff record. Weekly measurements with velocity observations at 15 verticals are preferable to biweekly measurements with 30 verticals if the station control is subject to considerable scour or fill. The reverse may be more desirable in field rating a man-made control.

All equipment on the inventory form shown in figure 2.71 is not needed to make a discharge measurement. The form has been useful, however, as a checklist for items that may be required. A semiannual inventory of quantity and condition of equipment is recommended.

Selecting the Measuring Station

The cross section for a discharge measurement should meet the following requirements, if possible:

- The section should be accessible.
- The section should be near the stage recorder and perpendicular to the direction of streamflow.
- There should be a straight and uniform channel for a distance upstream equal to at least five times the width of the stream and for a distance downstream equal to twice the width of the stream.
- No more than 15 percent of the flow should have a velocity less than 0.5 ft/s (15.2 cm/s), and the maximum velocity should not exceed 4 ft/s (1.2 m/s).
- No large overflow section should occur at flood stage. In some streams, a gaging section that is always free of turbulence cannot be found. Methods of gaging other than the velocity-area method may be more accurate for these streams. If piers and piling cause considerable turbulence under an existing bridge, the need for accurate discharge measurements should be weighed against the expense of spanning the stream with a special bridge or cableway.

Accuracy of the Price meter is poor in flow depths less than 0.5 foot (15.2 cm). If more than 15 percent of the flow is less than 0.5 foot (15.2 cm) deep, a Pygmy meter should be used in lieu of the Price meter. If a large amount of flow is less than 0.2 foot (6.1 cm) deep, an artificial section should be created by building a small dike out into the flow. This dike should be located downstream at a distance that depends on the new flow width.

Extreme caution must be used when entering a flowing stream to ensure against drowning caused by depths greater than anticipated or velocities too great to maintain footing. Excellent safety precautions are life preservers, which are mandatory when current meter read-
INVENTORY OF
DISCHARGE MEASUREMENT EQUIPMENT

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Item</th>
<th>Quantity</th>
<th>Item</th>
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<td></td>
<td>Crane (Special)</td>
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<td>Meter (Price)</td>
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<tr>
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<td>Reel (Type A)</td>
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<td>Meter (Other)</td>
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<td></td>
<td>Reel (Heavy Duty)</td>
<td></td>
<td>Headsets</td>
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<tr>
<td></td>
<td>Handline</td>
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<td>Batteries (Wading)</td>
</tr>
<tr>
<td></td>
<td>Rule (six ft. aluminum)</td>
<td></td>
<td>Batteries (Crane)</td>
</tr>
<tr>
<td></td>
<td>(graduated feet, tenths and hundredths)</td>
<td></td>
<td>Wading rod (4 sections, base plate and slide) or top-setting rod</td>
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<tr>
<td></td>
<td>Weights (100 lb.)</td>
<td></td>
<td>Hangar Bars</td>
</tr>
<tr>
<td></td>
<td>Weights (50 lb.)</td>
<td></td>
<td>Stop Watch</td>
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<tr>
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<td>Weights (30 lb.)</td>
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<td>Lights (Usable—flash)</td>
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<td>Lights (Usable—lantern)</td>
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COMMENTS:

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<th>Date of Inventory</th>
<th>Storage Location</th>
<th>Signature</th>
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FIGURE 2.71.—Inventory form of equipment used in discharge measurement with a current meter.

ings are obtained, and a two-man team with only one man in the flow.

Rod Suspension Measurement

The procedure for making streamflow measurements using the rod suspension method is as follows:

- Stretch the tape across the stream (fig. 2.72) as closely as possible at a right angle (90°) to the flow lines. Record location of measuring site (fig. 2.73).
- Observe the width of the water surface and divide this number by 20 to determine the position of the points of depth and velocity observations across the stream. Twenty observations will reduce the error in total gaging caused by inaccuracies of the single observations. If the stream width is 20 feet (6.1 m), make single observations at 1-foot (0.3 m) intervals. If this width is about 15 feet (4.7 m), 1-foot (0.3 m) intervals should be used along the banks when the velocity is low, and 0.5-foot (15.2 cm) intervals should be used in the stream section if velocity is high (fig. 2.72). The number of observations is not absolute. Conditions may warrant 15 or more observations across the stream. If the gage height changes rapidly, 15 observations or less may be necessary to com-
A. Cross Section

\[ Q = \frac{W_1 + W_2}{2} V_1 D_1 + \frac{W_2 + W_3}{2} V_2 D_2 \text{ etc.} \]

\[ W = \text{width, feet} \]
\[ D = \text{depth, feet} \]
\[ V = \text{velocity, feet per second} \]
\[ Q = \text{discharge, cubic feet per second} \]

B. Distribution of Velocities in a Vertical Section

FIGURE 2.72—Measurements needed to record channel cross section and vertical velocity curve.
**DISCHARGE MEASUREMENT NOTES**

**Little Mill Creek #95, Coshocton, Ohio.**

<table>
<thead>
<tr>
<th>Date</th>
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<th>Party</th>
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<td>Method coef.</td>
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<tbody>
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</table>

**Measurement notes:**
- Use a current-meter number and type of measurement—rod or weight suspension from cable (fig. 2.73).
- Record current-meter number and type of measurement—rod or weight suspension from cable (fig. 2.74).
- Read the record time and gage height of water surface at recorder gage. (See notes, fig. 2.74). Mark this time on the recorder chart by rotating the float wheel or clock.
- Complete the measurement before the stage changes too much—0.5 foot (15.2 cm) or more is too much change for some stages.
- Assemble the meter equipment. Check electric current and spin of the bucket wheel for friction tests. Check stopwatch. For low velocities, the meter should spin at least 90 seconds in no wind, after being given a good start. For high velocities, a 30-second spin should be satisfactory.
- For depths less than 1.5 feet (45.7 cm), set the center of the current-meter bucket wheel at 0.6 of the depth and record 0.6 in the column “Observation Depth.” If depth is 0.9 foot (27.4 cm), set the meter at 0.6 · 0.9 = 0.54 or 0.5 foot (15.2 cm) below the water surface. In streams of less than 0.5 foot (15.2 cm) depth, the standard-sized current meter does not measure velocity correctly. The Pigmy current meter often is used in shallow depths. Make corrections, however, to Pigmy meter velocities for depths of 0.3 foot (9.1 cm) or less. Avoid shallow depths wherever possible. Where shallow depth cannot be avoided, refer to reference (41) for correction coefficients.
- For depths 1.5 feet (45.7 cm) or greater, make two observations of velocity at each station—0.2 and 0.8 of the depth—and record these two figures in the column “Observation Depth.” If the depth of water at a station is 1.8 feet (54.9 cm), set the current meter at 0.2 · 1.8 = 0.36 foot and 0.8 · 1.8 = 1.44 feet (43.9 cm) below the water surface. Record velocity (revolutions per second) readings for both depths on their respective lines. For example, in figure 2.74 at station 18 (distance from initial point), the velocity at 0.2 of the depth was 10 revolutions in 90 seconds; that at the 0.8 depth was 10 revolutions in 25 seconds.
- If ice or aquatic growth disturbs the normal distribution of velocity in the vertical section, make additional velocity measurements in the vertical section to establish the true mean for the section.
- Hold the rod still, in a vertical position,
with the meter facing upstream. Position of observer and placement of meter are important in wading measurements. Research is needed to determine the effect of the observer's position on the accuracy of meter registration. Stand with your body streamlined to the flow as far from the meter as possible and at an angle of 45° with the tape and meter. This reduces the registered velocity less than 4 percent. If the stream is no more than two arms lengths wide, stay out of the water during velocity observations.

- Inspect the meter frequently and keep it free from debris. Listen to the rhythm of the electric contacts. If it changes greatly, check the meter.
- Count the revolutions of the meter bucket wheel as indicated by electric clicks on the earphone while observing the time on the stopwatch. If measurement is not needed quickly, count the revolutions for not less than 40 seconds, nor more than 70 seconds, stopping at a revolution count of 3, 5, 7, 10, 15, 20, 25, 30, 50, 60, and so forth. When flow stage is changing rapidly, cut the time in half—20 to 35 seconds—to finish the measurement of discharge without too much change in stage.
- Record the angle of flow correction.
where waterflow is not at 90° to the tape across the stream. Use the dot on the right margin and the numbers (angle coefficients) on the left margin of figure 2.74 to estimate the angle corrections. Hold this form in a horizontal plane with the dot next to you and the column lines parallel to the tape stretched across the stream. Watch the flow current and visually trace its direction across the form to get its angle. If the angle is about 90°, there is no correction. Note that the angle correction recorded for station 18 was 0.98 (fig. 2.74).

- Record the time when about halfway across the stream. (See station 19, 9:00 a.m., on fig. 2.74.) If stage is changing rapidly, record the time when one-third and two-thirds the way across the stream. This will help establish the weighted mean gage height for the entire measurement.

- Record edge of water and time at finish of measurement. Immediately observe water level at gage and mark the chart for later reference, if necessary.

- Make supplementary notes at the end of the form (fig. 2.74), which should be completed in the field as soon as possible after the discharge measurement.

**Cable Suspension Measurement:**

Streamflow measurements are made from a bridge or a cable car only when depth and velocity of the stream are unsafe for wading. As a rule of thumb, it is unsafe when produce of the depth and velocity exceeds 10. The procedure for making measurements from a bridge or cable car is the same as the procedure for wading measurements, except for the following:

- Measure bridge from the upstream side. Floating debris can be better observed and avoided in this way.

- Fasten streamline lead weight to the hanger in one of the bottom holes of the hanger bar. Suspend current meter in the hole marked for the size of weight being used as follows:
  
  15, $C' = 0.5$ foot (0.15 m);
  
  30, $C' = 0.5$ foot (0.15 m);
  
  50, $C' = 0.9$ foot (0.27 m);
  
  75, $C' = 1.0$ foot (0.30 m);
  
  100, $C' = 1.0$ foot (0.30 m); and
  
  150, $C' = 1.0$ foot (0.30 m).

  The first figure is the weight in pounds. The last figure is the vertical distance from the bottom of the weight to the center plane of the bucket wheel. This value must be used throughout the measurement. It is termed the depth constant of the weight below the meter. If you do not remember the value of $C$, the distance can be measured with a tape or rule to the nearest $\frac{1}{10}$ foot (3 cm). Selection of the weight size depends on the stream velocity and the equipment available for handling the weight.

- Zero the depth indicator with the center of the meter cups at the water surface. Lower the weight till it rests gently on the streambed. The depth is then the indicator reading plus the $C$-value. Velocity observations normally are made at 0.2 and 0.8 depth except in shallow water where the observation may be made at 0.6, 0.5, or 0.2 depth only. The weight should be large enough to prevent the line from drifting downstream more than 7' from the vertical. If this is impractical, make a depth correction depending on the size of the vertical angle. A 15-pound or 30-pound (6,810 g or 13,620 g) weight can be lifted by hand. Heavier weights require a hand- or power-operated reel. Where a rubber-covered hand cable (without reel) is used, the operator sets the meter cup centerline at the water surface; clamps a tape to the cable at a reference point such as the top of a handrail; lowers the weight to the stream bottom, allowing the clamped tape to follow; and reads the tape at the reference point. The tape reading plus the $C$-value is the water depth. Both air-line and wet-line correction tables are given in reference 41. Corrections also are given for placing the meter at 0.2 and 0.8 depth.

- Use the form illustrated in figure 2.74 during the preceding measurement. If the gage height changes rapidly, however; additional gage height readings are required to obtain an accurate mean-weighted gage height for the measurement. A gage height reading should be recorded at about every 5 percent change in maximum flow depth. Inside readings and chart gage height readings should be adjusted to the outside gage reading unless accuracy of the outside reading is questionable because of wind or wave action.
**Section Rating Method:**

This method is recommended for making flow measurements when the gage height may change more than 10 percent of the maximum flow depth during a discharge measurement. Select 10 to 20 verticals in the measuring section so that 5 to 10 percent of the flow will be between each pair of adjacent verticals. During storm runoff, observe the velocity at these verticals enough times to adequately define a rating curve for each portion or section of the cross section represented by each vertical. Section rating curves may be combined to make up a composite rating curve for the storm or the station if the curve has a stable control.

**Low Flow Estimates:**

Accuracy of the low flow runoff record at shifting control stations can be improved with little additional labor by estimating flows less than a few cubic feet per second each time the observer visits the station and does not make a discharge measurement. The area of a cross section of the flow may be determined by multiplying the estimated flow width by the estimated average depth of flow. The surface velocity of the flow may be estimated by timing the movement of a floating object over a course that is a few feet long. The surface velocity should be multiplied by a factor between 0.6 and 0.8 depending on the distribution of velocity across the stream. The discharge rate is the area times the average velocity. Since the accuracy of this measurement is not comparable to the accuracy of measurement with a current meter, this method should be used sparingly.

**Safety:**

The greatest hazard in measuring streamflow is probably inability to swim and to work free from equipment and clothing when footing is lost while wading or when the gaging structure fails. All streamflow observers should be able to swim and should wear a lifejacket at all times. When wading measurements are being made, a tag line should be installed at the gaging section for the hydrographer to grab if he falls in the water.

The second greatest hazard to the streamflow observer may be caused by traffic on bridges where he often is required to work. Warning signals and signs can help if they are approved by local traffic officials.

The observer should carry a well-stocked first aid kit in his vehicle and should be familiar with the kit's contents and standard first aid practices. It is best to work in pairs when gaging with one person on the shore in the event of an accident. Protection from lightning, such as grounding the cableway or bridge, must be provided.

**Gage Datum Maintenance**

The ability to determine the quantity of water flowing through a calibrated gaging station depends on several types of information, one of which is the depth of water flowing through the control section. Instruments described in the instrumentation section (p. ) are used to determine elevation of the water surface continuously or at a predetermined point in time. Flow depths are equivalent to the differences in elevations of the water surface and the lowest point of control over which the water can flow. Elevation of zero head through the control is referred to as gage datum elevation (GDE).

A permanent bench mark (BM) should be established for convenient use in checking and maintaining the proper relationship between the GDE and the water level recorder or gage. Elevation of the GDE (referenced to the BM) must be determined. For some flow controls it can be determined with an engineer's level backsight on the BM and a foresight on the low point of the flow control. For other controls, such as formed concrete weirs, the GDE of zero head should be computed by a method such as the application of least squares, based on a detailed and accurate survey of the flow control.

Recording water level gages have characteristics typical of most automatic equipment. Quality of the output (records of water surface elevation) varies directly with the amount and quality of equipment maintenance. The types of required maintenance depend to some extent on the type of instrument used. Some common situations that produce erroneous records of water surface elevation are:
Debris may accumulate in or around the stilling well intake or both;
Debris or aquatic growth may accumulate near or on the flow control;
Recorder float (if used) may develop a leak or acquire debris, causing the float to lose buoyancy;
Float tape or cable may jump a cog or slip;
Recorder may get out of adjustment;
Insects such as mud daubers may build nests on float tapes, restricting vertical movement.

For most flow controls, the nonlinear relationship between the flow depth and the quantity of water flowing produces a situation where small errors in flow depth measurements will result in large errors in computed streamflow. Procedures for checking recorder accuracy are required, therefore, for all types of instruments. These procedures vary with the instrument, but they should include techniques for quick visual comparisons of the actual and recorded elevations of water surface and for determining the water surface elevations, or depths of flow, to the nearest 0.001 foot (0.03 cm). Staff gages are used for quick visual comparison of elevations of water surface. Some techniques for accurately determining flow depths were discussed in the previous section. The procedure for checking gage datums follows:

For stations where streamflow is continuous, the water surface GDE can be checked by a backsight with an engineer’s level, on the FM, and a foresight on the water surface at a point outside the stilling well, which represents the same elevation as the water surface inside the stilling well.

The conventional level rod can be improved for use in obtaining water surface readings by attaching a sharp point to the lower end. Additional improvement can be made by adding a jig to the lower end of the rod. This jig will help support the weight of the rod in the soft material usually found in or near streambeds. It also will allow the rodman to lower or raise the rod under a steady condition (see fig. 2.75).

Checking the GDE by use of the engineer’s level requires at least two individuals. In lieu of this procedure, a system usually can be established that will enable one person working alone to make frequent GDE checks. This alternate system requires a conventional point gage and a small amount of initiative (fig. 2.76).

For stations where flow is not continuous and maintenance checks are made during periods of no flow, water must be transported to fill the gage well to the lowest opening and a point-gage mount must be installed inside the well. Set up the level so you can read the point gage when it is held on the crest as a rod and when it is mounted in the well. Use the point gage as a level rod and take backsight readings, B.S., on the crest (be aware that the point gage is graduated upside down), using the vernier for an accurate reading to the nearest 0.001 foot (0.03 cm). Fix the point gage in the mount inside the well. Sight the point gage with the level and move it until a mark, say 1,000, is on the line of sight. This is the foresight, F.S. Simultaneously obtain the point gage reading at the index of the vernier. This is point gage reading 1, PR 1. Take a point gage reading on the water surface in the well. This is point gage reading 2, PR 2. Calculate the head represented by the water level in the well as follows:

$$\text{Head} = PR_2 - PR_1 + F.S. - B.S. \quad (2-43)$$

A gage datum inspection form is shown in figure 2.77.

Runoff Into Farm Ponds and Reservoirs

A detailed topographical survey must be made of any pond or reservoir used for measurement of runoff. From this survey, the volume versus the water depth relations for the pond is determined. The pond may have to be resurveyed at regular intervals depending on the rate of which the volume of the pond is altered by deposition of sediment. For the common pond encountered on small watersheds, the survey should have sufficient detail to prepare at least a 1-foot (30.5 cm) contour map of the pond. Consult any good surveying reference for instructions on how to make the topographic survey.

Ponds with water stage recorders must be serviced and maintained regularly. If the time record of depth is to be differentiated for record of inflow rate, the most expanded time scales of the recorder must be used (that is, 1 division = 5 min or less). This necessitates changing the
chart at least once a week, winding the clock, and inking the pen. If feasible, change charts after any inflow into the pond. By doing so, the charts have a recording of one event with points of reference (beginning, end, and checks on the water level) easily determined.

Each time a chart is changed, all information to orient the record in space and time must be noted. Usual items of identification are:
- Watershed location name or number.
- Pond name or number.
- Date and time chart is put on recorder.
- Date and time chart is removed from recorder.

**FIGURE 2.75.—Attachment for converting the conventional level rod into a convenient point gage for use in determining water surface gage datum.**
FIGURE 2.76.—Support and permanent bench mark for a portable conventional point gage.
GAGE DATUM INSPECTION

Headwater ( ) Tailwater ( ) Gage at ________________________________

Party __________________________ Date ____________________________

Instrument No. __________________ Gage Zero ______________________

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</tr>
</tbody>
</table>

Inside Gage

(1) Elevation of R.P. =

(2) Bottom of tape weight or staff gage
    R.P. before adjustment =

(3) Observed gage zero
    (1) - (2) =

Gage zero not changed, corrected to
______ ft by adjusting tape weight
to ______ ft or adjusting R.P. to
______ ft.

Comments:

Outside Gage

(1) Elevation of R.P. =

(2) Bottom of tape weight or staff gage
    R.P. before adjustment =

(3) Observed gage zero
    (1) - (2) =

Gage zero not changed, corrected to
______ ft by adjusting tape weight
to ______ ft or adjusting R.P. to
______ ft.

Comments:

FIGURE 2.77.—Gage datum inspection form.
- Depth of water in pond with respect to same reference.
- Signature of person changing the chart.

Since a mechanical device makes the recording, it needs to be serviced periodically. Once a year, the recorder should be cleaned and oiled. At the same time, the recorder should be calibrated to assure that the clock is measuring time accurately and the travel of the float is proportioned properly on the chart. Plans should be made to repair occasional breakdown or damage caused by unexpected catastrophes or vandalism.

Items such as stilling well, instrument shelter, access ramps, and intake pipes are associated with mechanical recorders. These items will require general maintenance and upkeep. Intake to the stilling well must be watched closely to assure that the well is not plugged. Pond outflow structures must be maintained in good condition to assure accurate measurement of outflow from the pond if the outflow should spill.

Not as many explicit instructions regarding service and maintenance can be made for these instruments because configuration of such instrumentation varies from the old-style mechanical recorders fitted with an attached transducer driving an analog recorder (which may need weekly attention) to specially designed systems that can collect data from remote locations for long periods with no special servicing of the instruments. Any type of instrument will require periodic maintenance and calibration, and records must be collected with all the necessary identification.

**Data Reduction and Processing**

Runoff chart processing and basic runoff computations are accelerated with modern electronic equipment such as analog-to-digital converters and high-speed digital computers. If this equipment is unavailable, desk-sized calculators and slide rules should be used. Instructions for both types of computations are included in this section. Although both methods provide the same answers, electronic methods are faster, should have fewer errors, and can be made at lower costs where the number of computations is voluminous.

**Analog Chart Record Processing**

Special attention should be given to the recorder charts as soon as they are removed. Detect and note on the analog trace such abnormalities as faulty records due to clock stoppage; water level float failing to respond to water level changes in the stream because of ice, friction, or other causes; and debris lodged on the control or clogging of intake to recorder stilling well. By comparison with rainfall and runoff records from nearby stations, adjustments to the chart should be made to represent, as closely as possible, the true record. High watermarks observed at gaging stations and marked on the chart may help construct the true stage graph. Standardized procedures for chart annotation are needed to insure that all required information is recorded. Local situations usually dictate procedures to be used.

For procedures oriented around digital computer processing, the basic data, including breakpoint information adjusted for time or flow depth shift (or both if needed), should be tabulated directly on special forms for card punching. The format of these forms will depend on the computer program used to reduce and process the data.

Tabulation of data from water level recorder charts should supply sufficient detail to provide reasonable accuracy in determining instantaneous rates and total runoff. The method to be used in runoff calculation will influence the frequency with which points must be selected. Fewer points will be necessary where no pondage corrections are figured. Experience may indicate that greater or less refinement than the criteria given here will best fit a particular area. The record from water stage recorder chart (fig. 2.63) is tabulated in figure 2.78 as follows:

Fill in all data called for in the heading. Most items require no special explanation. The file number should include station designation, year, and sheet or storm number. The dates shown should include those periods with no runoff to give continuity of record to the tabulations.

On the first line of the form, show the period since the last runoff if it is more than one
calendar day. These dates are included in the heading.

Enter the month, day, and time in column 1 to correspond to the gage heights selected in column 3.

Enter gage heights obtained from water-level recorder charts in column 3 in accordance with the following steps:

1. Select groups of uniform time intervals (using whole minutes only) so that the gage-height interval during any time interval is approximately 0.30 foot (9.1 cm), where no pondage correction is to be applied; 0.20 foot (6.1 cm), when necessary to apply pondage correction; and 0.10 foot (3.1 cm) or less, where the pond area is more than 2.5 percent of the drainage area. These limits apply to that part of the chart with data of rapidly rising or falling stages. For slowly rising or falling stages, the increments of stage suggested must

calendar day. These dates are included in the heading.

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<table>
<thead>
<tr>
<th>Date and time</th>
<th>Time</th>
<th>Gage height</th>
<th>Rate of change in stage</th>
<th>Pondage correction</th>
<th>Observed discharge</th>
<th>Rate of runoff</th>
<th>Total runoff</th>
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</table>

<table>
<thead>
<tr>
<th>Time</th>
<th>Gage height</th>
<th>Rate of change in stage</th>
<th>Pondage correction</th>
<th>Observed discharge</th>
<th>Rate of runoff</th>
<th>Total runoff</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:00</td>
<td>1.50</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Conversion factor for drainage area: 1 cubic foot per second = 0.0058 cubic feet per hour.

Tabulated by G. R. Lloyd, 9/7/43
Checked by N. E. Minshall, 10/10/43

FIGURE 2.78.—Tabulation of a stage record at Fennimore, Wis.
be reduced. Where pondage corrections are required, use smaller intervals of gage height for some time before the peak stage is reached. Do not use a time interval of less than 1 minute. Computations will be easier if time intervals of 1, 2, 3, 5, or 6; 10 or 12; 20 or 30; and multiples of 60 minutes are used. Make the tabulation in accordance with the preceding steps until a head of 0.2 foot (6.1 cm) over the notch is reached on the falling stages.

2. For the part of the record below a head of 0.2 foot (6.1 cm), use the preceding time intervals with gage-height intervals of 0.02 to 0.05 foot (0.6 to 1.5 cm) (depending on the steepness of the recession) until the GDE of the notch or a reasonably constant stage is reached.

3. Where the stage becomes reasonably constant at a head of 0.2 foot (6.1 cm) or more, supply the tabulation in accordance with the first step to within 0.2 foot (6.1 cm) of the constant stage and continue in accordance with the second step until constant stage is reached.

4. Supply the gage-height intervals at and near peaks and troughs in about the same detail as for stages within 0.2 foot (6.1 cm) of the notch or constant stages.

5. Tabulate gage heights at midnight and at any noticeable break in the pen trace for runoffs involving more than 1 day.

Corrected data from the water stage recorder chart (fig. 2.63) are tabulated in columns 1 and 3 of figure 2.78. Use the criteria for a station where no pondage correction is to be applied. Note that on the rising stage the difference in stage from 5:00 to 5:01 a.m. is 0.65 foot (19.8 cm), which is controlled by the minimum time interval of 1 minute. Increments of stage from 5:10 to 6:00 average slightly less than the 0.3-foot (9.1 cm) limit for stations without pondage correction. From 7:30 to 9:00, the increments are about 0.05 foot (1.5 cm). Failure to pick enough points on the recession will result in values that are too high for total runoff.

Any constriction of the stream channel, such as the construction of a dam or spillway, will cause a certain amount of backwater or pondage upstream from the constriction. The effect of this pondage on the rate of flow should be considered in selecting the procedure for calculating runoff. If the runoff is flashy, a moderate quantity of pondage water may significantly reduce the peak outflow rates from the area and pondage corrections may be desirable. In areas where runoff rises and falls at moderate rates, these considerations may be generalized.

- If a pondage correction is applied on areas where the pond is small and the rate of change in stage is slow, the resultant hydrograph will shift a few minutes, with little difference in the shape or the peak rate. This shift probably will apply to pond areas of less than 0.5 percent of the drainage area.

- Where the pond area is 0.5 to 2.5 percent of the drainage area, a pondage correction may be necessary to obtain rates of inflow to the pond. After several storms have been computed, check to see if the pondage correction is justified. Plot the peak rate of inflow to the pond against the peak discharge over the weir for several storms. If the points fall in a reasonably straight line and do not vary more than 5 percent from a 45° line, assume that application of the pondage correction is unwarranted.

- On areas where the pond surface is more than 2.5 percent of the drainage area, consider the rain falling on the pond in addition to the pondage correction when figuring rates of runoff from the drainage area.

Since the rates of runoff are to be calculated in inches per hour and the quantities of runoff in inches, time can be saved if discharge values of the rating tables are converted to inches per hour. This will eliminate the necessity of computing rates of runoff in cubic feet per second and then applying a factor to each such rate to convert it to inches per hour. The conversion factor is obtained by dividing 0.99174 by the drainage area in acres.

A method of calculating runoff rates and amounts using a desk calculator was described by McGuinness and Royer (26). High-speed digital computers are much faster and more accurate and should be used when they are available.

**Digital Punch Tape Processing**

Although development of the analog-to-digital recorder (ADR) was a significant step in automation of streamflow data processing, final accuracy of streamflow computations depends
largely on the person who collects and edits ADR tapes and computer output. This section outlines a general procedure for automatic streamflow data processing and discusses five essential steps in the editing process (74). This procedure must be modified to meet specific needs and equipment capabilities and limitations.

The first step in a good edit program is to complete an inspection report, as shown in figure 2.66, each time the recorder is checked. Abnormalities in the recorder operation or in the record are noted on the reverse of this sheet. This form serves as a valuable permanent record when it is necessary to recheck past operation or to interpret some anomaly in flow. ADR's are to be inspected weekly. Five-minute and 15-minute tapes are changed each month and every 3 months, respectively. When a new tape is installed, the date, time, station identification, gage reading, and other identifying data should be written on the tape and initialed by the person performing the operation. The same information is written on the end of the tape being removed. At the beginning of each tape, eight punchouts are made manually before the starting time, without any skips between punches. These punches are needed to advance the translator to the proper beginning point for tape-to-card translation.

ADR tapes have punchout intervals that can vary from 2 minutes to 1 hour. The translator can be set to read each punchout on the tape or every second tape, fourth tape, sixth tape, and so forth. When streamflow rate is relatively steady, the translator can be set to read once each hour. The number of readouts punched on cards is thus reduced and translation is speeded considerably. Frequency of translation may be decided by referring to visual trace from a monitor watershed equipped with a chart recorder or by using a rain gage record. In this manner, 105,000 punchouts per year on the 5-minute tape are reduced to about 40,000. On the 15-minute tape, 35,000 punchouts are reduced to less than 20,000. Translator costs can be reduced considerably if this method is used rather than reading every point on the tape. Since these costs vary with machine time required for translation, tape should be edited to show the translation frequency desired.

The second step in a good edit program is to fill out and denote translation frequency (fig. 2.79) on a translator operator instructions form. Other remarks, such as missing data, also should be noted on this form. The tape editor must estimate the missing data and must attach a listing of time-head values (5-minute or hourly time intervals for each day of missing data) to this form. These data will be key-punched and inserted into the card deck during translation. Skipped sections of the tape and offset punches also should be noted with the time and date of each occurrence (head and time corrections can best be applied in later edit steps).

In addition to the translator operator instructions form, the tapes must be marked to show point of frequency change and the beginning and ending points of translation. The best method is to mark the tape with red and green felt-tipped pens (red for stop and green for start). The beginning point should be marked by a green line completely across the tape on the correct time line. When frequency changes are necessary, a red line is required at midnight of the day before the change, and a green line is required on the next point to read out (5-min, 15-min, or hourly line). The final point to be translated on the tape should be marked with a red line. Note: A complete day's record must be read at the same time interval; frequency of translation cannot be switched during a day's record. When tape editing is finished, the tape should be rewound so the beginning point is on the outside of the roll.

Translators such as Fischer and Porter will read three channels leaving off the units position, or they will read all four channels. Translator output may result in 1 card per day for 60-minute readouts, 4 cards for 15-minute readouts, or 12 cards for 5-minute readouts. The cards also contain watershed number, date, day of week, and card number within the day. The card format can be altered to fit the needs of the user. The card deck from the translator is edited in the third step.

The third edit step is done by the collector of the record either on the printed cards from the translator or on a printout of these cards. The card deck or printout is scanned for indications of anomalies caused by trash in the notch, wild
values, incorrect translation points, incorrect number of days in month, and so forth. Head corrections are penciled onto the printout, and the printout or a listing of errors is returned to the translator. The card deck will be corrected by replacing erroneous cards with corrected cards (magnetic or paper tape output from the translator is also available).

After the translation step and edits, cards are processed through the condense and edit program, which performs four separate functions in preparing data for final discharge integration and computations. These functions are further reduction of points, insertions of unit's position digit in head readings, generation of time increments between remaining head readings, and computer edit of the data.

Head values are dropped systematically by the computer when the difference between readings is less than prescribed limits. These limits are set so that during storm periods every punchout needed to define the storm is retained. To be sure that the hydrograph will be defined adequately during periods of gradual change, however, a head reading is retained at the end of each 3-hour interval regardless of the number retained during the interval (if desired, all punchouts can be retained, but this adds to computing costs). This technique reduces the number of points retained to between 3,000 and 5,000 per year.

A digital computer accumulates time intervals and inserts the time of day in hours and minutes for each retained head reading. The computer also checks the cards for sequence, day of month, day of week, and year.

Output from this program is a set of time-head cards and a listing. These cards contain watershed number, date, and eight sets of time-head readings. The listing contains the same information on each printed line.

The fourth edit step uses the printout from the condensed program. This printout is returned to the user for editing. The listing is scanned for errors not detected by computer and previous edit steps. Corrections are pen-
ciled on the listing. Time and head corrections also can be applied at this time. Rain gages or adjacent units can be compared to check for errors. The listing is returned to the translator for corrections in the card deck. The cards are now ready for the discharge integration program.

The final step of routine streamflow data processing is programmed for computer analysis. Formulas (preferably) or rating tables are used to convert head readings to discharge. Watershed areas also may be used to convert head readings directly to discharge rates in cubic feet per second per square mile (CSM). Computer programs may be used at the same time to determine discharge volume of the hydrograph, streamflow summaries, flow frequencies, and time—CSM coordinates. Programs will be written to provide specific information needed.

All computer output listings are returned to the user for a final check for errors. This is accomplished by comparing daily and monthly flows with those obtained from rainfall or nearby catchments. If discrepancies appear, the original records and all intermediate steps must be examined to determine if errors exist. If errors do exist, corrections should be penciled in for recomputation. If no errors occur after correction, all cards and printouts are ready for further use or for storage as permanent records of stream discharge.

**Discharge Measurement Calculation**

Obtain velocity values from a rating table (fig. 2.80) for the current meter and suspension used (rod, or 15, C - 0.5, and so forth). If shorter time intervals (20 to 35 seconds) are used, it is convenient to double the time and number of revolutions to obtain the velocity directly from the rating table. These values are listed in the “At point” column for each 0.2 and 0.8 depth observation of revolutions and time. For station 18, the velocity at 0.2 depth, taken from the rating table at 20 revolutions in 40 seconds, was 1.17 ft/s (35.7 cm/s); that for the 0.8 depth was 0.942. The average of these two values is 1.056—the mean velocity in the vertical. Since the current angle-correction factor was 0.98, the true mean velocity in the vertical is 0.98 times 1.056 = 1.035 ft/s (32.2 cm/s). As the 0.6-depth observation represents the mean velocity in the vertical, its value is recorded directly as the “Mean in Vertical.” (See value for station 18, fig. 2.74.)

The area to which the “mean in vertical” velocity is applied is taken as the depth at the section, times a width extending halfway to the preceding and following observation points. Thus, the area at station 18 is equal to the depth since the stations on either side are a distance of 1 foot (30.5 cm). Discharge for each station is the product of the area times the velocity.

Total discharge (fig. 2.74) is the sum of that for each section; total area is the sum of all section areas. These totals are recorded in figure 2.81. This form can be filled in at the office after computing the measurement data. Area and discharge values are rounded off to the nearest three significant figures. Total discharge of 31.23 becomes 31.2 ft³/s (0.94 m³/s).

Gage height of the discharge measurement (fig. 2.74) usually is determined by averaging the gage height at the beginning and end of the measurement. A weighted mean gage height must be determined for discharge measurements where the change in stage during the measurement is several tenths of a foot or more, and for stream cross sections where a large part of the flow is measured in a small part of the total stream width (fig. 2.81). Total stream width would occur where there is a wide overflow with low velocities and a narrow deep channel of high-velocity flow. For these streams, manual readings or gage-height values from the chart must be supplied several times during the measurement. These times are noted on the form illustrated in figure 2.74 at the point of velocity and depth observations. They are transferred later to the front sheet of this form (fig. 2.73). Using the times recorded in column one of figure 2.73, one can obtain gage-height values from the recorder chart (fig. 2.82). A method using a two-man team at alternate stations across a stream is reported by Blanchard and DeCoursey (5) for use on rapidly changing streams.

Stage-discharge relation is developed from current-meter measurements that are plotted (stage vs. discharge) on log-log paper (fig. 2.83).
It is usually desirable to plot the low-water section in this relationship separately for better definition. A best fit line is drawn through the plotted measurements.

High-stage measurements on small watersheds are difficult to obtain. Slope-area measurements or contracted opening measurements using flood peak high watermarks help to establish the upper end of the relation. These observations should be made as soon as possible after the flood.

With a permanent control at the runoff station, the stage-discharge relation should not shift. Once the relationship is established, occasional check measurements are made. Shifting of flow control due to backwater needs specific instructions.

### Table: Rating Table for Type Pec Current Meter No. 522

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**Computed by RH 3-3-37**

**Checked by AL 3-3-37**
1.00 to 1.10 feet (30.5 cm to 33.5 cm) is 1.42 \text{ ft}^3/\text{s} (0.04 \text{ m}^3/\text{s}). If this interval is divided into 10 parts, each 0.01-foot (0.3 cm) stage charge will be 0.142 \text{ ft}^3/\text{s} (0.004 \text{ m}^3/\text{s}). The difference in cubic feet per second per 0.01-foot (0.3 cm) stage is not uniform throughout the range from the 1.00 to 1.10-foot (30.5 cm to 33.5 cm) stage. The increment of 0.142 \text{ ft}^3/\text{s} (0.004 \text{ m}^3/\text{s}) per 0.01-foot (0.3 cm) stage applies to the center of the overall reach; that is, at about 1.15-foot (35.1 cm) stage (figure 2.83). Increment cubic feet per second values for the reach 1.00- to 1.03-foot (30.5 cm to 31.4 cm) stages are smaller, and those from 1.06 to 1.10 (32.3 to 33.5 cm) are larger than 0.142 \text{ ft}^3/\text{s} (0.004 \text{ m}^3/\text{s}). In making the rating table differences in \text{ ft}^3/\text{s} for the 0.01-foot (0.3 cm) stage, changes are to vary uniformly and smoothly without abrupt changes. Streambed flow can be converted from cubic feet per second to units of watershed inches per hour.

### Missing Records

The greatest cause of missing records is usually failure of the observer to wind the clock, ink the pen, place the pen on the paper, tighten the float pulley after adjustment, flush the intake pipes, change the clock on schedule, or adjust the paper properly in the recorder. Training the observer and providing adequate

#### COMPUTATION OF WEIGHTED MEAN GAGE HEIGHT

<table>
<thead>
<tr>
<th>Time</th>
<th>Gage height Reading</th>
<th>Discharge in intervals</th>
<th>Gage height times discharge</th>
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<tr>
<td></td>
<td>Feet</td>
<td>Feet</td>
<td>\text{ Ft}^3/\text{s}</td>
</tr>
<tr>
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<td>4.18</td>
<td>3.46</td>
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<tr>
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<td>3.46</td>
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<tr>
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<td>4.02</td>
<td>26.72</td>
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<tr>
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<td>9:32</td>
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<tr>
<td><strong>Totals</strong></td>
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<td><strong>199.09</strong></td>
<td></td>
</tr>
</tbody>
</table>

Weighted mean gage height: 199.09 - 51.00 = 3.90 ft.

**Figure 2.82.—Method of computing weighted mean gage height.**
checking forms are excellent means of preventing missing records.

When records are lost for any reason, take the following steps:

- Determine high watermarks at the gage site for the period.
- Examine runoff records from the nearest station to establish probable trends in the missing data.
- Examine precipitation and temperature records from the nearest stations.
- Correlate past runoff records with precipitation and runoff from nearby stations.
- Adjust data by an analysis of hydrograph recessions for similar seasonal events of record.
- Further adjust the probable hydrograph by an equation that accounts for difference in watershed retention.

**Estimating Recessions**

A visit to the runoff station should be scheduled immediately following or during any significant runoff event to prevent long periods of missing records caused by silting of intakes and instrument malfunctions. This action may provide a few valuable data points for fitting the recession curve.

The recession for a watershed may be plotted by comparing it with recessions from other storms on the same watershed. A template matched to a series of recession curves will provide a reasonable estimate of the missing data. This overlay may be prepared as follows:

- Search the runoff records and select flows that have complete recessions and are not influenced by precipitation (elongated). Use flows of similar gage height.

---

**FIGURE 2.83.—Low-water stage and high-water stage discharge relation developed from current meter measurements.**
Rating table for  
Crooked River nr Central,  

<table>
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<th>From</th>
<th>To</th>
<th>From</th>
<th>To</th>
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</thead>
<tbody>
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<td>June 1, 1946</td>
<td>October 10, 1948</td>
<td>June 1, 1946</td>
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<td>142.15</td>
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</tbody>
</table>

Computation by ABC 10/19/48, Checked by DEF 10/10/19/48

Figure 2.84.—Rating table for stage discharge relation.
- Tabulate these flows and plot the reces-
sions (log discharge vs time) on semilog paper. The curves are then superimposed so that an average curve could be chosen to represent the standard recessions curve. After superimposing several recession records, draw a straight line through the lower portion of the curves to extend the recession.
- Transfer the curve to be used for the standard recession from discharge into stage height readings. Plot this curve on a typical recorder chart and draw a line through the points to form the standard recession curve.
- Make a mylar overlay to place on the charts for easy appraisal where the standard recession curve should be applied if needed. Since each runoff is a unique event, this curve is used for estimation only. The recessions for a watershed vary according to moisture, seasons of the year, and changes in vegetation cover.

Analytical methods also can be used to estimate missing stage records. Polynomial equations can be used when the beginning and ending time and stage record are known, as was demonstrated by Mills and Snyder (197).

**High Watermarks**

Flood debris lines on walls, stilling wells, streambanks, and vegetation are valuable as a check on maximum recorded gage height and as a singular estimate of the peak discharge rate. Correlation of peak runoff rate with flood volume for similar events may provide much useful information in estimating runoff volumes for periods of missing or erroneous records. At peak stage in a pond the instantaneous runoff rates of inflow and outflow are used without pondage correction.

**Comparison With Runoff or Retention From Nearby Watersheds**

In comparing runoff from two watersheds, select periods that will not be affected by the conditions of cover and tillage. First, select a series of storms common to both areas and make sure each area has about the same cover conditions for all storms. This does not imply that both areas must be in the same cover. For example, an area could be 100 percent in hay crops and still obtain a comparable result. This method is best adapted to small adjacent areas and involves plotting runoff from one watershed against runoff from the other, for all storms selected, to develop an average relation.

Figure 2.85 illustrates the method applied to two small watersheds: W-I, 27.2 acres (11 ha) and W-II, 50 acres (20.2 ha) near Edwardsville, Ill. Watershed W-II was in 100 percent pasture during the entire period of record. Watershed W-I was in 100 percent alfalfa except for 4 years of record, when 96 percent was cultivated. The relationship when W-I was 100 percent alfalfa differed from the relationship pertaining to W-II when W-I was cultivated. Land use

---

**Figure 2.85.—Comparison of runoff from two adjoining watersheds as an aid in estimating data of missing records, Edwardsville, Ill.**
during the period of missing record must be considered in selecting the proper curve for estimating total runoff from one watershed, based upon its relationship to the other watershed. In these comparisons, different relations may exist for different seasons.

This method may not produce satisfactory results for some areas because rainfall varies between the areas being compared. These results are illustrated in figure 2.86, which is a comparison of two areas near Fennimore, Wis. Both areas have approximately the same shape and topography, but they vary considerably in size—W-2 is 22.8 acres (9.2 ha) and W-4 is 171 acres (69.2 ha). During 1942, 1943, 1950, and 1951, 0 to 7 percent of W-2 was cultivated and 45 to 50 percent of W-4 was cultivated. During the years 1944 and 1945, 60 percent of both watersheds was cultivated.

As shown in the lower graph of figure 2.86, land use affects the runoff relationship between these two watersheds, but scatter values during the 1944-45 period were not great enough to establish the curve. For these watersheds, a better relationship is obtained by comparing amounts of retention (that is, rainfall minus runoff) as in the upper graph of figure 2.86. Retention on the area for the missing record can be estimated by finding the retention on the area used for comparison, entering it on the chart, and reading the retention on the area in question. Estimated retention is subtracted from rainfall to estimate runoff.

Size of the drainage areas used in the preceding comparison need not be the same. In fact, drainage areas can be considerably different in size if all runoff is surface runoff resulting from precipitation in excess of infiltration rates, and if no base flow or interflow occurs.

In areas where the geology is such that streams are classed as gaining or losing or where the base flow or interflow represents a considerable part of the total runoff, it may become necessary to compare only watersheds that are approximately the same size. This method also may be useful in estimating peak rates of runoff. Maximum rates of runoff from the watershed are plotted, storm by storm, against maximum rates of runoff from a comparable watershed, to derive a curve for estimating missing records of peak flow for a given storm. As shown for total runoff, a comparison of retention rates of one area against another may give more consistent results.

**Estimate of Flow During Ice Periods**

Estimation of flow during ice periods is a complex problem at natural channel sections. Detailed site surveys are required to determine the area, wetter perimeter, roughness coefficients of the bed, and covering ice layer and water surface slope (10). At best, estimates usually apply only for short periods since an increase or decrease in rate of flow floods the ice layer or causes the ice to form a bridge over the flowing water. Frequent observations are necessary for reliable estimates of flow.
Flow at weirs and flumes often can be estimated by periodically removing the ice layer upstream and downstream from the control section. Higher velocity through the control often prevents serious ice formations. At locations where ice is a continuing problem, the weir or flume should be covered by a heated enclosure capable of resisting snow and wind loads expected in the area (fig. 2.87). Electric heating cables attached to the bottom and stilling well of metal flumes or buried in concrete, help to reduce the effect of ice on the runoff record.

Manual Calculations

Manual calculations without pondage corrections are fairly simple using a desk calculator. For pondage or a large pond requiring subtraction for precipitation on the pond, calculations must be made carefully of runoff.

Calculations for Pondage Corrections

The area of temporary pondage above the weir on the 50-acre watershed at Edwardsville, Ill., ranges from 544 ft$^2$ (50 m$^2$) at notch elevation, G.D.E. 1.50, to 33,000 ft$^2$ (0.14 to 2970 m$^2$), or 1.5 percent of the drainage area at maximum design stage, G.D.E. 5.20. The rating table for this station, prepared in accordance with instructions (42) is shown in figure 2.88. Follow these instructions:

- Enter data in columns 1 and 3 in figure 2.89. Note that the difference in stage between

FIGURE 2.87.—Typical weir enclosure for ice conditions.
<table>
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<th>Stage (ft.)</th>
<th>Observed Discharge over weir (c)</th>
<th>Pongage Correction (c_p)</th>
</tr>
</thead>
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<td>0.01</td>
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<td>0.01</td>
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<tr>
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<tr>
<td>0.09</td>
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FIGURE 2.88.—Discharge values for 3-to-1 weir and pondage correction data for station W-II, Edwardsville, Ill.
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<th>Rainfall</th>
<th>Rate-of-runoff from pondage correction of</th>
<th>Arreinee of sum total of</th>
<th>Time Factor</th>
<th>Total Runoff</th>
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**Conversion factor for drainage area: 1 cubic foot per second = inches per hour.**

**Figure 2.89.—Computations performed by using a desk calculator for pondage corrections of runoff at Edwardsville, Ill.**
successive time intervals is approximately 0.2 foot (6.1 cm).

• Enter in column 2 the difference in minutes between successive entries in column 1.

• Determine the rate of change in stage in column 4. The theoretical rate of change in stage at a point would be the tangent to the stage graph at that point. As the chart is curvilinear, the stage graph must be plotted on rectangular coordinate paper and the slope of the tangent must be determined at each tabulated point with a straightedge or template. Although it may require more points for accuracy, a satisfactory method is to determine the difference between gage heights corresponding to equal time intervals preceding and succeeding the point under consideration. Divide this difference by the total time interval between the gage heights. This gives the slope of the chord between two points immediately before and after the time in question. If the times between stage intervals are sufficiently small, the chord is approximately parallel to the tangent.

• Computations of the slope of the chords that are taken as the rates of change in stage may be simplified by use of a table of half rates of ponding (fig. 2.90). The rate of change in stage is obtained by adding the half rates for the interval before and after the time in question. Half rates for stage increments in excess of 0.10 foot can be interpolated by adding the half rate of the pertinent hundredth foot stage increment to that of the pertinent tenth foot increment. Thus, the half rate for the stage increment of 0.27 foot (0.20+0.07) in 2 minutes preceding 11:32 p.m. in figure 2.90 is computed as the sum of 0.050+0.0175=0.0675 ft/min. The half rate for the stage increment of 0.18 foot (0.10+0.08) in 1 minute following 11:32 p.m. is 0.0500+0.0400=0.0900. The tangent or rate of pondage at 11:32 p.m. is equal to the sum of the half rates: 0.0675+0.0900=0.1575 ft/min (4.72 cm/m). If the time between stages is more than 1 hour, the rate of change in stage normally will be so small that it may be disregarded. The rate of change in stage is positive for rising stages and negative for falling stages. At peaks and troughs of the pen trace (maximum-minimum gage heights) the rate of change in stage is always zero.

• The pondage correction in column 5 of figure 2.89 is obtained from the right side of the rating table (fig. 2.88). In using this part of the table, determine the value \( q_p \) for any rate of change in stage at a given gage height by multiplying the tabular value for the gage height by the rate of change in stage. Thus, at 11:32 the G.D.E. is 2.65, and the rate of change in stage is 0.1575 ft/min (4.72 cm/m); from the rating table, the G.D.E. 2.65 \( q_p \) is equal to 3.27 in/hr (8.3 cm/h) and the rate of ponding is 0.1575×3.27=0.515 in/hr (1.3 cm/h). The sign of the pondage correction is positive for rising stages and negative for falling stages.

• Obtain values of observed discharge \( q_o \) in column 6 directly from the rating table for each tabulated gage height.

• These entries are the discharges corrected for pondage or the algebraic sums of entries in columns 5 and 6. Carry the entries in column 8 to three significant figures, but never more than four decimal places.

• Obtain column 9 by averaging column 8 for the prior and current discharge. Obtain column 10 by multiplying column 9 by the time interval of column 2 and dividing by 60 minutes. Obtain column 11 by accumulating column 10. At the time of the peak rate of runoff in column 8, the pondage correction for this storm was almost equal to the discharge over the weir.

On areas with large ponds, apply corrections for ponding and for rain falling on the surface of the pond. The area of the pond at elevation of the spillway station at McCredie, Mo., is about 16 acres, or almost 10 percent of the drainage area. The drainage area in this instance is variable, depending on the stage of the pond; thus, a rating table cannot be made directly in inches per hour. The chart from this station for the period from June 6 to June 7, 1945, is shown in figure 2.91.

• Plot the stage graph G.D.E. versus time on cross-section paper, using an expanded time scale, and draw a smooth curve through the plotted points (fig. 2.92). Use large scales for these graphs, as they will give greater accuracy to the final results. Plot the graph only for that part of the runoff during which rainfall occurred, that is, 2:50 a.m. to 7:00 a.m. on June 7.

• Plot the accumulated rainfall diagram di-
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**Figure 2.90.—Tabular data of half rates of ponding during time interval, Edwardsville, Ill.**
rectly below the gage height curve, using the scales for the stage graph.

• Subtract the accumulated rainfall curve from the G.D.E. curve at a sufficient number of points to permit construction of another smooth curve. No fixed rule can be given for spacing these points except that they must be closer together where curvature in the stage graph is considerable at significant changes in rainfall intensities.

• Draw a smooth curve through points mentioned in the preceding step. This curve, shown as a solid line, represents the rise in water surface due to surface runoff in excess of outflow. When more than one sheet is necessary for plotting, duplicate a small portion of this sheet on the next sheet.

• Select and indicate groups of uniform time intervals on the graph, step 1, on slowly rising or falling stages. Use a uniform stage increment (0.01 foot (0.3 cm)) rather than a uniform time interval increment. Enter these times and stages in columns 1 and 3 of figure 2.93.

• Enter in column 2 the difference in time between successive entries in column 1.

• In column 4, tabulate the rate of change in stage for each time listed in column 1. For that part of the stage record plotted in figure 2.93, obtain the rate of change in stage at a given time from the stage curve corrected for rainfall by (1) placing a straightedge or triangle tangent to the curve, (2) reading the difference in intercepts on the vertical scale over a 100-minute interval, and (3) pointing off two decimals.

• The straight line shown in figure 2.94 is tangent to the curve at 4:50 a.m. The intercepts at 4:00 a.m. and 5:40 a.m. (100 min later) are 20.25 and 20.51, respectively. The rate of ponding (due to surface runoff) at this time is, therefore, (20.51 – 20.25) 100 = +0.0026 ft/min. The rate of change in stage is positive for rising stages and negative for falling stages.

• Use a template prepared on celluloid or heavy transparent plastic material, similar to the template shown in figure 2.94, to determine the rate of change in stage. To use this template, place the stage graph of figure 2.92 on a table or drawing board, using a T-square to line up the base line. Place the bottom of the template against the T-square and slide it along until one of the lines coincides with the curve, corrected for rainfall in step 4, at each time tabulated in column 1. Read the value on this line or interpolate between lines. The rate of change in stage for the part after rainfall ceases is determined according to the procedure used for figure 2.84.

• Obtain the rates of change as outlined. The pondage correction, \( q_p \), in column 5, fig. 2.93), will be obtained from the rating table (fig. 2.95). Values of \( q_p \) are given for each 0.1 foot (3 cm) of stage and can be interpolated for the nearest 0.01 foot (0.3 cm). Error generally will be less than 1 percent, however, if the nearest 0.1 foot (3 cm) is used. Obtain the value of \( q_p \) for any rate of change in stage at a given gage height by multiplying the tabular value of \( q_p \) for this gage height by the rate of change in stage. Thus, computation can be made with a
slide rule. The sign of the pondage correction, \( q_p \), is determined by the sign of the rate of change in stage.

- Obtain observed discharges \( (q) \) in column 6 directly from the rating table for each gage height.
- Obtain entries in column 7, "rate of runoff," by adding the entries in columns 5 and 6; carry entries to three significant figures but never more than four decimals.
- Obtain the values of \( q \) in inches per hour, column 8, by multiplying the values in column 7 by the conversion factor given at the bottom of the sheet. The conversion factor is taken as a constant for the entire storm period except when variation in size of the pond surface during a storm is more than 3 percent of the watershed area. If the range in stage is sufficient to produce significant variation in the pond surface area, vary the conversion factor accordingly. Conversion factors for elevations of the pond at the McCredie station are plotted in figure 2.91. Read the conversion factor from this curve from each gage height.
- Perform the rest of the computations in accordance with the instructions for figure 2.89.

**Check Method for Total Runoff**

An independent, quick method for checking total runoff often is desirable (37). Methods outlined in the first edition of this handbook (47) reduce the labor of computations without sacrificing accuracy. Gage heights are converted to discharge, and total runoff is determined from the area under the pen trace of the water level recorder chart. Two methods of summation are the use of horizontal strips and the use of vertical strips (fig. 2.96).
## RECORD OF RUN-OFF

| Time            | Factor | Flow per ft² | Runoff | Stage
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
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<td>0.00</td>
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<tr>
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<td>1.00</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
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<td>0.97</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
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<td>0.98</td>
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<td>0.00</td>
<td>0.00</td>
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<td>0.97</td>
<td>0.00</td>
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<tr>
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</tr>
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<tr>
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<td>5:40</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

### Peak Discharge

- Total June 7 = 2.212"
  - Beginning of Runoff
    - June 7 a.m.
    - Total June 7

*Conversion factor for drainage area: 1 cubic foot per second = 0.0055 cubic feet per minute.*

---

**Figure 2.93**—Computations for pond stage record of runoff at McCrude, Mo.
Computer Calculations

Digital computer processing of basic runoff data is more rapid, accurate, and efficient. Selection of the process depends on basic data, computer hardware available, programming talent available, and desired end results. A few principles will be discussed, and two examples will be given. Figure 2.97 illustrates the flow of runoff data processing at the Southern Great Plains Watershed Research Center (36). Figure 2.98 illustrates the process at the Southwest Watershed Research Center. Although both procedures have the same objective, each is tailored to specific needs and available computer hardware.

First, all analog records must be digitized, or digital information must be transcribed to punched cards, magnetic tape, or whatever is used as computer input. Digitized or transcribed data generally contain more than time and stage height values. Identification information, codes pertaining to processing programs, estimates, and machine operator signatures also are included. The runoff data format used by the Southwest Watershed Research Center is shown in figure 2.99. This format includes:

- Beginning time with elapsed time or the military time of each datum point;
- Estimation of time and stage height;
- A correction factor for adjustment of the stage heights;
- Codes to call for the addition of standard recessions to the record;
- Codes for standard or daylight savings time (all records in daylight savings time are converted to standard time); and
The following situations are checked, depending on the system used. This program usually is developed for a rate of change in stage of 1 ft/min.

<table>
<thead>
<tr>
<th>Stage</th>
<th>G.D.E. (feet)</th>
<th>Observed discharge over spillway (q_s) (Discharge in cubic feet per second)</th>
<th>Stage</th>
<th>G.D.E. (feet)</th>
<th>Swage correction (q_c) (Cubic feet per second for each 0.10 ft. of stage changes in stage of 1 ft/min.)</th>
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</thead>
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<td>0.01</td>
<td>0.00</td>
<td>20.3</td>
<td>0.01</td>
<td>0.00</td>
</tr>
</tbody>
</table>

- Initials of the technician reading the record. Estimates should be added to the record.

Computer Check of Digital Record

Any logical or possible error situations in recording or preparing the digital data may be detected with a computer program. A complete checking program depends on the processing system used. This program usually is developed by trial and error. Chronological order, proper sequence of codes, and other items, should be checked, depending on the system used. The only efficient way to make checks is by use of a computer program. The following situations are checked by the Southwest Watershed Research Center checking program:

1. Header card preceding first day of a given location.
2. First card of event preceded by end card for last event.
3. End card on event preceding header card.
4. Header card present where location and year do not change.
5. Location same as location on previous header card.
6. Header card out of order—station does not increase or year does not increase.
7. Endrun card in place of header card (events following endrun card).

FIGURE 3.95.—Discharge values for spillway and pondage correction data for McCredie reservoir.
Conversion factor — Cubic feet to inches per hour

8. Location of begin card of event compared to location on header card.
9. Location on records of an event compared to location of the begin card of event.
10. Station and year compared in same manner as location for (8) and (9).
11. Correct time note for single-record events.
12. Improper time note on regular events.
13. Correct time note for single-card event but incorrect position code.
14. Illegal depth note (not 1, 0, blank, or E).
15. Illegal position code (not 1, 2, 3, 4, or blank).
16. Illegal standard recession code (not 0, blank, 1, 2, or 3).
17. Standard recession code present on record with depth less than or equal to 1.50 (applies to certain locations).
18. Illegal type of time code (not 0, 1, or blank).
19. Standard recession code present on card other than end card of event.
20. Single-card event preceded by single-card event or end-card of event.
21. Date decreases within year; date decreases, station does not change (no header card before event).
22. Time interval within event greater than 24 hours.
23. Begin card after header card.
24. Middle card of event preceded by begin card or another middle card.
25. End card preceded by middle card or begin card of event.
26. Date decreases within event.
27. Time does not increase within station.
28. Date not changed at 2401.
29. Gage height constant does not equal zero—warning.
30. Depth value blank.
31. Depth value greater than 1.50, and no standard recession code present (applies to certain locations).

Updating the Basic Data

Once errors in the basic data have been detected by a checking program, they need to be corrected. The method selected to make the corrections depends on how the basic record is stored. If the basic data are processed from punched cards, corrected cards must be punched and filed. If these data are processed from magnetic tape or disc, corrections will be made by a program with the corrections as input. Once the corrections have been made, the basic data can be processed by a program to make desired tabulations.

Instantaneous Discharge Values

The measured depth of flow past the measuring station is associated with a discharge rate. This association is expressed by a rating table or a functional relation. It may be used with a computer program to determine the discharge rate each time a stage measurement is made. Once the flow rate is associated with the depth, the sequence of values can be integrated numerically to obtain the volume of the flow.

Numerical Integration With No Adjustment for Ponding

The following calculations must be programmed to make the numerical integration and adjust for the influences of ponding.

- Determine the \( n = 1 \) to \( N \) rates of discharge \([\text{in units of volume per unit time (ft}^3/\text{s)} \text{ or depth per unit time (in/hr)}]\) from the \( N \) stage values.
• Calculate the average rate between two successive discharge values by adding the two values and dividing by 2.

\[
R_{AVE} (n+1) = \frac{R(n)+R(n+1)}{2}
\]

where \(R_{AVE}\) is average discharge \(R(n)\) in rate interval \((n)\).

• Calculate the increment of volume by multiplying the average rate by the duration of time increment.

\[
\text{Vol.} (n+1) = [R_{AVE} (n+1)] [T (n+1) - T (n)]
\]

where \(T(n)\) is the time in interval \((n)\).

• Obtain the total volume by summing the several increment volumes.

\[
\text{Total vol.} = \sum_{n=1}^{N} \text{Vol.} (n).
\]

**Numerical Integration With Adjustment for Ponding**

The following calculations must be programmed to make the numerical integration with adjustment for ponding.

• Determine the \(n = 1\) to \(N\) rates of discharge [in units of volume per unit time (ft³/s) or depth per unit time (in/hr)] from the \(N\) stage values.

• Make provision in the program to also input a pondage correction table (amounts of volume for each increment in stage [that is, 0.01 foot (0.02 cm) of stage] for a constant rate of change of stage [that is, 1 ft/min (30.5 cm/m)]).

• From the basic data, calculate the change in stage. Theoretically, it would be the first derivative of the stage function at the particular time (or tangent to the recorded stage vs. time curve at the time of interest). Since the record of stage has been digitized (sampled at a finite number of points), a good approximation of the tangent at a point is to evaluate the slope of the chord between two points equal time increments preceding and succeeding the point under consideration.

• Multiply the rate of change of stage times the value from the pondage correction table of flow rate per unit rate of change in stage to obtain the rate of flow going into or coming out of storage.

• Add the amount of flow going into pond storage to the measured outflow for the total flow rate. Subtract the amount coming out of storage from the measured outflow for the total flow rate.

• Once adjustments for ponding have been made to the flow rate, continue the program with the previously described procedure for processing with no adjustments (p. 204) and continue with the steps outlined there.

**Numerical Integration With Adjustment for Pondage and Rain on the Pond**

Increase in the pond stage (depth) due to rain falling directly into the pond is deducted by subtracting the accumulated depth (in feet) of rainfall from the record of stage (in feet) during the rainfall. The unadjusted stage record is used to determine the \(n = 1\) to \(N\) rates of discharge past the measuring structure. With the adjusted record of stage from step A, proceed with the computations in step B of the previous section, "Numerical Integration With Adjustment for Ponding."

**Alternative Method for Discharge Determination**

Rates of inflow to a pond or small reservoir are calculated in the same way pondage corrections are made to flow through a flow-measuring structure. Use the outlined procedures described in section "Numerical Integration With Adjustment for Ponding" to calculate the flow rate for the particular situation.

An alternate method of calculating the rate of flow into a pond is (9):

1. Prepare gage height versus volume relation.

• Planimeter successive contours on topographic map of pond.

• Calculate volumes between contours, using the formula:

\[
V_i = \frac{1}{2} (A_{i-1} + A_i) h,
\]

where \(A\) is the area enclosed by the
contour and \( h \) is the difference in elevation of the contours. [Make volume calculations in \( \text{ft}^3 (\text{m}) \).]

- Plot gage height versus volume relation.

2. Prepare gage height versus volume table. [The plot is used only for the foot contours since the scale is not accurate enough to read the volumes at 0.10 or 0.01-foot (3.05 or 0.3 cm) intervals.]
- From the plot of gage height versus volume, read the volumes at successive 1-foot (30.5 cm) contours.
- Using the method of increasing first differences, find the volumes at each 0.10 and 0.01 foot (3.05 and 0.3 cm)

\[ GH = \text{gage height} \]
\[ Q_m = \text{measured discharge} \]
\[ Q_s = \text{steady flow discharge} \]

**Figure 2.97.—Data processing system for streamflow and sediment transport at the Southern Great Plains Watershed Research Center.**
但从田野仪器

1. 预检查程序
   数据放在磁带

2. 检查程序
   记录检查错误

3. 更新程序
   磁带记录更正

4. 汇总程序
   常规数据分析

输出

列出更正

图2.98.—处理方案图用于处理在西南流域研究中心的径流数据。
A. Data type code (Q = runoff).
B. Watershed I.D.
C. Station.
D. Response note. Cols. 16 & 17, give count of total number of runoff responses for a single rain. Cols. 18 & 19, give the position of the event among the several multiple responses.
E. Peak note. (1 = Simple; 2 = Complex).
F. Date (day, month, year).
G. Begin time of event. For the begin time-elapsed time mode of noting time (24 hour clock time).
H. The 24 hour clock time of each reading or the elapsed time.
I. Time note for indication of estimations.
J. Depth.
K. Depth note for indication of estimations.
L. Correction factor.
M. Time mode code (0 = 24 hour clock time for each data point; 1 = begin time and elapsed time for each reading).
N. Standard recession code.
O. Type of time code (0 = Standard time; 1 = Daylight savings or War time).
P. Card Position Code.
Q. Rating Table I.D.
R. Coder’s initials.

Figure 2.99.—Runoff data format from the Southwest Watershed Research Center.
between contours. Complete gage height versus volume table (fig. 2.83).

3. From a tabulation of gage height versus time (read from the recorder chart), calculate \( \Delta S/\Delta t \), the change in storage with respect to time.
   - Reading values from the derived table, tabulate the total storage versus time.
   - Calculate the actual storage for the time increment with the formula:
     \[
     \Delta S_{i+1} = S_{i+1} - S_i.
     \]
   - Calculate \( \Delta S/\Delta t \) by dividing \( \Delta S \) by the time increment in seconds. The result will be \( \Delta S/\Delta t \) in cubic feet per second.
   - From \( \Delta S/\Delta t \), determine the inflow hydrograph. The outflow, if any, is determined from the gage height and spillway cross section.

The inflow hydrograph is computed from:
\[
I = \frac{\Delta S}{\Delta t} + Q \tag{2-44}
\]
where

\( I \) is the inflow and \( Q \) is the outflow.

Use of the volume increment method to calculate a pond inflow hydrograph eliminates the intermediate step of calculating a rate of change of pond storage for a given uniform rate of change of stage relation. Comparisons of the results from the two methods (fig. 2.100 and 2.101) also show that little difference exists between the two methods, especially when the increment is small.

### Flow Duration Computations

The duration of flow within any period (whether it is the entire period of record, a calendar year, or any other specified length of time) can be tallied by a computer program. Where total flow duration is desired over a long period, a storage register can be set and the duration of each event can be added as it is tabulated. If the entire period of record or an entire year is not processed in one pass on the

![Flow Duration Computations](image)

**Figure 2.100.—Actual inflow rates with superimposed rates calculated by the volume increment method and chord slope method, comparing parabolic input to a parabolic pond cross section of unit length.**
computer, tally information must be carried over to the succeeding processes. Programs of the Southwest Watershed Research Center maintain a tally of flow duration that was estimated so that a comparison of estimated flow duration to total flow duration (including estimated duration) may be used to evaluate quality of the record.

If the desired information is duration of flow rates above set threshold values, slightly more elaborate accounting procedures must be programmed. An adequate procedure has been described by Woolhiser and Saxton (43). A description of the procedure and a definition sketch will be given for reference.

**Routine for Flow Durations and Volume**

After each incremental volume is computed, the portion of the volume \( \Delta t_i \) above a flow rate, \( \text{CLASS} \ (J) \), is accumulated as \( \text{VOLD} \ (J) \) and \( \text{DUR} \ (J) \). By using several flow rates, \( \text{CLASS} \ (J) \), as specified in the basic data cards, a flow-duration series is computed.

The volume of flow at rates equal to or greater than the rate \( \text{CLASS} \ (J) \) is shaded in the hydrograph of figure 2.102. A straight-line variation of discharge between tabulated points is assumed, and incremental volumes and durations are computed on this basis. For example, the equation for the incremental duration in triangle 1 is:

\[
\text{Length}(ac) = \frac{[Q_3 - \text{CLASS}(J)] \times (t_3 - t_2)}{Q_3 - Q_2}. \quad (2-45)
\]

The incremental volume is:

\[
\text{Area}(1) = \frac{[Q_3 - \text{CLASS}(J)]^2 \times (t_3 - t_2)}{2(Q_3 - Q_2)}. \quad (2-46)
\]

**Maximum (or Minimum) Volume for Selection Time Interval Computations**

Programs can be prepared to calculate the maximum (or minimum) flow volume for any

![Figure 2.102](image-url) - Actual inflow rate with superimposed rates calculated by the volume increment method and cosine method, comparing parabolic input to a parabolic pond cross section of unit length.
desired period of record, from a single event to the entire period. A good computer program procedure for these calculations was reported by Woolhiser and Saxton (43). This procedure is given for reference.

Annual maximum volumes of runoff occurring within the selected time intervals $P(J)$ are determined by a search of the previously calculated data. Two indexed variables, $V(L)$ and $T(L)$, are used. $V(L)$ is the accumulated runoff in inches, and $T(L)$ is its corresponding time in hours from the beginning of the calendar year.

The limit of storage in the computer for these values is set in the DIMENSION statement. Since one unit of storage for each variable is required for each input reading, the maximum number needed can be estimated. Since this represents a sizable amount of storage on the smaller computers, it may be necessary to store fewer values, search more often, and combine the results.

A mesh of time length $P(J)$ is set up to make this search. The mesh is indexed at $J = 1$, which sets its length equal to the first value specified in the basic constants. This mesh is shifted through the stored data to obtain the maximum volume accumulated (during this length of time and the beginning time) of this maximum amount. The mesh is reindexed, and the procedure is repeated for each successive length of time.

To make this search, $LL$ indexes the leading edge of this mesh and $LT$ indexes the trailing edge. These indices are assigned values equal to the index of a time value. Use the time value at which the mesh edge occurs if the mesh edge is coincidental with a time value or use the value immediately following if the mesh edge occurs between two time values. This substitution was made in the following three equations when incorporating them into the program.

Three possible positions of the search mesh with respect to the stored values of time as it is shifted through the data are:

- The leading and trailing edges exactly coincide with the stored values of $T$, as shown in figure 2.103. Thus, no interpolation is required, and the volume $V_J$ in the time period $P(J)$ is given by:

$$V_J = F_{t,x} - V_J. \quad (2-47)$$
\[ V_j = V_{j-1} - V_j + \frac{T_{j-1} - T_j - P(J)}{T_{j-1} - T_j} \left( V_{j-1} - V_j \right) \]  

(2-49)

### Summary Information

Summary information of the runoff data tabulation may be calculated and formatted for use by a computer program. The following information may be prepared by computer programs as a summary:

1. Number of runoff events.
2. Number of estimated events.
3. Number of known events but no record obtained.
4. Total (including estimated amounts) event flow duration per year.
5. Estimated event flow duration per year.
6. Table of durations of flow above selected rates.
7. Table of monthly volumes for each measured station.
8. Yearly total volumes for each measuring station.
9. Monthly average volume for period of record for each measuring station.
10. Yearly average volume for period of record for each measuring station.
11. Maximum peak discharge for the year.
12. Average peak discharge.

Incremental plotters are commonly available. Programs may be expanded or specifically written to prepare machine plottings of hydrographs, mass curves, and other information for which a plotting is desired. These programs
depend on the input data, hardware available, and programming talent available. A plotting program will call special system subroutines (supplied by the manufacturer of the plotting equipment) and will prepare a magnetic tape with plotting instructions. This tape is used as input to the plotting device on which the instructed plotting is done. Plotting programs can be incorporated within large overall processing programs as options to use, or they can remain as separate smaller programs using output tapes (see fig. 2.98) for their source data.

References


(3) BLAISDELL, F. W., and DONNELLY, C. A. 1956. THE BOX INLET DROP SPILLWAY AND ITS OUTLET. Transactions of the American Society Civil Engineers 121:955-994.


(30) -- 1953. PARSHALL FLUMES OF LARGE SIZE. Colorado Agricultural Experiment Station Bulletin No. 426-A, Fort Collins.


CHAPTER 3. CLIMATE

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INTRODUCTION

Meteorological measurements at an agricultural research facility usually are made to characterize the climate of that location and to supply meteorological information related to hydrologic processes. An accurate description of the near-surface environment is particularly important in agriculture because plants and animals are most productive within a limited climatic range and lethal limits may be sharply defined.

Meteorological data are especially important in agricultural hydrologic research because the climate and weather of an area exert a profound influence on most hydrologic processes. For example, temperature data are vital to any study of soil freezing or snowmelt. Windspeed and wind direction are at least partial determinants of rain or snow distribution over a watershed. The hydrologic regime is so intimately related to climatic factors that almost every hydrologic study has a meteorological aspect.

Evapotranspiration (ET) is one of the hydrologic processes most influenced by climatic conditions. ET can be measured by lysimeters or estimated by water balance accounting, but lysimeters are expensive and water balance accounting is imprecise. Potential evapotranspiration (PET) can be estimated by evaporation pans and tanks during nonfreezing periods. Daily ET can be estimated more easily on a year-round basis by using meteorological measurements with the energy balance, aerodynamic, or combination computation methods.

PET has been defined as the rate of evapotranspiration dependent on weather conditions from an extensive surface of a short green crop of uniform height, completely shading the soil and actively growing under conditions of optimum water supply (20, 21, 22). Van Bavel (22) modified the definition of surface conditions since the potential value is reached when the surface is wet and imposes no restriction upon the flow of water vapor.

Several methods for calculating PET exist. A useful review of methodology was made by the American Society of Civil Engineers (2). The American Society of Agricultural Engineers (I) published the proceedings of a conference on evapotranspiration and its role in management of water resources. A selected bibliography on evaporation and transpiration is available (27). A comprehensive review of actual evapotranspiration was given by Rijtema (26).

A recent comprehensive examination of ET computation methods was made by the American Society of Civil Engineers (2). Using 16 estimating methods, they computed monthly and seasonal PET for 10 worldwide locations for which meteorological information and suitable weighing lysimeter data were available. A wide range of results was obtained; however, certain methods usually performed best under coastal conditions while others were most suited for semiarid to arid inland locations. Some methods were found to be acceptable only for the limited conditions under which they were developed.

Anyone estimating ET or PET should consult the report by the American Society of Civil Engineers (2) before selecting a method. This report expresses the estimating methods in forms suitable for computer processing. Calculations are given for each method.

The report approaches, in a practical manner, the problems of adjusting or transforming measured data into the forms required by PET prediction methods. It also presents ways of estimating meteorological factors that may not have been measured (such as net radiation) by the use of more commonly available observations.
SITE REQUIREMENTS

The central meteorological station should be located to be as representative as possible of the macroclimate of the study area. When watershed conditions cover a wide range, such as in mountainous areas, several base stations may be needed to adequately sample the meso-scale regimes making up the watershed climate. These base stations could be supplemented with data from temporary substations on less important areas that could be correlated with from the base station. Microclimatology, the precise definition of the meteorological variables in a vertical section over a point, may be useful in special studies at the facility but is usually not part of the routine data-collection program.

In any event, most meteorological observations are point measurements that will be used to represent an area. Thus, there is an assumption of spatial conformity, more true for some variables than for others.

Exact specifications for locating a climatological station cannot be given. A site away from the immediate influence of nearby trees and buildings is necessary. It should not be on a steep slope, on a sharp ridge, or in a narrow valley. The site should be such that the exposure will not be changed over a long period. The ideal selection is an open, grassy area isolated from buildings, trees, and other obstructions by a horizontal distance of at least 4 times their height. In arid areas, a sparsely vegetated site would be more natural.

Instruments at the climatological station should be installed to provide a good exposure for each instrument, primarily in terms of isolation from other instruments. A plot layout showing one arrangement is given on figure 3.1, although many other arrangements are acceptable. Important to consider are such details as having the door of the instrument shelter open to the north, locating obstructions such as electric poles to the north of the plot to avoid shading the instruments, and maintaining a fence that will protect the site from animals. Exposure requirements for individual instruments are given in succeeding sections (p. 221, for example). A general discussion of factors to consider in setting up the meteorological facilities is given by Newman, Shaw, and Suomi (19).

Areas of concrete or gravel under or near instruments should be kept to a minimum. The fence should not exceed 3 feet (0.91 m) in height, should be made of large mesh wire at the top with smaller mesh below, and should be supported on posts with a small cross section. A perch higher than the other instruments may attract birds that would otherwise roost on the sensors. Extra space should be reserved in the plot for installation of additional instruments not planned for when the plot was established.

Whenever feasible, recording instruments should be used in lieu of instruments requiring manual observations. These instruments fur-

![Figure 3.1.—Climate index plot, Coshocton, Ohio.](image-url)
nish continuous observations over weekends and holidays—data that might be missed otherwise. Local standard time should be used for all observations. Daily averages, where required, should be for the calendar day. New stations should adopt the metric system for their observations.

A permanent record of the station should be kept in a looseleaf notebook. Such data should be entered as the latitude and longitude of the station, date established, a map showing the physical layout including electric lines and waterlines, and the ground elevation of the point where the rain gage is installed. The record book should contain a series of photographs that clearly show the exposure of the plot and the relationship of the instruments to each other. A record should be kept of instruments added to or removed from the plot. Names of observers and dates of service should be noted. Notes should be kept on general operations such as dates of mowing and painting of shelters. A separate page may be reserved for each instrument, with notes on serial and model numbers used, calibration data, problems in operation and their solution, and repairs or replacements made.

An inspector from the National Weather Service should look over the plot and instruments about once a year. He will be more apt to notice gradual changes in the exposure of the instruments than local people who see the plot every day.

Extensive climatological data compiled over the years by the National Weather Service should not be overlooked. Many meteorological readings, such as air humidity, are conservative in that the average of a series of readings taken at one location may be fairly representative of the daily average at another location some miles away. Frequency arrays from a long-term record can be used to judge the normalcy of climate observed for a short period at a nearby experimental site if the records at the two locations are correlated. The assistance of the National Weather Service should be sought when questions on long-term records arise. A file of daily weather maps and local climatological data sheets from one or two nearby long-term National Weather Service stations will prove useful.

The instrumentation suggested in this section may be considered minimal for most facilities for watershed research. The system described herein will insure that sufficient meteorological data are collected so that the research results of a facility may be compared on a climatic basis with results of nearby National Weather Service stations or other watershed facilities. The data collected should be sufficient to enable a calculation of potential evapotranspiration on a daily basis. If further detail is needed for a special study, the installations can be expanded accordingly.

This chapter will deal with common climatological measurements other than measurements of precipitation, which were covered in chapter 1. The climatological measurements covered are air temperature, air humidity, wind, solar radiation, evaporation, soil temperature, barometric pressure, and phenological observations.

Each section in this chapter gives the purpose of making measurements, usual instrumentation, operation instructions, and additional instruments that may be used. The last section gives some guidance on data processing of the climatological observations given in the introduction to this manual.

Detailed information on making climatological measurements are available in various texts (8, 17) and handbooks (4, 5, 6, 7), which the reader may consult for additional information.

**CLIMATOLOGICAL MEASUREMENTS**

**Air Temperature**

Temperature of the air is one of the most commonly measured meteorological variables at a research station in agricultural hydrology. Air temperature is so intimately related to evaporation, transpiration, soil freezing and thawing, and snowmelt that its measurement is almost mandatory. Daily maximum and min-
imum temperatures are needed to determine mean daily air temperature, a statistic required in most methods of computing daily potential evapotranspiration. A trace of the daily march of air temperature from a thermograph or hygrothermograph is useful in studies of snowmelt and as a backup system for maximum and minimum measurements.

**Instruments**

Separate liquid-in-glass maximum and minimum thermometers mounted on the cross board of a shelter with a thermometer support (such as those used by the National Weather Service) are recommended for obtaining daily extremes of air temperature (fig. 3.2). The maximum thermometer has a mercury-filled bulb exposed in a nearly horizontal position—the bulb end about 5° above the horizontal. The metal backing of the maximum thermometer is clamped securely to the lower (longer) shaft of the support at a point 3.5 inches (8.89 cm) from the high temperature end of the back and with the bulb end to the left. A rise in temperature forces the mercury through the constricted part of the tube into the graduated portion. The mercury remains in this part even though the temperature falls, thus permitting a maximum-temperature reading.

The minimum thermometer has an alcohol-filled tube exposed with the bulb end about 5° below the horizontal. The metal back of the minimum thermometer is clamped securely to the upper (shorter) shaft of the support, slightly

![Figure 3.2.—Inside of National Weather Service shelter.](image-url)
less than half the length from the high temperature end and with the bulb end to the left. The bore of the thermometer contains a dark dumbbell-shaped piece of glass called an "index." As the temperature rises, the alcohol expands and flows around the index without displacing it. Figure 3.3 shows the top of the alcohol column some distance to the right of the index. In figure 3.3, the alcohol column has retreated with falling temperature until the top of the column just touches the end of the index. Further cooling causes the top of the column to move nearer the bulb, carrying the index with it. When the temperature rises again, the alcohol column moves toward the top of the bore without moving the index, thereby leaving the index to indicate the lowest temperature reached.

Besides the maximum and minimum thermometers, a recording hygrothermograph should be operated on the floor of the shelter house (fig. 3.2). This will furnish a continuous trace record of the air temperature and relative humidity. A weekly time scale is adequate. Temperature pen readings are checked against maximum and minimum thermometer readings made in the same shelter. Adjustments are made to the pen setting whenever its error is more than 2°F (1.1°C). Separate winter and summer charts are used in localities having wide ranges of seasonal air temperatures. Winter charts cover a range in temperature from \(-30°\text{ to } 70°F\) \((-35°\text{ to } 20°C\) while the summer chart range is \(10°\text{ to } 110°F\) \((-10°\text{ to } 45°C\).

**Exposure**

The National Weather Service shelter shown in figure 3.2 has louvered sides and a double top to protect instruments from precipitation, condensation, and radiation. The floor of the shelter should be level and 4 feet (1.12 m) above ground. The door should face north. Rigid mounting of the shelter is necessary since wind-induced vibrations may displace the thermometer index, causing an erroneous reading. General site requirements are given on page 218.

**Operation**

Maximum and minimum thermometers should be read daily, preferably about 0800 or 0900 hours. Readings should be recorded immediately on the form specified by the project, using a minus sign before the figures to denote below-zero readings. Both maximum and minimum thermometers should agree within 1°F (0.5°C) after resetting the thermometers. A greater variation should be noted on the recording form.

Instructions for reading and setting maximum and minimum thermometers are given in National Weather Service Handbook No. 2 (7).

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![Figure 3.3.—Scale and index of minimum thermometer.](image-url)
This handbook should be in the files of the technician who will make the readings.

Maximum and minimum temperatures recorded by the hygrothermograph should be within 2°F (1.1°C) of the maximum and minimum thermometer readings. The temperature trace of a hygrothermograph (fig. 3.4) is adjusted as follows. Temperature sliding bar A may be used to increase or decrease the arc made by the pen on the chart as it increases or decreases the ratio between movement of the bourdon tube and the pen-arm linkage. To adjust, loosen the setscrew and slide the arm in the proper direction to accomplish the desired change. If the recorded range is greater than the range indicated by the maximum and minimum thermometers, lengthen bar A above the setscrew; if less, shorten the bar. Thumbscrew B is used to make the adjustment when maximum and minimum temperature recordings are off in the same amount and direction.

By operating the hygrothermograph with a weekly chart, time increments can be observed easily to the nearest half hour, if necessary. Recorded values of daily maximum and minimum temperatures can be read from the chart when maximum and minimum thermometer readings are unavailable (nonworkdays).

The clockwork-drive of the instrument should be checked for accuracy by comparing the time indicated on the chart with actual time. Adjustment or servicing of the drive mechanism is needed if the variation exceeds 2 hours on a weekly chart.

Data and chart annotations should be tabulated while events are still current. The chart should show the station designation, name of observer, and period covered by the trace. The number and dates on the chart and watch time of placement, inspection, and removal should be noted on the face of the chart. Noting the date on the centerline of each day will facilitate tabulations. Marking maximum and minimum thermometer readings on the chart helps in checking the pen readings. Malfunction of the instrument should be noted.

**Data Tabulation**

Daily maximum and minimum temperatures for the calendar day are tabulated on a standard form (fig. 3.5). When the thermometers are not read, values are obtained from the hygrothermograph chart. Care should be exercised in tabulating maximum and minimum temperatures since the thermometers are reset at 0800 or 0900 hours and calendar-day maximum and minimum values may occur before or after the thermometers are reset. Hygrothermograph values may be necessary for some days on which the thermometers are read. Maximum and minimum temperatures are tabulated on figure 3.5 to the nearest whole Fahrenheit degree.

The following values are computed from data on the standard form (fig. 3.5). Mean daily temperature is the average of daily maximum and minimum temperatures. Average monthly temperature is the average of all mean daily values for the month. Average annual temperature is the average of all mean daily values for the year.

While tabulated data are adequate for many statistical analyses, a graphical summary may be desirable. A multiple-graph summary covering related climatic data can be prepared for each year. Ranges and units of the vertical scales should provide readily discernible evidence of significant fluctuations and ample capacity to permit a standardized format in subsequent years.
Additional Instruments

Many instruments, other than the maximum and minimum thermometers and hygrothermograph described in the preceding section, are used to measure air temperature. The more common instruments will be described briefly.

A U-shaped thermometer of the Six pattern has been found useful in many situations. Maximum and minimum temperatures are indicated by metal indices, which are reset with a small magnet. This thermometer is inexpensive and easily reset but not as accurately as standard maximum and minimum thermometers.

Several types of maximum-minimum dial thermometers are available. Some have a tem-
perature-sensitive bulb, and others have a bimetallic strip connected to the dials. These devices use less space than the standard maximum-minimum set, and some of them can be obtained with up to 40 feet (12.2 m) of capillary tubing for remote mounting.

Electric thermometers are available that operate on a thermistor or thermocouple principle. The thermistor is based on the principle that the resistance of many materials varies with temperature while thermocouples generate a small electric output that varies with temperature. These devices can be very accurate, but the electric signals must be recorded, which adds to the cost. Wind-activated and motor-aspirated shields are available for housing temperature sensors outside the shelter house.

Thermographs usually use a liquid-filled bourdon tube or bimetallic coil to actuate the pen arm. They are available in many sizes and shapes and have recording capacities of 1 day to 1 month. Some are equipped with liquid-filled tubing so that the recorder may be installed at a location separate from the sensor. Multipen devices are available so that air and soil or air and water temperatures can be recorded on the same chart. A digital recording gage that punches out temperature data on a paper tape is also available.

Air Humidity

Humidity of the air near the surface has a definite influence on the rate of evaporation from lakes and ponds and on evapotranspiration from land areas. The basic process in evaporation and evapotranspiration is the physical change of water from the liquid to the gaseous phase. This process occurs more rapidly as the difference between the saturated vapor pressure at the water surface and the actual vapor pressure of the adjacent air increases. Thus, evaporation occurs more rapidly in dry air than in air with a high relative humidity. Several techniques for computing potential evapotranspiration, which are mentioned in the introduction of this chapter, require a measure of air humidity such as dew point or relative humidity.

Instruments

Instruments commonly used for measuring air humidity near the earth's surface fall into two general categories: (1) Those using thermodynamic principles and (2) those using the change in dimensions of hygroscopic substances. Instruments using thermodynamic principles are called psychrometers. Essentially they consist of two mercury thermometers, one of which has its bulb covered with a piece of muslin or wicking for wetting. These thermometers are mounted together on a common backing with the wet-bulb thermometer slightly lower than the dry-bulb thermometer.

Techniques for ventilating the thermometers can be classed into three general categories: (1) Natural ventilation; (2) moving thermometers rapidly through the air; and (3) forcing air movement over the thermometer bulbs with a fan or other device. The first method is characteristic of simple psychrometers that are mounted in a fixed position; these are sometimes designated "hygrometers." The second method is used by the sling psychrometer, which is a widely used portable psychrometer. The third method is represented by several instruments, but the best known is the Assmann psychrometer.

The most common instrument based on the change in hygroscopic substances to measure air humidity is the hair-element hygrograph. This instrument contains a banjo set of human hair that expands and contracts with changes in atmospheric moisture. Movement caused by expansion and contraction actuates a pen that records relative humidity on a chart. This chart is rotated in time by a clock movement. Usually the hair hygrograph is coupled with a device for recording temperature on the same chart. This combination instrument is called a hygrothermograph (fig. 3.4). The temperature portion of this instrument was described on page 222.

Several other instruments use special animal membrane elements to measure air humidity. These usually contain a dial and a needle that is linked to the membrane and calibrated so that relative humidity can be read directly. Thus, they are designated hygrometers.
Exposure

Required exposure of psychrometers varies with the type of psychrometer. Simple psychrometers for which artificial ventilation is not provided should be exposed so that they are protected from radiation and get adequate ventilation in relatively calm air. Sling psychrometers should be ventilated by whirling in a shady location since they are not shielded against solar radiation. The Assmann psychrometer and similar psychrometers should be exposed in an open situation, either suspended from an attachment or held at arm’s length with the inlets slightly inclined into the wind. Measurement should be made at the same height as the air temperature measurement, usually about 5 feet (1.5 m) above ground.

The hair hygrograph, or hygrothermograph, should be installed in a shelter where air can freely circulate from the outside. A National Weather Service-type shelter is recommended (fig. 3.2).

Operation

Operational procedures for psychrometers consist of providing moisture to the wet-bulb thermometer, ventilating the thermometers, obtaining wet and dry bulb readings, and converting these readings to relative humidity and dew point temperature with the use of psychrometric tables (16) developed from thermodynamic relationships. Special slide rules are also available for these computations.

Operation of a hygrograph, or hygrothermograph, involves routine changing of the chart at weekly intervals, winding the clock, and checking and replenishing the pen ink when necessary. Chart recordings of relative humidity should be checked periodically against values obtained with a psychrometer. Checks should be made in early morning or during rainy periods when humidity is high. Checks also should be made in the middle of the afternoon when humidity is usually at its lowest point. These checks should be made when relative humidity is not changing rapidly, as a certain amount of lag exists in the hygrograph. If the recorder chart trace disagrees with the psychrometer readings, the hygrograph should be adjusted.

Sliding bar C of figure 3.4 sets the ratio of movement between the hair element and the humidity recording pen. Adjust bar C carefully so as not to put undue strain on the hair element.

In making check points for this adjustment, use sling readings and the psychrometric tables to establish the proper percentage of relative humidity. If the recorded range is greater than the actual difference in relative humidity, move bar C to the right; if less, move it to the left. Screw D is used to make the adjustment for humidity when both upper and lower percentages are off the same in amount and direction.

When the hair element of the hygrograph becomes dirty, it should be cleaned with a soft brush dipped in alcohol or distilled water. If several hairs become broken or lose their moisture sensitivity, the hair elements should be replaced.

Muslin used as a wick on the wet bulb of a sling psychrometer must be clean, with no dust or finger marks. Distilled water should be used to moisten the wick when readings are made.

Data tabulation

Relative humidity values should be read from the chart at six or eight evenly spaced times during the calendar day. The average of these values should be entered to the nearest whole percent on the standard form (fig. 3.5). Average dew point temperature for the day can then be calculated from tables (16) or a psychrometric calculator.

Additional Instruments

In addition to the previously described instruments, other devices have been developed for measuring air humidity. One device is the infrared hygrometer, which operates on the principle that infrared rays of certain wavelengths are absorbed by water vapor. Two separate wavelengths of infrared light, one that is absorbed by atmospheric moisture and one that is not absorbed, are projected through the air to a detector where they are measured. The ratio of the infrared light transmitted by the different wavelengths indicates the amount of water vapor in the air through which the light passes.
Other humidity instruments use the absorption of water vapor on a chemically coated strip of plastic. The amount of water vapor absorbed on the strip indicates the amount of moisture in the atmosphere. To measure the amount of moisture absorbed, an electric current is passed over the surface of the strip to determine change in electrical resistance, which in turn reflects change in absorbed moisture. In the lithium chloride dew probe, current is used to evaporate some of the absorbed moisture until an equilibrium temperature is reached, a temperature which is related to the actual dew point temperature.

Other instruments have been developed for measuring the dew-point temperature of the air directly. These devices have a cooled surface on which condensation occurs when the dew-point temperature is obtained. One such device has a mirror cooled by a jet of refrigerant. An electrical heating coil is provided to maintain close temperature control. A small thermistor is embedded in the mirror to measure the temperature, and a photocell is used to detect changes in light reflected from the mirror as condensation occurs.

Wind

Wind is important in both agriculture and hydrology. Agriculturally, excessive gusts of wind can damage many crops. Hydrologically, wind influences the magnitude of evapotranspiration. Windspeed and wind direction also influence rain gage catch and the removal and deposition of soil and snow. The total run of wind for each day is the minimum measurement of wind that should be made at a hydrologic research station. A chart trace showing the direction of wind and the variability of wind velocities throughout the day will prove useful at most stations.

Instruments

Many commercially available anemometers are satisfactory for routine measurements of wind movement. Readings should be recorded continuously so that a permanent record of velocities is available. The anemometer also should record on a counting device to eliminate the necessity of counting tick marks on the chart or integrating the chart trace to obtain a daily total.

The standard anemometer is equipped with three conical, beaded cups mounted on a rotor with a turning diameter of 17 inches (43.2 cm). The rotor assembly drives a spindle that operates counter and a pair of wheels. The wheels are equipped with pins that close an electrical contact for every statute mile (1.6 km) of wind and every \( \frac{1}{10} \) mile (26.8 m) of wind. Electrical contacts are wired to a recorder for a continuous trace of windspeed and wind direction.

The wind direction transmitter operates from a 36-inch (91.4 cm) single-panel metal vane. Eight of the 10 switches are used to record direction continuously to 16 points. The event recorder notes time of occurrence and duration of wind from eight directions. A simultaneous recording of two directions, such as S and SW, indicates that wind was from the intermediate direction, SSW. A separate pen records each mile (1.6 km) of wind so that average velocity can be determined for any period. The remaining pen may be wired to record every \( \frac{1}{10} \) mile (26.8 m) of wind or movement of wind during precipitation or other special events.

The use of a series of counters to record the total miles (or km) of wind movement on a calendar-day basis should be considered. A timing clock can be used to activate a stepping switch every midnight. The stepping switch shunts the incoming signal from one counter to the next. The time saving is considerable compared to counting tick marks from a chart.

Exposure

A wind measurement system that supplies general information on speeds and velocities over a watershed area should be exposed at a height of 33 feet (10 m), the World Meteorological Organization standard. A hinged-base aluminum mast is advantageous because the instruments can be tipped down easily for servicing. The sidearms holding the instruments should be at least 12 inches (30.5 cm) long. Mount the anemometer crosswind from the mast to the prevailing wind direction. It must be level.

Site selection is hard to specify, but some general guidelines can be given. The instru-
ments should have a uniform fetch 100 times the height of the uppermost obstruction. Relatively level terrain is best; and cliffs, ravines, or other topography that cause wind eddies should be avoided. If the suitability of a site is doubtful, an experienced meteorologist should examine it.

If windspeed data are used in calculating potential evapotranspiration, the anemometer should be exposed at 6.6 feet (2 m) for the use in the Van Bavel (12) or Penman (11) methods, or at the evaporation pan height (2 ft or 61.0 cm) if the Weather Bureau method (15) is used.

To estimate windspeed at a second height, \( u_2 \), when windspeed at another height, \( u_1 \), is known, use the formula:

\[
\frac{u_2}{u_1} = \left( \ln \frac{z_2}{z_1} \right) \ln \frac{z_1}{z_2}
\]

where the exponent "\( a \)" usually varies from about 0.1 to 0.6 and is a function of atmospheric stability and ground roughness (28). The value of "\( a \)" for a given location can be determined by measuring the wind profile.

**Operation**

Day-to-day operation of the system is simple. The recorder chart is inspected, and any time corrections are noted and made. The ink supply is checked and pen traces are checked to see if the pens need cleaning. The total run of wind for the previous calendar day is noted on the observer's form, and the counter is reset to zero.

The anemometer should be serviced every 3 months. The spindle, upper ball bearing, and lower bearing assembly should be cleaned with a good solvent. A few drops of instrument oil should be used on the upper ball bearing, spindle, worm, lower bearing assembly, worm assembly, and contact operating pins (not the contacts themselves). The directional vane also can be inspected at this time, and a drop or two of oil should be applied to the bearings, if needed.

**Data Tabulation**

Calendar day totals of wind movement should be recorded to the nearest whole mile (or m) on the standard form (fig. 3.5). The annotated chart of windspeed and wind direction should be filed for future use in such studies as rain and snow catch or the areal distribution of snow cover.

**Additional Instruments**

If only the total wind run for each day is needed, anemometers are available that increment a counter every tenth mile (161 m). The counter must be read, and the value must be recorded each day. Anemometers are available that output an electrical signal proportional to windspeed. Pen traces of these signals are useful in recording the peak velocity of wind gusts.

Sensitive anemometers are available for use in microclimatological studies. These instruments are specially designed with very small starting thresholds and little tendency to overrun in gusts. Anemometers based on a hot-wire principle are very accurate and have extremely fast response times. Such devices, however, are generally limited to special studies.

**Solar Radiation**

Solar radiation provides the energy that drives regional and global hydrologic cycles. Radiation is generally the most important factor in the evaporation and transpiration processes. The energy for plant growth and production of dry matter is supplied by solar radiation.

Several methods for determining potential evapotranspiration use solar radiation data. An example is the equation developed by Jensen and Haise (14). The usefulness of such equations is being extended by studies to establish coefficients that account for stage of crop development and other plant and soil factors. These coefficients permit the conversion of calculated potential evapotranspiration to realistic estimates of actual evapotranspiration.

Evaporation and transpiration are more
closely related to net radiation than to solar radiation because a fraction of solar radiation is reflected back to the atmosphere and is not used in the conversion of radiant energy to the latent heat of vaporization. In the Eastern States and irrigated areas of the Western States, evapotranspiration frequently uses over 80 percent of the net radiation.

The best estimates of evapotranspiration amounts, particularly for short periods, usually are obtained with equations that involve net radiation as a term. Several equations are available for predicting evapotranspiration where water is not limiting. The potential evapotranspiration equations proposed by Penman and others (22) and Slayter and McIlroy (29) are examples. Equations using net radiation data, plant cover, and other information are being developed to estimate actual evapotranspiration under field conditions. Evapotranspiration rates determined from meteorological measurements by the Bowen ratio method require net radiation data as an essential element.

**Instruments**

Total incoming shortwave radiation is commonly measured with pyranometers, sometimes called solarimeters. They sense the intensity of radiation of wavelengths, less than 4 μ from the sun and sky, that falls on a horizontal plane. (These instruments are often erroneously referred to as pyrheliometers. A pyrheliometer measures direct solar radiation only.) A photo of a global (180°) pyranometer is given in figure 3.6.

The portion of the total radiation of all wavelengths that is transformed into other forms of energy is termed “net radiation.” Net radiometers measure this difference between the incoming (downward) radiation of all wavelengths and the outgoing (upward) radiation of all wavelengths. Figure 3.7 shows a popular miniature-type net radiometer (11).

The electrical output from a radiation sensing device often is recorded on a strip chart recorder fitted with an integrator. Data reduction is simplified if the integrator pulses are accumulated on counters. Two or more counters per recorder should be used, with an automatic mechanism for switching integrator pulses from one counter to another at midnight. Thus, the integrated 24-hour value displayed on a counter can be read the next day at the observer's convenience. Because net radiation varies from incoming to outgoing between day and night, it is sometimes desirable to integrate these fluxes separately. This is accomplished by having separate counters for the plus and minus integrations.

Electronic integrating systems are commercially available that amplify low-level signals, integrate the resulting current, and display the amount in digital form for visual readout. These integrating systems are available with single-stage amplification for use with circuits where the current does not vary in polarity (such as with a pyranometer) and with two-stage amplification for circuits where polarity reverses from time to time (such as with a net radiometer). They have an overall accuracy of about 2 percent, which is adequate for many applications.

**Exposure**

Pyranometers and net radiometers must be installed so that the solar beam is not obstructed at any time of the day, nor during any season. The view of the horizon from the instrument location should not be obstructed by nearby objects such as trees and buildings. In addition, glare or reflections should not be directed toward the instruments.
The site over which the net radiometer is exposed should be typical of the situation under investigation. This poses problems when mixed vegetation or other nonhomogeneities exist at watershed sites. Locating the instrument high above such a site gives a representative measure of the net radiation of the heterogeneous area because of the large field of view of the instrument.

Instrument heights much greater than 3.3 feet (1 m) cause some errors due to radiation divergence. These errors cause actual net radiation at instrument height to differ from that at the surface. Despite this theoretical difference, it is often best to expose net radiometers at a height of 3.3 to 9.8 feet (1 to 3 m) when heterogeneous conditions exist. When the sensor is $Z$ meters above a level surface, it receives 90 and 99 percent of its upward flux from areas with a radius of $3Z$ and $10Z$ meters, respectively.

**Operation**

The pyranometer and net radiometer should be kept level at all times, and cleanliness is very important. Whenever needed, the instrument should be washed with distilled water using a camel’s-hair brush or facial tissue. Coarse paper or cloth scratch the soft material used for the hemispherical-shaped windshields of miniature-type net radiometers. Care also is needed in cleaning the glass bulb of the pyranometer. The desiccant in the air supply line of pressurized net radiometers should be maintained in a charged condition to prevent condensation in the instrument.

Radiation instruments need to be checked every 2 or 3 months for calibration. This is especially true of net radiometers that deteriorate by weathering of plastic domes and changes in the character of the black absorbing surfaces of the sensors.

Net radiometers should be checked routinely for symmetry. During periods of reasonably steady net radiation (1000-1400, cloudless day), the net radiometer can be inverted every 10 minutes. Since inverting and leveling may take some time, a second radiometer should be operated next to it without inverting. Three normal and three inverted readings should be obtained. Readings from both faces of the radiometer should be within 5 percent of each other after correcting for any differences sensed by the continuous radiometer. If outside this limit, the sensor should be returned to the factory and recalibrated or discarded. This test should be done before checking the net radiometer against a pyranometer.

Since the pyranometer is less subject to change than a net radiometer, it can be used as a calibration device. Both instruments are shaded simultaneously from direct solar radiation with black matte discs on long slender dowels. The change in direct solar radiation is the same for both sensors so

$$\frac{\Delta_n}{C_n} = \frac{\Delta_{\mu}}{C_{\mu}},$$

where $\Delta_n$ and $\Delta_{\mu}$ are the measured changes in response (mv) of the net radiometer and pyranometer, respectively, and $C_n$ and $C_{\mu}$ are their calibration constants (mv/ly). Since $C_{\mu}$ is known and $\Delta_n$ and $\Delta_{\mu}$ are measured, $C_n$ can be calculated.

Approximately 6-inch (15.2 cm) diameter shades should be about 3 feet (0.91 m) away from the instruments. The solid angle of the obscured sky should be negligible, and the sensors of both instruments should lie within the shadow of the shades. A minimum of three cycles of shading and unshading is desirable.

Another method is to operate a standardized net radiometer of the same type as the one being calibrated next to the routine instrument for several hours or for a day. The standardized instrument must be kept in a good storage area and should be checked periodically against a pyranometer. Special care is required since the surface areas viewed by the two radiometers may not be identical. The sensors should be
interchanged, and the results should be averaged to overcome this problem.

Data Tabulation

Calendar-day totals of solar and net radiation should be recorded on a standard form (fig. 3.5). If available, the recorder charts should be annotated and filed for future use.

Available Radiation Information

Good discussions of radiation and radiant energy transformations as related to evapotranspiration and other phenomena are given in textbooks by Geiger (12), Munn (18), Sellars (28), Slayter and McIlroy (29), and Wang (33). These publications also discuss considerations in measurements of radiation and other meteorological factors.

Daily solar radiation measurements from about 75 National Weather Service stations are available at the National Climatic Center, Asheville, N.C. Data for any station may be obtained upon request. A charge is made to cover the cost of duplicating the machine listings.

The National Climatic Center intends to make solar radiation data readily available in published form. Publication awaits resolution of instrument calibration standards.

Published net radiation data are lacking. To be meaningful, data should be collected in an environment similar to the one of interest because of variations (especially outgoing radiation) that exist from situation to situation.

Evaporation

Evaporation of water from a pan or tank is influenced by several meteorological factors, the most prominent being solar radiation, air temperature, humidity, and wind. These are essentially the same meteorological factors that determine rate of evaporation from lakes and evapotranspiration from land. Thus, measurement of pan or tank evaporation provides an index of the integrated effect of meteorological conditions on evaporation from lakes and potential evapotranspiration from land when water is not limiting.

Conditions are usually more favorable for evaporation from a pan or tank than from lakes and land areas although moisture is not a limiting factor. Therefore, measured pan evaporation is usually greater than evaporation from lakes or evapotranspiration from the land. Coefficients and mathematical relationships can be determined, however, for relating pan evaporation to evaporation from lakes and potential evapotranspiration.

Instruments

The National Weather Service 4-foot (1.22m) diameter Class A pan is recognized as a standard for measuring evaporation throughout the United States. This pan can be constructed of No. 22 gage galvanized iron or an alloy similar to Monel metal. Seams of the pan must be fabricated carefully to prevent buckling of the bottom. If the inside diameter is $47\frac{1}{2}$ inches (1.21 m), a seam in the bottom usually can be eliminated.

The pan is mounted in a level position on a wooden platform as described in National Weather Service Observing Handbook No. 2 (7). Soil under the platform is leveled and tamped to provide a standard air space of about a half inch (12.7 mm).

A micrometer hook gage is used with a stilling well to measure the level of water in the pan. The brass stilling well provides an undisturbed water surface around the hook gage and a support for the gage. A small hole in the base allows water to seep into or out of the brass cylinder. Leveling screws and lock nuts are provided on the triangular base. The stilling well is located in the pan about 1 foot (30.5 cm) from the north edge.

The hook gage consists of a movable graduated stem with a vernier. The graduated stem is fitted on one end with a hook, the point of which touches the water surface when water level is measured.

A recording water-level gage sometimes is installed in a well connected to the evaporation pan. This provides a continuous record of water level changes. This gage usually is added to supplement the hook gage readings rather than to replace them. Other types of evaporation pans, such as a sunken 6-foot (1.83 m) diameter
pan or a floating pan, often are used to meet specific requirements.

To overcome deficiencies of the Class A pan due to heat transfer through the sides and bottom, an experimental insulated pan was designed and built by the National Weather Service. This pan is made of white fiberglass and is surrounded by freon-blown polyurethane insulation. It is painted black on the inside below the waterline to minimize reflected radiation. The pan is installed on a platform so that the rim is 3.3 feet (1 m) above ground level. Currently the pan is only in the testing stage and has not been adopted officially as a National Weather Service standard.

**Exposure**

The site for a Class A evaporation pan should be fairly level and sodded except in arid regions where maintenance of an artificial sod cover would induce unnatural modification of climatic conditions. Obstructions should not be closer to the pan than 4 times the height of the object. Weeds and grass should be mowed to keep growth below the level of the pan. Sites on the downwind side of large swamps or reservoirs should be avoided. Evaporation pans should not be located near large paved areas such as parking lots or airport runways. The site of the evaporation pan should be fenced to prevent animals from drinking from the pan, and the water surface should be kept free of shadows. When pans are installed over water or sunk in the ground, similar restrictions apply.

**Operation**

When in operation, the water level in Class A evaporation pans should be maintained at 2 inches (5.08 cm) below the rim, plus or minus 1 inch (2.54 cm). Water should be added or removed from the pan to maintain this level. This should be done at the time of observation. The water level may be lowered below the usual limit when heavy rainfall is forecast, thus avoiding loss of record due to pan overflow.

Hook-gage readings of the water level in the stilling well should be made daily. The micrometer hook-gage point is lowered into the well until it is below the surface of the water. The adjusting nut on the hook gage is then turned slowly, raising the point until it just pierces the water surface. The gage is removed from the well and the scale is read and recorded. Differences in readings for consecutive days give the daily evaporation amounts. When water is added or removed from the pan, hook-gage readings must be made before and after the water level change. Amounts added or removed are thus considered in computing evaporation. Any rainfall between observations should be measured with a nearby standard gage and should be used in computing pan evaporation.

If a recorder is used to obtain a continuous record of water level changes, the chart should be changed at the proper interval and the chart trace should be compared with the micrometer hook-gage readings. The pan must be kept clean. Insects and debris should be removed promptly from the water surface. A small amount of copper sulfate in the water will inhibit algae growth.

For some installations, water-temperature readings are made with floating maximum and minimum thermometers. The thermometers ride about 1/4 inch (6.35 mm) below the water surface and at least 1 foot (30.5 cm) from the edge of the pan and the hook-gage well. Floating thermometers are preferred to those that rest on the bottom of the pan.

Evaporation pans are operated throughout the year except for periods of ice cover. When long periods of freezing are expected, the pan is drained and inverted, or stored until placed in operation the next spring.

**Data Tabulation**

If the pan has been modified to give a pen record, calendar day totals of Class A pan evaporation should be computed and recorded to the nearest hundredth inch (0.254 mm) on a standard form (fig. 3.5). Care will be needed if a separate 0800–0800 record is made for publication by the National Weather Service. The insulated pan, normally not recorded in chart form, is tabulated on the basis of 0800 hour readings on workdays, as shown on standard forms (fig. 3.5).

**Additional Instruments**

Several evapotranspirometers have been developed for measuring potential evapotranspi-
Evapotranspirometers that are filled with soil and constructed to permit downward flow of water are called lysimeters. Most evapotranspirometers used in watershed hydrology investigations are lysimeters. They are classed as either weighing or nonweighing.

An economical weighing-type lysimeter was developed by Dylla and Cox (10). This lysimeter is a large soil-filled tank supported on a coil of butyl tubing filled with water. A hydraulic line connects the tubing coil with a manometer to measure pressure changes. With these measurements, changes in tank weight can be computed, thereby providing data for computation of changes in soil-water storage. Water is added and removed through a pipe that extends from the soil surface into a layer of gravel at the bottom of the tank. Evapotranspiration from the tank is computed from recorded amounts of water added and removed, and from changes in soil-water storage.

A weighing-type lysimeter of a somewhat different design was developed and used for ET studies at the North Appalachian Experimental Watershed at Coshocton, Ohio (13). This lysimeter is a large undisturbed soil monolith with soil that grades into fractured rock at a depth of 5 feet (1.52 m). Water drains from the soil into the rock cracks and then moves into a percolation collector pan at a depth of 8 feet (2.44 m). The lysimeter is mounted on platform beam scales; much of the total weight of 65 tons (59.0 t) is counterbalanced. Weights are printed every 10 minutes, providing data for changes in soil-water storage. Neutron moisture readings and fiberglass gypsum blocks provide data for defining patterns of water movement within the soil profile.

A nonweighing lysimeter was designed by Speir (30) and was used for evapotranspiration studies in southern Florida. This lysimeter is a reinforced concrete tank filled with soil. A free water chamber is provided at the bottom to insure uniform water levels throughout the soil block and to allow free circulation of drainage, or subirrigation water. A raised wood floor perforated with \(\frac{3}{8}\)-inch (9.53 mm) holes allows unhindered movement of water between the soil and the free water chamber. A 6-inch (15.2 cm) filter bed consisting of gravel, copper screen, and hardware cloth prevents soil particles from flowing into the water chamber. Access to the free water chamber for addition or removal of water is provided by a 2-inch (5.08 cm) vent pipe at each end of the tank. A float gage is inserted into the vent pipe to determine depth of water table in the tank.

The soil in the lysimeter is calibrated for stage-storage ratings by observing the rise or fall of the water table when known water quantities are added or withdrawn. This provides for computation of changes in water storage. Daily evapotranspiration is then computed from data on rainfall, amount of water added or removed, and change in water storage in the lysimeter.

A relatively simple and economical weighing lysimeter designed for evaluating hourly water use in row crops in dry land has been described by Ritchie and Burnett (25). Soil-water suction at the bottom of the soil container is controlled. The primary components of the weighing mechanism are commercially available. The electrical output signal from the load cell can be measured remotely.

**Soil Temperature**

Measurements of soil temperature indicate the sensible heat stored in the soil and are pertinent, therefore, to investigations of certain phases of hydrology, such as soil freezing and snowmelt. Soil freezing can drastically alter infiltration rates of the soil, causing significant change in the runoff regime of a watershed. Although small on a daily basis, snowmelt due to heat transfer from the soil may amount to several inches of water during an entire snow season. This could be enough to keep the soil saturated and to affect infiltration of snowmelt that results from other causes. Soil temperature is also important in seed sprouting and plant growth, which can have a significant effect on the hydrology of a watershed.

**Instruments**

Continuous records of soil temperature may be obtained with soil thermographs. The measuring unit of a soil thermograph usually consists of a Bourdon tube (expansion column) or thermocouple. Thermocouples are the most ac-
curate and reliable. The recording portion of the thermograph provides for rotation of a chart by a clock mechanism. Measured temperature is traced in analog form on the chart by pens linked to the measuring units. Several pens and measuring units are used so that temperatures are obtained at different depths in the soil. The World Meteorological Organization (J4) recommends standard depths of 10, 20, 50, and 100 centimeters.

**Exposure**

Measuring units of a soil thermograph should be placed in the soil so that conditions are as similar to the surrounding area as possible. If Bourdon tubes are used as measuring units, they must be protected from trampling or walking, which could influence the readings. Good contact between the soil and the sensor is imperative.

**Operation**

Eight-day charts usually are used with the soil thermograph and should be changed weekly. The ink supply for the pens and the general operation of the instrument should be checked when the chart is changed.

In the spring and fall, temperature elements should be calibrated with a mercurial thermometer. To do this, a mercury thermometer is placed in the soil at the depth being recorded and the pen reading of the thermograph is adjusted to that of the mercury thermometer. The extent of the adjustment is noted on the chart for the day.

**Data Tabulation**

The maximum, minimum, and mean temperatures for each depth should be tabulated on a calendar-day basis. They should provide sufficient data to judge soil freezing, snowmelt potential, and other questions relating to the hydrologic performance of a watershed. Much more detailed information is necessary for computations of soil-heat flux.

**Additional Instruments**

For special studies in which continuous records are unnecessary, spot readings may be taken by point-gage, bimetallic, or mercury thermometers. When mercury thermometers are used, insert a sharp-pointed object, such as a pencil, in the soil and then place the mercury thermometer in the hole. The holes should be slightly larger than the tube to eliminate contact of the tube with sharp objects and thus avoid breakage. The bulb end of the thermometer must be in good contact with the soil at the depth where a reading is taken.

Flux plates are available for measuring the transfer of heat into and out of the soil profile. These devices, usually buried about 2 inches (5.08 cm) below the surface, furnish data on the soil-heat flux of the energy budget.

A frost tube is useful for determining depths where the soil freezes and thaws. Rickard and Brown (J5) describe the instrument consisting of an outer tube that is permanently installed in the soil and an inner, removable tube filled with a fluorescein-sand mixture. A color change from green to pale yellow occurs in the dye upon freezing. The green color reappears upon thawing.

**Barometric Pressure**

The need for barometric pressure measurements will be determined by the research program. Measurements are incidental to the biological processes important in agriculture and are not directly related to hydrological activities except in special situations.

An estimate of the standard barometric pressure at the facility is required in calculating potential evapotranspiration by the combination method (J2). This value probably can be supplied by the nearest National Weather Service office with sufficient accuracy, after allowances are made for differences in elevation. A barometric pressure term appears in the psychrometric formula, but a standard barometric pressure term should be used in computing dew points unless extreme accuracy is required.

The water level in a well penetrating a confined or partly confined aquifer may rise and fall inversely with atmospheric pressure. If this effect is possible at the facility, a recording microbarograph should be used.

Some laboratory experiments may be affected by atmospheric pressure when air is entrapped in a water column, thus necessitat-
ing the recording of barometric pressure. The value of the barometric chart in making short-range weather predictions may be enough justification for operating a barograph.

**Instruments**

A microbarograph is recommended for routine readings of atmospheric pressure at the facility. A file of charts from which a selection of data that are pertinent to current needs should be maintained, rather than using one or two visual readings noted during a day. The microbarograph is not as reliable as a mercury barometer for indicating absolute pressure, but it gives a useful indication of pressure changes with time. It is sufficiently accurate for most hydrological and agricultural purposes. If absolute pressure values are required, they can be obtained from a mercury barometer once a day and intermediate values can be interpolated from the corrected microbarograph chart.

**Exposure**

Although the microbarograph usually is fitted with a damping device and can tolerate some vibration, it should be installed on a rubber pad on a shelf or table where it is not subject to shaking, vibration, or dust. Most microbarographs are temperature compensated but should not be located in direct sunlight or near other heat sources or drafts. An indoor location is best.

**Operation**

A weekly chart record is generally adequate. The barograph should be set to indicate the pressure at mean sea level by comparison with the reading of a mercury barometer. A telephone call or radio weather reports from a nearby office of the National Weather Service can be used to obtain the corrected reading. This should be done when the trace indicates steady pressure. A change of elevation of 100 feet (30.5 m) will cause a change of nearly \( \frac{1}{10} \) inch (2.54 mm) in the barometric pressure, depending on the elevation and the temperature. Thus, setting the barograph to the corrected mean sea level reading is accomplished most easily by reference to the reading from a well-tended mercury barograph. If actual station pressure is required, the nearest office of the National Weather Service can be consulted for instructions on setting the microbarograph.

A standard mercurial barometer reading can be obtained when the chart is changed. The correct reading is noted on the chart just removed, the new chart is installed, and the barograph is reset to the correct reading. Chart changing is similar to that described on page 00. A time mark on the chart, made by gently depressing the pen about \( \frac{1}{3} \) inch (3.18 mm) at the same hour each day, is helpful in later analyses of the record.

Very little attention is required in operating the microbarograph other than changing the charts and making the time marks. A thickening pen trace indicates that the pen needs to be cleaned or replaced. A stepped trace indicates excessive friction, and instructions for the instrument should be consulted for corrective action. The bearings and the pen yoke should be kept free from dust to eliminate any dust-catching film, but they should not be oiled.

**Data Tabulation**

Charts should be annotated completely before being filed. Notes include the corrected reading from the mercury barometer, dates and times of beginning and end of chart record, and clock time for each time mark. Routine tabulations should be made from the chart before it is put in the permanent record file.

**PHENOLOGICAL OBSERVATIONS**

Phenology is the study of natural phenomena that recur periodically, such as blossoming and fruiting, and their relation to climate and changes in season. Plants can be excellent integrators of climate, as evidenced by the widespread use of tree ring data in climatic analyses. A series of phenological observations will permit a gross discrimination between growing seasons that were favorable, average, or unfavorable for evapotranspiration.
Observations should be made on crops that make up most of the watershed cover. These phenological observations may be combined with observations on watershed conditions, cultural practices, and vegetative conditions. For annual crops, the dates of cultural operations, planting, emergence, flowering, fruiting, and harvesting should be noted. For trees or other perennial crops, the bud stage, full leaf, seed stage, and beginning of dormancy should be recorded. The percentage of ground cover afforded by the crops and their stage of growth and average height should be estimated. Any unusual conditions due to disease or insect infestation, over grazing or undergrazing, or drought also should be recorded.

In some situations special indicator plants should be used as indices of growing conditions. Sunflowers have been used because of their ready indication of moisture stress conditions, and pumpkins have been used because of their sensitivity to freezing conditions. The NE-35, NC-26, and W-48 regional research technical committees have been using the persian lilac as an indicator plant and, if special indicators seem warranted, this plant should be considered seriously. The advantages of tying a station's phenological observations into a network of similar observations are obvious.

Leaf area index, the leaf area of a crop canopy subtended per unit area of land, has been a worthwhile factor in studies of evapotranspiration and photosynthesis. A good discussion of this concept is given in Chang (9). Ritchie (14) used measurements of leaf area index in his mathematical model for predicting evapotranspiration from a row crop with incomplete cover.

DATA PROCESSING

Details of processing climatological data will vary with the purpose for which the data were collected. Summaries that may be useful in describing the relationship of climate to frost depth may be unsatisfactory for portraying the effect of other phenomena occurring in the watershed. This section presents only a sampling of the basic summaries that should be helpful in analyzing hydrologic data. Each project must determine the number and type of data summaries to process on a routine basis. Some general guidelines can be given, however.

The ideal situation is to have the measuring equipment output directly on magnetic or punch tape, or on punchcards, so that the data can be processed by computer. Data-logging systems designed for agricultural research are in operation (19, 31). Computer processing should include a check for invalid readings even when a concurrent pen trace or other visual display of the data is obtained.

Summarization sometimes can be obtained mechanically or electronically by additions to the measuring equipment. A series of counters operating through a stepping switch controlled by a timer can be used to record the total run of wind for the day, thus saving the time needed to count markings on a wind chart. The chart is always available for obtaining any detailed information that may be required. Several types of integrators are available for use with radiation equipment. These integrators give the integrated values for preselected periods. Printers are available that give a listing of the integrated readings. Any device that reduces the man-hours required to tabulate and summarize data deserves careful consideration.

Although computer processing may not be feasible when the routine data collection system is set up, the needs of electronic data processing should be kept in mind when designing the manual processing system. Figure 3.5 is a form that can be used to record daily meteorological observations. This tabulation is a concise summarization of the climate for the month from which mean values and extremes are easily found.

Figure 3.5 is readily adaptable for the electronic processing of data. For instance, if pan and lake evaporation values are to be computed by the National Weather Service method (15), a template can be made to blank out all the columns except date, maximum and minimum temperature, dew point temperature, wind at pan height, solar radiation, and Class A pan
evaporation. These data can be keypunched or read with an optical scanner for use as input to the computer program. They can be broken into time units of 1 hour or less rather than daily averages. Ink charts or printed integrated values are available from most instruments if more detailed tabulations are desirable. For routine use, however, the summary in figure 3.5 is usually sufficient.

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CHAPTER 4. SEDIMENTATION

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INTRODUCTION

Sedimentation, as referred to in this chapter, is the detachment, entrainment, transportation, and deposition of eroded soil. Techniques and procedures described are limited to those used in fluvial sedimentation research on agricultural lands. Sedimentation in major rivers, large reservoirs, estuaries, and harbors is not considered in this manual.

Although no single phase of the sedimentation cycle can be treated as an entity, the natural sequence of the cycle is as follows: Soil erosion—transportation—deposition. Soil erosion has been defined as “the detachment and movement of soil from the land surface by wind or running water” (5).

Most of the damage caused by sediment is the result of accelerated erosion, defined as erosion in excess of the geologic norm. Accelerated erosion is usually induced by activities of man such as: Deforestation, cultivation and overgrazing, reshaping the land surface for construction or mining, and disturbance of the natural drainage system.

In agriculture, sediment sources are classified as: (1) sheet and rill erosion, (2) erosion from gullies, arroyos, roads, rights-of-way and construction sites, and (3) channel bed and bank erosion. In most regions, sheet and rill erosion is usually the largest source of sediment.

In addition to being erosive forces, wind and water are the transporting agents for sediment. Although significant amounts of sediment are moved by wind, particularly in the arid regions, water is the major transporting agent. Sediment transported in a stream or watercourse is usually subdivided into two categories according to the dominant mode of transport, suspended load, and bedload. Total sediment load is the sum of the two. Other paired terms such as washload, bed material load, measured and unmeasured load, and sampled and unsampled load are also used to describe sediment transport. Figure 4.1 gives the relative location of these descriptive terms in the stream vertical.

Since sedimentation processes are complexly linked to the quantity and character of runoff, it is necessary that fluvial sedimentation data be associated with corresponding runoff for many interpretive analyses (chap. 2).

This chapter provides information on sediment sampling and measurement methods and techniques, provides guidance on the selection, installation and operation of sampling devices and equipment, and offers instructions and guidelines for reducing and processing data.

Sedimentation data are usually expressed in terms of weight or volume (pounds, tons, cubic feet, acre-feet, kilograms, cubic meters). Rates are usually expressed as tons, kilograms, acre-feet, or cubic meters per unit of time or land area. Conversion factors which will be helpful in converting from English to metric units are given in the appendix to this manual.

Terms most commonly used in sedimentation research are in the appendix to this chapter. Definitions established by professional engineering and scientific societies have been used where available. Many commonly used hydraulic and hydrologic abbreviations and symbols, described elsewhere in this manual, are also used in sedimentation research.

INSTALLATIONS

A variety of instruments and techniques has been developed for field measurement of soil erosion, sediment movement, and sediment deposition. In general, three basic types of measurements are required: (1) measurements of sediment in surface runoff from small experimental plots and watersheds and in stream channels, (2) measurements of eroded areas to
determine the volume of material removed, and (3) measurements of the volume and density of sediment deposits. Instruments, equipment, and techniques typical of those used in sedimentation research on agricultural lands are discussed in this section.

**Site Selection**

The objectives of the experiment and the type of data to be obtained determine the location of the experimental site. Other considerations include the availability of land, access to the area, topography, facilities for cultivating the land if cropping practices are a part of the experiment, availability of servicing personnel, management control of the experimental area, drainage and vertical head requirements for instruments, and sampling equipment.

**Plots and Small Watersheds**

Generally, fractional-acre plots and small watersheds a few acres in size are used to study basic erosion rates of various soil-cover complexes which are representative of a land resource area. This requires location of the experimental area on a specific soil type with the desired topography. Vegetative cover, except forest cover, is usually easily established within a relatively short time. Replicate plots are sometimes required to obtain representative data due to such factors as inherent errors in measurement and variations within soil types. For most experiments, tenure of the land is needed for 10 years or more to cover the normal range in weather patterns.

**Size and Shape of Plots**

Plot shape is determined by the objective of the study and can range from a small rectangular area to a naturally shaped watershed. Plot length should represent the length of slope on which soil losses occur. Lengths commonly used in feet are 36.3, 72.6, 92.0, 145.2, and 400 (11, 22.1, 28, 44.3, and 122 m). Plot widths may vary from 6 feet (1.8 m) for hand-tilled plots to 20 feet (6 m) or more when conventional farm machinery is used. Computations of results are aided when length × width results in a simple fraction of an acre (72.6 feet (22 m) length × 6 feet (1.8 m) width = 435.6 feet² (40.5 m²) = 0.01 acre (0.004 ha)).

**Figure 4.1.**—Schematic diagram of stream vertical showing relative position of sediment load terms.
Land Gradient

Sites should be selected to represent the range of slopes encountered in the general farming area. Plots on natural slopes are best because reshaped slopes usually do not contain normal soil profiles. Larger plots and small watersheds may have natural slopes ranging from convex to concave. Slopes low enough to cause soil deposition above the measurement site should be avoided, unless special provision is made for measurement.

Construction of Plots

Heavy gage sheet metal may be used for borders on small plots. Metal borders are easily removed when cultivation of the plots is required. Earthen ridges may be used on plots wide enough for farm equipment normally used in farming operations. Terrace interval plots may use only the terraces at the upper and lower boundaries with a grassed waterway to route flow from the lower end of the rows to the point of measurement.

Small watersheds usually do not require borders except dikes at the lower edge to direct flow to the point of measurement. Plots of all sizes are equipped with a trough or other collecting device to route the soil-water mixture to the sampling site. Sheet metal is used for the collecting trough on small plots. A concrete channel or earth dike may be used on large plots and small watersheds. Sheet metal borders, particularly those on the lower boundary, should be installed deep enough to prevent piping and tunneling underneath by rodents.

Cropping Treatments and Conservation Practices

When land use and conservation practices are to be evaluated, they must be considered when the site is selected. Cropping treatments may vary from continuous fallow (bare soil) to continuous sod or forest. Fallow soil serves as a basis for evaluating other treatments and provides a measure of the inherent erodibility of the soil. Cropping systems that employ a crop rotation pattern should have all years of the rotation represented on separate plots at all times after the rotation is fully established. Conservation practices may include terraces, minimum tillage, strip cropping, contour plowing, and others.

Stream Sampling Stations

Generally, sites selected for water discharge measurements in natural channels are adequate for suspended sediment measurements. In addition to the usual requirements of access and availability, a straight channel reach with uniform velocity and sediment distribution is desirable. Consideration is also given to the construction of walkways, cables, and bridges and to the installation of sampling equipment.

Sampling equipment has not been perfected that will sample the entire depth of flow in a natural channel. Conventional depth integrating samplers are limited to sampling the flow from the water surface to about 0.3 foot (9.1 cm) above the streambed. Therefore, artificial or natural grade controls which provide an overfall and permit sampling through the entire flow vertical are necessary if total load sampling is to be accomplished. Artificial or natural turbulence sections which uniformly suspend transported sediments also provide an alternative approach to total load sampling. Many flow-measuring devices such as weirs, rectangular notches, and flumes can be designed to provide sufficient overfall for total load sampling. Highway box culverts and other hydraulic structures may also be used.

Reservoirs

Reservoirs selected for sedimentation investigations are usually chosen to represent typical land use patterns in a region or land resource area. Most studies are directed toward determining the quantity, characteristics, and distribution of sediment deposits as indicated by periodic volumetric surveys of the reservoir. Measurements of sediment outflow or inflow, or both, are also required if sediment trap efficiency of the reservoir is to be determined.

The specific objectives of a study will determine the number and type of reservoirs selected. Such factors as reservoir size, shape, capacity, inflow rates and amounts, and watershed characteristics must be considered. Access for volumetric surveys and the installation, servicing and maintenance of sampling equip-
ment is always required. Land use and cover condition surveys of the drainage area may be needed.

Channels, Gullies and Other Major Sediment Sources

Sediment investigations in a land resource area may require measurements of sediment yield from channels, gullies, and other major sediment sources. Typical sites may not exist, but sites selected should represent local conditions as nearly as possible. There must be access to instrumentation to install and service sampling equipment. Detailed topographic surveys may be needed.

Sampling and Measurement Devices and Equipment

No attempt has been made to cover all sediment sampling and measuring devices and equipment. Only those used most commonly in sedimentation research on agricultural lands in 1976 are discussed. Variations and adaptations of basic instruments are often made to fit local conditions.

Total Collection Devices

A simple total collection device for very small plots may be constructed to measure erosion by installing a suitable collection tank large enough to contain the total runoff (water and sediment) expected in a 24- or 48-hour period. The weight or volume, or both, of the water-sediment mixture is then determined and the material sampled for subsequent laboratory analysis and computation of the weight or volume of sediment.

Total collection devices are not generally recommended for erosion studies because runoff storage requirements are excessive even for very small drainage areas. Small drainage areas, in turn, are not normally representative of large, complex field conditions. Slot-type samplers, which collect a known portion of the runoff-sediment mixture, are preferred because they can be used on larger areas, and the sample volume is reduced to manageable quantities.

Slot-Type Samplers

Slot-type samplers are used in basic erosion studies on small plots and watersheds (16, 26, 50, 57). These samplers are automatic in the sense that no attendant is required during the sampling operation, and sampling is continuous during the runoff event. The samplers provide a storm integrated or discharge weighted sample for determining sediment yield. The multislot divisor, with a stationary slot, and the Coshocton wheel sampler, with a revolving slot, have been used extensively. Construction, installation, and maintenance details for these two are given below.

The Multislot Divisor

A typical field installation using the multislot divisor to sample runoff from small field plots is shown in figure 4.2. Figure 4.3 shows a plan view sketch of the equipment as it is installed in the field. An alternate scheme presented in figure 4.3 shows how the H flume may be used in conjunction with the multislot divisor. (The H-flume, a flow measuring device, is described in volume I, chapter 2 on runoff.) Under conditions where sediment deposition in the flume is not a problem, the H flume will provide a hydrograph and more accurate measurements of runoff volume. Unless the H flume is used to measure runoff, the aliquot sample extracted by the divisor is used to compute runoff volume.

Runoff is routed from the collector through the conveyance channel to a sludge tank where the heavier sediment particles are deposited. Overflow from the sludge tank is routed...
through the multislot divisor, figure 4.4, where an aliquot sample is obtained from a single slot and routed to a sample storage tank. A second or third sample storage tank may be connected to the first if additional sample storage is needed.

Many investigators prefer to install a small, removable intertank directly below the inflow spout in the sludge and sample (aliquot) tanks. This greatly reduces the time and labor required to sample and cleanup after small storms which do not overflow the small intertanks. It also improves the accuracy of volume measurements.

**Design requirements.**—The size and capacity of the sampling apparatus are determined by the anticipated maximum rate and amount of runoff and sediment to be sampled. For small fraction-acre plots it is assumed for design purposes that maximum runoff rate will equal the maximum 5-minute rainfall rate. Sample storage based on 100 percent runoff should be provided for a 100-year, 48-hour storm (50).

Sediment storage requirements vary greatly with location, soil type, land use, and climatic conditions. Sediment rates as high as 50 tons per acre have been recorded from single runoff events under adverse conditions. Bulk densities of trapped sediment may range from 40 to 100 lb/ft³ (640.8–1602 kg/m³). The size and geometry of the collector trough and conveyance channel are determined by the maximum flow requirements. Flow velocities in conveyance channels should be fast enough to prevent sediment deposition through a wide range of flows. Minimum velocities of 2 ft/s (.61 m/s) at flow rates of about one-fifth of the maximum will prevent excessive deposition for most soils.

The collector acts as a weir at the end of the plot. It is installed so that the elevation can be

![Figure 4.3](image-url) Typical plan of runoff plot equipment (50).

![Figure 4.4](image-url) Multislot divisor and entrance box (50).
adjusted to the plot surface as erosion occurs. It is attached to an end plate which should extend at least 8 inches into the soil below the collector trough. Although the collector and end plate may extend across the entire length of the plot, it is best to concentrate runoff before it reaches the collector on wide plots as shown by figure 4.5, plan a.

The depth is usually the same as the conveyance channel with about 0.4 foot (.12 m) freeboard. The width may vary but should be wide enough to clean easily, 8 to 10 inches (20-25 cm). The bottom should slope to the center by at least 5 percent (fig. 4.5, plan b). Screens of one-half or one-inch (1.3 to 2.5 cm) mesh should be installed over the collector to keep trash out of the system (fig. 4.5, plan c).

Construction details—The collector, conveyance channel, sludge tank, and sample tanks may vary in design to meet specific needs.

**Figure 4.5.**—Runoff collector: **Left,** dimensions for a 30-foot (9.15 m) wide plot; **right,** section through the collector trough showing trash screen cover; **bottom,** critical dimensions for the collector trough.
Generally, they are constructed from readily available galvanized sheet steel, small angles, and metal tanks.

The multislot divisor must be constructed from detailed plans and specifications with close tolerances. Construction drawings for a 9 slot (1/2 inch (1.3 cm) width slots) sampler are given in the appendix. Drawings for other sizes may be prepared using these as a guide. Dimensions and weights for divisors with peak runoff capacities from 0.9 to 4.0 ft³/s (0.02-11 m³/s) are given in table 4.1.

The slots and precision plate should be square edged and should not deviate from a straight line by more than 0.005 inch (0.13 mm) (see drawings in appendix to this chapter). Slot dimension tolerances should not exceed 0.25 percent in width and 0.5 percent in height. The precision plate should be electrically spot welded to the slot plate so that its top edge forms an angle of 90° ± 10 minutes, with the vertical sides of the slots, and all slots should be the same height. Slots should not deviate more than 0.02 inch (0.51 mm) from the vertical plane.

New, high grade, galvanized sheet steel and angles should be used in the construction of multislot divisors—stainless steel is recommended for the slot and precision plates. Fabricate by welding, soldering and riveting. All seams and soldered joints must be watertight, and all inside surfaces should be smooth with no dents, warps, blemishes, solder or tool marks, or other irregularities. The floor must be level, the slot plate perpendicular to the floor, and all cross sections of the divisor must be symmetrical about the longitudinal axis.

**Installation and maintenance**—The multislot divisor is designed to function with the floor and precision plate level. It is bolted to the sludge tank so that the top of the divisor entrance box is level with the bottom of the inlet pipe to the sludge tank. An adjustable support under the downstream end is required for leveling. A rectangular pipe, connected to the divisor spout, carries the sample to the first storage tank. Additional sample storage tanks may be connected to the first tank with plastic pipe. Drain valves or plugs are required in all tanks.

Since most of the runoff from the experimental plot is wasted around the sampling tanks, good drainage from the site is required. Slightly elevated working platforms, constructed from wood or other cheap material, around the sampling tanks are desirable. Covers are required for all tanks, the multislot divisor, the collector, and conveyance channel to prevent precipitation from falling directly into the system. All foundations supporting the apparatus should be deep enough to prevent frost-heaving. In cold climates heating equipment is required to prevent water from freezing in the tanks.

**Coshocton-Type Runoff Sampler**

The Coshocton-type runoff sampler is constructed to form a single unit with the small H flume (fig. 4.6 (52)). Three basic models, N-1, N-2, and N-3, have been designed for use with the 0.5, 1.0 and 1.5-foot (15.2, 30.5 and 45.7 cm) H flumes. Models N-1 and N-2 have been used extensively in the field. A typical field installation is shown in figure 4.7.

**Design requirements.**—Capacities, sampling rates, and other pertinent information on Coshocton-type samplers are given in table 4.2. Sampler size and capacity for a given experiment are determined by the capacity of the H flume required to measure peak runoff rates. Slightly oversized flumes and samplers are recommended because the sampling error increases significantly at discharges above 80 percent of flume capacity. For small plot studies the maximum runoff rate is assumed to equal the maximum expected 5-minute rainfall rate. Sample storage capacity is provided for the aliquot sample from the maximum 48-hour runoff event.

**Construction details.**—Detailed construction drawings for Coshocton-type runoff samplers, N-1, N-2, and N-3, are included in the appendix to this chapter. New, high grade, galvanized sheet steel and angles should be used. Fabrication is by welding, soldering, riveting, and screws. Construction precision is much greater than that generally associated with sheet metal work. To minimize warping, heat should be limited to that necessary to obtain good water tight soldered joints on the wheel plate, sampling slot, and outlet edge of the flume. Clamps
used to hold plates and stiffeners for welding and soldering should not cause metal stress which will cause deflections when clamps are removed.

The size of the sampling slot opening must be exact. A taper gage is recommended for checking slot widths. Allowable tolerances for other dimensions on the wheel and frame should not exceed 0.5%. Good machine shop practices are required in the fabrication and assembly of the slot, wheel, and bearing assembly. Construction details for the H flume are given in chapter 2 on Runoff.

Water discharge from the H flume falls on the water wheel, which is inclined slightly from the horizontal, and causes the wheel to rotate. An elevated sampling slot mounted on the wheel extracts an aliquot sample as the slot

### Table 4.1.—Schedule of multislot divisor dimensions and capacities

<table>
<thead>
<tr>
<th>Number of slots</th>
<th>Slot width</th>
<th>Slot height</th>
<th>Maximum capacity</th>
<th>Dimensions</th>
<th>Sheet metal</th>
<th>Approximate weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In</td>
<td>In</td>
<td>Ft” x”</td>
<td>W</td>
<td>L</td>
<td>D</td>
</tr>
<tr>
<td>3</td>
<td>1/2</td>
<td>4</td>
<td>.09</td>
<td>4</td>
<td>24</td>
<td>7 3/4</td>
</tr>
<tr>
<td>5</td>
<td>1/2</td>
<td>4</td>
<td>.15</td>
<td>6 1/2</td>
<td>24</td>
<td>7 3/4</td>
</tr>
<tr>
<td>7</td>
<td>1/2</td>
<td>4</td>
<td>.21</td>
<td>9</td>
<td>24</td>
<td>7 3/4</td>
</tr>
<tr>
<td>9</td>
<td>1/2</td>
<td>4</td>
<td>.27</td>
<td>11 1/2</td>
<td>24</td>
<td>7 3/4</td>
</tr>
<tr>
<td>11</td>
<td>1/2</td>
<td>4</td>
<td>.33</td>
<td>14</td>
<td>24</td>
<td>7 3/4</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>6</td>
<td>.33</td>
<td>7 1/4</td>
<td>24</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>6</td>
<td>.55</td>
<td>11 3/4</td>
<td>24</td>
<td>9</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>6</td>
<td>.77</td>
<td>16 1/4</td>
<td>32 1/2</td>
<td>9</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>8</td>
<td>1.2</td>
<td>16 1/4</td>
<td>32 1/2</td>
<td>11</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>8</td>
<td>1.5</td>
<td>20 3/4</td>
<td>40</td>
<td>11</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>8</td>
<td>1.9</td>
<td>25 3/4</td>
<td>40</td>
<td>11</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>12</td>
<td>3.4</td>
<td>25 3/4</td>
<td>40</td>
<td>15</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>12</td>
<td>4.0</td>
<td>29 3/4</td>
<td>40</td>
<td>15</td>
</tr>
</tbody>
</table>

1 See sketch below.
Source: Harrold and Krimgold (26).
traverses the flow jet with each revolution of the wheel. The sample is routed through the base of the wheel to a sample storage tank.

Installations and maintenance.—Field installation of the Coshocton-type sampler depends upon topography (slope) below the experimental area. Two schemes, figure 4.8, show possible installations and limiting distances and slopes when a rectangular approach channel, equal to the \( H \) flume width, is used. Runoff is concentrated in a suitable collector (see previous discussion of collectors) at the plot end from which it flows into the approach channel. The short channel section immediately upstream from the flume in scheme B provides room for the hydraulic jump which usually occurs in this type installation, which has only enough slope for good drainage. Good drainage from the site is important. Excavation and the installation of drainage ditches or tile may be necessary at some locations.

### Suspended Sediment Samplers and Measurements

The development of suspended sediment sampling equipment and procedures and techniques for making field measurements of sediment discharge in streams and rivers has been well documented \((32, 33, 34, 36)\). Suspended sediment samplers currently used by most U.S. Government agencies were developed by the Federal Inter-Agency Sedimentation Project now located at the St. Anthony Falls Hydraulics Laboratory, Minneapolis, Minn.

### Suspended Sediment Samplers

Suspended sediment samplers are designed to obtain samples of the water-sediment mixture. Two basic types have been developed; depth integrating and point integrating \((39)\). Basic requirements of suspended sediment samplers have been reported as follows \((65)\):
Raising the sampler too rapidly will result in the opposite phenomenon. Inflow through the exhaust port may also occur. If the sampler transit speed is too slow, the sample container will overfill before the sampler is returned to the surface, circulation will occur, and the sample will be enriched. Ideally, the sample container should be from two-thirds to three-fourths full when depth integration is completed. Detailed information on sampler transit speeds, filling times and sampling depths is given in the section on Field Observations, page 279.

**Point integrating samplers.**—Point integrating samplers are equipped with an electrically controlled rotary valve which opens and closes

---

### TABLE 4.2.—Size schedule for Coshocton-type runoff samplers

<table>
<thead>
<tr>
<th>Sampler No.</th>
<th>Diameter (Ft)</th>
<th>Capacity (Ft^3/s)</th>
<th>Headroom Requirement</th>
<th>Aliquot (Pct)</th>
<th>Approximate Weight (Lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-1</td>
<td>1</td>
<td>1/2</td>
<td>1</td>
<td>1</td>
<td>26</td>
</tr>
<tr>
<td>N-2</td>
<td>2</td>
<td>2</td>
<td>2 1/2</td>
<td>1/2</td>
<td>85</td>
</tr>
<tr>
<td>N-3</td>
<td>3</td>
<td>5 1/2</td>
<td>3 3/4</td>
<td>1/2</td>
<td>270</td>
</tr>
</tbody>
</table>

Source: Parsons (52).

---

**Depth integrating samplers.**—Depth integrating samplers are designed to continuously extract a sample as they are lowered from the water surface to the streambed and returned at a constant rate of travel. Ascending and descending speeds need not be the same, but the rate of travel must be constant in each direction. As the sample is collected, air in the container is compressed so that the pressure balances the hydrostatic pressure at the air exhaust and the inflow velocity is approximately equal to the stream velocity.

If the sampler is lowered too fast, pressurization will not equal hydrostatic pressure and the inflow velocity will exceed stream velocity.
The sampler on command. They are designed to take a sample at any point in a stream over a short time interval. The diving bell principle is used to balance the air pressure in the sample container with the hydrostatic pressure at the nozzle to prevent an initial inrush of water when the valve is opened. With the control valve fixed in the open position, these samplers are also used to obtain depth integrated samples. One-way depth integrated samples may be obtained by opening the valve with the sampler at the water surface and lowering it to the streambed at a constant speed. This permits sampling to greater depths.

Brief descriptions of suspended sediment samplers most frequently used by U.S. Government agencies are given in Table 4.3 (67). All of these samplers, fabricated from cast aluminum or bronze, are streamlined with tail fins to orient the sampler so that the intake nozzle points directly into the approaching flow. Round or square glass milk bottle sample containers are inserted directly into the sampler body cavity. The bottles are easily removed.

<table>
<thead>
<tr>
<th>Sampler designation</th>
<th>Type</th>
<th>Weight</th>
<th>Length</th>
<th>Sample nozzle sizes</th>
<th>Sample volume</th>
<th>Sampling conditions and operation</th>
<th>Auxiliary equipment required</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. DH-48</td>
<td>Depth—integrating</td>
<td>4.5</td>
<td>13</td>
<td>1/16 and 1/4</td>
<td>1 pt</td>
<td>Wading depths &amp; velocities.</td>
<td>Sampler is affixed to 1/2-in rod or small diameter pipe.</td>
</tr>
<tr>
<td>U.S. D-49</td>
<td>Depth—integrating</td>
<td>62</td>
<td>24</td>
<td>1/8 and 3/16</td>
<td>1 pt</td>
<td>Depths 15 to 18 ft. Low to moderate flow velocities. Sampler is usually operated from a bridge, cableway or truck-mounted rig.</td>
<td>1/8-in in steel cable, reel &amp; crane.</td>
</tr>
<tr>
<td>U.S. DH-59</td>
<td>Depth—integrating</td>
<td>22</td>
<td>15</td>
<td>3/16 and 1/4</td>
<td>1 pt</td>
<td>Moderate depths &amp; flow velocities. Sampler is usually operated from a bridge or cableway.</td>
<td>Hand line or long suspension rod.</td>
</tr>
<tr>
<td>U.S. D-74</td>
<td>Depth—integrating</td>
<td>60</td>
<td>24</td>
<td>3/16 and/or 3/8</td>
<td>1 pt and/or 1 qt</td>
<td>Depths 15 to 18 ft. with 1 pt container. Usually operated from bridge, cableway or truck.</td>
<td>1/8-in in steel cable, reel, and crane.</td>
</tr>
<tr>
<td>U.S. P-61-A1</td>
<td>Point—integrating</td>
<td>105</td>
<td>28</td>
<td>3/16</td>
<td>1 pt and/or 1 qt</td>
<td>Point-integrated samples to 150 ft. Also used to obtain 2-way depth-integrated samples to 18 ft in moderate velocities. Usually operated from bridge, cableway or truck-mounted rig.</td>
<td>1/8-in steel, 2-conductor electrical suspension cable, reel &amp; crane. 48 V d.c. power source to operate sampler valve. Additional power source &amp; electric motor to operate reel.</td>
</tr>
<tr>
<td>U.S. P-63</td>
<td>Point—integrating</td>
<td>200</td>
<td>34</td>
<td>3/16</td>
<td>1 pt and/or 1 qt</td>
<td>Point-integrated samples to 180 ft depth-integrated samples in deep high velocity streams. Usually operated from bridge, cableway or truck-mounted rig.</td>
<td>Rugged 2-conductor steel suspension cable, reel &amp; crane. 48 V d.c. power source to operate sampler valve. Additional power source &amp; electric motor to operate reel.</td>
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</table>
after the sample has been collected. Plastic bottles can be used in some of these samples, and some can be equipped with teflon nozzles and bushings to minimize contact between the sample and metal surfaces.

Photographs of the U.S. DH-48, the U.S. D-49 and the U.S. P-63 Samplers are shown in figures 4.9 through 4.11. Additional information on these and other samplers listed in table 4.3 may be obtained from the Federal Inter-Agency Sedimentation Project. \(^{4,1}\)

\(^{4,1}\) Communications regarding availability, drawings and reports on these samplers may be addressed to: Federal Inter-Agency Sedimentation Project, St. Anthony Falls Hydraulic Laboratory, Hennepin Island and 3rd Avenue, SE, Minneapolis, Minn. 55414.

**FIGURE 4.9.**—Depth-integrating suspended-sediment Wading-type hand sampler, U.S. DH-48: *Top*, assembled sampler with extra pint milk bottle; *bottom*, disassembled sampler (32).
Coarse particles, sand size and larger, account for most of the variation. Fine particles, silt and clay, are usually fairly evenly distributed throughout the stream cross section. Variations and fluctuations in concentration in the vertical are affected by stream turbulence, velocity, depth, temperature, the particle size of the bed material, concentration of fine material, and some chemical properties of water. Lateral concentration in stream cross sections varies with channel geometry, slope and alinement.

**Suspended Sediment Discharge Measurement**

Sediment measurement involves sampling the water-sediment mixture to determine the mean suspended sediment concentration, particle size distribution, specific gravity, temperature of the water sediment mixture, and other physical and chemical properties of the transported solids. Suspended sediment concentration in a natural stream varies from the water surface to the streambed and laterally across the stream. Concentration generally increases from a minimum at the water surface to a maximum at or near the streambed. Vertical distribution of both sediment and flow velocity in a typical stream vertical is illustrated in figure 4.12.

![Figure 4.10. Depth-integrating suspended-sediment sampler, U.S. P-63: Top, closed position; bottom, open position.](image1)

![Figure 4.11. Point-integrating suspended-sediment sampler, U.S. P-63: Top, closed position; bottom, open position.](image2)
velocity, depth, bed form, and sediment particle size.

Suspended sediment discharge in a stream is the product of the water discharge and the mean suspended sediment concentration ($G_{ss}$). Symbolically, suspended sediment discharge, $G_{ss}$, may be defined as:

$$G_{ss} = \frac{w}{w} \int_{w=d}^{w=0} C U \, dy \, dx = C_m \, Q \quad (4-1)$$

where

- $w$ is the stream width;
- $d$ is the stream depth;
- $C$ and $U$ are the concentration and velocity, respectively, at any point, $(x, y)$ above the streambed;
- $\delta$ is an indefinite point above the streambed, usually a few times the mean size of the bed sediment;
- $C_m$ is the mean suspended sediment concentration (discharge-weighted); and
- $Q$ is the stream discharge.

The suspended sediment discharge per unit width $g_{ss}$ is:

$$g_{ss} = \int_{d}^{0} C U \, dy = C_m \, q \quad (4-2)$$

in which $q$ is the water discharge per unit of width and $C_m$ is the suspended sediment discharge concentration (discharge-weighted) at the vertical where $C$ and $U$ were measured.

The mean spatial concentration, $\bar{C}$, for the sampled zone in the stream vertical is:

$$\bar{C} = 1/(d - a) \int_{a}^{d} C \, dy \quad (4-3)$$

in which $a$ is the distance from the bed to the lowest sampling point. By plotting the point concentration $C$ against the position of $y$ above the bed, the mean concentration is readily determined. In the absence of a measured velocity distribution, the spatial concentration may be used as an approximation of $C_m$. However, in most fieldwork discharge-weighted concentrations are needed for computations of sediment transport.

In most streams the sediment concentration and flow velocity vary vertically and laterally, and sometimes erratically, and samples must be collected systematically at selected points to be representative of the flow cross section.

**FIGURE 4.12**—Vertical sediment concentration and flow velocity distribution in a typical stream cross section.
“Equal transit rate method”.—In this method the samples are collected at equally spaced verticals in the flow cross section. The transit rate of the depth integrating sampler must be uniform and the same at all verticals. The composite sample from all verticals will then represent the mean (discharge-weighted) cross section concentration. Suspended sediment discharge is then computed as the product of the mean cross section concentration and the total water discharge. The number of sampling verticals required, normally 6 to 12 for most small streams, to obtain a representative sample depends upon the accuracy desired, the channel width, the velocity distribution and the sediment concentration and particle size distribution. This is the most commonly used method on small agricultural streams.

**Depth integrated samples at uniformly spaced verticals.**—In this method a relatively large number of depth integrated samples are taken at the midpoint of equal fractions of the stream width. This method gives a good indication of the distribution of sediment across the stream. Mean sediment concentration in the stream is determined by weighting the mean concentration in each sampling vertical with respect to stream discharge in the vertical. Suspended sediment discharge is then computed as the product of mean cross section concentration and total water discharge.

**Depth integrated samples at centroids of equal water discharge.**—This method requires depth integrated samples at selected sampling verticals which represent areas of equal discharge across the stream as determined by water discharge measurements. The sampling vertical is then located at the centroid of each section (area). Location of the sampling verticals may be determined graphically as illustrated in figure 4.13, (36). The water discharge for individual sections is determined and cumulated for the stream cross section. Cumulated discharge in percent of the total for various water stages is then plotted against the lateral distance of each vertical from a fixed reference point.

Table 4.4 gives the cumulative percentage of water discharge in the stream cross section for selected numbers of sampling verticals. After selecting the number of sampling intervals, the location of each interval is determined from the percentage values given in table 4.4 and the graph of cumulated water discharge versus location in the stream cross section (fig. 4.13).

For example, if six verticals are selected, the first sampling vertical would be at the point (distance from reference point) representing 8 percent of the total flow, the second vertical at the point representing 25 percent of the total flow, etc. The mean cross section concentration is the average of the concentrations of the verticals, and the suspended sediment discharge is computed as the product of mean concentration and water discharge.

**Point integrated samples at selected depths in stream verticals representing areas of equal or known water discharge.**—In this method, samples are taken at selected points in the stream vertical which represent areas of equal or known water discharge. Samples representing areas of equal water discharge may be averaged to determine the mean vertical concentration. Samples representing areas of unequal water discharge must be discharged-weighted to give the mean vertical concentration.

The number of point samples required to determine the mean concentration will depend upon the accuracy desired, the particle size distribution, stream velocity, and turbulence. Obviously, the accuracy of the method increases with the number of samples. Fewer samples are required for streams transporting mostly fine materials since the concentration of

<table>
<thead>
<tr>
<th>Table 4.4.—Cumulative percentage of stream-flow in cross sections</th>
</tr>
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<tbody>
<tr>
<td>Number of sampling verticals</td>
</tr>
<tr>
<td>Vertical number</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>12</td>
</tr>
<tr>
<td>14</td>
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</tbody>
</table>

Source: Federal Inter-Agency River Basin Committee on Water Resources (34).
clays and silt will not vary significantly in the stream vertical.

This method is rarely used on small upland streams. It is best suited to large streams with relatively steady flow and rated streams where cross section geometry remains relatively constant. Point sampling is not normally used for depths shallow enough for depth integration.

**Bed Material Samplers**

Bed material samplers are designed to collect samples from the bed of a stream, or from lake or reservoir deposits. Some of the most frequently used samplers for bed material, which is predominantly sand or sand and gravel, are described below. These samplers were developed by the Federal Inter-Agency Sedimentation Project (37).

**U.S. BMH-60 Hand-Line Bed Material Sampler**

This lightweight sampler (fig. 4.14) is approximately 22 inches long (56 cm). If constructed from cast aluminum, it is 30 pounds (13.6 kg). Because of its light weight, the sampler is only used in tranquil streams and moderate to slightly compacted bed materials.

A spring loaded sampling bucket, which holds about 10.7 in$^3$ (175 cm$^3$) of material, is located on the bottom side of the sampler. In the cocked position the sampling bucket is fully retracted within the sampler body. It remains in this position ready for sampling as long as tension is maintained on the supporting handline. When the sampler is lowered into the stream and touches bottom, tension on the handline is released and the bucket snaps...
sampler is suspended by a steel cable and raised and lowered by a suitable reel and crane. Operation is the same as that for the U.S. BM-60 sampler described above.

**U.S. BM-53 Piston-Type Bed-Material Hand Sampler**

This is a lightweight piston-type sampler which is used to sample bed material in streams or reservoirs shallow enough for wading (fig. 4.16). It is constructed of readily available steel pipe and fittings. The sampling cylinder is 2 inches (5.1 cm) in diameter and 8 inches (20.3 cm) long. A handle is provided at the top of the sampler frame for pressing the cylinder into the streambed. As the sampler is forced into the streambed, a piston in the cylinder is retracted. Suction created by the piston holds the sample in place. Upon removal from the stream, the piston is used to force the sample out of the cylinder.

**Auxiliary Equipment for Suspended Sediment and Bed Material Samplers**

Cranes and reels are required to raise and lower the heavier bed material and suspended sediment samplers. At some locations foot-
FIGURE 4.16.—Piston-type bed-material hand sampler, U.S. BMH-53 (33).
bridges, cable cars, or other suitable working platforms are also needed.

**Cranes**

Two basic cranes, developed by the U.S. Geological Survey, have been used extensively in sediment sampling (13).

The type-A crane (fig. 4.17) is recommended for weights not in excess of 150 pounds (68 kg). A slightly heavier model, type-D, (fig. 4.18) is used for weights up to 200 pounds (91 kg). Use of these cranes mounted on dollies is restricted to bridges suitably decked for rolling the equipment. These basic designs have various modifications. Figure 4.17, right, shows a type-A crane mounted on a small truck.

A heavier truck-mounted telescoping crane developed by the Science and Education Administration is shown in figure 4.18. The crane was designed for use with the 200-pound (91 kg) U.S. P^-3 (fig. 4.11) suspended sediment sampler. Detailed drawings of the crane are included in the appendix.

**Cableways**

One- and two-man cable cars, mounted on cables across streams at sampling stations, are used as movable working platforms (fig. 4.19). The cable car is equipped with a mounting bracket for a reel and handline and has adequate space for sample bottles and other necessary equipment. Cable cars are commercially available in the United States. Specifications and construction details for cableways are given in chapter 2 on Runoff, and by Pierce (53).

**Reels**

Three basic types of reels have been developed for stream gaging and sediment sampling. All are similar in construction. They are equipped with depth indicators, 0.1 to 0.125 inch (0.25–0.32 cm) flexible steel cables, a threading sheave for laying the cable smoothly in a single

\[13\] Communications regarding reels, cranes and cableways may be addressed to: Chief, Branch of Service and Supply, U.S. Geological Survey, Reston, Va.
layer on the drum, electrical connections for
two conductor cables and a pawl and ratchet
which are used to hold the sampler at any
desired elevation. Mounting holes and dimen-
sions are essentially the same for all reels so
they are interchangeable on all cranes, cable
cars, boats, and so forth.

The type-A reel, the smallest, has a fixed
crank and no brake (fig. 4.20). The type-B reel
is equipped with a brake and a quick-releasing
crank which permits lowering the sampler by
force of gravity with speed control by the brake
(fig. 4.21). The type-E reel was designed for use
with heavier samplers and power equipment.
Figure 4.22 shows a type-E reel, powered by a
24 volt direct current motor, mounted on a
specially designed crane. Reels are commer-
cially available from manufacturers of hydro-
logic instruments and equipment in the United
States.

Bedload Samplers

Suspended sediment samplers will only sam-
ple to a point about 0.3 foot (9.1 cm) above the
streambed as illustrated in figure 4.23. The
sediment transported in the unsampled zone is
composed of both suspended load and bedload.
The bedload portion is composed of particles
having a density or grain size which precludes
movement far above or for long distances out
of contact with the streambed.

In wide sand-bed streams with shallow flow
depths and high sand concentrations, more
sediment may be transported in the unsampled
zone than in the sampled zone. As flow depth
increases, the proportion of sediment in the
unsampled zone becomes smaller, often ac-
counting for only a small fraction of the total
sediment load.

The bedload portion of sediment discharge in
slot, powered by an electric motor, traverses back and forth through half of the flow cross section extracting a sample from the bottom 12 inches (30.5 cm) of flow. The water sediment mixture passing through the slot is routed through a series of graded sieves where the coarse bed material particles are trapped. The trapped sediment is subsequently removed, measured and packaged for laboratory analysis. The sample includes only particle sizes larger than the smallest sieve opening.

The preferred method of sampling bedload is in restricted turbulent stream cross sections or uncontrolled stream channels is the most difficult to sample. Although many portable samplers have been constructed and tested, none have proved entirely satisfactory for all conditions (21, 30, 36). For this reason and because the use of portable bedload samplers in uncontrolled stream cross sections requires a detailed study and evaluation of the site conditions, the samplers are not discussed in this manual.

At controlled stream cross sections, fixed bedload samplers can sometimes be developed to provide an adequate sample. The Tombstone Automatic Bedload Sampler (figs. 4.24 and 4.25) is an example of instrumentation designed for a specific location (45). This sampler was designed to take a sample of bedload (sand and gravel) on the downstream side of a concrete measuring flume.

The 1-inch by 12-inch (2.5–30.5 cm) sampling
overfalls where the total sediment load is in suspension and suspended sediment samplers can be used. The sheet piling grade control structure with footbridge and manually operated sampling device (fig. 4.26) is typical of instrumentation that may be developed for total load sampling. A U.S. DH-48 suspended sediment sampler (fig. 4.9) is attached to a rigid strut and raised and lowered by a cable and reel arrangement. The sampler passes through the entire flow vertical on the downstream side of the sheet piling control. It is moved across the channel on a dolly attached to the bridge handrails.

**Automatic Suspended Sediment Samplers**

Automatic suspended sediment samplers denote samplers that extract while unattended. There are three types currently used.

**U.S. U-59 Single Stage Suspended Sediment Sampler**

This sampler, which operates on the siphon principle, is used to automatically collect sus-
suspended sediment samples from flashy, intermittent streams at remote locations (37, 36). The sampler consists of a one-pint glass bottle or other suitable container and 3/16- or 1/4-inch (4.8-6.4 mm) copper tubing (fig. 4.27). The tube is formed to the proper shape and inserted through a stopper which fits tightly into the top of the milk bottle. One or more samplers may be mounted on a suitable support (fig. 4.27) so that samples are obtained at several water surface elevations as the water stage rises.

The vertical intake sampler is recommended for suspended sediment finer than 62 microns. This sampler is less subject to the collection of debris and sediment deposits on the intake nozzle. The horizontal intake sampler was designed to sample suspended sediment containing fine sand coarser than 62 microns. However, field experience suggests that sand concentration obtained with this sampler may not always be representative of the stream sand concentration. The sampler intake is also more susceptible to plugging by surface and near-surface debris.

The U.S. U-59 sampler has several disadvantages. The sample is always taken near the water surface during the rising stage, and the original sample may be altered by subsequent submergence. Intake velocities are not the same as streamflow velocities. Because of these limitations, concentration data obtained with these samplers should be used with caution. More detailed information on the limitations and operation of this sampler is given in Inter-Agency Committee Report No. 13 (40).

**Pumping-Type Samplers**

These samplers pump streamflow from one or more fixed points in the stream cross section, usually near the streambank. A portion of the pumped streamflow is retained as a sample. Pump samplers are particularly suited to flashy, intermittent streams and remote locations where observer services are not readily available (2, 3, 35, 39).

Three sample handling systems have been developed for pumping-type samplers: (1) the accumulative weight system, (2) the volume recording system, and (3) the individual-sample bottle system. The accumulative weight system and the volume recording system have not been perfected to the extent that they are recommended for field use. The bottling system has been the most satisfactory, and several versions are currently being used by government agencies.

Major components of pumping samplers are:

- The intake nozzle, located in the stream.
- Power supply (batteries or A.C. power source)
- Pumping system
- Flushing system
- Sample handling system
- Control unit

Located in a small shelter on the stream bank. At some locations the pump is located in a separate shelter near the water's edge to meet pump lift requirements.

Figure 4.24.—Tombstone bedload sampler: A, mounted on a critical depth flume; B, schematic sketch of field installation.
The cycle of operation is electrically controlled. The sampler is usually activated by a float controlled switch when the water stage reaches a predetermined elevation. Samples are pumped into bottle containers at regular, predetermined time intervals until the water level recedes or until the capacity of the sample handling system is reached. Before each sample is pumped, the intake system is back flushed to remove any debris or sediment that may have accumulated in the system during the interval between pumping cycles.

A typical pumping-type sampler, the Chickasha sediment sampler, is shown in figure 4.28 (48). This sampler, with a capacity of 28 one-pint samples, is powered by a 12-volt d.c.
The sampling time interval may be varied to meet the needs of the experiment.

The first step in the operational sequence is the activation of the sample bottle tray advance solenoid which places a bottle in position to receive the sample. Following the advance of the sample bottle tray, the pump operates for about one minute. During most of the pumping period the flow is wasted, thus flushing the line of all sediment and debris from the previous sample. Near the end of the pumping period, the flow is diverted into the sample bottle. Pumping time required to obtain a sample of the desired volume varies with the pumping head.

At most field installations, the sampler is located near a water stage recorder and flow discharge measurement station. When flow is diverted into the sample bottle, a sampling event marker is activated which marks a trace on the water stage chart or tape. This relates the sample to water stage and gives the approximate time the sample was taken.

Pumping-type samplers, models U.S. PS-69 and U.S. PS-73, developed by the Federal Inter-Agency Sedimentation Project, are shown in figures 4.29 and 4.30(55, 37). The operational sequence for these samplers is essentially the same as that described for the Chickasha sampler, but they differ somewhat in construction.

The U.S. PS-69 sampler is equipped with a sample trap arrangement which provides a fixed sample volume and separate pumps that are used for back flushing and sampling. Construction details and information on the availability, installation, operation, and maintenance of pumping-type samplers may be obtained from the Federal Inter-Agency Sedimentation Project.43

While the sampling interval for most pumping samplers currently in use remains constant, unless or until changed manually, instrumentation is now available to vary the sampling frequency as the stream discharge (stage) varies. The instrument, called a "Proportional Frequency Controller, U.S. PFC-72," triggers pumping samplers in such a manner that the frequency of sampling increases proportionally with stream discharge (37). Therefore, each sample represents a constant volume of water discharge that flowed passed the sampling site. Several pumping-type samplers, developed by private industry, are now commercially available, but a discussion of the performance and

FIGURE 4.26.—Sheet piling control, footbridge and specially constructed sampling apparatus for total load sampling: Top, close-up view; bottom, downstream view.
FIGURE 4.27.—Suspended sediment samplers: Left, single stage, U.S. U-59; right, single stage mounted at various elevations on a single support.
suitability of these samplers is beyond the scope of this manual.

**Columbia Spillway Sampler**

The Columbia spillway sampler, figures 4.31 and 4.32 is a good example of an automatic suspended sediment sampler developed for a specific application (55). This gravity operated sampler was designed to sample outflow from a reservoir spillway. Activated by water stage in the spillway, this sampler extracts a sample of reservoir outflow at specified time intervals. Sampling times are electrically controlled with a 12-volt battery power source. Adjustments are easily made to vary the sampling time interval and sample volume.

Research and development of automatic samplers utilizing radioisotopes, monochromatic light, electrical impedance, density and ultrasonic sound for sensing sediment concentration are currently underway, but these samplers have not been perfected to the extent that they are recommended for field use.

**Samplers for Deposited Sediments**

Samples of deposited sediments are needed to determine the physical and chemical properties of the material. While disturbed samples may be used for most analyses, samples of a known volume of undisturbed material are required for specific weight (bulk density) determinations.

Disturbed samples of aerated sediments are relatively easy to obtain, and no special equipment is required. The auger, bucket and spatula, and tube type samplers are used. So-called “undisturbed” samples and samples of inundated sediments are more difficult to acquire. Typical commonly used samplers are described in the following paragraphs.

**Sediment Spud**

Although primarily used to determine sediment depth, the sediment spud (figs. 4.33 and 4.34) provides a small sample of the material at
FIGURE 4.29.—Federal Inter-Agency Sedimentation Project pumping-type suspended sediment sampler, Model U.S. PS-69; Left, closed position; right, open for removal of sediment samples.

FIGURE 4.30.—Federal Inter-Agency Sedimentation Project pumping-type sampler, Model U.S. PS-73; Left, closed position; right, open position.
different elevations throughout the depth of penetration (19). Depth of penetration depends on the density of the sediment, the diameter of the spud, and the force used to plunge it into the sediment. If total penetration is accomplished, the distinction between sediment deposits and old soil is usually discernible by comparing softness, color, and lack of coarse sand in the deposits. Sandy noncohesive sediments tend to wash out of the notched cups as the sampler is removed from the water. To reduce washout, the spud should be raised slowly. Dimensions and construction details given in figure 4.34 may be used to construct spuds of various lengths.

**Sampling Rings**

Soil sampling rings (fig. 4.35) are used to obtain volumetric samples of sediment deposits in flood plains or in reservoirs above the water surface. They are constructed to exact dimensions from high grade thin wall drawn steel tubing with a beveled cutting edge on one end. Rings 3 to 5 inches (7.6 to 12.7 cm) in diameter and 2 to 3 inches (5.1 to 7.6 cm) long work well in fine sediments. Driving caps, also shown in figure 4.35, are used in forcing the rings into the soil or sediment. Light blows should be used in driving the rings to minimize sample disturbance. After the sampling ring has been driven in to the sediment, the ring is removed from the sample core in place and the core trimmed on each end to the exact length of the ring. This provides a relatively undisturbed sample of a known volume.

**Piston-Type Sampler**

The SEA piston-type sampler is used to obtain volumetric samples of inundated reservoir
FIGURE 4.32.—Schematic diagram of Columbia spillway suspended sediment sampler (55).
and lake sediments (figs. 4.36 and 4.37). The sampling barrels have a 3-inch (7.6 cm) inside diameter and are constructed of high strength stainless steel pipe with smooth interior surface. Interchangeable barrel lengths range from 3 to 9 feet (0.95 to 2.74 m) depending on the sediment depth to be sampled.

A circular driving weight, mounted around a smaller 3/4-inch (1.9 cm) pipe extending upward from the sampling barrel, is raised by handline and dropped to force the sampler into the sediment. A piston inside the sampling barrel is held stationary as the sampler is driven. This creates a partial vacuum inside the barrel which assists in holding the sample in place when the sampler is removed from the water.

In some sediments, it is necessary to drive the sampler into relatively firm material to prevent the sample from slipping out of the barrel when the sampler is raised. The volume of the sampler is determined from the known diameter of the sample barrel and the length of the extruded sample as it is forced from the barrel with the plunger. The force of the plunger often compacts the sample, however, which causes erroneous volumetric determinations unless a correction is applied.

**Nuclear Density Probes**

The nuclear density probe may be used to determine the density of deposited sediment in situ (27). A radioactive source, enclosed in a cylindrical metal probe, is forced into the sediment deposit. Gamma rays, emitted by the radioactive source, are partially absorbed and partially backscattered by the surrounding water-sediment mixture. The quantity of backscattered rays reflected to a detector, located within the probe, is inversely proportional to the volume weight (bulk density) of the water-sediment mixture in a zone roughly ellipsoidal in shape around the source and detector.

The volume of the zone of measurement depends on the density of the material and the distance between the radioactive source and the detector. For most probes currently in use, 15 to 18 inches (38 to 46 cm) of sediment depth is required for good measurements. Figure 4.38 shows the probe and auxiliary equipment needed for field measurements. Extension tubes facilitate sampling to various depths.

The relationship between the wet volume weight of the sediment and the count or impulse rate from the reflected rays is established by a calibration curve. (A calibration curve is required for each probe.) The dry weight of the
sediment is readily determined from the wet volume weight, if the specific gravity of the sediment is known, by the following equation:

\[ D = \frac{G(W - \gamma)}{G - 1} \]  

(4-4)

where

- \( D \) = dry volume weight, pounds per cubic foot;
- \( G \) = specific gravity of sediment;
- \( W \) = wet volume weight, pounds per cubic foot; and
- \( \gamma \) = specific weight of water, pounds per cubic foot.

A typical calibration curve for a gamma probe is shown in figure 4.39. The conversion to dry volume weight was based on a specific gravity of 2.66 for the sediment. Even though manufacturers normally provide calibration data, it is best to recalibrate probes using soils or sediments similar to those in which density measurements are to be made (46).

The accuracy of field measurements depends partially on impulse counting time per meas-
urement. For counting rates greater than 10,000 counts per minute, 2 minutes counting time is usually sufficient. For slower counting rates, longer counting periods are recommended.

Figure 4.36.—ARS piston-type sediment sampler for sampling sediment deposits in lakes and reservoirs.

The dual probe (fig. 4.40) is a more recent development in nuclear density instrumentation (47). The principle of operation is the same as the single probe except for the location in separate probes of the radioactive source and the detector. Density measurements are made in a narrow band between the two parallel probes. This probe offers the possibility of density measurements in thin layers, 1 to 2 inches thick. It is more difficult, however, to force the dual probe into deep sediments because of the added resistance.

Nuclear density probes are delicate instruments and extreme care must be exercised in their use. Frequent testing and recalibration are necessary to assure good results.

**Boats, Platforms, and Other Accessory Equipment for Reservoir Sedimentation Surveys and Sampling**

In addition to the sampling equipment discussed in the preceding section and conventional surveying equipment such as the transit, plane table, alidade, and level, certain items of auxiliary equipment are needed to make sedimentation surveys of small reservoirs and lakes (56). Items most frequently used are shown in figure 4.41. They include:

- Small lightweight boats equipped with motors and life preservers.
- A reel and flexible galvanized steel cable (⅛-inch (0.64 cm) diameter is preferred) to keep the boat on line along the range across the reservoir.
- A productometer and cable to measure distance across the reservoir.
- A fathometer or other suitable sounding equipment to measure water depths.
- A small A-frame equipped with reel, cable, and depth indicator to use as a hoist in raising and lowering sampling and sounding equipment.

When small boats are used, particularly round bottom boats, it is desirable to fasten two together with planking to provide a working platform. This prevents tilting when heavy sampling equipment is suspended from the side. A raft, as shown in figure 4.42, may be used for larger reservoirs and when sampling with the nuclear density probe.
Other Landform and Channel Surveys

The delineation of changing channels and landforms by survey is an important procedure in sedimentation research. Measured changes in channel slope and cross section, gully growth, and upstream movement of gully scarps are routinely required. Also needed are components of the hydraulic geometry of waterways—width, depth, slope, and other conveyance properties—which are a consequence of erosive forces that act along the flow boundary. Similarly, the configuration of a field surface, created by rilling, surface sheet erosion, and colloval deposition, is the result of many of these same forces. By measuring these ero-

![Diagram of SEA piston-type sediment sampler](image)

Figure 4.37.—Details of SEA piston-type sediment sampler (56).

![Gamma probe with operating accessories](image)

Figure 4.38.—A single (gamma) probe with operating accessories: (1) Gamma probe containing the radioactive source, shielding, Geiger-Mueller detection tubes, and transistorized preamplifier; (2) aluminum connecting sections for inserting probe; (3) stopwatch; (4) personnel exposure pencils; (5) personnel exposure badge; (6) radiation meter; (7) portable scaler; (8) connecting cable; (9) carrying box, with lead shield, for gamma probe.
Calibration Chart for
Tech/Ops Model 497
Serial No. 3
Sediment Density Probe
Voltage = 1000 V

FIGURE 4.39.—Typical calibration curve for a gamma probe.
sional changes, it is possible to relate them to causal variables and to formulate predictive erosion models.

Most mapping requirements for sedimentation research involve planimetric and topographic details more accurate than are possible from the existing USGS map series or standard aerial photos with scale smaller than 1:6000 (flown at an attitude of 3,000 ft (915 m) or more with a 6-inch (15.2 cm) focal length aerial camera). Smaller scale maps or aerial photos can adequately define land use and treatment on agricultural watersheds and such general watershed characteristics as shape, drainage density, land slope, and relief ratio. More precise information can only be obtained by ground survey or by special photogrammetric procedures that produce large-scale maps.

Ground surveys were compared with photogrammetric mapping methods for two applications in sedimentation research (2, 18). In a special application using large scale photogrammetric techniques, erosion and deposition patterns were determined for a 5-year period for a 900 foot × 75 foot (275 × 23 m) transect along a hillslope (54).

Photogrammetric mapping of landform and channel changes has several advantageous features. The extent of the mapping and the needed survey accuracy is often not known—being dependent upon the relative magnitude of change or other criteria not known at the beginning of study. The researcher can often design his photogrammetric survey to meet the most stringent accuracy by obtaining a photographic record with that capability—but can save money by reverting to a less refined mapping if the situation warrants.

Because sedimentation research mapping goals are so varied and the photogrammetric mapping potential so great, the reader is urged to consult with personnel familiar to the field. Planning such flight details as scale and type of photography, type and density of control, map scale, contour interval, and the capabilities of stereoplotting equipment and operators is very important.

For example, for large scale photogrammetric mapping, it is often feasible to install extra preflight targets that can increase mapping accuracy tremendously. With the advent of the electronic computer, control survey techniques are now routinely available that can shorten field target survey procedures and increase accuracy of target location.

Some investigations will require detailed maps with closely spaced contours and precise elevations and distances that can only be obtained by ground survey. Some surveying techniques and procedures for making channel, valley, and gully surveys are given in the section on Field Observations, page 296. Procedures and techniques for measuring and interpreting accelerated valley sediment deposits are given in the ASCE Manual on Engineering Practice No. 54 (60).
FIGURE 4.41.—Field equipment for small reservoir sedimentation surveys: Top left, small boats and A-frame; top right, fathometer mounted on side of boat; bottom left, productometer; bottom right, reel and cable.
FIELD OBSERVATIONS

This section gives generally accepted procedures and techniques for collecting field data in sedimentation research on drainage areas varying from fractional-acre plots to over 100 mi² (259 km²) in size. Field measurements and sampling methods to determine rates and amounts of fluvial sediment discharge, amounts and distribution of reservoir deposits, and amounts and locations of channel scour or accretion are given. Information on site selection, sediment samplers, and auxiliary equipment was given in the section on Installations.

Plots and Small Watersheds

Total Sediment Collection Devices

Although impractical for most erosion studies, total collection devices are still used infrequently for special purpose studies. Routine service consists of periodic inspections to see that (1) collection tank covers are in place, (2) no damage has been done by vandals or animals, and (3) each tank is empty and clean. Inspection frequency during periods without runoff varies with location and season of the year.

Detailed procedures for servicing and collecting data from total collection devices are not included here because they are essentially the same as those given for multislot divisors which are described in the following subsection. Only that portion of the multislot divisor procedures pertaining to tank 1 (or sludge tank) should be followed.

Multislot Divisor Samplers

The multislot divisor (fig. 4.3) is used primarily to sample runoff from small fractional-acre plots. Sampling and servicing procedures will vary with the amount, nature, and sediment concentration of runoff. Runoff within each sample tank generally can be classified into one of the following groups:

- **Clear water.** If the bottom of a tank is visible, sampling is not necessary.
- **Normal runoff.** All sediment in a tank can be thoroughly suspended by stirring.
- **Heavy soil loss.** Soil material in a tank cannot be suspended by vigorous stirring.

These three classes of runoff will be considered for each tank.

For purposes of explanation, the sludge tank will be designated T₀. The first and second aliquot tanks will be designated T₁ and T₂, respectively. Large metal cans, designated C₁ and C₂ usually having a 20-gallon (75.7 l) capacity, are often placed inside the tanks—C₁ can in T₀, C₂ in T₁. This permits more accurate volumetric measurements of small sample volumes and reduces time and labor required for sampling and cleaning following low runoff events.

When the inter-cans overflow, the entire contents are poured into the associated tank, before sampling begins. Measurements and samples are taken directly from the cans only when they do not overflow. The volume of water in the C₁ must exceed the equivalent of 0.005 inch (0.13 mm) of runoff to be considered measurable runoff. Lesser quantities are usually discarded without measurement.

Field experience will determine the best servicing procedures for a given location. The following procedures can be used as a guide.

**For All Types of Events**

- Check collector and conveyance for plant residue and remove if present.

![Figure 4.42.—Small raft equipped with nuclear probe and scaler for sediment density measurements.](image)
• Drain and clean all tanks and cans.
• Replace drain plugs, tank screens, cans, tank covers, and collector screens.
• Remove tank covers and tank 1 trash screens. If the water surface in T₁ is at or near the multislot divisor overflow, the center slot should be plugged with a small, wet sponge to prevent overflow while sampling.
• If soil material is present in the collector or conveyance, remove the collector trash screen and flush the soil into T₁ with water taken for T₁. The flush water should be taken carefully from T₁ with a container having a pouring spout. Several flushings may be required and extreme care should be taken to avoid wasting any of the flush water.
• Make depth measurement from the top of T₁ to the water surface to nearest 0.01 foot (3 mm) and record in the proper space on the field form (fig. 4.43).
• Repeat the above step for tanks T₁ and T₂.

Note: If inter-cans C₁, C₂, and C₃ have not overflowed, depth measurements and subsequent volumetric determinations are made in these cans.

For Clear Runoff Events
Sampling is unnecessary. Record “clear event” in the spaces normally used for sample bottle numbers.

For Normal Runoff Events
• Place three quart jars near each tank containing runoff and record jar numbers on the field form.
• Thoroughly mix contents of tank T₁ by stirring with paddles or other mixing devices until all soil material is evenly suspended. Two or more men stirring vigorously are usually required for this.
• After soil material is in suspension, one man takes three 1-quart (0.94 l) dip samples (one man continues stirring until sampling is completed) with a ½-pint (0.47 l) dipper. Dip samples are poured into sample jars previously arranged with a funnel in each. Do not fill jars completely at one time, but add one dipper to each jar before starting the next round until four rounds are completed. (As a check on the thoroughness of agitation during the entire time required to fill three jars, the first jar—lowest number of the three-jar series—may be completely filled with four dippers and the same procedures continued until all three jars are filled.) Be sure that each dipper is full and that all of its contents are emptied into the jar.
• Repeat preceeding two steps for T₂ and T₃ if they contain runoff.

For Heavy Soil Loss Runoff Events
As previously mentioned, a heavy soil loss event is considered one where brisk stirring in T₁ will not suspend all the sediment deposits. Samples are required of both the supernatant and sludge.
• Drain and clean all tanks and cans.
• Replace drain plugs, tank screens, cans, tank covers, and collector screens.
• Slowly decant the supernatant with one or more siphons to within about 0.1 foot (3.05 cm) of the sludge. Three 1-quart (0.95 l) samples should be taken to represent each third of decanted fluid. Fill each jar by periodically passing it through the siphon outflow. Avoid disturbing the deposited sediment when siphoning. Record jar numbers as before.
• Mix sludge thoroughly by hand until sufficiently fluid for self-leveling.
• Allow sludge surface to settle, measure depth to sludge surface to the nearest 0.01 foot (0.3 cm), record on the field form, and determine sludge volume from tank calibration tables.
• Record numbers of three pint bottles in the proper space on the field form. Remove lids and place bottles near tanks for easy access.

Stir sludge by hand until mixed to a uniform consistency. Two men are usually required. Hand stirring permits the feel for consistency of the sludge slurry. Thus, sampling can be avoided when heavy deposits of sludge occur on the bottom of the tank or “lumps” are present in the slurry.
• After a uniform consistency of the slurry is obtained, one man continues mixing while the other collects samples with a ¼-pint dipper. Dip samples randomly and rapidly to prevent particles settling in the dipper. Fill three pint bottles in rotation using care to avoid spilling. Record bottle numbers on the field form.
• Sample tanks T₂ and T₃ following proce-
<table>
<thead>
<tr>
<th>Plot No.</th>
<th>Time of service</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sludge Tank</th>
<th>Can C₁</th>
<th>Depth to water (ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Runoff volume (ft.³)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tank T₁</td>
<td>Depth to water (ft.)</td>
</tr>
<tr>
<td></td>
<td>Runoff or supernatant volume (ft.³)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quart Jar Nos. (suspended sediment)</td>
<td></td>
</tr>
<tr>
<td>For Heavy Soil Loss:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Depth to sludge (ft.)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sludge volume (ft.³)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pint Bottle Nos. (sludge)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>First Aliquot Tank</th>
<th>Can C₂</th>
<th>Depth to water (ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aliquot volume (ft.³)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tank T₂</td>
<td>Depth to water (ft.)</td>
</tr>
<tr>
<td></td>
<td>Aliquot volume (ft.³)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quart Jar Nos. (suspended sediment)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Second Aliquot Tank</th>
<th>Can C₃</th>
<th>Depth to water (ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aliquot volume (ft.³)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tank T₃</td>
<td>Depth to water (ft.)</td>
</tr>
<tr>
<td></td>
<td>Aliquot volume (ft.³)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quart Jar Nos. (suspended sediment)</td>
<td></td>
</tr>
</tbody>
</table>

Remarks:

1/ If a sludge volume is determined, supernatant volume (T₁ volume less sludge volume) should be recorded here.

**FIGURE 4.43.—Sample field data form for the multislot divisor.**
dures described under subsection. For Normal Runoff Events, page 280.

**Coshocton-Type Runoff Samplers**

The Coshocton-type runoff sampler is illustrated in figure 4.7. Inspect the sampler periodically during periods of no runoff to assure that the equipment is operational and free of soil particles and other debris. Weekly, and after each flow event, the stage recorder (if used) is serviced as described in chapter 2 on Runoff. After each runoff event the following steps should be taken:

- Collect and weigh sediment deposits in the collector, flume, and approach channel. Record in the space provided on a suitable data form (fig. 4.44). Take two or three representative samples, 6 to 12 ounces (170–340 g), in soil moisture cans for subsequent determinations of moisture content. Record can numbers on form.

- Measure the depth of water from the top of the sample storage tank to the nearest 0.01 foot (3 cm) and record on the field form for tank 1 (fig. 4.44). If an overflow tank is used, measure water depth in a similar manner and recorder under tank 2. If a small intertank is used inside tanks 1 and 2 for small runoff events and the intertank has not overflowed, measurements and samples are taken from the intertank. When the intertanks overflow, their contents should be poured into the outer tank before sampling. Field notes should clearly show which tanks were sampled.

- Thoroughly mix the contents in the sample tank suspending all sediment. One man continues mixing while another fills two or more quart (0.94 l) jars with a 1/2-pint (0.24 l) dipper. Dips should be made quickly and at random locations in the tank. Each jar should be filled with alternate dips. Jar numbers should be

<table>
<thead>
<tr>
<th>Date(s) of Runoff Event(s)</th>
<th>Date Serviced</th>
<th>Crew</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plot No.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time of service</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collector, Flume and</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Approach Channel Deposits:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet Weight (lbs.)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Can Nos.                  |               |      |
| Depth to water (ft.)      |               |      |
| Sample volume (ft.³)      |               |      |
| Quart Jar Nos.            |               |      |

| Tank 1 | | | |
|--------|---------------|------|
| Depth to water (ft.)      |               |      |
| Sample volume (ft.³)      |               |      |
| Quart Jar Nos.            |               |      |

| Tank 2 | | | |
|--------|---------------|------|
| Depth to water (ft.)      |               |      |
| Sample volume (ft.³)      |               |      |
| Quart Jar Nos.            |               |      |

Remarks: Example: Bottom inch of slot obstructed with hair roots.

**Figure 4.44.—Coshocton sampler field data form.**
recorded in the proper space on the form for tank 1. Repeat performance for overflow tank, T2, if required.

- Drain and clean the tanks. Replace covers.
- Clean all lodged debris from wheel and slot.
- Record any unusual circumstances. For example, "sampler slot partially clogged", or "T1 cover found on ground."

Streams and Other Drainageways

Suspended Sediment Samples

The primary objective is to obtain a sample or a group of samples that are representative of the suspended sediment in the flow cross section. Methods and techniques described in this section have been used successfully by many investigators in small streams and rivers.

Since sediment concentration varies both vertically and laterally in the flow cross section, systematic sampling is required to determine the sediment discharge of a stream. Samplers and four generally accepted sampling procedures were described in the section on Installations, page 245.

Selecting the Sampler

In selecting the sampler, the flow depth and velocity must be considered. Normally, the lightest sampler that will do the job is used. For wading samples, the US DH-48 sampler is used. (If the product of flow depth in feet and velocity in feet per second does not exceed 10, the stream is usually safe for wading.) For deeper flows and higher velocities a heavier sampler is required which can be operated from a bridge or cableway.

Flows less than 15 feet (4.6 m) deep may be depth-integrated on a round trip basis with the US DH-49 and the D-74 samplers, although depths to 18 feet (5.5 m) may be sampled in many situations without appreciable error. Flows from 15 to 30 feet (4.6 to 9.2 m) deep are usually one-way integrated from surface to bottom with point integrating samplers such as the US P-61-A1 or the US P-63. The sampler nozzle is electrically opened before it enters the flow and closed immediately when the sampler touches the channel bed.

Sampling Frequency

The ultimate objective is to define, as accurately as possible, the trend with time of both the sediment concentration and discharge. Sediment yield is then the summation of incremental products of concentration, flow, and time. On the rising side of the hydrograph the sediment concentration is usually greater and changes more rapidly, thus requiring more frequent sampling than the falling stage.

In larger streams, changes in stage and discharge are usually much slower, thus requiring fewer samples per unit time. Table 4.5 may be used as a guide until more precise sampling needs for a particular gaging station can be determined from experience.

Where less accuracy is required, the sediment-transport curve, flow-duration curve method (65) may be used. This method, which

<table>
<thead>
<tr>
<th>TABLE 4.5.—Sampling frequency guide for continuous concentration method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of watershed</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>320 acres</td>
</tr>
<tr>
<td>320 acres up to 50 square miles</td>
</tr>
<tr>
<td>50 square miles and over</td>
</tr>
</tbody>
</table>

1 For ephemeral streams, sampling can be stopped when roughly 90 pct of total flow volume has passed. For perennial streams, weekly sampling may be started when stream stage approaches normal base flow.
2 Cultivated cropland at early crop stages may require samples as close together as 2 min to accurately define the concentration.
works very well for many intermediate and large size watersheds, requires the development of a general relation between instantaneous sediment transport rates and the respective flow rates. Numerous samples are needed at all stages for several small, medium, and large flow events for the initial calibration. Thereafter, occasional samples are needed to determine significant shifts in the original relationship.

Samples for Particle-Size Distribution

Often in suspended sediment work, concentrations of particle-size ranges are needed in addition to the total concentration. These are usually obtained by analyzing a suspended sediment sample for particle-size distribution and multiplying the percent of sample in the desired size range by the total concentration.

Samples for particle-size-distribution analyses should be obtained with the same samplers and sampling methods as for total concentration. A 1-pint (0.47 l) sample is usually sufficient for a total concentration determination, but a larger sample is often needed for a particle-size distribution because the quantity of sediment is not adequate. The sample quantity required depends on the size range to be analyzed and the method of analysis.

If the distribution of sand-size particles (>0.063 mm) is needed and a visual accumulation tube apparatus is used, the minimum weight of sand needed for analysis is 0.05 grams. A pint sample bottle containing a sample volume of 350 milliliters and at least 150 p/m sand (approximately 0.05 g) could be used for both the total concentration and particle-size-distribution analyses.

A size distribution of silt and clay requires from 1 to 5 grams if the pipette method is to be used. An estimated concentration of 1,000 p/m of silt and clay would require three pint bottles of 350 milliliter sample volume to obtain the required minimum weight of material. However, it is better to collect a larger than minimum size sample because concentration estimates are inaccurate, and the accuracy of pipette analyses increases with sediment quantity. Because of possible weighing errors in a pipette analysis, an additional sample should be taken for total concentration determination.

Sampling frequency for particle-size-distribution determinations depends upon how the data will be used. Where particle-size distribution is desired throughout a runoff event, table 4.5 can serve as a guide.

Making the Sediment Discharge Measurements

Equal-Transit-Rate (ETR) Sampling Method

Because this sampling procedure is widely used and has distinct advantages over other methods, it will be covered in detail. A depth-integrating sampler is used to obtain depth-integrated samples at equally spaced verticals in the stream cross section. (The sampler travel speed must be uniform and the same in all verticals.) This gives a discharge-weighted sample for the flow cross section. When more than one bottle is collected, they may be composited and processed as one sample in the laboratory. The sampler path is illustrated in figure 4.45.

Equipment needs for a wading measurement of sediment discharge include a US DH-48 sampler, a steel measuring tape or tagline, sample bottles and carrying rack, a thermometer, and boots or waders. A detailed step-by-step procedure for taking the samples follows:

- Select a reach of the stream near the runoff gaging station where the cross section is somewhat constricted and fairly uniform in depth. Sections where much of the width has shallow flow should be avoided.
- Stake out the tagline (or tape) at 90° to the flow and 1 to 2 feet (0.3 to 0.61 m) above the water surface. Always walk downstream from the measurement site when laying out the tagline.
- Determine the number of verticals to be

![Figure 4.45.—Path of sampler during typical equal-transit-rate (ETR) suspended sediment measurement.](image)
sampled. Six to 12 verticals will usually produce a discharge-weighted suspended sediment sample of sufficient accuracy in most small streams. Generally fewer verticals are needed for streams at lower stages than at high stages. Fewer verticals are needed on streams whose loads are composed predominantly of silt and clay, on sections that are uniform, and on narrow, deep streams.

As an example, 6 or 7 verticals should be adequate for a stream 35 feet (10.7 meters) wide with a uniform depth of 3 feet (0.91 m) and a 30 percent sand load. The uniform spacing between verticals is thirty-five feet (10.7 m) divided by 7 feet, or 5 feet (2.1 or 1.5 m). If the first vertical is 2 feet (0.61 m) from the water's edge on one bank, the final vertical will be 3 feet (0.92 m) from the water's edge on the opposite bank.

- Immediately before sampling, obtain the water stage from the outside gage or from the water stage recorder chart. If the stage is changing, another stage reading should be obtained immediately after sampling. For rapidly changing stages, an intermediate stage reading should be taken.

- The wading sampler should be rinsed in the water and inspected to see that the nozzle is unclogged and the gasket in place before the sample bottle is inserted. Use the largest nozzle that flow velocities and depth will permit. From a position about 2 feet (0.61 m) downstream from the tagline, sample the selected verticals near the tagline. Hold the rod vertically, and maintain a constant lowering and raising speed at all verticals throughout the stream cross section. The sampler transit speed should not exceed 0.4 of the stream velocity. The sampler should lightly touch the bed at each vertical. When a bottle is two-thirds to three-quarters full (280 to 420 ml), replace with a clean bottle. When a bottle is removed from the sampler, record time, bottle sequence number, and vertical number or numbers on the cap. Continue until all selected verticals are sampled. The last bottle in a set may be less than two-thirds full. The number of bottles per wading set will obviously vary widely. Occasionally, for low flows, a set might consist of only one bottle. For deeper flows on wider channels, five or six bottles may be required.

- Read water temperature after holding the thermometer bulb in the flowing water for at least 2 minutes.

- For streams transporting sizable quantities of sand it is good practice to routinely collect a duplicate or check set of samples immediately after the first set. This practice will help eliminate sampling errors associated with sand bed streams, such as when the operator inadvertently dips the sampler nozzle into the back of a sand dune. Many investigators prefer to sample immediately prior to and after a stream discharge measurement.

The US DH-59 handline sampler works well for flows too deep to wade but not deep or swift enough to require larger, heavier samplers. The in-water portion of the handline should be a stranded steel cable with a simple take-up reel to adjust the wet-line depth. The upper part of the line can be ½-inch (12.7 mm) cotton rope, or, if more convenient, the rubber-covered coaxial cable used in making handline discharge measurements.

The US DH-59 cannot be swished in the flow to rinse sediment from the nozzle as can the hand samplers. However, the sampler can be visually inspected for contaminants in the nozzle or stoppages in the exhaust lines prior to use and cleaned if necessary. The sampling procedure is very similar to that already described for wading measurements. Before lowering the sampler into the water, the sampler nozzle is oriented upstream by barely touching the sampler tail in the water to align the sampler. Prior to sampling each vertical, the excess handline should be laid out on the bridge rail or floor so that it will not become entangled when the sampler is lowered and raised. When working from a bridge, no tagline is used, but the stream verticals are marked on the bridge rail.

For deeper flows ETR samples are collected
NOTES
For sorting convenience, principally in the laboratory, these items are duplicated on the bottle cap.

River Washita
Location Alex, Okla.
Date 4-20-76
Time 0815
G. ht. O.G. 12.87
Station 64, 70, ETR 1/4
Temperature 64°
Initials WMB

Watershed or stream name or number
Location if further identification is necessary
Military time
Gage height; outside gage reading is usually preferable to recorder readings
Bridge, cableway, or tagline station numbers are infrequently desired. 1/4 signifies the first of 4 bottles in an ETR measurement set (where duplicate check sampling is carried on the second series of bottles would read 1/4A, 2/4A, 3/4A and 4/4A).

Water temperature
Initials of person taking the sample

Other notes - Soft lead pencils work best. Remaining space at bottom can be used for remarks pertaining to conditions of flow or other factors that might affect sampling accuracy.

Figure 4.36.—Field documentation of suspended sediment sample bottles.
with the US D-49 or D-74 depth-integrating samplers or the US P-61-A1 or US P-63 point-integrating samplers used in a depth-integrating mode. Auxiliary equipment required includes a reel, crane, and crane truck.

Figure 4.47 may be used to select a nozzle size and sampler travel speed when depths and mean velocities of various verticals in the flow cross section are known. For example, at a depth of 12 feet (3.7 m) and a mean velocity of 6.0 ft/s (1.8 m/s), a 3/16-inch (1.6 cm) diameter nozzle and two-way integration would give an “R” value of 0.34. The optimum sampler travel speed to obtain a 350- to 400-ml sample would be 0.34 times 6.0 or 2.0 ft/s (1.8 to 0.61 m/s). A sampling speed less than 2.0 ft/s (0.61 m/s) would overfill the 1-pint (0.47 l) bottle.

As indicated in figure 4.47 sampling errors occur when the “R” value becomes too high. These sampling errors occur in two ways. First, if the angle between the sampler nozzle and the resultant flow approach vector formed by the flow vector and the sampler travel vector exceed about 20°, some sands are not sampled. Secondly, errors also occur when the air compression rate in the bottle during lowering exceeds the sampler intake rate. Under this condition, streamflow may enter the bottle from the exhaust port, causing sampling errors in the sand fraction of the load. These errors can usually be avoided by one-way depth integration with the US P-61-A1 or US P-63 samplers.

Tests have shown that it is better to one-way sample in the surface to bottom direction. Bottom to surface samples usually give slightly higher concentrations, probably due to the accumulation of sediments in the outer end of the nozzle as the sampler is lowered to the bottom starting point.

In ETR sampling, where a constant sampler transit speed is required throughout the cross section, an optimum transit speed for the main part of the flow may fall in the error region of figure 4.47 for the slower velocities near the banks. However, the error induced is not serious because sediment transport near the banks is usually a minor percent of the total. An instrument called a vertical transit rate pacer is available to help maintain accurate sampler travel speeds.

**Figure 4.47.—Diagrams to assist the selection of nozzle size and optimum sampler speed.**
**Depth-Integrated Samples at Stream Verticals Representing Areas of Equal Water Discharge**

This method requires the selection of sampling verticals that represent areas of equal water discharge in the stream cross section. Depth-integrated samples are then taken at the center of each area of equal discharge. Sampler travel speed must be uniform in the vertical but not necessarily the same for all verticals. The cross section concentration is the mean of the concentrations of the verticals.

The number of verticals required will depend upon accuracy desired, particle size and distribution of sediment in the cross section, and stream channel geometry. Normally 6 to 12 verticals will provide adequate data for most upland streams in agricultural watersheds. Data acquired during the first few runoff events should be used to determine the number of verticals required.

Sections of equal discharge are determined from discharge measurements in the manner described in the section on installations, page 250. The sediment sampling procedure is very similar to the ETR method except that samples from each vertical must be analyzed separately for sediment concentration.

A variation of the above procedure is sometimes used for convenience. Verticals are selected without regard to discharge and sampled as before. A discharge measurement is made soon after sampling and the discharge associated with each sampled vertical is determined. Each vertical concentration is then weighted by the percent of total flow for the respective vertical. The discharge-weighted concentration for the cross section is the sum of the individually weighted concentrations.

**Point-Integrated Samples**

Several methods for determining suspended sediment transport require the systematic collection of point-integrated samples (36). Procedures for obtaining point samples are described briefly.

After setting up the crane and reel and attaching the point-integrating sampler to the reel cable, apply the proper voltage to the sampler to make sure the intake and exhaust valves are working properly. Inspect the sampler to make sure the nozzle and exhaust ports are clear. With a bottle inserted and the voltage applied, a good check is to blow into the nozzle. Air should flow freely out the exhaust port. After zeroing the reel depth gage with the point-integrating sampler nozzle at the water surface, lower the sampler to the desired sampling depth below the water surface. Open the electrically controlled valve for a short period of time until the desired quantity of sample is accumulated. Filling times for 1-pint (0.47 l) capacity samplers with various nozzle sizes may be determined from figure 4.48. Information recorded on the bottle should be essentially the same as shown in figure 4.46, except under “station” show the location of the stream vertical and the location of the sampling point in the vertical. For example, in the space opposite “station” (fig. 4.46) the notation R/15, S/5 would indicate that the sample was taken 15 feet (4.6 m) from the right water’s edge and 5 feet (1.5 m) below the surface.

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**Figure 4.48.—Relation of filling time to intake velocity for suspended sediment samplers with 1-pint capacity.**
Pumping-Type Samplers of Suspended Sediment

Although several types of pumping samplers are being used to sample suspended sediment in streams and reservoirs, only the Inter-Agency US PS-69 and the Chickasha sampler will be referred to here because of their wide use at present. Samples obtained with pumping-type sediment samplers are point samples because the intakes are either at a fixed elevation in the flow or they are attached to hinged floats so that samples are pumped from a fixed or variable ratio of flow depth.

Pumped samples usually do not represent the discharge-weighted concentration for the flow cross section because they are point samples. Therefore, when a pumping sampler is installed, sufficient discharge-weighted samples must be taken simultaneously with pumped samples during several runoff events to establish a relationship between the pumped sample concentration and the cross-section concentration. Thereafter, less frequent discharge-weighted samples are required unless the relationship shifts with time. If the concentration shifts significantly with time, either another intake site should be selected or a few discharge-weighted “check” samples will be required for nearly all runoff events. On some wide and shallow streams the relationship between point and cross-sectional concentrations may be so poorly defined that pumping samplers cannot be used.

Routine servicing of pumping-type samplers.—At weekly intervals routine service for pumping samplers should include:

- A visual inspection to determine that the sampler has not been damaged by vandals, that all bottles are clean, that the bottle fill nozzle (or tray in the Chickasha sampler) is set in the initial position, and that the flush tank is filled to the proper level (does not apply to the Chickasha sampler).
- A visual inspection of the sampler intake to determine that it is free of debris, that any exposed waterlines are intact, and that the structure has not been damaged by scouring or floating debris.
- If an ink-type event marker is used, inspect to see that the pen is marking properly and refill the ink reservoir to the proper level. If other types of event markers are used, such as a spark-type or float-tape bumper, test mark by manually closing the contacts on the relay in the control box. This is usually the sample trap solenoid relay in the US PS-69 or the diverter solenoid relay in the Chickasha sampler. The word “test” should be written beside the test mark on the stage recorder chart.
- Using a battery hydrometer, check the specific gravity of the battery electrolyte. If the hydrometer reads less than about 1.220, the battery should be exchanged for a fully charged one. Where a trickle charger is used, less frequent checks will be necessary. Chargers should be adjusted so that the hydrometer reads at least 1.270 but not more than 1.290 when the sampler is inoperative. During or after long flow events it may be desirable to increase the trickle charge rate. More satisfactory battery operation results from using a trickle charger with an adjustable charge rate of 0.1 to 1.0 amperes.

Setting the pumping-type sampler during the runoff event.—After arriving at a pumping sampler station during a runoff event the technician should:

- First determine that the sampler is operating properly. Then check for skipped, overfilled, or underfilled bottles, and determine that the sampling event marker is marking properly.
- If equal-transit-rate samples are taken, the mean time of each ETR sample should correspond as nearly as possible to the time that a pumped sample is taken.
- Label ETR sample bottles as previously described bearing the notation “with PS.” The corresponding pump sample should be capped and the following information recorded on the cap: station name or number, pump sample number (the first bottle pumped is PS No. 1), date, time, initials of technician, and “with ETR.” In addition, a notation giving the pump sample number, date, time, initials, and “with ETR,” should be made beside the event mark on the water stage chart. (PS-69 bottles cannot be capped while still in the sampler; however, a cap can be prepared and left near the sampler.)
- When ETR check samples are not required, it is desirable to cap and label occasional
pumped samples and to label the event mark as described above. In case of event marker or sampler malfunctions, these notations will help determine when other samples were taken.

**Servicing the pumping-type sampler after the runoff event.**—After a runoff event, filled bottles should be removed and labeled in the following manner:

- Cap the filled bottles before they are removed from the sampler and label caps as follows (PS–69 samples will have to be capped and labeled as each bottle is removed); Station name or number, pump sample number (number samples consecutively as they were pumped), date, time (taken from the event marks on the stage recorder chart), initials of the servicing technician on the first and last bottle cap, and write “end” on the last bottle cap to denote the last sample in the set or series.
- Install clean bottles in the tray and set the bottle nozzle (or tray in the case of the Chickasha sampler) at the start position.
- Check the specific gravity of the batteries. If no trickle charger is used and the hydrometer reads below about 1220, replace batteries. Where a trickle charger is used and the hydrometer reading after a storm is below 1220, increase the charge rate slightly for a week or more.
- Inspect intake structure for damage and remove debris.

**Care of the pumping-type sampler during cold weather.**—During freezing temperatures, pumping samplers may be treated in three ways:

- Heating equipment can be installed near all places subject to freezing (including bottles) and the sampler left in an operative mode.
- Locations in the pumping system where water is trapped such as the flush tank, pump, and low places in pipes may be filled with alcohol and the sampler left in an operative mode. For this situation, filled bottles will have to be removed promptly and the sampler rewinterized after each runoff event.
- The pumping system can be drained and the power shut off until the freezing season is over. Alcohol should be forced into any pumps in water lines that will not drain.

**Total Load Samples**

Samples of total load may be obtained with either of the following methods:

**Total Load Sampling Through Overfall**

Flow depths and velocities at the controlled cross section will determine the sampling equipment required. For shallow depths and moderate velocities the US DH–48 hand sampler can be used. Deeper flows and higher velocities will require heavier, rigidly constructed equipment such as that shown in figure 4.26. The selection of sampling verticals and the sampling procedure is the same as that described for suspended sediment samples.

Care must be taken to be sure the nozzle passes completely through the flow at each vertical. It is also undesirable for the nozzle to pass more than 0.2 foot below the bottom of the flow nappe because sampling errors may result from submergence or inadequate weir aeration. Stops should be provided on the apparatus shown in figure 4.26 to assure proper sampler reversals.

**Total Load Sampling in a Turbulent Section**

Natural or man-made highly turbulent cross sections are required, particularly if coarse sediments are being transported. The sampling procedure is identical to that previously described for suspended sediment measurements. Care should be taken in selecting turbulent sections to avoid sampling in plunge pools or eddy currents below weirs or rock overfalls. In such cases coarse material may be in suspension but not actually in transport.

**Sampling Bed and Bank Materials**

A variety of tools such as the auger, bucket and spatula, and piston-type samplers are used to take disturbed samples of streambed and streambank materials. Although some systematic method of locating the samples is required, the sampling procedure will vary with the objectives of the experiment. In sampling at successively greater depths at the same location, care must be taken to prevent contamination of samples by material falling from the upper part of the hole. Dry sandy material may have to be dampened to prevent sloughing.
Samples of known volume are required for the determination of specific weight. Volumetric samples below the water table may be obtained with the SEA piston-type sampler, or the US BMH-53 piston-type sampler. To avoid distortion of the sample, the sampler should be driven straight and evenly with light blows.

The exact depth of penetration is required to locate the sample in the vertical. Depth of penetration will vary with the depth and density of sediment. Removal of the sampler is difficult in some sediments if it is driven more than 3 or 4 feet (0.92 or 1.2 m). Cores may be extruded from the barrel and cut into desired lengths or divided according to visual compositional changes.

Sampling rings are usually preferred over the piston-type samplers for volumetric samples of streambed and streambank materials above the water surface. The rings must be driven slowly with light blows to prevent distortion of the sample. Rings are then removed by excavating material from around the outside, the sample ends trimmed to the exact length of the ring, and the sample sealed in the ring or transferred to a suitable carton for transporting to the laboratory. The moisture content of the sediment which will permit the most accurate sampling will vary with the material.

Bed and bank material samples are usually collected at previously established stream cross sections or gaging stations. Identification will normally include: Stream, cross section or range number, station, depth increment, date, time, gage height (if sampling at gaging station), and initials of observer.

Investigations of sediment transport in streams may require samples of the bed material during periods of storm runoff. The BM-54 (fig. 4.15) and the BMH-60 (fig. 4.14) bed material samplers are used. The sampling procedure is as follows:

- Suspend the sampler at the bridge working level and cock the sampler bottom scoop with a \( \frac{1}{2} \)-inch (0.56 cm) hex head socket wrench.
- Lower the sampler to the bed and momentarily release tension on the cable to trip the scoop.
- Raise the sampler to the working level and open the scoop with the socket key so that the sample empties into a \( \frac{1}{2} \)-quart (0.47 l) cardboard carton or a plastic bag.
- Identifying data includes: Stream (and location if needed), date, time, gage height, stream vertical, and initials of operator.

Due to fairly large changes in gradation of the streambed particles, numerous samples may be needed equally spaced across the stream. If frequent sampling is done to define changes, it is best to sample the same verticals repeatedly.

Reservoir Sedimentation Surveys

Most reservoir sedimentation surveys are made to provide information on the distribution and amount of sediment deposits and reservoir area and volume. The surveying methods and techniques described in this section will provide reasonably accurate results if used properly. They were developed primarily for small reservoirs of moderate depth. Conventional surveying equipment is used since this is all that will be available to many field locations.

Three basic types of surveys are described: The contour method, the combination contour and range method, and the range method. Generally, the first two are more accurate than the range method. The method selected will depend upon local conditions and the accuracy required.

Types of Reservoir Surveys

Contour Method

Topographic maps may be constructed in the field with a plane table or from sufficient sets of elevation, distance, and azimuth data collected with a transit. Contours may be located in either survey method by the trace contour, coordinate, or controlling points procedures described in surveying texts. Accuracy is proportional to the number of elevation points obtained and the smoothness of the topography. The contour method is generally best adapted to very small reservoirs or stock ponds that require only two or three plane table or transit setups.

A minimum of two and preferably three horizontal control bench marks are needed. If these bench marks are deep enough for stabil-
ity under local freezing and thawing conditions, they may also serve as elevation bench marks. The elevation above mean sea level should be used if available and bench mark elevations determined to the nearest 0.01 foot (3 mm). Transit angles on distant shots are commonly read to the nearest 15 or 20 seconds, stadia horizontal distances at each elevation point to the nearest foot, and ground surface elevations to the nearest 0.1 foot (30.4 mm).

The contour method can be used when the reservoir is dry or flooded. If flooded, the rodman wades for instrument shots in shallow water area, and a boat is used for the deep water. In transit surveys it is usually more convenient to first determine the water surface elevations and then at each rod setting the rodman relays the depth below the water surface to the notekeeper.

**Combination Contour and Range Method**

This method is essentially a variation of the contour method. However, because of its wide use, it is treated here as a separate method. It requires less time per unit of mapped area and is generally more accurate for determining the sediment volume accumulated between successive surveys, because elevations are determined at the same points in successive surveys. Figure 4.49 illustrates how different branches of a reservoir are surveyed with ranges at 90 degrees to base lines.

This makes the field data more versatile because stage-volume relations can be gained from constructed contour maps or computed by one of the reservoir volumetric formulas (see Laboratory Analyses and Data Reduction section, p. 299). To supplement the range data, two contours, usually at the principal and emergency spillway elevations, are established with the plane table or transit. These contours are then used as a guide in establishing the remaining contours.

**Range Method**

The range method is similar to the combination range and contour method in the layout of ranges. It differs in that ranges are usually more widely spaced, and no contour map is constructed. On very large reservoirs ranges are located individually in the field and securely marked at the range ends rather than ranges being tied to a baseline. Volume determinations with range data are presented under the Laboratory Analyses and Data Reduction section, page 299.

**Detailed Procedure for Making Combination Contour and Range Surveys**

If possible, the original survey should be made soon after the reservoir is constructed and before water is ponded. This greatly shortens the survey time because boats and a range cable are not required. Greater accuracy is achieved because irregularities can be detected in the pool area, thus permitting proper selection of elevation data points. The usual steps in surveying a small reservoir are as follows:

- Take aerial photographs and inspect the reservoir and surrounding area to determine the best location for the baseline, range orientation, and approximate location of permanent bench marks. The baseline should be located above the permanent pool elevation. Short lengths of the baseline may pass through inlets up to 150 feet (45.8 m) wide at the permanent pool elevation if no transit work is needed in these short lengths. The baseline should be straight, if possible, and roughly parallel to the valley so that the principal ranges will be approximately perpendicular to the reservoir.
- Unless already available, establish at least two permanent bench marks at the site. If sea
level elevations are not available, assume an elevation for a permanent bench mark.

- Establish the baseline and reference with distances and angles to permanent bench marks. Points on the baseline where ranges intersect should be chained and marked with 2 inch by 2 inch (5.1 x 5.1 cm) wooden hubs and tack points. The hubs should be flagged and also marked with flagged stakes. The first range should lie along the upstream toe of the dam.

Spacing of ranges will vary depending upon the size and shape of the reservoir, the desired accuracy of the survey, and the uniformity of the reservoir area. As a general guide, ranges should be placed so that not more than 10 percent of the reservoir area exists between adjacent ranges. If the reservoir topography is uniform, this distance can be increased. Conversely, where nonuniformity exists, such as near an inlet, the distance should be decreased. Ranges should be laid out parallel to each other where possible and preferably at 90 degrees to the baseline.

- Using the transit, locate ranges with reference to the baseline. Range lines should be marked every 300 to 400 feet (91.5 to 122 m) with stakes and flagging. Ranges should be cleared sufficiently of tall grass and underbrush for the transit line layout and for chaining and level work to be done later.

- After all ranges are staked out, establish the elevation of one or more temporary bench marks, such as large nails in trees, along each range.

- Next, chain each range, taking elevation shots with a level of all topographic break points. In the permanent pool area, elevation shots should be taken at even 20-foot (6.1 m) intervals in addition to topography break points. This is assuming that the reservoir is new and not yet flooded. Repeat the procedure until all ranges have been surveyed.

- Establish several permanent horizontal and vertical control bench marks during the original survey to simplify relocation of ranges during successive surveys. These should be placed, if possible, near fence lines and other out-of-the-way places. Elevation bench marks should be placed deep enough to prevent upheaval by frost. Resurvey work is expedited if one or more semipermanent markers such as short iron pipes are installed on each range. If frequent resurveys are planned, it may be desirable to establish permanent-type range end markers.

- Using the plane table, establish the location of at least two contours, usually at the principal and emergency spillway elevations. Locate baseline and ranges on the plane table map.

When making an original survey of a flooded reservoir or when making resurveys, a different procedure is followed in laying out ranges.

- Establish the original baseline and an auxiliary baseline, parallel to the original, on the opposite shore.

- Lay out ranges as before from both baselines.

- Survey cross-section profiles down to the waterline for each range and place a stake, marked with the station, a few feet from the water's edge. Record the elevation of the water surface in the notes for each range.

- After the cross sections have been surveyed to the water's edge on both sides, boats, a range cable and reel, and a depth sounding device are needed to complete the survey. Secure the reel on the opposite shore from range station 0 + 00 with a heavy rod driven into the bank.

- Using the boat, string the cable across the lake. If other boats are on the lake, floats should be placed along the cable as a safety measure.

- Thread the cable through the line meter and secure with a clamp to another heavy steel rod driven into the bank.

- Tighten the cable and set the line meter on the proper footage by measuring with a tape back to the bank stake marked with the range station.

- Move the boat along the range by hand or outboard motor and take soundings at stations where elevations were taken in the original survey. For an original survey, take readings 20 feet (6.1 m) apart unless, through sounding, it is determined that additional points are needed because of irregular topography.

- Upon reaching the other shore, measure the distance from the meter to the bank stake, add to the line meter reading, compare for
error, and record in the notes. A sonic depth recorded (fathometer) will greatly reduce the
time required for sounding and provide a con-
tinuous record of the range profile.

- Take sediment samples and make sedi-
ment density measurements as required (see
following subsection).
- Retrieve cable and proceed to the next
range.
- Repeat above procedure for all ranges.
Notekeeping should be in the usual form for
cross sectioning or running cross profiles as
described in surveying texts. The sample field
note page shown in figure 4.50 may be used as
a guide.

### Sampling Reservoir Sediments

Samples of reservoir sediments are required
to determine thickness, weight per unit volume,
particle-size gradation, and other physical and
chemical properties. Equipment needed to sam-
ple small reservoirs is listed on page 274 and
shown in figure 4.41.

When sediment deposition has already oc-
curred at the time of the first survey, depth, or
thickness, of the deposits is usually determined
by spudding. The spud is dropped vertically
into the sediment and then retrieved with the
handline. Prior to each use, all soil material is
removed from the spud by washing in the lake
or with a coarse bristle brush.
The original lakebed can usually be determined by observing soil color and gradation change. Discerning sediment deposition from the original soil material is largely a matter of individual judgment. This is especially true for reservoirs on alluvial sites with rapidly aggrading valleys. The number of observations will depend upon the desired accuracy in computing the volume of deposits. Accuracy will, in general, increase with the number of spudded points. Spudded points should be taken on established ranges in a manner similar to that described for sounding measurements. If a spudded reservoir is to be repeatedly surveyed, the accuracy of the spudding survey should be proportional to the accuracy desired in successive surveys.

Samples of a known volume are required if the weight of sediment deposits is to be determined. Samples should be taken throughout the sediment profile to the original lake bottom in each survey because, with additional top deposits and age, the specific weight (often called bulk density of volume weight) of lower deposits often increases.

Many volumetric samples are needed to determine the average weight of sediment deposits. Specific weights can vary from 30 to 120 lb/ft³ (481 to 1922 kg/m³) in the same reservoir. Heavier and coarser deposits are found near the upstream end of the reservoir, usually above the principal spillway elevation. Normally, deposits become progressively lighter and finer in texture near the lake outlet. Ideally, volumetric samples are taken on each range where measurable deposition has occurred.

The number of samples along each range should be sufficient to cover the variation in specific weight and particle-size distribution. Spacing along the range may range from 50 to 200 feet (15 to 61 m) depending upon the characteristics of the deposits. Generally, small reservoirs will require more samples per unit area; large reservoirs less. Deposits from soils with a wide range in particle size will require more samples than deposits from soils of a uniform texture.

The following steps may be used as a guide in taking reservoir sediment samples with the SEA or similar piston-type samplers:

- Before sampling, flush the sampler with water and push the piston to the bottom end of the sampling tube. Allow sampler tube to fill completely with water.
- Remove slack in the sampler and piston ropes and, holding both ropes together, gently lower sampler to the sediment surface.
- When the sampler reaches the sediment surface, hold the piston rope stationary, release tension on the sampler rope, and drive the sampler into the sediment by repeatedly lifting and releasing the drive weight. Drive sampler to the original reservoir bed, to point of refusal, or until the barrel has been filled with sediment. Deposit thickness may be determined from recent and original survey notes.
- Retrieve the sampler by evenly and slowly holding and pulling on both ropes as if they were one.
- To extract samples, lay the sampler horizontally on the boat or working platform so that the sampling end overhangs a few inches. Extrude about 0.05 to 0.1 foot (1.5 cm to 3.0 cm) of sample by pushing on the piston rod. Shear off evenly with the end of the sampler tube with a spatula and discard. If the piston rod is calibrated, record reading before any of the sample is forced from the cylinder. If uncalibrated, take measurements and record so that exact location of samples in the sediment profile can be determined. Extrude 4-inch (10.1 cm) long samples, shear off evenly with the spatula and place in a suitable container such as a soil moisture can or a plastic jar with tight fitting top. As a general rule, for sediment depths to 3 feet (0.92 m) all 4-inch (10.1 cm) long samples should be kept and analyzed. For depths from 3 to 6 feet (0.92 to 1.8 m) every other 4-inch (10.1 cm) long sample should be kept. For depths over 6 feet (1.8 m), every third 4-inch (10.1 cm) long sample should be kept. The depth increment for each sample retained is determined from the known elevation of the water or sediment surface.
- Identifying data for each sample (data may be recorded on the container or in a notebook) should include: Watershed number, reservoir name and number, range number, station number, depth increment, date, and name or initials of persons taking the sample.
Considerable sampling time can be saved by using a nuclear sediment density probe for most of the specific weight measurements. Sediment depths of 18 inches (45 cm) or greater are required for valid readings with the single probe currently in use. The following operating procedure for this probe is explained in Heine-mann (28):

When the boats have advanced to a point where a measurement is to be made, they should be situated in a fixed position by attachment to a cable stretched across the lake, by means of a strong anchor, or otherwise. The coaxial cable is then strung through sufficient sections of the 6-ft. aluminum pipe (premarked every tenth of a foot) to exceed the maximum water plus sediment depths and attached to the probe and scaler. A few sections of aluminum pipe are then fastened to the gamma probe and the instrument lowered into operating position.

The first reading should be taken with the probe under several feet of water but not in the compacted sediment. If the unit count for a duration of 2 minutes is near the water count shown on the calibration curve, the equipment is in operating condition. If the test count is considerably different, then the system should be reviewed. If everything is in working condition, the voltage on the scaler should be checked and possibly adjusted until the water count approaches that on the calibration curve. All water counts should be recorded in the notes. The top of the sediment deposit can be determined by using a fathometer, sounding bell, aluminum pipe with a disc at the end, or other means. The gamma probe, with the necessary extension pipes attached, is then lowered in a vertical position until the tip of the probe is at the top of the consolidated sediment deposit. A gamma probe reading is made at this point and two more readings should be made at 6-inch increments of depth in an effort to obtain the volume-weight of possible semi-fluid material above the firm deposit. Below this, readings can be taken at 6-inch, 1-foot, or other depth intervals, as desired, until the sediment deposit has been penetrated completely, or it is impossible to push the gamma probe deeper.

All readings, the time period, and the depth of the probe should be recorded in the field notebooks. As the probe progresses to greater depths, and a reading appears to be out of line, a second or third confirming reading should be made before moving the gamma probe. Care must be taken to push the extension pipe and probe in a straight, downward direction without any change in angle. If the probe is moved back and forth after it has started into the sediment deposit, a cavity (water filled) may be formed in the sediment next to the probe and result in an erroneous measurement of the sediment volume-weight.

When the density probe is used, sufficient samples should be taken with a piston sampler to check the performance of the nuclear probe, provide particle-size gradation data, and for analysis, to determine the amount of iron, calcium, manganese, and barium, which are known to affect the probe calibration curve.

**Reservoir Safety**

Many safety hazards are involved in making reservoir sedimentation surveys. Boats should always be in good condition and have built-in Styrofoam floats. A Coast Guard approved vest-type life preserver should be worn by each person in the boat. Range cables are a hazard because they are under considerable tension. Personnel working near the cable should exercise extreme caution. Backlash from a broken cable can cause serious injury. Use extreme care in releasing tension on the reel as loss of control results in a spinning crank. When working on lakes with other boat traffic, the range cable should be clearly flagged to warn boats to stay clear.

USDA employees using the density probe must obtain approval from the USDA radiological safety officer. Others need approval of the appropriate government agency. In addition, some State governments have licensing requirements. All personnel working with the density probe are required to carry dosimeters. These should be turned into the proper radiological safety officer after each 2 weeks of use. Work should be arranged so that no person remains near the source in the probe for extended periods.

**Channel, Valley, and Gully Surveys**

Channel, valley, and gully surveys are usually made to determine the volume of material eroded from or deposited at the site. They can be either cross sectional or topographic. For convenience here gully surveys will be classed as channel surveys.

Cross sections may be either channel or valley sections depending upon whether they cross the channel or entirely cross the alluvial valley. Cross sections are run perpendicular to the channel or valley. Because cross sectioning is thoroughly described in most surveying texts and handbooks, only a generalized procedure will be presented here.
Normally, the minimum size for a survey party is three men: A head chainman who also carries the rod, a tail chainman, and an instrument man who also acts as notekeeper. In rough terrain or in heavily vegetated areas where line clearing is required, a fourth man is needed.

Conventional surveying equipment consists of a transit, level, leveling rod, one 100-foot (30.5 m) chain, one 200-foot (61 m) chain, 2 plumb bobs, machetes, ax, hatchet, a set of 11 chaining pins, 2 range poles, plastic flagging of various colors, and field notebooks.

Initially the area to be surveyed and the approximate distance between cross sections must be selected. Where sections are more than about 500 feet (152.5 m) apart, prelocate all cross sections on aerial photographs. Select locations which will miss major obstacles such as farm structures. Valley cross sections that do not cross the channel at right angles will require a turn on each side of the channel. Turn points should be outside the anticipated meander range of the channel.

Select the 0+00 starting station for each range. Establish permanent bench marks at these points or reference them to permanent bench marks in the vicinity as shown in figure 4.51. Determine elevations and distances to topographic break points for each cross section.

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<td></td>
<td></td>
<td></td>
<td>9.4</td>
</tr>
<tr>
<td>0+63</td>
<td></td>
<td></td>
<td></td>
<td>4.7</td>
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<tr>
<td>0+75</td>
<td></td>
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<td>2.4</td>
</tr>
<tr>
<td>0+91.5</td>
<td></td>
<td></td>
<td></td>
<td>0.98</td>
</tr>
<tr>
<td>BM2</td>
<td>2.55</td>
<td>1091.17</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.51.—Sample cross section field notes including location sketch.
using accepted surveying procedures. Use mean sea level elevations if possible. Keep detailed, accurate notes (fig. 4.51). For very long cross sections, establish permanent bench marks at both ends. Because bench marks are frequently destroyed, additional iron pipe markers at stations along the range, such as fence lines, are desirable. These pipes also save time on later surveys when only a portion of the section is resurveyed.

Where channel cross sections are less than 500 feet (152.5 m) apart, an open-ended traverse should be surveyed approximately parallel to the channel. Beginning and ending stations should be referenced to permanent markers. Channel cross sections can then be located along and referenced to the traverse line.

Although topographic maps with contour intervals ranging from 10 to 100 feet (3.0 to 30.5 m) are available for much of the United States, these maps are usually inadequate for sedimentation research where elevation differences of 0.1 foot (3.0 cm) may be required. Recently aerial photos taken from a plane 500 feet above the ground have been used to develop contour maps with 1/2-foot (15.2 cm) contours. This is about the minimum practical elevation for fixed-wing aircraft. Pictures taken closer to the ground, even with a shutter speed of 1/1000 second, will have ground blur.

Contours of 1/10 foot (3.0 cm) have been obtained from photos taken with a boom-suspended camera 60 feet (18.3 m) above the ground (l). Elevation accuracy for this method is comparable to surveys with conventional surveying equipment.

Ground control surveying is necessary with all low-flight aerial photogrammetry. Prior to each flight, lay out panels for vertical and horizontal control. The center point of panels, where possible, should be semipermanent markers, such as concrete posts which extend 6 inches above the ground. Where farming or other activities prevent such markers, wooden surveyor stakes are used. A closed traverse with a maximum error of closure of 1 foot (30.4 cm) per 2,500 feet (762.5 m) of traverse should be run connecting all markers. This traverse should be referenced to permanent markers or landmarks.

The suggested sizes of panels for the panel arrangement shown in figure 4.52 are given in table 4.6. In most cases, panels should be white. However, for areas with dormant, light-colored grass or sandy, denuded areas, black panels will give greater contrast.

A minimum of four elevation points are needed toward the corners of each photo for tilt adjustment and leveling of the stereomodels. For elevation accuracy desired in most sedimentation research, however, approximately six more elevation points spaced systematically across each stereomodel will be needed. A min-

![Figure 4.52. Suggested target panel design for ground control in topographic mapping from aerial photographs.](image)

**TABLE 4.6.—Suggested panel sizes for indicated flight heights**

<table>
<thead>
<tr>
<th>Flight height above ground</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 ft (2)</td>
<td>2 ft</td>
</tr>
<tr>
<td>500 ft</td>
<td>4 ft</td>
</tr>
<tr>
<td>1,000 ft</td>
<td>8 ft</td>
</tr>
<tr>
<td>2,000 ft</td>
<td>20 ft</td>
</tr>
<tr>
<td>5,000 ft</td>
<td>34 ft</td>
</tr>
</tbody>
</table>

1 Crane suspended.

2 Use 1-ft square panel with identifiable center point.
imum of one horizontal distance between two sharply visible points is needed per photo. Horizontal distance checks should be toward the center of the photo and span about 25 percent of the photo height or width.

Although less desirable, vertical and horizontal ground control can be obtained after aerial photographs are taken and without using panels by surveying elevations and distances specified by a photogrammetric mapping contractor. Due to the specialized nature of this work, the reader should consult with the mapping contractor prior to the flights concerning ground control.

LABORATORY ANALYSES AND DATA REDUCTION

This section is intended to aid in the reduction and processing of field data. In addition to notes, charts, and other field records, data reduction in sedimentation investigations involves processing and analyses of physical samples. A laboratory equipped for measurement of the physical properties of sediment is an essential part of the total program. Methods of laboratory analyses of samples and computations of sediment discharge and sediment deposition rates and amounts are given in this section.

Field Notes and Records

Most field records will be entered on the water-stage recorder chart, in field notebooks, or recorded on the sample container. Information on field samples may include all or part of the following: (1) the name or number of the stream, watershed, field plot, reservoir, or other research location, (2) the gaging station or location, (3) the water stage or discharge rate, (4) the date and time, (5) water temperature, (6) type of sample (total load or suspended sample), point or depth integrated sample, and number of bottles or containers comprising a single composite sample, (7) name or initials of person collecting the sample, and (8) notes concerning any unusual circumstances and the observer's evaluation of the sample quality. This information should be checked for errors and omissions before data processing begins.

Types of Sediment Samples

Sediment samples are broadly classified into six general categories: Storm integrated samples, suspended sediment samples, bedload samples, and bed and bank samples, samples of reservoir, lake, and valley deposits, and samples of flume and approach channel deposits.

Storm Integrated Samples

Samples collected with the multislot divisor, the Coshocton-type sampler or similar devices are generally storm integrated, for example, they are a sample of a larger sample collected continuously throughout a runoff event. Generally, three or more samples are analyzed for each runoff event and the data averaged.

Suspended Sediment Samples

Suspended sediment samples may be point samples or single or multiple vertical samples. They may be representative of the total or only a portion of the suspended sediment load. Discharge-weighted samples may be contained in one or several bottles. The objective of the experiment will determine whether discharged-weighted samples are analyzed separately or combined.

If a determination of the total suspended sediment discharge is the only objective, the samples may be combined before analysis. If sediment distribution in the stream cross section is an objective, samples representing a single vertical must be analyzed separately. In addition to location, time, and stage, it is ex-
tremely important for the laboratory records to show the type of sample.

**Bedload Samples**

Bedload samples, normally high in sand and gravel content, are usually collected for the purpose of determining particle size distribution and the bedload discharge of a stream. Although difficult to obtain, good samples are sometimes acquired with sampling equipment designed for a specific location or project.

**Bed and Bank Material Samples**

Samples of streambed and streambank material may be collected in a disturbed or so-called “undisturbed” state. Disturbed samples are usually collected to determine the particle size distribution, organic matter content, specific gravity, Atterberg limits, and other physical and chemical characteristics. Undisturbed samples of a known volume are required for bulk density (specific weight or volume weight) determinations and for measurements of erosion resistance or susceptibility characteristics. Undisturbed samples are also needed for soil strength and permeability determinations.

**Samples of Reservoir, Lake, and Valley Deposits**

Laboratory analyses of both disturbed and undisturbed samples of valley and reservoir sediment deposits are often required. Specific weight (or volume weight) determinations require undisturbed samples of a known volume. The exact location where samples were obtained is important in computations of sediment weight in reservoirs and lakes and should be shown on laboratory worksheets.

**Sediment Deposits in Flumes and Approach Channels**

In erosion studies on plots and small watersheds, significant quantities of sediment are frequently deposited in flumes and approach channels. As this material is removed it is usually measured or weighed, and samples are collected to determine the proportion of dry material per unit weight or per unit volume. Total dry weight of the deposits is then determined and added to the sediment discharged through the flume or other measuring device.

**Laboratory Analyses**

Many physical and chemical properties of sediments are of interest to soil physicists, geologists, and engineers, and there are many methods of analyses reported in available literature. Discussion of all of these and the various methods of analyses is beyond the scope of this field manual. Only those physical properties necessary for the computation of sediment discharge and sediment accumulation rates and amounts are considered. Some of the most universally accepted laboratory methods and procedures for determining the sediment concentration of the water-sediment mixture, the particle size distribution, the specific gravity, and the bulk density or specific weight of deposited sediments are given in the following paragraphs.

The quantity of sediment in a sample may vary, and the particle size may range from boulders or coarse gravel to fine clay. Storm integrated and suspended sediment samples seldom contain particles coarser than fine gravel (4.0 mm) and usually contain considerable silt and clay. These samples, as well as other wet samples, should be stored at cool temperatures and protected from light to prevent algal growth unless analysis is begun soon after they reach the laboratory. Samples containing mostly sand may be stored wet or air dried. Samples containing sufficient clay to cause particle binding if dried should be sealed to prevent evaporation before storing.

**Sediment Concentration**

Sediment concentration is usually expressed in parts per million, percent by weight, or milligrams per liter. Since it is easier and more convenient to work with weights, rather than volumes, the concentration is normally first determined as a ratio of the dry sediment weight to the weight of the water-sediment mixture. Conversion to parts per million and milligrams per liter is readily accomplished. Data are usually reported to the nearest parts per million or milligrams per liter for concentra-
tions to 1,000 parts per million and to 3 significant figures for higher concentrations.

Evaporation and filtration are the two more frequently used methods for determining sediment concentration. The filtration method is faster if the quantity of sediment in the sample is small. When the Gooch crucible is used with a suitable filter material, the need for a dissolved-solids correction is eliminated. Laboratory procedures for both methods are well documented in the literature (23, 24, 35, 66).

**Evaporation Method**

The evaporation method is usually best for the higher concentrations frequently encountered in sedimentation research. However, for low concentration a correction for dissolved solids is frequently required. Detailed laboratory procedures are subsequently discussed.

Equipment and supplies, as outlined below, will meet the minimum requirements for satisfactory analyses of suspended sediment samples by the evaporation method:

- Tared sample containers (glass milk bottles, 1-pt (0.47 l) or 1-qt (0.94 l) capacity, are used in most suspended sediment samplers currently in use).
- A distilling system or supply of distilled water.
- A vacuum source.
- Evaporating dishes or beakers of various sizes.
- Convection-type drying oven.
- Containers, one-gallon capacity or larger.
- 100-ml pipette.
- Desiccator.
- Flocculating agent.
- Balances are accurate to 0.1 gram and an analytical balance, 200-gram capacity, accurate to 0.1 milligram. Other supplies incidental to the care of the equipment and handling of samples may be required. There is also leeway for logical substitution for some of the listed items.

**Analytical procedures** are as follows:

- Prepare a laboratory worksheet to record the data and make the computations. The format of this form may vary depending upon the objectives of the experiment. A typical form, which contains all of the essential information for most analyses, is shown in figure 4.53.
- Weigh samples as soon as practical after they are received in the laboratory to avoid possible evaporation losses. Subtract tare weight of container from total weight of sample and container to determine sample weight. Record sample weight to 0.1 gram on bottle and in the space provided on the laboratory worksheet.
- Arrange samples in an orderly sequence according to location, station, date, and time of collection.
- Set up a laboratory worksheet (fig. 4.53) for each sampling location for each group of samples, and enter information in spaces provided at the top of the forms. A set of consecutively numbered worksheets is prepared for each sampling location.
- Transfer date, time, gage height or discharge rate, sampling station, water temperature, and remarks from sample bottle to laboratory worksheet. The space opposite sampling station is used to record the location of the sample in the stream cross section. In the example, figure 4.53, the symbols \( \text{V/3} \) and \( \text{L/R} \) denote the first of three discharge weighted samples collected from left to right across the stream. For a point sample, the entry would be \( \text{R/15 S/5} \) which would denote that the sample was collected at a point 15 feet (4.6 m) from the right waters edge and 5 feet (1.5 m) below the water surface. The letters "A. B." shown under remarks in the example are the initials of the person who collected the sample. In addition to the laboratory worksheets, some laboratories also keep a logbook of all samples processed (fig. 4.54). Samples are entered in the logbook when processing begins, and the completion date is added when processing is completed. This provides a concise record of all samples collected and analyzed for a given location.
- Record gross, tare and net weight of sample in the space provided on laboratory worksheet.
- If colloidal material is in suspension, flocculate the sample with alum. The addition of 0.4 milliliter of 0.2 molar solution, aluminum ammonium sulfate \( \text{Al NH}_4(\text{SO}_4)_2 \cdot 12 \text{H}_2\text{O} \) per liter of sample is usually sufficient. (Prepare flocculant by dissolving 90.7 g/l of solution.
Allow sample to settle over night or for about 12 hours. Samples which are relatively free of colloidal clay will not usually require the addition of a flocculating agent. Settling will occur normally if samples are allowed to sit undisturbed for several hours.

Generally, a flocculant should not be used if the sediment concentration is < 1,000 parts per million or if precipitation or dissolution occurs with the addition of the flocculant. The relative magnitude of the error associated with use of flocculants can be estimated. For example, assume a sediment concentration of 1,000 parts per million and a flocculant concentration of 50 parts per million (adequate for flocculation as determined by experimentation). Then the maximum error in the determination is 5 percent, assuming all of the flocculant is sorbed by the sediment. If sediment concentration is < 1,000 parts per million, proceed with filtration method without addition of flocculant.

- Using the vacuum source, a large container, and necessary tubing, remove excess liquid from the sample leaving about 30 milliliters. (This amount may vary but should be the same for all samples from a specific location if a dissolved solids correction is necessary.) The effluent from all samples for a location (gaging station) collected on the same date or during a runoff event is combined in a large container.
- Wash the remaining portion, approxi-
approximately 30 percent of the sample into an evaporating dish identified by number, using distilled water. Place evaporation dish in oven and dry overnight at 105 to 110° C. Care must be taken to prevent boiling sediment out of the evaporation dish. This may require drying at temperatures slightly below the boiling point until all visible moisture has evaporated. The sample may be dried in the sample container bottle if desired and if adequate drying and weighing facilities are available for the large vessels.

- Remove evaporation dish from oven, and place in a desiccator until cool. Weigh immediately to nearest 0.1 milligram upon removal from desiccator.
- Record gross and tare weights of dried sample in space provided on laboratory worksheet. Compute net weight to nearest 0.1 mg and record.
- Thoroughly mix all effluent from a group of samples (item 8) for a given location and withdraw 100 milliliters. Place in tared evaporation dish, and oven dry at 105 to 110° C. Weigh residue and record to nearest 0.1 milligram in the placed provided for dissolved solids on the laboratory worksheet. Compute net weights of dissolved solids to nearest 0.1 milligram and record. (Under some conditions, the relationship between conductivity and dissolved solids may be used to make the dissolved solids correction.)
- Compute correction factor for the group of samples by dividing the net amount of dissolved solids (residue) by the aliquot volume, for example, 100 milliliters, and multiply by the volume of water left in the sample container. Record in the space provided.
- Compute sediment concentration parts per million as follows: Subtract correction factor for dissolved solids from net sediment weight. In figure 4.53:

\[
0.3755g - 0.0035g = 0.3720g.
\]

- Divide oven dry weight of sample by the net sample weight of the sediment plus water and multiply by one million. In the example:

\[
\frac{0.3720g}{177.7g} \times 10^6 = 2,090 \text{ p/m}
\]

Many scientists now prefer to report sediment concentration in mg/l. The computations are as follows:

\[
\text{Concentration in mg/l} = \frac{B \text{weight of sediment} \times 10^8}{\text{weight of water-sediment mixture}}
\]

The values of factor “B,” given in table 4.7, are based on specific weights of water and sediment of 1.000 and 2.65 g/cm³.

Naturally dissolved solids in streamflow or runoff will vary considerably with location. However, at a given location the dissolved solids content usually does not change significantly from day to day for normal base flow. Frequently the dissolved solids content can be related to stage or discharge. Consequently, the number of laboratory determinations can be reduced as these relationships are established.

**Filtration Method**

As explained previously, the filtration method works well for low sediment concentrations and eliminates the need for a dissolved solids correction. The procedures outlined below utilize a Gooch crucible with a suitable filter material. Other types of filtration crucibles are available commercially and may be used if desired.

**Equipment and supplies**, as outlined below, will meet the minimum requirements for sediment concentration analysis by the filtration method:

- Gooch crucibles, 25 milliliter capacity or
TABLE 4.7.—“Β” factors for computation of sediment concentration in mg/l when used with ratio (times 10^ of weight of sediment to weight of water-sediment mixture

<table>
<thead>
<tr>
<th>Ratio</th>
<th>B</th>
<th>Ratio</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0- 15,900</td>
<td>1.00</td>
<td>322,000-341,000</td>
<td>1.26</td>
</tr>
<tr>
<td>16,000- 46,900</td>
<td>1.02</td>
<td>342,000-361,000</td>
<td>1.28</td>
</tr>
<tr>
<td>47,000- 76,900</td>
<td>1.04</td>
<td>362,000-380,000</td>
<td>1.30</td>
</tr>
<tr>
<td>77,000-105,000</td>
<td>1.06</td>
<td>381,000-398,000</td>
<td>1.32</td>
</tr>
<tr>
<td>106,000-132,000</td>
<td>1.08</td>
<td>399,000-416,000</td>
<td>1.34</td>
</tr>
<tr>
<td>133,000-159,000</td>
<td>1.10</td>
<td>417,000-434,000</td>
<td>1.36</td>
</tr>
<tr>
<td>160,000-184,000</td>
<td>1.12</td>
<td>435,000-451,000</td>
<td>1.38</td>
</tr>
<tr>
<td>185,000-209,000</td>
<td>1.14</td>
<td>452,000-467,000</td>
<td>1.40</td>
</tr>
<tr>
<td>210,000-233,000</td>
<td>1.16</td>
<td>468,000-483,000</td>
<td>1.42</td>
</tr>
<tr>
<td>234,000-256,000</td>
<td>1.18</td>
<td>484,000-498,000</td>
<td>1.44</td>
</tr>
<tr>
<td>257,000-279,000</td>
<td>1.20</td>
<td>499,000-513,000</td>
<td>1.46</td>
</tr>
<tr>
<td>280,000-300,000</td>
<td>1.22</td>
<td>514,000-528,000</td>
<td>1.48</td>
</tr>
<tr>
<td>301,000-321,000</td>
<td>1.24</td>
<td>529,000-542,000</td>
<td>1.50</td>
</tr>
</tbody>
</table>

* Based on density of water of 1.000 g/ml, plus or minus 0.005 in range of temperature 0°-29° C, dissolved solids concentration between 0 and 10,000 p/m and the specified gravity of sediment of 2.65.

Source: Vanoi (65).

larger, with perforated bottom which may be connected to a vacuum system.

- Filters. Commercial glass fiber and cellulose filters are available which are satisfactory for most sediments. Some fine sediments may require a glass or cellulose filter used in conjunction with an asbestos matt.
  - A vacuum system.
  - Distilled water.
  - Convection type drying oven.
  - Desiccator.
  - Flocculating agent.
  - Balance, one accurate to 0.1 gram and an analytical balance, 200-g capacity, accurate to 0.1 milligram.
  - Beakers, evaporation dishes, and so forth.

Analytical procedures are as follows (since detailed instructions have been given for arranging the samples, computing and recording the data for the evaporation method, these items are omitted here):
- Prepare a laboratory worksheet to record the data, and make the computations. The form shown in figure 4.53 may be used if desired.
- Determine weight of the sample (water-sediment mixture).
- Allow sample to remain undisturbed until solid material has settled. When clear, decant excess liquid and transfer sample into a beaker. After transfer allow a short settling period, and make another decantation if possible.
- Install suitable filter on Gooch crucible and determine tare weight.
- Connect crucible to the vacuum system. Transfer sample to crucible. When filtration is complete, place crucible and contents in oven and dry at 105 to 110° C. Remove from oven and place in desiccator until cool.
- When cool, remove crucible from desiccator, weigh immediately to nearest 0.1 mg and compute concentration.

The Gooch crucible is only one of many filtration methods used in making a sediment concentration analysis. For large volume samples with relatively high colloidal content, the filtration process is greatly expedited by using commercially available filter tubes instead of crucibles. One of the simplest methods is to use a filter paper in a glass funnel and allow the filtration process to proceed under the forces of gravity (35). This will give satisfactory results if used properly and with care.

In the foregoing procedures for determining the concentration of the water-sediment mixture, no provisions are given for removal of organic matter from the sample. Normally, this is not done in a concentration analysis. If concentrations of organic matter are high, removal of organic matter may be necessary, and some laboratories may prefer to report concentrations on an organic matter-free basis. A procedure for removing organic matter from the sample is given in the procedures for particle size analyses.

Separation of Fines and Sands

Separation of the fine material from the sands is frequently required for data analyses. The separation is usually made at 0.062 millimeter, although preferences may range from 0.050 to 0.10 millimeter or more. If the visual accumulation tube is to be used for subsequent particle size analysis of the sands, the separation should be made at 0.053 millimeter.

Equipment and Supplies are the same as those required for the evaporation method, in
addition to the use of a small sieve with 0.062 millimeter or 0.053 millimeter-mesh.

Analytical procedures are the following when the concentration of both the fines and sands is required. (A typical laboratory worksheet is shown in fig. 4.55.)

- Follow the first six steps of the evaporation method.
- Wet sieve on 0.062 millimeter sieve using (native) sample water.
- Remove material, < 0.062 millimeter, dry, and weigh, or proceed with the remaining steps of the evaporation method for the fines.
- Remove sands from sieve and place in a tared evaporation dish. Oven-dry sample, and record weight to nearest 0.1 milligram.
- Adjust to pH 3-5 with HCl using pH paper. Add about 1 milliliter or more of 30-percent H₂O₂ per gram of dry sample depending upon the sample size and organic matter content, in about 40 milliliters of water. Allow to stand for a few hours to oxidize the organic matter. If no sediment is attached, remove floating organic matter by skimming. Destroy remaining organic matter and excess hydrogen peroxide by slowly bringing sample to a boil.
- Ovendry sand sample and weigh to nearest 0.1 milligram. Determine organic content by

<table>
<thead>
<tr>
<th>Location</th>
<th>Sta. 4C, Chews Creek, Holly Springs, Miss</th>
<th>Computed by W.G.S.</th>
<th>Checked by J.B.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>4-5-69</td>
<td>4-5-69</td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>12:38 A</td>
<td>12:37 A</td>
<td></td>
</tr>
<tr>
<td>G. H.</td>
<td>2.24</td>
<td>2.25</td>
<td></td>
</tr>
<tr>
<td>Samp. Sta.</td>
<td>4.5%</td>
<td>4.5%</td>
<td></td>
</tr>
<tr>
<td>Temp.</td>
<td>65°</td>
<td>65°</td>
<td></td>
</tr>
<tr>
<td>Remarks</td>
<td>A.B.</td>
<td>A.B.</td>
<td></td>
</tr>
<tr>
<td>Gross</td>
<td>536.8</td>
<td>627.9</td>
<td></td>
</tr>
<tr>
<td>Tare</td>
<td>358.6</td>
<td>363.4</td>
<td></td>
</tr>
<tr>
<td>Net. wt.</td>
<td>178.2</td>
<td>243.0</td>
<td></td>
</tr>
<tr>
<td>Sample</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gross</td>
<td>497.0</td>
<td>490.0</td>
<td>39.0</td>
</tr>
<tr>
<td>Tare</td>
<td>60.148</td>
<td>56.386</td>
<td>40.712</td>
</tr>
<tr>
<td>Corr.</td>
<td>0.0830</td>
<td>0.1231</td>
<td>0.4341</td>
</tr>
<tr>
<td>Net. wt.</td>
<td>2.389</td>
<td>1.231</td>
<td>0.0055</td>
</tr>
<tr>
<td>Conc. (ppm)</td>
<td>1340.690</td>
<td>1780</td>
<td>1650</td>
</tr>
<tr>
<td>Total Conc. (ppm)</td>
<td>2030</td>
<td>3430</td>
<td>2220</td>
</tr>
</tbody>
</table>

**FIGURE 4.55** — Sample laboratory worksheet for sediment concentration analysis for filtration method.
subtracting gross weight of sands from gross weight of sands obtained in the evaporation method (before peroxide treatment) and record in the space provided on the laboratory worksheet (fig. 4.55.)

- Record gross and tare sand weights in space provided on the laboratory worksheet. Compute net sand weight, and record to nearest 0.1 milligram.
- Subtract weight of organic matter from weight of sand, and record on worksheet. Note, no correction is made for dissolved solids as the effluent was washed into the fines portion of the sample during wet sieving.
- Compute sands and fines concentrations in the manner previously prescribed for the evaporation method, page .
- Compute total concentration by totaling the concentration of the fines and sands.

**Particle-Size Analysis**

Sediment samples will usually require more than one method of analysis because of the broad range of particle sizes normally encountered. In addition to the size determinations, the total concentration may be obtained by adding the concentrations of the different size fractions. The selection of particle size classes or grades to be determined will depend upon the objectives of the experiment. Size classes recommended by the Subcommittee on Sediment Terminology of the American Geophysical Union are given in table 4.8 and by the U.S. Department of Agriculture, Soil Conservation Service, in table 4.9 (43, 62).

Recommended quantities of sediment in the sample, desirable range in concentration, and recommended particle size range for the most frequently used methods of particle size analysis are given in table 4.10. Many suspended sediment samples will not contain the desired quantity of sediment for accurate analyses. In such cases, the analyses may be limited to a determination of the percentage of fines and sands. In others, consideration may be given to combining samples from the same location for the same runoff event.

On the other hand, bed and bank material samples and samples of deposited sediments will usually require splitting to obtain the desired quantity of sediment for analysis. Dry samples may be reduced by using a commercially available sample splitter or by quartering. Moist samples may also be reduced by quartering or by simply inserting a thin-walled tube to the bottom of the sample container at two or three locations and withdrawing a portion of the sample.

**Fine Sediments**

The hydrometer, the bottom withdrawal tube, and the pipette are the most commonly used methods for determining the particle size

### Table 4.8.—Grade scale of sediment particle sizes

<table>
<thead>
<tr>
<th>Soil textural class</th>
<th>Large sizes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Metric unit</strong></td>
<td><strong>English unit</strong></td>
</tr>
<tr>
<td><strong>Millimeters</strong></td>
<td><strong>Inches</strong></td>
</tr>
<tr>
<td>Very large boulders</td>
<td>4096-2048</td>
</tr>
<tr>
<td>Large boulders</td>
<td>2048-1024</td>
</tr>
<tr>
<td>Medium boulders</td>
<td>1024-512</td>
</tr>
<tr>
<td>Small boulders</td>
<td>512-256</td>
</tr>
<tr>
<td>Large cobbles</td>
<td>256-128</td>
</tr>
<tr>
<td>Small cobbles</td>
<td>128-64</td>
</tr>
<tr>
<td>Very coarse gravel</td>
<td>64-32</td>
</tr>
<tr>
<td>Coarse gravel</td>
<td>32-16</td>
</tr>
<tr>
<td>Medium gravel</td>
<td>16-8</td>
</tr>
<tr>
<td>Fine gravel</td>
<td>8-4</td>
</tr>
<tr>
<td>Very fine gravel</td>
<td>4-2</td>
</tr>
<tr>
<td><strong>Small sizes</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Metric units</strong></td>
<td></td>
</tr>
<tr>
<td>Very coarse sand</td>
<td>2-1</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>1-1/2</td>
</tr>
<tr>
<td>Medium sand</td>
<td>1/2-1/4</td>
</tr>
<tr>
<td>Fine sand</td>
<td>1/8-1/16</td>
</tr>
<tr>
<td>Very fine sand</td>
<td>1/16-1/32</td>
</tr>
<tr>
<td>Coarse silt</td>
<td>1/16-1/32</td>
</tr>
<tr>
<td>Medium silt</td>
<td>1/32-1/64</td>
</tr>
<tr>
<td>Fine silt</td>
<td>1/64-1/128</td>
</tr>
<tr>
<td>Very fine silt</td>
<td>1/128-1/256</td>
</tr>
<tr>
<td>Coarse clay size</td>
<td>1/256-1/512</td>
</tr>
<tr>
<td>Medium clay size</td>
<td>1/512-1/1024</td>
</tr>
<tr>
<td>Fine clay size</td>
<td>1/1024-1/2048</td>
</tr>
<tr>
<td>Very fine clay size</td>
<td>1/2048-1/4096</td>
</tr>
</tbody>
</table>

Source: Lane (43).
distribution of fine sediments 0.062 mm (25, 35, 65). The hydrometer has been used extensively in the study of soils, and laboratory procedures for this method are well documented in the literature (14). Although a relatively simple and inexpensive method, its use in analyzing small sample quantities encountered in sedimentation research has been rather limited.

The bottom withdrawal tube method requires specially constructed and calibrated tubes (14, 65), not usually available to small field laboratories. It is not used extensively because it is time consuming even though it is more accurate for very low concentrations of fine materials.

The pipette is probably the most accurate and routinely used method in fluvial sediment research. Detailed laboratory procedures for this method are subsequently described. The pipette method is based on the principle that thoroughly dispersed particles of a given size in a suspending medium will settle below a given point of withdrawal in a given time. The time and depths of withdrawal are predetermined according to Stokes law:

\[ W = \frac{g d^2 \gamma_s - \gamma}{18 v} \]  

(4-5)

where

- \( W \) = settling velocity;
- \( g \) = acceleration of gravity;
- \( d \) = diameter of particle;
- \( v \) = kinematic viscosity;
- \( \gamma_s \) = specific weight of sediment; and
- \( \gamma \) = specific weight of fluid.

Predetermined depths and times of withdrawal are given in table 4.11 for various sediment size ranges.

### Table 4.9. Size limits for sand and finer particles

<table>
<thead>
<tr>
<th>Soil textural class</th>
<th>Range in diameter (Millimeters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very coarse sand</td>
<td>2.0 - 1.0</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>1.0 - 0.5</td>
</tr>
<tr>
<td>Medium sand</td>
<td>0.5 - 0.25</td>
</tr>
<tr>
<td>Fine sand</td>
<td>0.25 - 0.10</td>
</tr>
<tr>
<td>Very fine sand</td>
<td>0.10 - 0.05</td>
</tr>
<tr>
<td>Silt</td>
<td>0.05 - 0.002</td>
</tr>
<tr>
<td>Clay</td>
<td>below 0.002</td>
</tr>
</tbody>
</table>


### Table 4.10. Recommended size range, analysis concentration, and quantity of sediment for commonly used methods of particle size analysis

<table>
<thead>
<tr>
<th>Method of particle size analysis</th>
<th>Recommended size range</th>
<th>Desirable range in analysis concentration</th>
<th>Range in optimum quantity of sediment (Mg/l)</th>
<th>( Mm )</th>
<th>( G )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sieves</td>
<td>0.062-0.32</td>
<td>10.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VA tube</td>
<td>0.062-2.0</td>
<td>0.05 - 15.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pipette</td>
<td>0.002-0.062</td>
<td>2,000 - 5,000</td>
<td>1.0 - 5.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BW tube</td>
<td>0.002-0.062</td>
<td>1,000 - 3,500</td>
<td>0.5 - 1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrometer</td>
<td>0.002-0.062</td>
<td>25,000 - 50,000</td>
<td>20 - 200</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 Based on use of 3-inch diameter sieves and a median size of 0.5 mm or less.
2 If necessary, may be expanded to include sands up to 0.35 mm, the accuracy decreasing with increasing size—the concentration and size increased accordingly.
3 Quantity depends on size of settling container—a 1,000-ml cylinder has about the minimum diameter for most hydrometers.

**Equipment and supplies** required are as follows:

- A 25-milliliter pipette apparatus (fig. 4.56) mounted on a movable carriage with suitable mechanism for raising and lowering the pipette.
- A vacuum source.
- A supply of distilled water.
- Sedimentation cylinders, 1,000 milliliter capacity, with rubber stoppers.
- Stirring rods made from \( \frac{1}{4} \)-inch (6.4 mm) by 24-inch (61 cm) brass rods with a perforated plastic disk 2 inches (5 cm) in diameter attached to one end.
- Thermometers.
- Evaporating dishes.
- Desiccators.
- Stopwatch.
- Laboratory worksheets.
- No. 230 (0.062 mm) sieve.

Before a pipette analysis is performed, many samples will require removal of organic matter...
### Table 4.11—Time of pipette withdrawal for given temperature, depth of withdrawal, and diameter of particles

<table>
<thead>
<tr>
<th>Diameter of particle (mm)</th>
<th>0.062</th>
<th>0.031</th>
<th>0.016</th>
<th>0.008</th>
<th>0.004</th>
<th>0.002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of withdrawal (cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>15</td>
<td>10</td>
<td>10</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Temperature °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time of withdrawal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seconds</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>44</td>
<td>7:40</td>
<td>30:40</td>
<td>61:19</td>
<td>4:5</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>42</td>
<td>7:29</td>
<td>29:58</td>
<td>59:50</td>
<td>4:0</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>41</td>
<td>7:18</td>
<td>29:13</td>
<td>58:22</td>
<td>3:54</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>40</td>
<td>7:07</td>
<td>28:34</td>
<td>57:50</td>
<td>3:48</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>37</td>
<td>6:39</td>
<td>26:38</td>
<td>52:22</td>
<td>3:33</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>36</td>
<td>6:31</td>
<td>26:22</td>
<td>52:22</td>
<td>3:32</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>35</td>
<td>6:22</td>
<td>26:22</td>
<td>50:52</td>
<td>3:32</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>34</td>
<td>6:12</td>
<td>25:43</td>
<td>50:42</td>
<td>3:19</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>33</td>
<td>6:02</td>
<td>24:53</td>
<td>49:42</td>
<td>3:15</td>
<td></td>
</tr>
</tbody>
</table>

Note: Values in this table are based on particles of assumed spherical shape with an average specific gravity of 2.65, the constant of acceleration due to gravity = 980 cm/s², and the viscosity varying from 0.010087 cm²/s at 20° C to 0.00004 cm²/s at 30° C.

...and soluble salts. Organic matter is removed by oxidation. First, using HCl and pH paper, adjust sample pH to 3 to 5 for oxidation. Then add about 1 milliliter of 30 percent H₂O₂ for each gram of dry sample in 40 milliliters of water. Stir thoroughly, and allow to stand for a few hours. If free of sediment, large floating particles of organic matter may be removed by decanting or skimming. Samples will often require heating (do not exceed 70°C) and additional H₂O₂ to obtain oxidation of all organic matter. After reaction has stopped, the H₂O₂ is destroyed by boiling the sample or washing the sediment with distilled water.

The presence of Mg and Ca carbonates and exchangeable divalent cations causes flocculation of soil particles in suspension. Small quantities of carbonates will normally be adequately dispersed by sodium hexametaphosphate (see following discussion of deflocculation under Analytical Procedures). For efficient dispersion of samples containing large quantities of carbonates, it will be necessary to remove them by washing with a slightly acid sodium acetate (Na₃H₂O₄ • 3H₂O, 1N, 136 g/l adjusted to pH 5 with acetic acid).

Effervescence, when a few drops of diluted HCl acid is applied to a spoonful of the sample, indicates that carbonates are present. To remove carbonates, add 50 milliliters of Na O Ac buffer solution to each 5 grams of sample and bring to suspension by stirring with a rubber tip on a glass rod (policeman). Digestion is aided by placing the beaker in a near-boiling sand or water bath for 30 minutes. The suspension is then washed by filtering with a filter candle equivalent to the Pasteur-Chamberlain candle, or Selas-type FP porcelain candle (02 or 03 porosity). Some samples may require two or more treatments.

After soluble salts and organic matter have been removed from the sample, filtration is required. Remove excess liquid with the filter candle. When the filter candle becomes coated with soil, reverse the stopcock, and apply pressure with the rubber bulb touching the candle lightly against the inner wall of the beaker to dislodge the soil from the candle. Resume filtration process, removing the coatings frequently to reduce impedance of flow.

After free water has been removed, add distilled water and mix the suspension by a jet of water. Filter again and repeat the mixing and filtering several times. After filtering is completed, apply pressure to the filter candle, as before, to dislodge as much soil as possible and wash remainder back into the beaker with a water jet using a policeman to dislodge particles. Remove filter and proceed as outlined as follows.

**Analytical procedures** described below will not provide a record of the quantity of organic matter and soluble salts in the sample. The proportions in the various particle size ranges are computed on an organic-free basis. If the quantity of organic matter and soluble salts is required, the supernate is removed, the sample is dried and the net dry weight determined before these items are removed. The following procedures may be used:

- Pretreat samples if necessary in accordance with procedures outlined. After pretreat-
FIGURE 4.56.—Pipette apparatus for determining particle size of fine sediments: Top, laboratory arrangement with vertical moving rack and horizontal moving carriage for pipetting from several cylinder; bottom, diagram showing relationship of components.
ment, remove excess water with a filter candle, place samples in a tared evaporation dish, dry at 100 to 110°C and weigh to nearest 0.1 milligram. (Note: If sample to be analyzed is a suspended sediment sample and both concentration and particle are required, determine the net weight of the water-sediment mixture to the nearest 0.1 g before sample processing begins.)

- Determination of ultimate particle sizes which will require dispersion of the sample. Obtain deflocculation by adding a dispersing agent. Ten milliliters of dispersing agent (40 g of sodium hexametaphosphate \([\text{Na}_6\text{PO}_{10}\text{O}_{24}]\), and 8 grams sodium carbonate in distilled water diluted to one liter) per 5 to 10 grams of sample is usually sufficient to obtain dispersion. After adding the dispersing agent, obtain dispersion by: (1) transferring the sample to a 250-milliliter shaker bottle, adding distilled water to bring the volume to 180 milliliters and shaking overnight in a horizontal reciprocating shaker, or (2) stirring with a mechanical analysis stirrer (malt machine) for 2 to 5 minutes.

- Determine the dissolved solids correction for each new solution of the dispersing agent. This can be accomplished by: (1) adding 10 milliliters of dispersing agent to a calibrated sedimentation cylinder, (2) diluting to volume with distilled water, (3) mixing thoroughly and withdrawing 25 milliliters, (4) transferring aliquot to a tared evaporating dish, (5) drying overnight at 105 to 110°C, and (6) weighing the dish and contents to the nearest 0.1 milligram. Perform in triplicate and use the average. The net weight of the dissolved solids is subsequently subtracted from the net weight of each pipette withdrawal.

Even though most analyses will be made to determine the ultimate particle size, and dispersion will be required, it may be desirable to make some analyses in native water without deflocculation to determine fall velocity characteristics most closely resembling those in the natural state. In other cases, the concentration of chemical constituents may be so low that dispersion is not required.

- Weigh each sedimentation cylinder while empty, fill to calibration mark, for example, 500 to 1,000 milliliters with distilled water and weigh again for at least three times. Do the same for each 25-milliliter pipette. The ratio of the mean weight of the water in the cylinder to the mean weight of the water in the pipette is subsequently used as a volume ratio in computing the results of the withdrawals.

- Select particle size determinations to be made, and using table 4.11, set up a schedule for time of withdrawal and depth from which withdrawal is to be made.

- Using a No. 230 (0.062 mm) sieve and distilled water, wet-sieve the dispersed sample and transfer all the material passing through the sieve to a sedimentation cylinder. Dilute the sample to one liter with distilled water. Place sands portion of sample in a tared evaporation dish, dry in oven, weigh to nearest 0.1 milligram and determine net weight.

- When ready for pipetting, place a rubber stopper in the end of the sedimentation cylinder. Suspend the material by vigorously shaking the cylinder while turning it end over end. After this, stir the sample for 1 minute with an up and down motion of the brass plunger stirring rod.

- As soon as the stirring operation is finished, immediately lower the pipette 10 centimeters into the sample and take a "zero time" withdrawal for computing the total concentration of the fines. Take the temperature, and stir the sample again for 1 minute. After this, proceed with subsequent withdrawals according to the time and depth schedule selected. Always measure the sampling depth from the existing surface of the suspension and not from the level used for an earlier withdrawal.

- The initial withdrawal and all subsequent withdrawals, together with one pipette flushing of distilled water for each sample, are emptied into numbered and tared evaporating dishes. After each flushing, touch the tip of the pipette to the side of the evaporating dish to remove any remaining suspension. A pressure bulb may be used to blow any remaining droplets from the pipette tip.

- Ovendry the pipette withdrawals overnight at 100 to 110°C, cool in a desiccator, weigh on an analytical balance to the nearest 0.1 mg, and determine net sediment weight. Pipette analyses may be tabulated in a format as shown in figure 4.57, may be used in reporting the results. Enter sample location date, time
Sample Data

<table>
<thead>
<tr>
<th>Stream or Station:</th>
<th>Lab. Crk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location:</td>
<td>Oxford, Miss.</td>
</tr>
<tr>
<td>G.H.:</td>
<td>3:20</td>
</tr>
<tr>
<td>Date:</td>
<td>4-15-69</td>
</tr>
<tr>
<td>Time:</td>
<td>10:15 P.M.</td>
</tr>
<tr>
<td>Composite:</td>
<td></td>
</tr>
<tr>
<td>No. Bottles:</td>
<td></td>
</tr>
<tr>
<td>Sample Weight:</td>
<td></td>
</tr>
<tr>
<td>Gross:</td>
<td>463.16 g</td>
</tr>
<tr>
<td>Tare:</td>
<td>358.6 g</td>
</tr>
<tr>
<td>Net:</td>
<td>105.0 g</td>
</tr>
<tr>
<td>Remarks:</td>
<td></td>
</tr>
</tbody>
</table>

Dispersing Agent Correction

| Vol.:             | 25 cc. |
| Dish No.:         | 241    |
| Gross:            | 45.0389 g |
| Tare:             | 45.6293 g |
| Net:              | .0096 g  |

Remarks:

Fines < .062 mm.:*  
Sand > .062 mm.:  
Total Sediment

| Gross:            | 41.4886 g |
| Tare:             | 41.3378 g |
| Net:              | 150.8 g   |
| Conc.:            | 1436 ppm  |

| Gross:            | 103.1467 g |
| Tare:             | 102.0000 g |
| O.M.:             | .01368 g   |
| Net:              | .1331 g    |
| Conc.:            | 10.791 ppm |

**Fines by immediate withdrawal, i.e., "zero time".

Note: Fines by difference and fines by immediate withdrawal should not differ by more than 5 or 10 percent.

Figure 4.57.—Sample laboratory worksheet for pipette analysis.
and other information at the top of the form. Record gross, tare and net weights of the total sample, sands portion, and dispersing agent in spaces provided. Prior to pipetting, record the temperature of the suspension, the depth of withdrawal, settling time, and the weights of the numbered containers for each withdrawal. The calculations are carried out as follows:

• From the initial “zero time” withdrawal, determine the net weight of the fines in the suspension and record on the form. Make a dissolved solids correction if a dispersing agent was used prior to pipetting. Compute the total weight of fines by multiplying the weight of fines in the suspension by the volume ratio.

• Determine the net dry weight of the sediment in each subsequent pipette withdrawal and multiply by the volume ratio. This gives the weight of sediment in suspension finer than the size corresponding to the time and depth of withdrawal.

• To obtain the fraction of total sediment finer than the indicated size, divide the weight of sediment in the sample finer than the size corresponding to the time and depth of withdrawal by the dry weight of the total sediment in the sample.

• To obtain the concentration of the fines, sands and total sample in parts per million, divide the total net weight of each by the weight of the total sample (water-sediment mixture) and multiply by one million. Enter in the spaces provided on the form.

Coarse Sediments

Two generally accepted methods, sieving and the visual accumulation tube, are given for determining the size distribution of sand sizes (0.062 to 32.0 mm) particles. Larger size particles, including rock and boulders, require direct measurement, measurement by volume displacement, or some other means (65).

Sieving.—Both wet and dry sieving methods are used to separate sand particles. In wet sieving, as the name implies, material finer than the sieve opening is washed through, preferably while the sample and sieve screen are submerged in water. Dry sieving requires a completely dry sample.

In sieving, the size of the sample is important. Care must be taken to prevent overload-
usually 0.062 millimeter, is analyzed by other methods. For dry sieving the following analytical procedures are used:
- Set up a nest of sieves on a mechanical shaker with the coarsest sieve on top and the finest on the bottom.
- Place sample on the coarsest sieve, and simultaneous separation of fractions is obtained by shaking for about 10 minutes on a mechanical shaker and tapping machine. Weights of material for each size fraction are determined in the manner prescribed for wet sieving.

Data can be reported as follows:
- The sizes outside the sieving range are analyzed by methods described for large particles and the weights entered on a suitable worksheet as single entries for sizes larger and sizes smaller, figure 4.58.
- The weights and percentage of material for each sieved fraction are determined and entered on the form. Concentration of each size in parts per million or milligrams per liter may be computed if desired.

**Visual accumulation tube method.**—The visual accumulation (VA) tube method is intended

<table>
<thead>
<tr>
<th>Location</th>
<th>H.S. Exp. Sta. # 92</th>
<th>Date</th>
<th>9-1-67</th>
<th>Time</th>
<th>10:30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station</td>
<td>Washd #2-Comp-1</td>
<td>Gage Height</td>
<td></td>
<td>Water Discharge</td>
<td>cfs</td>
</tr>
<tr>
<td>Method of sampling</td>
<td>Grab Sample - Sample # 92</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Analysis:**
Method 3IN SIEVE Date 10-13-67 By J.T.B. Comp. by J.T.B. Checked by S.L.T.

**Remarks**
Dish # 249 - Rotap - Time 10 min.

<table>
<thead>
<tr>
<th>Sieve size in mm.</th>
<th>&lt;2.000</th>
<th>2.000-</th>
<th>1.000-</th>
<th>0.500-</th>
<th>0.250-</th>
<th>0.125-</th>
<th>0.062-</th>
<th>&lt;0.062</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross</td>
<td>57.8441</td>
<td>58.0334</td>
<td>59.1319</td>
<td>60.6241</td>
<td>60.8169</td>
<td>61.3415</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tare</td>
<td>57.8253</td>
<td>57.8441</td>
<td>58.0334</td>
<td>59.1319</td>
<td>60.6241</td>
<td>60.8169</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net</td>
<td>0.0188</td>
<td>0.1893</td>
<td>1.0985</td>
<td>1.4922</td>
<td>1.928</td>
<td>5.246</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% of Total</td>
<td>0.53</td>
<td>5.38</td>
<td>31.24</td>
<td>42.44</td>
<td>5.48</td>
<td>14.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Finer*</td>
<td>100.00</td>
<td>100.00</td>
<td>99.47</td>
<td>94.09</td>
<td>62.85</td>
<td>20.41</td>
<td>14.92</td>
<td></td>
</tr>
</tbody>
</table>

Total Sediment Portion >4.00 mm. Portion <0.062 mm.
Gross 61.3415 g. Gross __________ g. Gross __________ g.
Tare 57.8253 g. Tare __________ g. Tare __________ g.
Net 3.5162 g. Net __________ g. Net __________ g.

* % Finer than upper limit.

**Figure 4.58.—Sample sieve analysis worksheet.**
primarily for particle size analyses of sand size material. The suggested size range is from 0.053 to 2.0 millimeters. Sizes outside this range should be removed by sieving and analyzed by methods described for large particles.

The VA tube is a simple, fast, relatively inexpensive method based on the hydraulic properties of the particles and the fall velocity or fall diameter. Stratification of the settled particles is, however, not a definite indication of physical sizes, especially if the sample contains considerable amounts of organic matter and heavy or light minerals. The results are expressed as the sedimentation diameters of the particles which are usually better suited for studies of sediment transport and deposition.

Samples must be prepared so that each particle falls as an individual unit. Particles should be free of clay, organic matter, and air bubbles. Dry samples must be dispersed in water before analyses and should be allowed to soak for several hours. Samples which have been stored for a period of time may require a dispersing agent to obtain complete separation of particles, and hydrogen peroxide may be required to remove algae.

Detailed instructions on the operation of the visual accumulation tube have been prepared by the Federal Inter-Agency Sedimentation Project (38). A condensed version of these instructions is given below. It is recommended, however, that the laboratory technician obtain a copy of the operator's manual before analyses are attempted.

**Equipment and supplies** required are as follows:
- • VA apparatus (fig. 4.59).
- • Tubes for VA apparatus of all sizes shown in table 4.12.
- • VA recording charts (fig. 4.60).
- • Special funnel for VA apparatus.
- • Stirring rod for use in mixing chamber.
- • Evaporating dishes and drying oven.
- • Sieves for separating the fines and materials larger than 2.0 millimeters from the VA sample.

**Analytical procedures** are as follows:
- • Prepare the sample by wet-sieving out all materials smaller than 0.053 millimeters and all materials larger than 2.0 millimeters. After sieving, treat the sample with 30 percent hydrogen peroxide solution to remove organic matter and to destroy algal growth. Add dispersing agent if necessary to obtain complete separation of particles. Distilled water of the same temperature as the water in the tube ±2° C, should be added to the sample until about 40

---

4 Communication regarding drawings, specifications and availability of the visual accumulation tube may be addressed to: Federal Inter-Agency Sedimentation Project, St. Anthony Falls Hydraulic Laboratory, Hennepin Island and Third Avenue, S.E., Minneapolis, Minn. 55414.


<table>
<thead>
<tr>
<th>Station</th>
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<th></th>
<th></th>
<th></th>
</tr>
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<tbody>
<tr>
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<td></td>
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</tr>
<tr>
<td>C.Ht</td>
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<tr>
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<tr>
<td>Rate analyzed</td>
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<tr>
<td>Remarks</td>
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</tbody>
</table>

**SIZE DISTRIBUTION**

<table>
<thead>
<tr>
<th>Diameter (microns)</th>
<th>Percent finer than (from graph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>100</td>
</tr>
<tr>
<td>700</td>
<td>94</td>
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<td>125</td>
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<td>88</td>
<td>11</td>
</tr>
</tbody>
</table>

**Figure 4.60.—Visual accumulation tube recorder chart for 120-centimeter tube showing method of reading particle size distribution.**
null
coarser percentages of a given size, a scale calibrated from 0 to 100 is used. To read percentages, finer than a given size, place the scale on the chart so that the 0 mark coincides with the total accumulation level and the 100 mark with the baseline (fig. 4.60). Maintaining this position, move the scale horizontally to the intersection of the accumulation curve with the desired size and temperature line. The scale reading at the point of intersection then gives the percentage of the sample which is finer than the size for which the reading is made. To obtain the coarser percentage, the scale is inverted and the same procedure followed.

In most cases, the VA sample will only be a portion of the total sample. If desired, the above procedure can be modified so that the readings will be in percentages finer than the specified size for the total sample. For example, if 50 percent of the sample is removed as finer material and 10 percent is removed as coarser material, the 90 mark on the calibrated scale is placed on the baseline and the 50 mark on the total accumulation line. The scale reading at the desired intersection will then be the percentage of the total sample finer than the specified size.

Normally, samples brought to the laboratory will not contain particles larger than very coarse gravel (table 4.8). Particle size of larger particles is usually determined in the field by direct measurement. For relatively spherical particles, the diameter or circumference may be measured directly with calipers or tape. For irregularly shaped particles, the nominal diameter may be obtained by averaging three mutually perpendicular diameters as determined by direct measurements (65).

The nominal diameter of relatively large particles may be determined in the laboratory by volume displacement. Measurements are readily made by placing a particle in a graduated cylinder filled with fluid and determining the volume of fluid displaced. The displaced volume \(V\) is converted to the nominal diameter \(d_n\) of an equivalent sphere by the equation:

\[
d_n = 1.24 \, V^{1/3}
\]  

(4-6)

Cylinders of various sizes are required. To assure reasonable accuracy the diameter of the cylinder should not be more than about two times the nominal diameter of the particle to be measured.

### Specific Gravity

Specific gravity of soil or sediment is defined as the ratio of the total mass of the solid particles to their total volume, excluding pore space between particles. The mass of the particles is obtained directly by weighing the soil or sediment. The volume of the particles is determined by measuring the volume of water they will displace. Specific gravity is usually expressed in grams per cubic centimeters \((g/cm^3)\) (15).

#### Equipment and supplies

Requirements are constant volume pycnometer, drying oven, thermometer, balance and distilled water.

#### Analytical procedures

- Weigh pycnometer filled with distilled water, preferably at 20°C, to the nearest 0.1 milligram.
- Remove a small amount of water, and add a known weight of oven dry sediment.
- Apply suction slowly, or boil the mixture to remove air bubbles. Finish filling pycnometer with distilled water at the same temperature.
- Weigh pycnometer filled with water and sediment to nearest 0.1 milligram.
- Compute specific gravity as follows:

\[
SG = \frac{W_s \times d_n}{W_w - W_{ws} + W_s}
\]  

(4-7)

where

- \(SG\) = specific gravity;
- \(W_s\) = weight of sediment, g;
- \(W_w\) = weight of water, g;
- \(W_{ws}\) = weight of water-sediment mixture, g;
- \(d_n\) = density of water at ambient temperature.

Water temperature should remain relatively constant throughout the procedure. If some liquid other than water is used, the computations must take into account the specific gravity of the liquid and the results should be converted to terms for water.
Specific Weight (Volume Weight) or Bulk Density

Specific weight, volume weight or bulk density is weight per unit volume. It is expressed in grams per cubic meter or, in the English system, in lb/ft$^3$. Specific weight in lb/ft$^3$ is presently the most frequently used form in the United States.

The determination of specific weight of soils or sediment requires the dry weight of an undisturbed sample of a known volume. Although various methods have been developed for soils, undisturbed samples of sediments, particularly submerged sediments, are difficult to obtain (15, 22, 29).

Equipment and supplies required for determining specific weight are a drying oven, drying pans and a balance.

Analytical procedures are as follows:

1. Determine volume of sample. This is usually determined by the size of the sampler used and will be included in the field records.
2. Place sample in a tared drying pan and dry to a constant weight at 105 to 110° C, determine and record net dry weight to nearest 0.1 gram.
3. Compute specific weight as follows:
   
   \[
   \text{Specific weight} = \frac{\text{dry weight of sample (g)}}{\text{sample volume (cc)}}
   \]

   and convert to desired units. Multiply grams per cubic meter by 62.4 to obtain pounds per cubic foot.

   The procedure described above for specific-weight determinations is also used for sludge samples obtained from erosion plot studies. Most sludge samples will be collected in metal or glass containers of a known volume. These containers are usually tared and suitable for oven drying so transfer of the sample is not required. Care must be taken to remove all soil material from the outside of the container before drying and weighing.

Moisture Content

The moisture content of deposited sediments is frequently required in the computations of dry sediment weight.

Equipment and supplies required are a balance, drying oven and drying pans or cans.

Analytical procedures are as follows:

1. Dry sample in the sample can.
2. Weigh wet sample to nearest 0.1 gram as soon as possible after sample is received in the laboratory and before evaporation occurs. Subtract can tare weight and record net wet sediment weight. Be sure all soil and debris are removed from the outside of the can before weighing.
3. Dry sample at 105° to 110° C to a constant weight, subtract can tare weight and record dry sediment weight to nearest 0.1 g.
4. Compute percent moisture as follows:

   \[
   \text{Percent moisture (dry basis)} = \left(\frac{W_{sw} - W_{sd}}{W_{sd}}\right) \times 100
   \]  

   where

   \[
   W_{sw} = \text{weight of wet sediment; and}
   \]

   \[
   W_{sd} = \text{weight of dry sediment.}
   \]

   In erosion studies it is often more advantageous to determine the percent dry matter based on the total weight of the wet sediment:

   \[
   \text{Percent dry matter} = \frac{W_{sd}}{W_{sw}} \times 100
   \]

Computations

Computational procedures described in this section are limited to calculations of sediment discharge from plots and small watersheds, suspended sediment discharge in streams and volume and weight of sediment deposits in reservoirs. The development of sediment-runoff relationships, estimates of bedload transport and calculations of unmeasured (unsampled) sediment load in streams are given in the section on Data Processing.

Sediment Discharge

Runoff rates and/or amounts and sediment concentration of runoff are required for calculations of sediment discharge. Computational procedures vary depending upon the type of data available.
**Plots and Small Watersheds**

Most sediment samples from plot and small watershed investigations are collected with continuous sampling devices such as the multislot divisor and the Coshocton-type sampler. These storm integrated samples are assumed to be representative of the total runoff. The following equations 4.5 may be used in calculations of sediment discharge.

\[
G_s = \frac{Q \times C \times 0.0312}{10^6 \times A}
\]  (4-9)

where:
- \(G_s\) = sediment discharge in tons per acre;
- \(Q\) = storm water discharge in cubic feet;
- \(C\) = storm weighted concentration in parts per million by weight; and
- \(A\) = plot area in acres.

In metric units, equation 4-9 becomes:

\[
G_s = \frac{Q \times C}{A \times 10^3}
\]  (4-10)

where:
- \(G_s\) = sediment discharge in kilograms per hectare;
- \(Q\) = water discharge in cubic meters;
- \(C\) = storm weighted sediment concentration in parts per million; and
- \(A\) = plot area in hectares.

Since runoff from small areas is usually computed in inches depth on the study area, equation 4-9 may be reduced to:

\[
G_s = Q_i \times C \times 113.3 \times 10^6
\]  (4-11)

where:
- \(Q_i\) = instantaneous sediment discharge rate in tons per second;
- \(q\) = water discharge in cubic feet per second; and
- \(C\) = concentration in parts per million by weight for runoff rate \(q\).

In metric units equation 4-13 reduces to:

\[
g_i = \frac{q \times c}{10^6}
\]  (4-14)

where \(g_i\) is in kg/s and \(q\) in m³/s.

In addition to suspended sediment discharge, most plot and small watershed installations will require the measurement of sediment deposits in the flumes, approach channels and aprons. This is usually accomplished by collecting and weighing the material in the field. Samples are taken as the material is weighed, and the percentage of dry material determined in the laboratory. Dry weight of the deposits is computed as follows:

\[
W_{dn} = W_{sw} \times P_{dm}
\]  (4-15)
where

\[ P_{dm} = \text{percent dry material and } W_{od} \text{ and } W_{st} \]

are as previously defined.

The procedure is as follows:

- Enter plot identification information and the sampler ratio in spaces provided at the top of the form (fig. 4.10). The sampler ratio is the proportion of the total runoff extracted by the sampler.
- Enter date of storm, storm number, volume of runoff sample, sediment concentration, weight and percent dry matter of flume and channel deposits, in columns 1, 2, 3, 6, 8, and 9, respectively. This information is obtained from the field and laboratory records. Chart runoff, column 5, is obtained from the runoff records, for example, from the stage-discharge relationship for the \( H \) flume. Assignment of storm numbers is optional.
- Compute quantity of runoff from sample volume, and record in column 4.

**FIGURE 4.61.—** Percentage error introduced and correction factor to be applied when a constant specific weight (1 g/cc) is assumed for the water-sediment mixture in computations of sediment discharge.
The constant $K$ converts runoff in cubic feet to inches of depth over the plot area. The value of the constant is computed as follows:

$$K = \frac{1 \text{ ft}^3}{(\text{Plot area, ft}^2) \text{ ft}}$$  \hspace{1cm} (4-17)

- Compare runoff values in columns 4 and 5. If they are approximately equal, either may be used in the computations of sediment discharge. If they differ significantly, the field notes may indicate that one or the other is incorrect. Most investigators prefer to use the chart runoff values unless field records indicate they may be erroneous.

- Compute sediment discharge and enter in column 7:

$$(\text{Column 5})(\text{Column 6})(0.000113) = \text{Sediment discharge (tons per acre)}$$

- Compute dry weight of flume and channel deposits and record in column 10:

$$(\text{Column 8})(\text{Column 9}) = \text{dry weight (lb)}$$

- Convert dry weight, column 10, to tons per acre and record in column 11:

$$\frac{\text{Column 10}}{2000} (\text{Plot area, acre}) = \text{tons per acre}$$

- Add Columns 7 and 11 to obtain total sediment discharge and record in column 12.

Plots equipped with multislot divisor samplers.—Field and laboratory data from a typical runoff event will include: (1) volume or weight and percent dry matter of sludge, flume and channel deposits, (2) volume and sediment concentration of the sample collected in the aliquot tanks and (3) volume and suspended sediment concentration of water in the sludge tank. Unless the $H$ flume or other flow measuring device has been used to measure runoff, it is determined by multiplying the volume of the sample in the aliquot tanks by the number of slots in the divisor unit. This quantity plus the volume of runoff trapped in the sludge tank equals total plot runoff.

![Table](image)
In determining the volume of runoff trapped in the sludge tank, the volume occupied by sludge must be considered. Normally, this is done by taking volumetric samples of the sludge and determining the average volume of water per unit volume of sludge. For a given soil type, the same values may be used from storm to storm without appreciable error.

A summary calculations and tabulation sheet, figure 4.6, will expedite computations and provide a permanent record of the results. The computational procedure is as follows:

- Enter plot identification information and number of divisor slots in spaces provided at the top of the form.
- Insert data in columns 1, 2, 3, and 4 from field record sheet. The sum of the volumes in both the first and second aliquot tanks (fig. 4.2) is recorded in column 3. Subtract volume of sludge from total volume of water and sludge before recording water volume in column 4. Assignment of storm numbers is optional.
- Compute plot runoff and enter in column 5:

\[
\text{Column 3} \times \text{(Number of Divisor Slots)} + \text{Column 4} = \text{Runoff (ft}^3)\]

- Compute plot runoff in inches and enter in column 6:

\[
\frac{\text{Column 5}}{\text{Plot area (acres) (43560)}} \times 12 = \text{Runoff (in)}
\]

- Obtain suspended sediment concentration in the aliquot and sludge tanks from laboratory worksheet, and enter in columns 7 and 9. If a sample is collected in both the first and second aliquot tanks, a volume weighted concentration is determined and entered in column 7.

\[
\frac{(\text{Vol. Tank #1} \times \text{Conc.}) + (\text{Vol. Tank #2} \times \text{Conc.})}{(\text{Vol. Tank #1}) + (\text{Vol. Tank #2})} = \text{Weighted Concentration}
\]

- Compute weight of suspended sediment discharge and enter in column 8:

\[
\frac{(\text{Column 4}) \times (\text{Column 9}) \times (62.4)}{10^6} = \text{Sediment weight (lb)}
\]

- Compute weight of suspended sediment in the sludge tank and record in column 10:

\[
\frac{(\text{Column 4}) \times (\text{Column 9}) \times (62.4)}{10^6} = \text{Sediment weight (lb)}
\]

- Obtain weight of sludge and percent dry matter from field and laboratory records, and enter in columns 11 and 12. Compute dry weight of sludge and record in column 13:

\[
\frac{(\text{Column 11}) \times (\text{Column 12})}{\text{(Vol. Tank #1) + (Vol. Tank #2)}} = \text{Sludge dry weight (lb)}
\]

Note: If the volume of sludge is measured, instead of weighed, the dry weight of material per unit volume, as determined in the laboratory from samples of a known volume, must be used in the computations and the form revised accordingly. Sludge volume is usually recorded in cubic feet and the dry weight in pounds per foot. Dry weight is then the product of the two.

- Obtain weight of flume and channel deposits in column 14 and percent dry matter in column 15 from field and laboratory records.

- Compute total dry weight of flume and channel deposits and enter in column 16:

\[
\frac{(\text{Column 14}) \times (\text{Column 15})}{\text{Sediment dry weight (lb)}} = \text{Sediment dry weight (lb)}
\]

- Compute total sediment weight and enter in column 17:

\[
\text{Column 8} + \text{Column 10} + \text{Column 13} + \text{Column 16} = \text{Total sediment weight (lb)}
\]

- Convert total sediment weight to tons and record in column 18:

\[
\frac{\text{Column 17}}{2000} = \text{tons}
\]
• Determine sediment discharge in tons per acre or other suitable units and record in column 19:

\[
\frac{\text{Column 18}}{\text{Plot area (acres)}} = \text{tons per acre}
\]

**Computation of Suspended Sediment Discharge From the Sediment Concentration-Water Discharge Relationship**

Computation of suspended sediment discharge from watersheds too large for continuous sampling require the development of a water discharge-sediment concentration relationship. This relationship is established by frequent sampling at various water discharge rates throughout the runoff event. The following procedure may be used when the sediment concentration values are representative of the total flow cross section.

• Plot sediment concentration values directly on the water-stage chart, and draw in a smooth concentration curve (fig. 4.64). This will require interpolation between sample points. If only two or three samples were obtained during a runoff event, it will be necessary to use data obtained from similar runoff events or from a previously established sediment rating curve. The development of sediment rating curves is discussed in the section on Data Processing, p. 329).

• Prepare a computations form similar to the one shown in figure 4.65, and enter the station number or name, location and other pertinent information in the spaces provided.

• Enter date, time, gage height (stage), and concentration from the time-stage-concentration chart in columns 1, 2, 3, and 4. Tabulate gage heights (water stage) and concentrations at all noticeable break points in the runoff hydrograph. When daily sediment values are required, an entry is made at midnight.

• Determine the discharge for each water stage selected from the station's rating table (table 4.13), and enter in column 5.
• Determine the time interval between break points, and enter in column 6.
• Compute the mean concentration for each time interval, and enter in column 7.
• Compute the mean water discharge rate for each time interval, and enter in column 8.
• Compute watershed constant to convert average water discharge rate for time interval to volume. In figure 4.65, the constant was computed to provide interval runoff in inches as follows:

\[
\frac{1 \text{ ft}^3/s \times 60 \text{ s/min}}{43,560 \text{ ft}^2/\text{acre} \times 44.3 \text{ acre}} \times 12 \text{ in/ft} \times \text{min/interval} = 3.73 \times 10^{-4} \text{ in/interval}
\]

• Compute interval runoff, and enter in column 9:

(\text{Col 6}) (\text{Column 8}) (3.73 \times 10^{-4}) = \text{Runoff (in)}

• Compute a constant to convert sediment volume to weight. This constant is computed to provide sediment discharge in the units desired. In figure 4.65, the constant was computed to provide tons per time interval.

\[
\frac{1 \text{ ft}^3/s \times 60 \text{ s/min}}{\text{min/interval} \times 62.4 \text{ lb/ft}^3} \times \frac{2,000 \text{ lb/tons}}{10^6} = 1.872 \times 10^{-6} \text{ tons/interval}
\]

• Compute sediment discharge, and enter in column 10:

(\text{Column 6}) (\text{Column 7}) (\text{Column 8}) (1.872 \times 10^{-6}) = \text{Sediment (tons)}

Add columns 9 and 10 to obtain total water and sediment discharge in inches and tons for the day or for the runoff event.

For some large perennial streams, it is often desirable to compute a mean daily water and sediment discharge. Changes in water stage and discharge in large streams are usually much slower which permits tabulation of discharge rates at multiples of a fixed time interval. This simplifies the computations.

A typical data tabulation sheet for a large
stream is shown in table 4.14. Mean water and sediment discharge rates were selected in multiples of 15 minutes. Suspended sediment discharge rates for each time interval were computed as follows:

\[ G_s = Q \times C \times 0.0027 \]  

(4-18)

where

- \( G_s \) = sediment discharge in tons per day,
- \( Q \) = water discharge in cubic feet per second
- \( C \) = sediment concentration in parts per million.

The mean daily suspended sediment discharge rate was determined by multiplying the number of 15-minute time periods in each time interval times the mean interval sediment discharge rate, summing the values and dividing the total by the total number of 15-minute time periods.

Converted to metric units, equation 4-18 becomes:

\[ G_s = Q \times C \times 86.4 \]  

(4-19)

where

- \( G_s \) is in kilograms per day
- \( Q \) in cubic meters per second.

Stage-Area Curve Method

The stage-area method is probably the most accurate for all types of small reservoirs. A detailed topographic map is required. One- or two-foot contour intervals are usually adequate. The procedure is as follows:

- Prepare a detailed contour map of the reservoir (fig. 4.66) from the field survey notes. Field data usually consist of elevations at break points across selected ranges and a field determination (plane table map) of the contour at the upper spillway elevation and one lower elevation. Additional contours are drawn by interpolating between established elevations along the ranges.
- After the contour map is prepared, the area enclosed by each contour is determined with the planimeter. Planimetering is usually done in segments with dividing lines along established ranges. Segments should be approximately equal in length.
- Determine total area enclosed by each contour by totaling each of the contour areas for all segments and plot the stage-area curve (fig. 4.67).
- Using the stage-area curve, determine the volume between each set of adjoining contours by planimetering the area between the curve and corresponding elevations on the stage axis. The capacity or volume between elevations 7295 and 7296, figure 4.67, is represented by the shaded area. If the graph scales are selected so that 1 acre equals 1 inch (12.8 mm) and 1 foot (30.4 cm) equals 1 inch (12.8 mm) the area of the shaded portion in square inches is also the capacity in acre-feet. (If the stage-area curve is drawn in straight lines between contour elevations, as in figure 4.67, the shaded area may be calculated directly. Refer to the average-contour method described by Rausch and Heinemann (56). This closely approximates the stage-area curve method.
- Add the volumes between all sets of adjoining contours to obtain total reservoir capacity. Check summation by planimetering total area bounded by stage-area curve and the stage axis. A typical tabulation form is shown in figure 4.68.
- Determine volume of sediment deposits (segment by segment) between successive ele-
vation increments by subtracting present capacity from original capacity. Add volumes for all increments to obtain total sediment volume.

- Compute weight of sediment deposits by segments by (1) plotting cross sections for each range on an expanded depth scale (fig. 4.69); (2) locating sample points on each cross section; record sediment volume-weight (specific weight) from laboratory records and draw equal weight contour lines (dashed lines mostly horizontal); (3) subdividing range cross section into areas represented by each sample (vertical dashed lines, fig. 4.69); (4) computing weighted average volume-weight of sediment deposits, by each segment between ranges, as illustrated in table 4.15; (5) multiply weighted volume-weight of sediment in segment between ranges by volume of segment deposits, as determined in the step for obtaining the weight of segment sediment deposits.

- Add weights of segment deposits to obtain total weight of sediment deposits in reservoir.

**Modified Prismatic Method**

The modified prismoidal method is probably less accurate than the stage-area curve
method, but the computations are relatively simple and easily automated. The equation is:

\[ V - L/3 \left( A = \sqrt{AB} + B \right) \]  

(4-20)

where:

- \( V \) = capacity between contours, acre-feet or cubic meters;
- \( L \) = contour interval, feet or meters;
- \( A \) = area of lower contour, acres or square meters; and
- \( B \) = area of upper contour, acres or square meters.

A schematic representation of the symbols is given in figure 4.70.

The computational procedure is as follows:

Following procedures given in the first two steps for the stage-area curve method, prepare a contour map and determine the area of each contour.

- Compute volume or capacity between contours using equation 4-11. Sum to obtain total reservoir capacity.
- Tabulate capacity, area and stage as illustrated by figure 4.18. Determine volume of sediment deposits for each vertical segment by

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### TABLE 4.13.—Rating table, Watershed C-3, Chickasha, Okla.

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<thead>
<tr>
<th>Head</th>
<th>Discharge in cubic feet per second</th>
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<td>199.8</td>
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<td>3.0</td>
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</table>
TABLE 4.14.—Sample computations form—mean daily water and sediment discharge, Station W-92, Cuffawa Creek, Marshall County, Miss.

<table>
<thead>
<tr>
<th>Time</th>
<th>Number of intervals</th>
<th>Water stage</th>
<th>Water discharge</th>
<th>Sediment concentration</th>
<th>Sediment discharge</th>
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<td>Ft</td>
<td>Ft/s</td>
<td>P/m</td>
<td>Tons</td>
</tr>
<tr>
<td>May 5, 1960</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12:00 pm- 5:15 am</td>
<td>21</td>
<td>3.53</td>
<td>0</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>5:15 pm- 5:30 am</td>
<td>1</td>
<td>4.02</td>
<td>25</td>
<td>800</td>
<td>54</td>
</tr>
<tr>
<td>5:30 pm- 6:00 am</td>
<td>2</td>
<td>4.12</td>
<td>40</td>
<td>840</td>
<td>91</td>
</tr>
<tr>
<td>6:00 pm- 6:15 am</td>
<td>1</td>
<td>4.75</td>
<td>540</td>
<td>7,200</td>
<td>10,500</td>
</tr>
<tr>
<td>6:15 pm- 6:30 am</td>
<td>1</td>
<td>5.90</td>
<td>1,330</td>
<td>14,900</td>
<td>53,500</td>
</tr>
<tr>
<td>6:30 pm- 6:45 am</td>
<td>1</td>
<td>7.03</td>
<td>2,320</td>
<td>16,000</td>
<td>100,000</td>
</tr>
<tr>
<td>6:45 pm- 7:00 am</td>
<td>1</td>
<td>8.00</td>
<td>3,300</td>
<td>15,900</td>
<td>142,000</td>
</tr>
<tr>
<td>7:00 pm- 7:15 am</td>
<td>1</td>
<td>8.15</td>
<td>3,390</td>
<td>15,700</td>
<td>144,000</td>
</tr>
<tr>
<td>7:15 pm- 7:30 am</td>
<td>1</td>
<td>8.00</td>
<td>3,210</td>
<td>14,400</td>
<td>125,000</td>
</tr>
<tr>
<td>7:30 pm- 8:00 am</td>
<td>2</td>
<td>7.64</td>
<td>2,780</td>
<td>12,300</td>
<td>92,300</td>
</tr>
<tr>
<td>8:00 pm- 8:15 am</td>
<td>1</td>
<td>7.25</td>
<td>2,500</td>
<td>10,000</td>
<td>67,500</td>
</tr>
<tr>
<td>8:15 pm- 8:45 am</td>
<td>2</td>
<td>6.68</td>
<td>1,960</td>
<td>8,200</td>
<td>43,400</td>
</tr>
<tr>
<td>8:45 pm- 9:15 am</td>
<td>2</td>
<td>6.18</td>
<td>1,580</td>
<td>6,630</td>
<td>28,300</td>
</tr>
<tr>
<td>9:15 pm- 9:45 am</td>
<td>2</td>
<td>5.80</td>
<td>1,250</td>
<td>5,620</td>
<td>19,000</td>
</tr>
<tr>
<td>9:45 pm-10:30 am</td>
<td>3</td>
<td>5.33</td>
<td>852</td>
<td>4,670</td>
<td>10,700</td>
</tr>
<tr>
<td>10:30 pm-11:15 am</td>
<td>3</td>
<td>4.88</td>
<td>620</td>
<td>3,960</td>
<td>6,630</td>
</tr>
<tr>
<td>11:15 am- 1:00 pm</td>
<td>7</td>
<td>4.83</td>
<td>360</td>
<td>3,140</td>
<td>3,060</td>
</tr>
<tr>
<td>1:00 pm- 3:30 pm</td>
<td>10</td>
<td>4.75</td>
<td>149</td>
<td>2,190</td>
<td>881</td>
</tr>
<tr>
<td>3:30 pm- 6:00 pm</td>
<td>10</td>
<td>4.46</td>
<td>84</td>
<td>1,380</td>
<td>313</td>
</tr>
<tr>
<td>6:00 pm-12:00 pm</td>
<td>24</td>
<td>4.24</td>
<td>38</td>
<td>660</td>
<td>68</td>
</tr>
<tr>
<td>Total</td>
<td>96</td>
<td>48,013</td>
<td>261,490</td>
<td>1,095,648</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>438</td>
<td>2,720</td>
<td>11,400</td>
<td></td>
</tr>
</tbody>
</table>

subtracting the present capacity from the capacity at the time of the original survey.

- Compute sediment weight following procedure given in step 7 under the stage-area curve method.

**Average End Area Method**

The average end area method requires a detailed survey and closely spaced cross sections if accuracy is to be obtained. This method requires a determination of the cross sectional area of each range to the same elevation, usually the emergency spillway elevation. The average cross sectional area of adjacent ranges is multiplied by the distance between them to obtain reservoir volume for the segment (fig. 4.71).

Segment volumes are summed to obtain total reservoir capacity. The computational procedure is as follows:

- Plot the cross sections with an expanded depth scale as shown in figure 4.71.
- Determine the area of each cross section to the spillway elevation by planimetering.
- Determine the average cross sectional area of two adjacent ranges, \( A_1 \) and \( A_2 \), and multiply by the distance, \( L \), between them to obtain segment volume, \( V_i \):

\[
V_i = \frac{A_1 + A_2}{2} L \tag{4-21}
\]

- Sum the volumes of each segment to obtain the total reservoir capacity.
- Subtract total reservoir volume from volume at time of original survey to determine volume of sediment deposits.
- Compute sediment weight following procedures given in step 7 for the stage-area curve method.
Figure 4.66.—Contour map of Kiowa Creek Reservoir, Kiowa, Colo.

- If the volume of sediment deposits is all that is required, the area of the sediment deposits (shaded area, fig. 4.71) is planimetered and the sediment volume computed directly.

Data Automation

Much of the drudgery of routine data processing has been alleviated by the use of electronic equipment in recent years. Equipment such as the punch tape water-stage recorder, the chart reader, and the digital computer has greatly reduced the time and effort required for routine computations.

Digital computer programs have been developed to perform all of the computations given in this section. Programs are not included in this manual, however, because they vary in format depending upon the computer equipment available and the output desired.

DATA PROCESSING

This section is primarily intended to aid in the preparation of computations and data summaries that are basic inputs for sedimentation research. Field surveys, hydrologic records, and laboratory analyses of streamflow, reservoir, and soil samples are involved. The purpose of this research is to develop a better understanding of such basic sedimentation processes as
soil erosion, sediment transportation, and sediment deposition or yield. This can be accomplished by: (1) measuring rates of soil erosion, sediment in transport, and sediment deposition, along with probable causative variables, and (2) relating measures of each sedimentation process to causative variables by regression, correlation, and other techniques or by formulation and testing of special laboratory or mathematical models.

Specific methods for handling data from fractional-area field plots and small watersheds are reviewed. Attention is then directed to erosion rates and sediment yields from larger areas, channel erosion, and sediment transport processes. Finally, methods and techniques for proc-

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**Figure 4.67.**—Stage-area curve for K-79, Kiowa Creek Reservoir, Kiowa, Colo.
Essing and evaluating data on sediment deposits in reservoirs, lakes, and valleys are discussed. Figure 4.72 adapted from Guy (25) and Johnson (41) enumerates many of the factors affecting sedimentation that must be measured.

**Erosion From Plots and Small Watersheds**

The different methods for measuring soil erosion rates from small experimental areas have been reviewed in the field observations section, page 279. Regardless of method of measurement, data processing should be sufficient to define sediment concentrations and soil loss rates by storm, day, and month.

The most useful data summary can be used for interpretive analyses. In theory, it would be desirable to have a continuous record of runoff and soil loss rates, but such records are costly. Aside from the advantage this affords the hydrologist in interpreting rainfall-runoff relations, it is possible to develop useful relationships between soil loss and affecting variables; for example, rainfall energy or runoff intensity versus sediment concentration or soil loss rate.

In practice, however, soil loss data for small areas are usually collected on a storm basis because (1) collection tank devices are used for

<table>
<thead>
<tr>
<th>Reservoir: K-79, Kiowa Creek</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location: Kiowa, Colorado</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Elevation (ft. msl)</th>
<th>1956 Survey</th>
<th>1965 Survey</th>
<th>Volume of Sediment deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area (ac.)</td>
<td>Capacity (ac. ft.)</td>
<td>Area (ac.)</td>
</tr>
<tr>
<td>7290</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>91</td>
<td>0.61</td>
<td>0.28</td>
<td>0.07</td>
</tr>
<tr>
<td>92</td>
<td>1.09</td>
<td>1.14</td>
<td>0.70</td>
</tr>
<tr>
<td>93</td>
<td>1.90</td>
<td>2.63</td>
<td>1.36</td>
</tr>
<tr>
<td>94</td>
<td>3.09</td>
<td>5.12</td>
<td>2.32</td>
</tr>
<tr>
<td>95</td>
<td>4.03</td>
<td>8.67</td>
<td>3.42</td>
</tr>
<tr>
<td>96</td>
<td>4.81</td>
<td>13.07</td>
<td>4.37</td>
</tr>
<tr>
<td>97</td>
<td>5.48</td>
<td>18.21</td>
<td>5.20</td>
</tr>
<tr>
<td>97.9*</td>
<td>6.19</td>
<td>23.45</td>
<td>5.87</td>
</tr>
<tr>
<td>7300</td>
<td>8.61</td>
<td>38.86</td>
<td>8.23</td>
</tr>
<tr>
<td>02</td>
<td>10.73</td>
<td>58.18</td>
<td>10.44</td>
</tr>
<tr>
<td>04</td>
<td>12.64</td>
<td>81.58</td>
<td>12.42</td>
</tr>
<tr>
<td>06</td>
<td>15.39</td>
<td>109.6</td>
<td>14.85</td>
</tr>
<tr>
<td>07.23**</td>
<td>17.66</td>
<td>129.91</td>
<td>17.20</td>
</tr>
</tbody>
</table>

^Elevation of normal pool — principal spillway

**Elevation of flood pool — emergency spillway**

FIGURE 4.68.—Reservoir sedimentation data tabulation sheet.
economy and field personnel cannot measure and drain these tanks more frequently; (2) these storm data are still quite useful, however, because many concurrent hydrologic variables which affect erosion, such as antecedent soil moisture and rainfall and runoff amounts and intensities, are storm unique and the effect of each can be readily examined.

The SEA National Soil Loss Laboratory at Lafayette, Ind. has defined a storm as a precipitation event greater than 0.50 inch (12.8 mm), or an event of less than 0.50 inch (12.8 mm) having a 15-minute intensity greater than 1 inch per hour. The storm is considered as ended whenever 0.01 inch (.25 mm) or less is recorded in a 6-hour interval. Storm data can be reported in tabular or graphical form as in table 4.16 and figure 4.73.

For a variety of reasons, soil loss rates from a plot or small watershed must sometimes be

![Figure 4.69: Volume-weights in typical segment X bounded by ranges 8 and 9 (56).](image-url)
Figure 4.70.—Schematic representation of symbols used in the modified prismoidal formula (65).
estimated for a storm, a series of storms, or for longer periods. If the missing data are from a replicated plot, one of the most reliable estimates is based on the replicate. Other procedures include the use of double mass comparisons and a method recommended by SEA Biometrical Services.

Storm soil losses for 1969 at McCredie, Mo., plots 30 and 36, are compared by the double mass curve in figure 5.4. Corn is planted on both plots, which have the same fertility and culture background. The cumulative values

### TABLE 4.15.—Example of weighted average volume-weight computations for one segment bounded by 2 ranges

<table>
<thead>
<tr>
<th>Range and number and location on range</th>
<th>Volume-weight reading</th>
<th>Representative X-sectional area</th>
<th>Product of Col. 3 and Col. 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>8: A</td>
<td>30</td>
<td>200</td>
<td>6,000</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>100</td>
<td>4,000</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>200</td>
<td>8,000</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>200</td>
<td>10,000</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>100</td>
<td>6,000</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>150</td>
<td>5,250</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>950</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>39,250</td>
</tr>
<tr>
<td>9: D</td>
<td>35</td>
<td>200</td>
<td>7,000</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>50</td>
<td>2,000</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>200</td>
<td>8,000</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>150</td>
<td>6,750</td>
</tr>
<tr>
<td></td>
<td>55</td>
<td>50</td>
<td>2,750</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>200</td>
<td>8,000</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>100</td>
<td>5,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>950</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>39,500</td>
</tr>
</tbody>
</table>

**Weighted averages:**
- Range 8: $39,250 \div 950 = 41.3 \text{ lb/ft}^2$
- Range 9: $39,500 \div 950 = 41.6$
- **Segment (sum of ranges 8 and 9):** $78,750 \div 1,900 = 41.4 \text{ lb/ft}^2$

where $B$ represents the measured soil loss at plot 36 for the same period as the missing data and $\theta$ is indicated by the slope of the trend line. A missing value for plot 30, for example, is approximated by

$$A = B \tan \theta$$

usually define a more or less consistent ratio of one plot to the other, which is indicated by the slope of the trend line. A missing value for plot 30, for example, is approximated by

$$A = B \tan \theta$$

The double mass curve method should not be the sole basis for estimating missing records for a period as short as a storm or day. Its principal use is for discerning changing erosion tendencies between plots. Independent estimates should be made on the basis of several plots in the vicinity of plot 30 and then averaged. In passing, it should be mentioned that plots 30 and 36 were replicates, and the degree of variation for the June 23rd storm is somewhat surprising. Some variation in the relation was
Figure 4.72.—Principal factors affecting soil erosion and movement.
caused by a rainstorm which delayed the plowing of plot 30.

Another estimating technique was recommended by SEA Biometrical Services because many soil loss records are of insufficient length or the cultural pattern of the plot may not be permanent due to experimental design. Actually, the plot erosion characteristic may also exhibit seasonal or year-to-year changes. Referring to the following tabulation,\(^4^6\) the procedure would be as follows: (1) Select two (or preferably three) measured storms that encompass the period in which a missing value occurred for a plot; (2) Select three or four plots (or more) in which one would expect the relative soil loss performance to be similar to that of the plot where soil loss is missing for a storm; and (3) Compute the missing soil loss value, \(X\), as follows:

\[
X = \frac{PS_1 + sS_2 - G}{(p - 1)(s - 1)} = \frac{4 \times 75 + 3 \times 70 - 381}{(4 - 1)(3 - 1)} = 22
\]

where

- \(P\) = number of plots selected;
- \(S_1\) = total soil loss in plot with a missing value for the selected storms;
- \(s\) = number of storms selected;
- \(S_2\) = total soil loss for the storm in which the missing value occurred for the selected plots; and
- \(G\) = grand total soil loss for selected storms and plots.

\(^4^6\) March 1955 memo from R. E. Uhland (SEA soil and water conservation research specialist) to SEA project supervisors.

<table>
<thead>
<tr>
<th>Storm</th>
<th>Plot</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>(\Sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>42</td>
<td>55</td>
<td>16</td>
<td>143</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>X</td>
<td>26</td>
<td>30</td>
<td>14</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>48</td>
<td>50</td>
<td>25</td>
<td>168</td>
<td></td>
</tr>
<tr>
<td>(\Sigma)</td>
<td>75</td>
<td>116</td>
<td>135</td>
<td>55</td>
<td>381</td>
<td></td>
</tr>
</tbody>
</table>

\[
X = \frac{PS_1 + sS_2 - G}{(p - 1)(s - 1)}
\]

<table>
<thead>
<tr>
<th>Month and day</th>
<th>Rain fall</th>
<th>Run off</th>
<th>Soil loss</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-21</td>
<td>Spread 0-0-60 @ 23 lb acre, Lime @ 1380 lb per acre, and 33-0-0 @ 300 lb per acre, plowed.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-27</td>
<td>Disked and leveled.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-28</td>
<td>Spread aldrin and disked.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-29</td>
<td>Planted corn and spread 6-24-24 @ 200 lb per acre.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-30, 31; 6-1</td>
<td>Spread 33-0-0 @ 250 lb per acre and cultivated corn.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7-9, 7-10</td>
<td>1.88</td>
<td>.75</td>
<td>.86</td>
<td>Sprayed with DDT.</td>
</tr>
<tr>
<td>7-11</td>
<td>Thinned corn to 9-in spacing.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7-18</td>
<td>Spread 33-0-0 @ 125 lb per acre.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9-15, 9-16</td>
<td>5.22</td>
<td>.89</td>
<td>.23</td>
<td></td>
</tr>
<tr>
<td>10-10, 11, 12,</td>
<td>13</td>
<td>8.26</td>
<td>4.86</td>
<td>.53</td>
</tr>
<tr>
<td>10-27</td>
<td>Harvested corn yield—87.8 bu/acre.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-29</td>
<td>Shredded corn stalks.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Sediment Discharges and Watershed Sediment Yields from Streamflow Samples

#### Sampling Methods

Previous sections included methods for collecting streamflow samples and computing sediment discharges. It had been assumed that
FIGURE 4.73.—Storm soil loss and associated hydrologic data, Plot 36, near McCredie, Mo., 1969.

June 23 soil loss at plot 36 = 9.2 tons per acre. From chart: estimated soil loss at plot 30 = 6.6 tons per acre compared with a measured soil loss of 5.6 tons per acre.

FIGURE 4.74.—Double mass curve comparing storm soil losses between experimental plots, near McCredie, Mo.
the sample concentrations represented the run-off-weighted sediment concentration (not the instantaneous or spatial concentration) in the stream cross section at the time of sampling. This is not always the case, because it is often more convenient to collect samples at a single point in a stream cross section (as with the automatic pumping samplers) or in a single vertical of a cross section (as from a depth-integrating sampler mounted on a bridge in some fixed position over midstream) or from a sampling of storm flows near the water's edge (on occasions when sampling access to the entire cross section is impossible). In all these circumstances, it is desirable to establish a relationship between single point (or single vertical) concentration and the mean cross section concentration in order to compute sediment discharge.

Samples drawn from a single point or a single vertical will closely represent the mean cross section concentration in streams where turbulent suspension of sediments is appreciable and/or the sediment particles in transport are nearly all in the silt-clay size range. However, Knisel and Baird ([2]) show some small but statistically significant differences in concentration between depth-integrated and dipped samples, especially during rising stages. Where appreciable quantities of coarse sediment are in transport, a considerable lateral and vertical concentration gradient can exist throughout any given stream cross section. Sample concentrations collected from a single point or single vertical traverse of the stream cross section may vary considerably from the mean. Figure 4.75 shows that the discharge-weighted concentration of suspended sediment for the Missouri River at Kansas City varies appreciably with water depth for coarser sediments but is fairly uniform for fine sediments. Although the data shown in figure 4.76 are from a large drainage system outside our scope of interest, it clearly illustrates several important aspects of sediment transport, even under conditions of nearly steady flow.

Firstly, it should be noted that consecutive sample concentrations of the same vertical traverse show a random fluctuation. Secondly, there is considerable variation of concentration from one vertical to another, so that periodic samples collected at sampling station 30, for example, would tend to be higher than the discharge-weighted mean. Finally, the sediment concentration varies somewhat according to velocity, since water depth is relatively constant throughout the cross section.

Streamflow sampling situations from Pigeon Roost Creek Basin, Miss. show that sample concentrations can be appreciably higher and

![Figure 4.75.—Discharge-weighted concentration of suspended sediment for different particle-size groups.](image-url)
lower than the average in the cross section. The sediment discharge of streams in this part of the Gulf Embayment region of Mississippi is usually composed of one-third sand coarser than about 0.1 millimeter, and the remaining two-thirds is silt and clay. Stationary sediment sampling installations are often located on bridges at midstream, and an observer may be hired to collect depth-integrated samples during storm periods.

Even when the channels are uniform in cross section—with depths at midstream about the same as the depths near the banks—the velocities tend to be higher at midstream. This velocity difference, together with concomitant differences in turbulence, can result in a higher transport rate of the coarse sediment fractions at midstream. The ratio of midstream to cross section concentration can be much greater than unity. Figure 4.77 shows that the ratio tends to decrease with increasing runoff rate. Table 4.17 shows the relation between the single vertical concentration (Y) and the cross section concentration (X) at seven selected locations in the Washita River Basin. The Washita River Basin sediments are mostly fine sand and silt.

Suspended sediment concentrations from the automatic single-stage samples, by contrast, are usually lower than the equal transit rate (ETR) samples which are representative of the entire cross section. Sampling experience in Pigeon Roost Creek Basin and other locations where sands are being transported shows that this coarse sediment fraction is inadequately sampled. It is probable that the design feature of the intake system that prevents recirculation of samples—during periods when the sampler is inundated—also prevents the coarse sediments from entering the sampler.

The degree to which samples collected at a point can represent the stream cross section depends on the location of the sampler intake.
FIGURE 4.77.—Concentration ratios between single vertical sediment samples and samples that represent the entire cross section.

and peculiarities of the instrument, in addition to the runoff rate and the size and quantity of sediment in transport. Such sediment concentrations can be higher or lower than the cross section average.

A typical comparison of pumped samples, with an intake at a single point in the stream, versus representative cross section samples is shown in figure 4.78 for an Oklahoma stream. At higher concentrations (and runoff rates), the pump sampler sediment concentration tends to be somewhat higher than the cross section mean, but the agreement is still quite good. Similar relationships were noted at five other gaging stations where the intake was functioning properly. Regression coefficients were near unity; linear correlation coefficients varied from 0.96 to 0.99 and were significant at the 1-percent level.

In summary, various samplers can be used to determine the discharge-weighted sediment concentrations to satisfactory accuracy; in some circumstances, however, an appreciable adjustment may be necessary.

Evaluating the Accuracy and Consistency of Sample Concentrations

It is occasionally difficult to distinguish sampling errors (or occasional errors in laboratory analysis) from random fluctuations caused by the dynamic conditions of sediment transport. For an effective research effort into some aspects of sediment transport, it has been necessary to distinguish between these sampling inaccuracies and inconsistencies due to turbulence or other random fluctuations. Estimates of the accuracy or representativeness of sediment sample concentrations (and therefore sediment discharges) have not been resolved, but useful discussions on the subject by Colby (8), and Coleman (12), and Guy (23) can furnish insights to specific problems of this nature.

The concentration fluctuations shown in figure 5.6 are seemingly random. A more thorough sampling program at this same location (fig. 4.79) shows the frequency distributions of sample concentrations at single cross section verticals. Samples were collected consecutively un-
TABLE 4.17.—Correlation between suspended sediment samples collected from single vertical and equal-transit-rate samples representing entire cross section, Washita River Basin, Okla.

<table>
<thead>
<tr>
<th>Station and vertical</th>
<th>Correlation coefficient</th>
<th>Regression equation</th>
<th>Number of observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anadarko:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SV-177 ........</td>
<td>0.993</td>
<td>Y = 0.955X + 92.9</td>
<td>7</td>
</tr>
<tr>
<td>SV-178 ........</td>
<td>0.987</td>
<td>Y = 1.072X + 100.9</td>
<td>10</td>
</tr>
<tr>
<td>SV-210 ........</td>
<td>0.988</td>
<td>Y = 0.989X - 117.0</td>
<td>14</td>
</tr>
<tr>
<td>SV-213 ........</td>
<td>0.994</td>
<td>Y = 0.950X + 10.2</td>
<td>5</td>
</tr>
<tr>
<td>Verden:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SV-63 ........</td>
<td>0.975</td>
<td>Y = 0.884X + 174.0</td>
<td>58</td>
</tr>
<tr>
<td>Turnpike:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SV-36 ........</td>
<td>0.971</td>
<td>Y = 1.008X + 255.6</td>
<td>31</td>
</tr>
<tr>
<td>SV-51 ........</td>
<td>0.964</td>
<td>Y = 1.005X + 113.3</td>
<td>33</td>
</tr>
<tr>
<td>Tabler:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SV-110 ........</td>
<td>0.997</td>
<td>Y = 0.915X + 321.3</td>
<td>7</td>
</tr>
<tr>
<td>SV-160 ........</td>
<td>0.999</td>
<td>Y = 1.010X + 186.0</td>
<td>13</td>
</tr>
<tr>
<td>Alex:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SV-160 ........</td>
<td>0.987</td>
<td>Y = 0.920X + 102.8</td>
<td>27</td>
</tr>
<tr>
<td>SV-200 ........</td>
<td>0.986</td>
<td>Y = 1.020X + 79.1</td>
<td>21</td>
</tr>
<tr>
<td>West Bitter:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SV-36 ........</td>
<td>0.998</td>
<td>Y = 0.989X + 79.7</td>
<td>14</td>
</tr>
<tr>
<td>East Bitter:</td>
<td>0.990</td>
<td>Y = 1.010X + 26.5</td>
<td>23</td>
</tr>
</tbody>
</table>

1 Significant at 1-pct level.

under flow conditions that were essentially steady. Note, by the slope of the lines, that sampling variability above a dune bed is roughly five times the variability above a plane bed.

Estimating Concentrations or Sediment Discharges for Short Unsampled Periods

Sediment yields from a watershed can be adequately estimated for some purposes by a minimum sampling program, but accurate computations of sediment discharge for many research purposes require that the sediment concentrations of streamflow be measured or closely estimated at all times. The required number and spacing of samples is dependent on the erosion and drainage characteristics of the watershed. Frequent sampling is desirable on small watersheds because both runoff and sediment concentration vary markedly over a short time, but infrequent sampling of storm runoff from large watersheds may be adequate to define concentration trends.

If sample coverage is not sufficient to define the changing concentration pattern, the most reliable methods for estimating the sediment concentration for unsampled periods—depending on the length and reliability of prior records—are; (1) simple interpolation between concentrations, with some reliance on the trend of the runoff graph with time and a knowledge of the concentration fluctuation trends for similar runoff events, and (2) the use of the runoff versus sediment concentration (or load rate) relationship derived from a prior sampling history of the stream. A knowledge of concentration fluctuation trends throughout a storm—and seasonal or other concentration differences—is also desirable.

Data from the sampled storm of figure 4.80 can better illustrate this estimating procedure. The points of the runoff-sediment relation of figure 4.81 represents only two of the previously sampled storms but clearly show both the “loop” pattern and the seasonal shift of each storm from the trend line which was defined by samples for the 5-year record. Note that if some portion of the May 22, 1965 storm had been unsampled, a knowledge of sediment fluctuation, by season and by storm, would have been helpful in providing a reliable estimate of sediment discharge.

The seasonal variation of sediment (concentration and discharge) is not always straightforward for a given storm or for a sediment record of short duration. On a long-term basis, however, it should be related to some indices of the erosivity of rainfall. The monthly distribution of a rainfall erosion index (67) for western Iowa is shown in figure 4.82. It is not adjusted for seasonal variation in vegetative cover but represents only the effect of varying rainfall amounts and intensities.

The reader can obtain a “feel” for estimating the sediment concentration for any portion of the storm of figure 4.80 by merely assuming that no samples exist for that interval of the storm. If, for example, a field sampling team had not reached the site until the stream had
Line of Equal Concentration

\[ \hat{y} = 0.9025x + 77.76 \]
\[ r = 0.99 \]

FIGURE 4.78.—Comparison of pump sampler concentration with representative cross section concentrations, Washita River at Anadarko, Okla.
crested, a fair estimate of the sediment concentration would be provided by the average curve of figure 4.81. Guy (25) summarized the observation of Colby (8) and other researchers in characterizing the relationship of the sediment concentration graph to the hydrograph for small watersheds:

If the distance of travel from the point of erosion is short or the stream channels contain little flow prior to the storm runoff, the peak concentration of fine material usually coincides with the peak flow or somewhat precedes it. Peak concentration of fine material early in the runoff is consistent with the idea that loose soil particles at the beginning of a storm will be eroded by the first direct runoff of appreciable amount.

Procedures for estimating sediment concentrations are acceptable for computing sediment discharge if only portions of a storm concentration graph are unsampled or if only occasional storms are unsampled. Whenever sampling deficiencies are too great, there is little to be gained by estimating sediment concentrations and discharges on a storm-to-storm basis. Accuracy does not warrant this method, even though the computations can be done rapidly by electronic computer. Instead, the annual, seasonal, or long-term sediment discharges can be estimated by "short-cut" procedures which utilize flow duration data and the water-sediment relation. This is discussed in some detail in a following section.

### Reporting Sediment Transport Rates and Sediment Yields

Sediment transport rates and quantities are reported in many formats, according to the research objective. Typical presentations involve peak sediment discharges and peak concentrations, sediment yields by storm, day, and longer intervals, and graphical representations of sediment concentrations and discharges. Runoff values are nearly always included in sediment summaries. Many plottings and tabulations are now accomplished using the electronic computer.

Table 4.18 summarizes sediment data, by storm, from three field-size watersheds near Treynor, Iowa. Additional columns may be inserted to report the mean sediment concentration for the storm, or to list such sediment-affecting variables as rainfall amounts, intensities, and energies. Table 4.19 summarizes daily
sediment discharges and associated rainfall and runoff data, and it shows the runoff hydrograph and the graph of suspended sediment concentration for a storm on an 83-acre watershed and includes information on overall storm runoff and sediment discharge, along with the basic computations.

**Estimating Long-Term Sediment Yields From the Relationship Between Sediment Discharge and Streamflow**

Annual and long-term sediment yields are generally much less variable than within-storm sediment transport rates and daily or storm sediment discharges. The year-to-year sediment yield variation for small watersheds can be great, however, if rainfall amounts, intensities, and energies are variable, and if the seasonal occurrence of rainfall differs appreciably.

Consider the sediment yield from a 75-acre corn-cropped watershed. For the 5-year-period, illustrated in table 4.20, the average annual rainfall is greater than the 100-year norm of 29-inches (73.7 cm) for this area; the rainfall erosivity (R) is slightly below the norm of 160 cited by Wischmeier and Smith (69). The greatest sediment yield, 20 tons per acre (4.48kg/m²), was measured for the year with the least rainfall erosivity.

This seeming contradiction was primarily the

![Graph](image)

**FIGURE 4.80.—Computation of sediment discharge, Watershed 2, near Treynor, Iowa, May 22, 1965.**
result of abnormal variations in the intensity and seasonal occurrence of rainfall. Three modest rainfall events occurred in May 1971 during the early crop stages when there was little vegetative cover on the land. The most intense rainstorm of the 5-year period occurred August 2, 1970 when the corn canopy was complete. The highest rainfall year, 1973-74, was characterized by numerous showers of only moderate intensity, primarily occurring during the July-September “tall corn” period.

Preparation of the Sediment Transport Curve

The graphical relation of water discharge versus sediment discharge or concentration from a watershed is called the sediment transport (or sediment rating) curve. It can be prepared in many forms (fig. 4.81), and is often used for estimating missing periods of record and for extrapolation of sediment yields. To estimate the sediment discharge for a missing
record or to extrapolate the record, guidelines for the construction and use of the sediment transport curve are of value. If a sediment transport curve can be deduced which most correctly averages the effect of such major variables as rainfall and runoff intensity, season and availability of fine and coarse sediment fractions, this curve can be put to practical use. The construction of such a representative sediment transport curve is now discussed.

Runoff occurring promptly after rainfall or snowmelt is termed "direct runoff." It forms the bulk of the "flood" or "storm" hydrograph and is usually responsible for most of the sediment in transport in agricultural watersheds. This runoff from a given area represents the integrated effect of all characteristics of the drainage basin and the superimposed environment upon sediment production. The fine sediments, which form the wash load of a stream, are readily entrained in runoff. They are relatively insensitive to flow parameters, being mostly a matter of supply to the stream. The transport of the coarse sediment fraction, for example, the bed sediment load, is dependent on a balance between supply and flow parameters and may not be adequately sampled by suspended sediment samplers.

If the runoff event is of low intensity, the stream sediment concentration is comparatively low at the start of direct runoff and increases slowly with increasing runoff rate, to a high point, and then slowly recedes, as illustrated in figure 4.83. If the storm is intense, the stream sediment concentration is comparatively high at the start of direct runoff and increases rapidly, as shown in figure 4.84.

These storm conditions result in a "loop" effect on the sediment transport graph for a given storm, as shown in figures 4.85 and 4.86. Under certain conditions, as in figure 4.81, it is possible for high-intensity runoff events to attain a maximum, or near-maximum concentration at the beginning of runoff. This is especially true for watersheds where weathering of soils and/or stream beds during long, dry periods has produced a large transportable load of fine material.

Consider the effect of this on the "long-term" sediment transport curve at low and medium rates of runoff. If random samples from storm runoff had been collected through many storms during the year, one would expect considerable scatter in the suspended sediment concentration derived from these samples. The sediment concentrations for a particular rate of storm runoff on Pigeon Roost Creek, for example, could be 300 parts per million on the rising side of a low-intensity storm hydrograph and about the same on the falling side.

For a high-intensity event, the concentration on the rising side of a hydrograph could be many times the recession concentration for the same runoff rate. The lower concentrations during falling stage are the result of a greatly reduced supply of fine sediments; the bed sediment is still in plentiful supply in these channels and comprises nearly one-third of the total sediment discharge. Figure 4.87 shows the typical scatter that can occur from a single year of sampling. In the mid-portion of the figure, the seasonal effect upon point scatter is also discernible.

As illustrated in table 4.21, the upper range of sediment discharge for a particular low or medium rate of direct runoff, such as 10 or 20 cfs (.28 or .56 m³/s), can be more than 50 times that of the lower range. This observed 50-times variation in the sediment discharge at Pigeon Roost Creek is typical of many locations. In-
spection of streamflow sample records from a 75-acre (30.4 ha) watershed in cultivation near Treynor, Iowa, for example, shows a suspended sediment concentration range from about 2,000 parts per million to nearly 230,000 parts per million for direct runoff rates of 5 to 10 cfs (.14 to .28 m³/s). It is probable that the concentration of some snowmelt runoff is much lower than 2,000 parts per million and that the concentration extremes for given low and moderate rates can vary much more than 100:1. Despite this scatter, an average trend line through these points would accurately characterize the overall water-sediment relation at these runoff rates if the same population were representative.

The extremely high variations in suspended sediment discharge or concentration for a given water discharge occurred for the low and medium discharge ranges. At extremely high discharges, observations indicate that this variation diminishes appreciably because extremely high rates of runoff and sediment discharge can only be reached, for a given watershed, by a very limited combination of hydrologic circumstances. Any chance recurrence of these

<table>
<thead>
<tr>
<th>Watershed description</th>
<th>Date</th>
<th>Rainfall Duration</th>
<th>Amount</th>
<th>Runoff Duration</th>
<th>Amount</th>
<th>Peak</th>
<th>Sediment from sheet erosion</th>
<th>Sediment from all erosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (74.5-acres corn-on-contour)</td>
<td>1/15,16</td>
<td>Snowmelt</td>
<td>1330</td>
<td>0800</td>
<td>0.30</td>
<td>2.9</td>
<td>0.6</td>
<td>11.0</td>
</tr>
<tr>
<td></td>
<td>2/23,24</td>
<td>Snowmelt</td>
<td>1030</td>
<td>0400</td>
<td>0.20</td>
<td>2.4</td>
<td>1.9</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>2/24,25</td>
<td>Snowmelt</td>
<td>1040</td>
<td>0600</td>
<td>0.22</td>
<td>2.8</td>
<td>.9</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>2/25,26</td>
<td>Snowmelt</td>
<td>0600</td>
<td>0500</td>
<td>0.34</td>
<td>5.4</td>
<td>8.2</td>
<td>29.0</td>
</tr>
<tr>
<td>2 (82.8-acres corn-on-contour)</td>
<td>1/15,16</td>
<td>Snowmelt</td>
<td>1300</td>
<td>0730</td>
<td>0.39</td>
<td>3.3</td>
<td>6.6</td>
<td>58.0</td>
</tr>
<tr>
<td></td>
<td>2/23,24</td>
<td>Snowmelt</td>
<td>0800</td>
<td>0600</td>
<td>0.17</td>
<td>2.1</td>
<td>2.6</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>2/24,25</td>
<td>Snowmelt</td>
<td>1000</td>
<td>0900</td>
<td>0.22</td>
<td>2.8</td>
<td>.7</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>2/25,26</td>
<td>Snowmelt</td>
<td>0900</td>
<td>0400</td>
<td>0.36</td>
<td>6.3</td>
<td>3.8</td>
<td>14.0</td>
</tr>
<tr>
<td></td>
<td>4/16</td>
<td>0230</td>
<td>0234</td>
<td>0748</td>
<td>0.01</td>
<td>0.6</td>
<td>3.4</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>4/17</td>
<td>0735</td>
<td>0839</td>
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<td>1.0</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>6/24</td>
<td>1130</td>
<td>1137</td>
<td>1400</td>
<td>0.01</td>
<td>3.3</td>
<td>.8</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>7/17</td>
<td>0545</td>
<td>0556</td>
<td>1200</td>
<td>0.16</td>
<td>19.0</td>
<td>32.0</td>
<td>37.0</td>
</tr>
<tr>
<td></td>
<td>7/18</td>
<td>0124</td>
<td>0130</td>
<td>0600</td>
<td>0.06</td>
<td>8.7</td>
<td>9.0</td>
<td>14.0</td>
</tr>
<tr>
<td></td>
<td>8/20</td>
<td>0515</td>
<td>0520</td>
<td>0920</td>
<td>0.20</td>
<td>67.0</td>
<td>55.0</td>
<td>58.0</td>
</tr>
<tr>
<td>3 (107-acres grass)</td>
<td>1/15,16</td>
<td>Snowmelt</td>
<td>1230</td>
<td>0800</td>
<td>0.31</td>
<td>3.5</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>2/23,24</td>
<td>Snowmelt</td>
<td>0001</td>
<td>0900</td>
<td>0.12</td>
<td>3.8</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>2/24,25</td>
<td>Snowmelt</td>
<td>0900</td>
<td>0830</td>
<td>0.24</td>
<td>1.8</td>
<td>1.8</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>2/25,26</td>
<td>Snowmelt</td>
<td>0830</td>
<td>0930</td>
<td>0.43</td>
<td>9.9</td>
<td>1.0</td>
<td>9.4</td>
</tr>
<tr>
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<td>0215</td>
<td>Trace</td>
<td>Trace</td>
<td></td>
<td>Trace</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td>0730</td>
<td>Trace</td>
<td>Trace</td>
<td></td>
<td>Trace</td>
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</tr>
<tr>
<td></td>
<td>6/26</td>
<td>1127</td>
<td>Trace</td>
<td>Trace</td>
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<td>Trace</td>
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<td></td>
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<tr>
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<td>7/17</td>
<td>0542</td>
<td>0600</td>
<td>1127</td>
<td>0.16</td>
<td>10.0</td>
<td>3.3</td>
<td>8.1</td>
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<td></td>
<td>7/18</td>
<td>0045</td>
<td>Trace</td>
<td>Trace</td>
<td></td>
<td>Trace</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>8/20</td>
<td>0450</td>
<td>0524</td>
<td>1000</td>
<td>0.15</td>
<td>14.0</td>
<td>1.7</td>
<td>3.9</td>
</tr>
</tbody>
</table>

1 Based on Thiessen weight of 2 gages representing each watershed.  
2 Represents sampled streamflow upstream from active gullies.  
3 Represents sampled streamflow downstream from fields and active gullies.
rates must be accompanied by much the same watershed and meteorologic conditions that previously occurred and, therefore, must produce comparable sediment conditions.

This pattern is common to streams in the central United States where maximum rainfall amounts and intensities are mostly associated with thunderstorm activity in late spring and early summer—and are less frequently the result of hurricane movements originating off the Atlantic and Gulf coasts in early autumn. The runoff response to these maximum rainfall occurrences varies greatly according to season and the condition of the land surface. As a result, most large runoff events, and nearly all events with large sediment discharges, occur at crop planting time or in the early growing season when the land is almost devoid of vegetative cover and is most vulnerable to erosion. At other times of the year, the sediment supply is less, and the runoff potential per unit of rainfall is low.

The slope of the suspended sediment transport curve of figure 4.87 is steepest at low discharges and least steep at the highest discharges so that the curve is concave downward.

<table>
<thead>
<tr>
<th>Day</th>
<th>May Precipitation</th>
<th>May Runoff</th>
<th>May Sediment</th>
<th>June Precipitation</th>
<th>June Runoff</th>
<th>June Sediment</th>
<th>July Precipitation</th>
<th>July Runoff</th>
<th>July Sediment</th>
<th>August Precipitation</th>
<th>August Runoff</th>
<th>August Sediment</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>0.0048</td>
<td></td>
<td></td>
<td>0.24</td>
<td>0.0088</td>
<td>t</td>
<td>0.87</td>
<td>0.2096</td>
<td>108.7</td>
<td>0.0090</td>
<td>t</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0.0088 t</td>
<td></td>
<td></td>
<td>0.128 t</td>
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<td>t</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.047 t</td>
<td></td>
<td></td>
<td></td>
<td>0.121 t</td>
<td></td>
<td></td>
<td>0.080 t</td>
<td></td>
<td></td>
<td>t</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.03</td>
<td>0.0045 t</td>
<td></td>
<td>0.32</td>
<td>0.0252</td>
<td>6.2</td>
<td></td>
<td>0.080 t</td>
<td></td>
<td></td>
<td>t</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.15</td>
<td>0.0049 t</td>
<td></td>
<td>0.45</td>
<td>0.0284</td>
<td>4.6</td>
<td></td>
<td>0.080 t</td>
<td></td>
<td></td>
<td>t</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.0044 t</td>
<td>0.0044 t</td>
<td></td>
<td>0.69</td>
<td>0.3841</td>
<td>292.8</td>
<td></td>
<td>0.139 t</td>
<td></td>
<td></td>
<td>t</td>
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</tr>
<tr>
<td>7</td>
<td></td>
<td>0.0124 t</td>
<td></td>
<td></td>
<td>0.121 t</td>
<td>0.16 t</td>
<td></td>
<td>0.080 t</td>
<td></td>
<td></td>
<td>t</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>0.0052 t</td>
<td></td>
<td>0.081 t</td>
<td>0.121 t</td>
<td></td>
<td></td>
<td>0.080 t</td>
<td></td>
<td></td>
<td>t</td>
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</tr>
<tr>
<td>9</td>
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<td>0.0046 t</td>
<td></td>
<td>0.081 t</td>
<td>0.121 t</td>
<td></td>
<td></td>
<td>0.080 t</td>
<td></td>
<td></td>
<td>t</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>0.0046 t</td>
<td></td>
<td>0.081 t</td>
<td>0.121 t</td>
<td></td>
<td></td>
<td>0.080 t</td>
<td></td>
<td></td>
<td>t</td>
<td></td>
</tr>
<tr>
<td>11</td>
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<td>0.0050 t</td>
<td>0.05 t</td>
<td>0.080 t</td>
<td>0.111 t</td>
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<td></td>
<td>0.080 t</td>
<td></td>
<td></td>
<td>t</td>
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</tr>
<tr>
<td>13</td>
<td>0.0048 t</td>
<td>0.0087 t</td>
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Total 6.53 2.0196 1903.9 8.50 2.4043 1474.7 4.25 0.6037 118.4 3.54 0.4731 66.1

14t" denotes trace, less than 0.001 ton.
TABLE A.20.—Hydrology-sediment yield information, 75-acre, row-cropped watershed near Treynor, Iowa, May 1, 1969—May 1, 1974

<table>
<thead>
<tr>
<th>Year</th>
<th>Rainfall</th>
<th>R\textsuperscript{1}</th>
<th>RC\textsuperscript{2}</th>
<th>Storm runoff</th>
<th>Sediment yield from sheet rill source</th>
</tr>
</thead>
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<td>1969-70</td>
<td>31.4</td>
<td>111</td>
<td>59</td>
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<td>1970-71</td>
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<tr>
<td>1971-72</td>
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<td>98</td>
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<tr>
<td>1972-73</td>
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<td>118</td>
<td>59</td>
<td>1.5</td>
<td>7.5</td>
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<tr>
<td>1973-74</td>
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<td>195</td>
<td>97</td>
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<tr>
<td>Total</td>
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<td>745</td>
<td>435</td>
<td>13.6</td>
<td>42.1</td>
</tr>
<tr>
<td>Av. annual</td>
<td>33.5</td>
<td>149</td>
<td>87</td>
<td>2.7</td>
<td>8.4</td>
</tr>
</tbody>
</table>

\textsuperscript{1} Represents \( \zeta \) of product of kinetic energy or rainfall and maximum 30-min rainfall intensity for all storms (\( \zeta \)) according to criteria (68).

\textsuperscript{2} Represents interaction of R term and cropping factor, C.

This shape is typical of suspended sediment curves for many streams. Segments of the transport curve can be approximated by a relation of the form

\[ G_{ss} = L Q^n \]  \hspace{1cm} (4-22)

in which \( G_{ss} \) is the suspended sediment discharge, \( Q \) the water discharge, and \( L \) is a factor which can be taken as an index of relative erodibility. The exponent, \( n \), is the slope of the curve on logarithmic paper. If equation 4.22 is fitted to segments of a transport curve such as the one in figure 4.88, the exponent, \( n \), will diminish as the segments cover higher and higher ranges of water discharge.

In Figure 4.87, the curve is drawn so that it approaches a slope of unity (\( n = 1 \)) at some high value of \( Q \). For a slope of unity, the sediment concentration \( G_{ss}Q = L \) is constant and independent of \( Q \). The value of unity for \( n \) appears to be a common minimum value attained by many streams at high flood discharge.

The values of sediment discharge for high flows are important in estimating sediment yield, since a large fraction of the total sediment yield is produced by the high flows. Data for plotting the sediment transport curve in the high discharge range are sometimes scarce or lacking entirely, and it is often necessary to extrapolate the curve to cover this range. Information on the shape of the curve may be used as a guide in this extrapolation.

The fine sediment or wash load of a stream usually originates from sheet and rill erosion on the watershed, and its concentration is determined by the amount brought to the stream and not by the capacity of the stream to transport it. On the other hand, the concentration and discharge of bed sediment is determined by the hydraulic forces capable of moving it. For purposes of discussing the relation between sediment discharge and water discharge, it is convenient to treat the wash load and bedload separately. The wash load discharge, \( G_w \), is assumed to be given by

\[ G_w = A Q^n \]  \hspace{1cm} (4-23)

and the discharge concentration for wash load, \( C_w \), is then

\[ C_w = B Q^{n-1} \]  \hspace{1cm} (4-24)

in which \( A \) and \( B \) are basic erodibility constants for wash load and, for high discharges, \( n \) has a value near unity. Dawdy (4) derived a relation between discharge of bed sediment, \( G_{bs} \), and runoff, \( Q \). He assumed that \( G_{bs} \) varies as \( V^4 \), where \( V \) is the mean velocity of the stream, and that the stream is wide and has a constant Manning roughness factor. The latter assumption gives \( V \sim d^{1.4} \) or assumes that \( Q \sim d^{1.4} \). Eliminating \( V \) from the relation between \( G_{bs} \) and \( V \) gives

\[ G_{bs} = K Q^{1.2} \]  \hspace{1cm} (4-25)

in which \( K \) is a constant for any given channel. The total suspended sediment discharge, \( G_{ss} \), is then the sum of the wash load and bed sediment discharge, or

\[ G_{ss} = A Q^n + K Q^{1.2} \]  \hspace{1cm} (4-26)
Since, for high discharges, $m$ is probably not too different from 1.2 and $G_{fr}$ is usually several times $G_{fs}$, equation 4-26 can be approximated by equation 4-22 with $n$ only slightly different from $m$.

This is an idealized construction of the sediment-transport curve. In practice, the sediment-transport curve can have a slope exceeding the foregoing values for the following reasons:

- Some types of erosion can occur whereby sediment discharges and concentrations are increased during the course of a storm. Massive outwash from steep slopes, severe gully erosion, extensive slumping of streambanks, or locations where most of the sediment load originates from the channel degradation of a truly alluvial stream are examples.

- Many curves are assumed to be linear on logarithmic paper (a forced fit), although the general shape of the curve is concave downward as in figure 4.88. The resulting slope value is therefore greater than the true slope of the upper portion of the curve, especially if base flows are considered.

- Many curves are prepared from records that are of insufficient duration to experience representative storm events of high intensity.

In summary, the relative variation of plotted points in the low runoff portion of sediment transport curves based on sediment samples can be a hundredfold (2 log cycles), while the relative variation at the high runoff end is considerably less—the actual amount depending on length of record and the occurrence and coverage of storm events during the period. A

**Figure 4.83.—Sediment concentrations during a low-intensity storm event.**
## Table 4.21—Computation of runoff and suspended-sediment yields by the flow duration-sediment rating curve procedure

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<th>Flow duration interval</th>
<th>Duration of interval</th>
<th>Dura-</th>
<th>Flow midpoint</th>
<th>2 x 4</th>
<th>Sediment rate</th>
<th>2 x 6</th>
<th>Flow mid-</th>
<th>2 x 8</th>
<th>Sediment rate</th>
<th>2 x 10</th>
<th>Sediment rate</th>
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<td>1.2</td>
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<td>14.0</td>
<td></td>
</tr>
<tr>
<td>0 - .02</td>
<td>.02</td>
<td>.01</td>
<td>4,300</td>
<td>8.6</td>
<td>51,000</td>
<td>10.2</td>
<td>6,700</td>
<td>1.3</td>
<td>78,200</td>
<td>15.6</td>
<td></td>
</tr>
</tbody>
</table>

**Mean daily rate**

- Flow `ft/s`
- Tons per `ft/s`
- Days

- `x 365.25`
- `x 365.25`
- `x 365.25`

**Mean annual yield, computed**

- `41,000`
- `284,000`
- `43,000`
- `322,000`

**Mean annual yield, measured**

- `39,932`
- `283,246`
- `113,200`

**Percent difference**

- `.27`
- `.27`
long-term sediment transport curve can be constructed from streamflow measurements and sediment samples of a few storms by (1) considering the behavior of the runoff-sediment relation for the storms, and (2) a knowledge of how closely these storms represent the long-term experience. The slope of the upper portion of the sediment transport curve is further constrained within the theoretical limits cited. Many of the attributes of an instantaneous sediment transport curve (for example, a curve based on sediment samples) apply to curves that are compiled from daily, monthly, annual, or storm discharges.

**Figure 4.84.**—Sediment concentrations during a high-intensity storm event.
Figure 4.85.—Sediment transport graph for low-intensity storm.
FIGURE 4.86.—Sediment transport graph for high-intensity storm.
Figure 4.87.—Sediment transport curve showing typical point scatter from random samples of storm runoff.
**Sample Computation of Long-Term Sediment Yield**

Most of the foregoing discussion on the sediment transport curve deals with the runoff-sediment relation at specific sampling times, but it is also applicable to daily sediment discharges. A step-by-step procedure for computing long-term sediment discharge using the 1957-60 daily runoff-sediment record from Pigeon Roost Creek Watershed No. 34 follows:

- Using the record of daily runoff, compile the flow duration data and plot the flow duration curve. The flow duration data are in terms of percentage of time that flow is equal to or greater than indicated discharge versus flow rate. It is best to break the flow into at least 20 classes. The 4-year daily flow duration is summarized in columns 1 through 4 of table 4.21 and is plotted in figure 4.88.

- The relation of daily runoff to sediment discharge is plotted in figure 4.89. Curve fitting if accomplished by calculating the mean value of the dependent variable (sediment) for small increments of the independent variable. Several other methods for curve fitting can be used but, with typical point scatter as in figures 4.87

---

**FIGURE 4.88.—Flow duration curves for Watershed 34, Pigeon Roost Creek, Marshall County, Miss.**
and 4.89, the reader is cautioned that a linear least squares fit of the logarithms will result in a curve that is too low and use of such a curve would underestimate actual sediment yield.

- Tabulate the sediment discharge rate for each midpoint flow rate listed in table 4.21, column 4. Enter in column 6.
- Compute the incremental flow and sediment quantities, columns 5 and 7, respectively, by multiplying columns 4 and 6 (in turn) by the duration increment of column 2.
- Summation of columns 5 and 7 gives the mean daily water and sediment discharge for the period of record (4 years in this example).

These figures can be compared with the actual record, and they provide a partial check of procedures. If the short-term flow duration and sediment transport relation were correctly summarized, the short-term runoff calculation should check within 1 or 2 percent and the short-term sediment calculation should check within 5 percent. Now the long-term sediment yields can be calculated. Refer to columns 9 to 11 of table 4.21.

- Extend the short-term runoff record to represent "long-term" runoff conditions on the watershed. There are a variety of methods for doing this, depending on data available to the researcher. The index station procedure of Searcy (67) may be used where records of runoff from one or more long-time gaged watersheds are compared with that of the subject watershed. The flow duration data for the concurrent, short-term period of an index station are shown in figure 4.90 along with a 31-year record that is here assumed to adequately represent the long term. Discharges for equal durations of the short-term record for each location are plotted against each other in figure 4.91 and the adjustment to the long-term Pigeon Roost Creek record is accomplished by examining the long-term Tombigbee River record as illustrated in figure 5.26. The resulting long-term, flow-frequency data are shown in figure 5.23 and are given in column 9 of table 4.21.

- The long-term, water-sediment relation curve must now be drawn from a consideration of the short-term record, and the theories previously advanced. In this example, the only change from the short-term curve was a slight extension of the upper end of figure 4.89.

- Column 10, table 4.21 can now be filled and columns 9 and 11 calculated to obtain long-term runoff and sediment yields.

### Summarizing the Physical Properties of Sediment

The routine reporting of the physical properties of eroded, transported, and deposited sediments involves a description of the particle-size distribution, shape characteristics, particle densities, settling behavior, and other attributes.

Sediment sizes may be expressed in terms of settling characteristics in water or by sieve diameters. For many applications either characterization may be adequate. The sedimentation diameter of a particle is the equivalent
diameter of a sphere of the same density having the same settling velocity in the same fluid at the same temperature. The sieve diameter of a particle is that opening dimension in a square mesh sieve which will just pass the particle. Because individual particles are irregular in shape and vary in density, physical size is not a good index of the fluvial character of sediments. Dynamic properties are best described by fall velocities, which are a function of particle volume, shape, and specific gravity, and the viscosity of the entraining fluid.

For fine sediments (<0.062 mm), the sedimentation diameters are usually determined by such settling methods as the pipette, bottom withdrawal tube, and the hydrometer, except for occasional measurement by microscope. Table 4.22 (37) compares sedimentation diameters of several irregularly shaped sediments with those of quartz spheres (for several viscosities).

The particle diameters of sands are determined by the visual accumulation tube (up to about 2 mm) or by sieving (up to about 8 mm). Most sediments larger than 16 mm are sized by measuring along one or more axes of the particle, or by measuring the volume and converting the results to the diameter of an equivalent sphere. Further details are given in the section on Laboratory Analyses and Data Reduction, page

The total range of particle sizes of a given sediment or soil sample can be divided into size classes, and the percentage of the total weight occurring in each class can be represented by a frequency histogram. Examination of a large number of samples indicates that, when the logarithm of the particle size is plotted versus percentage of total weight in the class, the symmetrical histogram of figure 4.92 is approximated.
If a particular sample is large and is divided into many size classes, the histogram approaches the shape of the curve of figure 4.92. The curve of figure 4.92 is usually converted to a plot of percent sediment particle size, by weight, finer than the indicated size. The objective is to vary the coordinate scales to achieve a linear or near-linear relation, which can be more easily described than a curvilinear function. Such a cumulative size-frequency distribution is shown in figure 4.93. Although there are many mathematical formulations available for fitting a frequency distribution, the normal or Gaussian distribution can be utilized for most purposes. Pertinent data on this distribution are given in standard statistical tables.

**Arithmetic Probability Paper**

When plottings on probability paper can be fitted with a straight line, the distribution is termed normal (Gaussian), and many statistics can be determined graphically. The mean sediment particle diameter is the value of the 50 percent probability. The standard deviation, in millimeters, is the difference between the mean size and the size for either the 84.1 percent or 15.9 percent probability. The standard deviation is a measure of the range of the grain sizes.

**Logarithmic Probability Scale**

Figure 4.93 shows the cumulative frequency distribution of sediments from Pigeon Roost Creek.
Mississippi, as plotted on logarithmic probability paper. This plotting scale is similar to that for arithmetic probability paper, but the particle size coordinate is logarithmic. The

\[
\text{Mean sediment diameter} = \bar{D} = \frac{\sum D_i \cdot f_i}{\sum f_i}
\]

\[
\text{Geometric standard deviation} = \sigma_g = \frac{D_{95}}{D_{50}} = \frac{D_{95}}{D_{15.9}}
\]

\[
\text{Temperature} = T
\]

\[
\text{Specific gravity} = 2.65
\]

\[
\text{Shape factor} = S
\]

\[
\text{Sphere} = S
\]

\[
\text{Temperature} = (C)
\]

\[
\text{Nominal diameter} = 0.20 \text{ mm}
\]

\[
\text{Nominal diameter} = 0.55 \text{ mm}
\]

\[
\text{Nominal diameter} = 1.00 \text{ mm}
\]

\[
\text{Nominal diameter} = 2.00 \text{ mm}
\]

\[
\text{Nominal diameter} = 4.00 \text{ mm}
\]

\[
\text{Nominal diameter} = 8.00 \text{ mm}
\]

\[
\text{Sample Weight} = W
\]

\[
\text{Per Class Interval (Pet.)}
\]

\[
\text{Logarithm of Particle Size (mm)}
\]

\[
\text{Figure 4.92.—Size-frequency distribution curve and histogram.}
\]
if the concentration of suspended sediment in the sampled zone is also representative of the concentration in the unsampled zone. This is the case when there is little or no variation in the sediment concentration with depth by reason of the particular particle size in transport (relatively small) or the velocities and turbulence of streamflow (relatively high).

When concentration gradients occur and the stream is in effect moving a "bedload," the computed sediment discharge based on streamflow measurements and suspended sediment samples must be adjusted upward to obtain the total sediment discharge. The sampled concentration of suspended sediment, applied to total measured water discharge, is the "measured" sediment discharge that is routinely reported in U.S. Geological Survey Water-Supply Papers.

These circumstances, coupled with the need to differentiate sediment according to the dominant mode of transport—as rolling particles primarily in contact with the channel boundary or as suspended particles buoyed by turbulent eddies and diffused throughout the flow—have forced researchers in many cases to consider the component sediment discharges. The channel may be transporting quantities of coarse sediments that do not have a uniform, vertical
distribution throughout the stream cross-section. If so, this is evidenced by the presence of larger sizes of material in the streambed than exist in suspended sediment samples and by an increase in concentration with depth that can be defined by collecting "point" samples. From these data, the so-called "unmeasured" sediment, the bedload, and the bed material discharges can be estimated.

Figure 4.92 shows typical vertical velocity and concentration profiles, along with sediment discharges derived from the profiles. Note that the sediment concentration profiles defined and extrapolated by samples, when applied to the velocity distributions over the entire depth of flow, may result in a realistic total sediment discharge because the lower velocities in the unsampled zone compensate somewhat for the higher sediment concentrations there.

Several types of sediment discharges based on the curves of figure 4.94 and data in table 4.23 are calculated in the inset. The total stream depth is arbitrarily selected as 3.5 feet (1.1 m), and it is assumed that the conventional suspended sediment sampler cannot sample the bottom 0.4 foot (12 cm). The data are tabulated so that the sediment discharge for each particle size range (sand, silt, or clay) can be compared. The sediment discharges for the sampled and unsampled zones are computed separately. Each entry in the discharge columns represents the rate of movement (of water, sand, silt, or clay) through an incremental area 1 foot (30.4 cm) wide and 0.1 foot (3 cm) deep.

For the sampled zone, the sediment discharge (case I) consists of clay 4.99 lb/min (2.26 kg/min), silt 9.35 lb/min (4.24 kg/min), and sand 3.26 lb/min (1.48 kg/min) totaling 17.6 lb/min (7.98 kg/min). This compares with 21.56 lb/min (9.78 kg/min) total sediment discharge through the entire depth (per foot of width). Therefore, the sediment discharge in the unsampled zone is 3.96 lb/min (1.8 kg/min), 18 percent of the total.

The measured sediment discharge, as previously defined, is computed under the assump-

![Figure 4.94](https://via.placeholder.com/150)

**Figure 4.94.**—A comparison of typical sediment discharges, sampled and unsampled, measured and unmeasured.
TABLE 4.23.—Sediment computations—a comparison of typical sediment discharge, sampled and unsampled, measured and unmeasured

<table>
<thead>
<tr>
<th>Water</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>Conc</td>
<td>Conc</td>
<td>Conc</td>
</tr>
<tr>
<td>Ft</td>
<td>Discharge</td>
<td>Lb/ min</td>
<td>Discharge</td>
</tr>
<tr>
<td>Ft/s</td>
<td>P/min</td>
<td></td>
<td>P/min</td>
</tr>
<tr>
<td>0.0-0.1</td>
<td>0.501</td>
<td>1.0002</td>
<td>119</td>
</tr>
<tr>
<td>0.1-0.2</td>
<td>0.509</td>
<td>3.006</td>
<td>122</td>
</tr>
<tr>
<td>0.2-0.3</td>
<td>0.516</td>
<td>6.012</td>
<td>125</td>
</tr>
<tr>
<td>0.3-0.4</td>
<td>0.520</td>
<td>8.016</td>
<td>128</td>
</tr>
<tr>
<td>0.4-0.5</td>
<td>0.525</td>
<td>10.020</td>
<td>131</td>
</tr>
<tr>
<td>0.5-0.6</td>
<td>0.528</td>
<td>12.024</td>
<td>133</td>
</tr>
<tr>
<td>0.6-0.7</td>
<td>0.530</td>
<td>15.030</td>
<td>137</td>
</tr>
<tr>
<td>0.7-0.8</td>
<td>0.531</td>
<td>18.036</td>
<td>139</td>
</tr>
<tr>
<td>0.8-0.9</td>
<td>0.530</td>
<td>20.040</td>
<td>142</td>
</tr>
<tr>
<td>0.9-1.0</td>
<td>0.528</td>
<td>22.043</td>
<td>145</td>
</tr>
<tr>
<td>1.0-1.1</td>
<td>0.525</td>
<td>26.051</td>
<td>148</td>
</tr>
<tr>
<td>1.1-1.2</td>
<td>0.521</td>
<td>30.059</td>
<td>151</td>
</tr>
<tr>
<td>1.2-1.3</td>
<td>0.518</td>
<td>33.044</td>
<td>154</td>
</tr>
<tr>
<td>1.3-1.4</td>
<td>0.513</td>
<td>37.071</td>
<td>157</td>
</tr>
<tr>
<td>1.4-1.5</td>
<td>0.508</td>
<td>41.078</td>
<td>160</td>
</tr>
<tr>
<td>1.5-1.6</td>
<td>0.502</td>
<td>48.086</td>
<td>163</td>
</tr>
<tr>
<td>1.6-1.7</td>
<td>0.497</td>
<td>51.095</td>
<td>166</td>
</tr>
<tr>
<td>1.7-1.8</td>
<td>0.489</td>
<td>56.103</td>
<td>170</td>
</tr>
<tr>
<td>1.8-1.9</td>
<td>0.482</td>
<td>62.112</td>
<td>173</td>
</tr>
<tr>
<td>1.9-2.0</td>
<td>0.474</td>
<td>69.122</td>
<td>177</td>
</tr>
<tr>
<td>2.0-2.1</td>
<td>0.466</td>
<td>76.133</td>
<td>182</td>
</tr>
<tr>
<td>2.1-2.2</td>
<td>0.458</td>
<td>84.144</td>
<td>187</td>
</tr>
<tr>
<td>2.2-2.3</td>
<td>0.450</td>
<td>92.155</td>
<td>192</td>
</tr>
<tr>
<td>2.3-2.4</td>
<td>0.440</td>
<td>101.166</td>
<td>200</td>
</tr>
<tr>
<td>2.4-2.5</td>
<td>0.430</td>
<td>111.179</td>
<td>208</td>
</tr>
<tr>
<td>2.5-2.6</td>
<td>0.420</td>
<td>122.192</td>
<td>215</td>
</tr>
<tr>
<td>2.6-2.7</td>
<td>0.409</td>
<td>136.208</td>
<td>224</td>
</tr>
<tr>
<td>2.7-2.8</td>
<td>0.395</td>
<td>151.225</td>
<td>235</td>
</tr>
<tr>
<td>2.8-2.9</td>
<td>0.381</td>
<td>110.242</td>
<td>248</td>
</tr>
<tr>
<td>2.9-3.0</td>
<td>0.336</td>
<td>196.263</td>
<td>262</td>
</tr>
<tr>
<td>3.0-3.1</td>
<td>0.343</td>
<td>221.294</td>
<td>280</td>
</tr>
<tr>
<td>3.1-3.2</td>
<td>0.326</td>
<td>235</td>
<td>320</td>
</tr>
<tr>
<td>3.2-3.3</td>
<td>0.289</td>
<td>515</td>
<td>557</td>
</tr>
<tr>
<td>3.3-3.4</td>
<td>0.238</td>
<td>860</td>
<td>757</td>
</tr>
<tr>
<td>3.4-3.5</td>
<td>0.145</td>
<td>1,230</td>
<td>668</td>
</tr>
</tbody>
</table>

Total discharge rates (lb/min)

<table>
<thead>
<tr>
<th>Case</th>
<th>Sample load</th>
<th>Total load (pet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (Sampled zone)</td>
<td>17.6</td>
<td>21.56</td>
</tr>
<tr>
<td>II (Unsampled zone)</td>
<td>14.34</td>
<td>16.00</td>
</tr>
</tbody>
</table>

| Measured load |
| d | d-a |

where

- $C_y$ is the concentration at a distance $y$ above the streambed;
- $C_d$ is the concentration at some reference level "a" above the streambed;
- $d$ is the depth of flow;
\[ Z = \frac{w}{Ku} \]

\( w \) is the fall velocity of the particles;
\( K \) is the turbulence constant, usually 0.4;
\( U \) is the shear velocity; it equals \( \sqrt{gRS} \);
\( R \) being hydraulic radius, and
\( S \) the slope of the energy gradient.

The object of the preceding discussion is not to recommend a procedure but to make the reader aware of exactly what is being measured and what limitations are present in field measurements of sediment.

Unmeasured Sediment Discharge

The unmeasured sediment discharge is the difference between total sediment discharge and the measured sediment discharge. It includes the bedload, which moves by sliding, rolling or skipping along the bed or close to it; it also comprises that part of the suspended sediment discharge which is below the sampled zone but is not encompassed in the measured sediment discharge. As figure 4.94 and the accompanying calculations show, the unmeasured sediment discharge can be a significant portion of the total.

Researchers needing to adjust measured sediment discharges to total sediment discharge before interpretive analyses are referred to Colby (10) and Colby and Hubbell (11). Other approaches to the problem of defining the total sediment discharge are considered in the following subsection.

Sediment Discharge Formulas

Sediment discharge formulas and other empirical procedures are available for computing the bed material discharge. A chronological listing of their development is given in the appendix containing selected references (p. 371).

The formulas have proliferated because the sediment transport problem is complex and no best method is presently available for all field conditions. With some testing, the researcher who must rely on some method for determining bed material load can select the procedure best suited to his conditions. Two of the foregoing relationships are now discussed; information about the other procedures can be obtained from the literature, such as Rouse (59), Schulitz (63), and Task Committee on Preparation of Sedimentation Manual (64).

The Schoklitsch formula (60) is recommended by Schulitz because of its simplicity. It is

\[ g_s = \sum_i^nP_i \frac{25.0}{d_i^{1/2}} S^{1/2} (q - q_r) \quad (4-29) \]

where
\( g_s \) is the bedload in pounds per second per foot of width
\( P_i \) is the fraction of the bed sediment having a mean size \( d_i \)
\( d_i \) is the mean particle diameter of the size fraction of the bed sediment, feet
\( q \) is the stream discharge, per foot of width, cubic feet per second;
\( q_r \) is critical stream discharge, cubic feet per second per foot of width, at which sediment motion begins; and
\( S \) is the channel slope.
\( n \) number of particle sizes

For sediment specific gravity of 2.65,

\[ q_r = 0.0638 \frac{d_i}{S^{4/5}} \quad (4-30) \]

The basis for equation 4–30 is flume data, where, for a given \( q \) and \( d_i \), a curve of bedload \( (g_s) \) as ordinate versus slope \( (S) \) as abscissa is extrapolated to zero bedload.

The Schoklitsch equation is best suited to locations where medium sands to fine gravels are in transport.

The Colby (11) method gives estimates of total bed sediment discharge (and therefore total sediment discharge if suspended sediment samples of streamflow are collected). The semi-empirical relationships used are based on a fairly large number of measurements of streamflow and sediment samples. These include data from sections of rivers where natural or artificial turbulence devices created a near-uniform suspension of sediment with depth—and therefore made accurate measurement of total load possible. The procedure,
sometimes called the mean velocity method, requires the mean stream velocity \( (V) \), the stream width \( (b) \), the mean depth \( (d) \), the median size of sediment \( (D) \), and the mean suspended sediment concentration of fine sediments (smaller than 62 \( \mu \)m) as determined from conventional suspended sediment samples.

Three variations of the estimating procedure are used, depending on field conditions. If the bed material sizes, water temperature, and other conditions are quite similar to those cited by Colby for the streams of figure 4.95, that graph will yield satisfactory answers. If the bedload is being estimated for a channel where the depth, water temperature, or concentration of fine sediments is appreciably different from those of figure 4.95 then figures 4.96 and 4.97 must be used.

**Erosion and Sediment Yield Relationships**

An important phase of sedimentation is the utilization of the results of plot erosion studies for computing sediment yields from field-size and larger areas and computing the trap efficiency or sediment delivery of a watershed by considering the retardation effect of watershed variables on sediment movement from erosion source areas to a given downstream point.

In other words, one of the variables in the equation

\[
Y = ED
\]  
\( (4-31) \)

is solved by measuring or calculating the other two where

\( Y \) is the sediment yield at a downstream location, quantity/time;

\( E \) is the total erosion of the upstream watershed, quantity/time; and

\( D \) is the watershed trap efficiency or sediment delivery ratio. Procedures for processing these data depend on the variable being investigated.

For some research purposes, the measured sediment yield from a watershed is compared with a value that is derived from existing procedures for calculating soil losses from small source areas of sheet, rill, and channel erosion.

**Figure 4.95**—Curves showing relationship between discharge of sands and mean velocity for five sand-bed streams at average temperature of about 60°F. (8.)
FIGURE 4.96.—Relationship of discharge of sands to mean velocity for six median sizes of bed sands, four depth of flow, and a water temperature of 60°F (8).
This is one method for checking the validity of soil loss equations and for improving them. Whenever the "E" term for each component area of a watershed can be sufficiently defined by measurement and/or computations and when the "Y" term of the foregoing equation is also determined by sediment yield measurement procedures, it becomes possible to isolate watershed and drainage variables that affect the sediment delivery. Regardless of which of the two objectives the researcher has in mind, climatologic, physiographic, and land use data are required to find the factors influencing E and D.

The methods for summarizing and processing these factors associated with soil erosion and sediment delivery ratios are too variable for extended discussion here, and the reader is referred to the chapters on hydrology, climate, soils, and geology for methodology in tabulating hypsometric curves, drainage densities, and other parameters. It is sufficient to mention some standard variables used in soil loss equations.

The Universal Soil Loss Equation (68) expresses mean annual soil loss, \( E \) (tons per acre), in terms of:

\[
E = RKLSCP
\]

\((4-32)\)

\(R\), a factor expressing the erosion potential of average annual rainfall in the locality. It is a summation of individual storm products of the kinetic energy of rainfall, in hundreds of foot-tons per acre and the maximum 30-minute rainfall intensity, in inches per hour, for all
significant storms, on an average annual basis;

\( K \), a soil erodibility factor representing the average soil loss, in tons per acre per unit of rainfall factor, \( R \), from a particular soil in cultivated continuous fallow, with a standard plot length and percent slope arbitrarily selected as 73 feet (22.2 m) and 9 percent, respectively;

\( S \) and \( L \), topographic factors for adjusting the estimate of soil loss for a specific land gradient (S) and length of slope (L). The land gradient (slope) is measured in percent. Slope length is defined as the average distance, in feet, from the point of origin of overland flow to whichever of the following limiting conditions occurs first: (1) the point where slope decreases to the extent that deposition begins, or (2) the point where runoff enters well-defined channels;

\( C \), a cropping management factor representing the ratio of the soil quantities eroded from land that is cropped under specified conditions to that which is eroded from clean-tilled fallow under identical slope and rainfall conditions; and

\( P \), the supporting conservation practice such as strip-cropping and contouring. For straight-row farming \( P = 1.0 \).

**Reservoir Sedimentation Measurements**

With the field survey, sample analysis, and basic reservoir computations completed, as explained in the Data Reduction section, these and other pertinent variables may be recorded on a summary sheet such as SCS Form 34, 1962 (fig. 4.98). Additional data are often collected to define the reservoir trap efficiency and the density and distribution of deposited sediments. Nearly all these reservoir sedimentation characteristics are being examined for correlation with watershed and reservoir characteristics not included in the standard form.

The rate of deposition in a reservoir can vary from complete filling during a single large storm to a negligible fill during several decades. The location of deposits and trap efficiency is a function of storm size. Mundorff (49), at Reservoir K-79 on Kiowa Creek, Colo., measured a trap efficiency of about 60 percent for the July 30, 1957 storm, compared with 75 percent for the 1956-65 period. Trap efficiency is also a function of flow detention time, often expressed as the ratio of reservoir volume to the volume of average annual water inflow (7, 17).

The distribution of sediment affects the life and operation of the reservoir and Lane (44) describes typical depositional patterns in figure 4.99. Relationships similar to Heinemann's (28) (figs. 4.100 to 4.102) are useful, because they specifically relate the volume-weight of sediment to reservoir depth, particle size, and distance from the dam.
FIGURE 4.98.—Reservoir sedimentation data summary form, page 1.
FIGURE 4.99.—A sketch of the longitudinal cross section through a reservoir operating at constant water level showing various types of deposits.

FIGURE 4.100.—Depth versus volume-weight relationship for deep sediments (28).

FIGURE 4.101.—Volume-weight at constant sediment depth versus distance from dam (28).
Selected References on Chronological Development of Sediment Discharge Formulas and Procedures

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The following list of terms and definitions used in the manual includes only those associated with sedimentation research and for which meaning may not be readily apparent. The list in not intended to be comprehensive. Definitions established by professional engineering and scientific societies were used where available. Principle sources of definitions are given in the references at the end of the definitions.

Acre-foot—The volume required to cover one acre one foot in depth, or 43,560 ft³.

Antidune—A sand wave, indicated on the water surface by a regular undulating wave, in appearance like that formed behind a stern wheel boat. These ridges usually move upstream. The surface waves become gradually steeper on their upstream sides until they break like surf and disappear. These waves are usually in series and often reform after disappearing.

Area, drainage—The area tributary to a lake, reservoir, stream, or measurement site.

Capacity, reservoir—Total storage capacity in a reservoir below a designated elevation.

Bed, plane—A sedimentary bed without elevations or depressions larger than the maximum size of the bed material.

Capacity, reservoir, sediment pool—That portion of reservoir capacity reserved for sediment storage, usually below the principal spillway elevation.

Capacity, reservoir storage, flood—That portion of reservoir capacity reserved for temporary storage of flood waters to reduce downstream peak flows.

Colloids—Finely divided solids which will not settle but may be removed by coagulation or biochemical action. In soil physics, a discrete mineral particle less than 0.002 micron in diameter.

Concentration, sediment—The ratio of the quantity of the sediment in a water-sediment mixture to the total quantity of the mixture, usually expressed by weight in parts per million or milligrams per liter.

Control—A section or reach of an open conduit or stream channel where artificial or natural conditions exist, such as the existence of a dam or a stretch of rapids, that make the water level above it a stable index of the discharge.

Control, shifting—A control section which changes with scour or fill variations in the streambed, changes in the bedform or in the sediment load or other physical conditions that causes a change in the water level-discharge relationship.

Cover Complex—In hydrology, a term used to designate a specified combination of soil, crops, or vegetation, and tillage.

Cubic foot per second—A unit of discharge for measurement of flowing liquid, equal to a flow of one cubic foot per second past a given section.

Curve, flow-duration—A cumulative frequency curve that shows the percentage of time that specified discharges are equaled or exceeded.

Curve, frequency—A graphical representation of the frequency of occurrence of specific events.

Density—The ratio of mass of a substance to its volume; mass per unit volume.

Density, bulk—Mass per unit bulk volume of soil or sediment that has been dried to constant weight at 105° C, usually ex-
pressed in grams per cubic centimeter or pounds per cubic foot.

Diameter, sedimentation—The diameter of a sphere of the same specific gravity and the same terminal uniform settling velocity as the given particle in the same sedimentation fluid.

Discharge, sediment—Weight of sediment transported per unit of time.

Dune—A sand wave of approximately triangular cross section (in a vertical plane in the direction of flow) formed by moving wind or water with gently upstream slope which travels downstream by movement of sediment up the upstream slope and the deposition of it on the downstream slope.

Erodibility—The relative ease with which one soil erodes under specified conditions of slope as compared with other soils under the same conditions.

Erosion—Wearing away of the land surface by running water, glaciers, winds, and waves. The term erosion is usually preceded by a definitive term denoting the type or source of erosion such as gully erosion, sheet erosion, bank erosion.

Erosion, gully—The removal of soil by concentrations of flowing water sufficient to cause formation of channels that cannot be smoothed completely by normal cultivation methods.

Erosion, rill—The removal of soil by small concentrations of flowing water, with the formation of channels that are small enough to be smoothed completely by normal cultivation methods.

Erosion, sheet—The gradual removal of the earth surface in a sheet of more or less uniform thickness through the action of wind or water.

Fill, valley—The sedimentary deposits laid down in a valley subsequent to the time of its formation.

Land use—The culture of the land surface which has determining effect on the broad social and economic conditions of a region and which determines the amount and character of runoff and erosion. Three general agricultural classes are recognized: Crop, pasture or range, and forest.

Load, bed—Sand, silt, gravel, or soil and rock detritus carried by a stream on or immediately above its bed. The particles of this material have a density or grain size such as to preclude movement far above or for long distances out of contact with the streambed under natural conditions of flow.

Load, bed-material—That part of the sediment load of a stream which is composed of particle sizes found in appreciable quantities in the shifting portions of the streambed.

Load, contact—Sediment rolling or sliding along the bed, or moved, directly or indirectly by the impact of the bouncing particles.

Load, saltation—The portion of the stream load which bounces from the bed into the flow and is transported a short distance before it again falls to the bed, or is moved directly or indirectly by the impact of the bouncing particles.

Load, suspended—The portion of stream load moving in suspension and made up of particles having such density or grain size as to permit movement far above and for long distance out of contact with the streambed. The particles are held in suspension by the upward components of turbulent currents or by colloidal suspension.

Load, wash—(1) In a stream system the relatively fine material in nearpermanent suspension, which is transported entirely through the system without deposition; (2) That part of the sediment load of a stream which is composed of particle sizes smaller than those found in appreciable quantities in the shifting portions of the streambed.

Loop, rating—A rating curve with higher values of the discharge for a given stage when the river is rising than when it is falling. The curve thus describes a loop with each rise and fall of the river.

Material, bed—In a stream system, the geologic formations and alluvial deposits through which the stream channel is cut.

Parts per million—Parts of a substance in a million parts of water, usually expressed on a weight basis. Parts per million as used in this manual is the ratio of the sediment-
weight to the weight of the water-sediment mixture.

Plain, flood—Land bordering a stream, usually built of sediments from the stream and subject to flooding unless protected artificially.

Plot, experimental—A small area, usually less than one acre in size with artificial boundaries, established for the field measurement of runoff and soil loss.

Reach—(1) A comparatively short length of a stream, channel, or shore. (2) A portion of a stream between two gages.

Rill—A very small stream or intermittent water course, usually only a few inches in depth.

Size, particle—The effective diameter of a sediment particle measured by sedimentation, sieving, or other methods.

Soil loss—Soil material removed from a plot, field, or small watershed by erosion.

Sediment—Any material entrained and carried in suspension by wind or water. Fine waterborne or aeolian matter deposited or accumulated.

Sediment Delivery Ratio—A measure of the diminution of eroded sediments, by deposition, as they move from the erosion sources to any designated downstream location, expressed as a percentage or ratio of the on-site eroded material that reaches a given measuring point.

Sediment Transport Relation—The relationship between runoff rate on an instantaneous, storm, daily, or other basis, and sediment discharge, usually expressed in graphical form.

Sediment Yield—The total sediment outflow from a watershed or drainage area past a point of reference, usually expressed in weight per unit of time.

Station, gaging—A location on a stream, usually at a controlled cross section, where measurements of water and sediment discharge are customarily made.

Volume weight—See density, bulk.

Wave, sand—A ridge on the bed of a stream formed by the movement of the material, which is usually approximately normal to the direction of flow, and has a shape somewhat resembling a water wave.

Weight, specific—See density, bulk.
Construction Drawings for Runoff Samplers

Notes
1. Assembly by spotwelding.
2. Attach angle to slotplate and box with 3 rivets equally spaced.
3. Solder seams watertight — unit to convey water without leaking — scrape inside seams smooth.

Multislot Divisor

Notes
2. Make slot plate from single piece — bend after making slots.
3. See specifications for slot tolerances.
4. Spotweld precision plate to slot plate as shown — see spec's for further requirements.
5. All dimensions are in inches.

Fig. 4.103.—Plans for the ½-inch (9 slots) multidivisor.
Notes

1. All dimensions are in inches — dim. ± 1/16 unless otherwise specified.
3. Assemble by spotwelding.

Spout and Hood for Multislot Divisor

Divisor Box
(Material — 20 Ga. Galvanized Steel)

Box Lid
(Material — 20 Ga. Galvanized Steel)

Support Angle
(Material — 1 1/4 x 1 1/4 x 1 3/16 Galvanized Angle)

FIGURE 4.103.—Continued
\( \frac{1}{4}\)" Drill
2 Holes

\[ S = \text{Sum of the widths of the divisor slots} \]
\[ W = \text{Width of divisor box} \]
\[ D = \text{Depth of divisor box} \]

Entrance Arrangement for Multislot Divisors — Type I

Figure 4.103.—Continued
Figure 4.104.—Plans for the N-1 Coshocton-type runoff sampler.
**H-Flume Template**

(24 Gauge galvanized steel. Make 1, 9" x 23" sheet required)

- Side flange holes drilled on 2 1/2" centers
- Bottom flange holes drilled on 2 1/2" centers
- Drill all holes 1/16"

Drill holes after bending flume so that mounting of cross brace will leave a 6 60" throat opening at brace

**Bend on dotted lines**

**Fasten flume to base plate**

3 places shown. Use rivets or machine screws. Solder heads watertight

**Notes**

1. Tolerances for decimal dimensions = 0.3" or 1/16", whichever is larger, except as noted
2. Solder all joints unless specified otherwise
3. Detail drawings full-scale. All others 1" = 2

**Detail "A"**

Galvanized Steel Angle Iron Brace

(Make 1)

**Detail "B"**

Stiffeners

(24 Gauge galvanized steel. Make 2, bent in opposite directions. See Section "A-A" for mounting detail)

**Section "A-A"**

Stiffener Mounting Detail

**Detail "C"**

Flange Corner Braces

(Make 2
24 Gauge galvanized steel)

**Drill holes after mounting brace using flange holes as guides**

**FIGURE 4.104.—Continued**
Turning Vanes B-H
Vaness E, F, and G are 7 1/2, 0 1/2, 2 1/2 respectively
Drill No 40 holes near inner ends as shown

Section "B" "B"
Slot Opening
True inside dimensions. Width
tolerances = 0.005. Use
micrometered spacers at indicated points
during assembly.

Slot Stiffeners
(Make 2. Bend about 80°)

Turning Vane A

Bend 4 1/2

U-Band Reinforcer

Bend 4 1/2

Splash Deflector
(Make 1. Bend about 60°)

U-Band Reinforcer

Turning Plate

Bearing Housing
(Brass)

Bearing Post
(1/4" Hex or round brass)

Notes
1. All parts made of 22 Gauge galvanized
   steel except as noted.
2. Soft solder all joints except as noted.
3. Increase the slope of the sampler while
   balancing the wheel.
4. Pan, Sampling Head, and connection between
   Sampling Head and Wheel are to be water-
tight.

FIGURE 4.104.—Continued
FIGURE 4.105.—Plans for the N-2 (2-ft Coshocton-type runoff sampler, model N-2, 1/2 of 1 percent).
Flume Sheet Layout

Flume Edge Stiffeners
(Make 2, but bend oppositely. Solder to Flume Sides at ⅛" from edges of downstream opening.)

Tie Angle
1" x 1" x ⅛" Steel

Flange Corner Pieces
Make 2

Note: Tolerance for decimal inch dimensions, 1% or .03 inch.
All parts 22 Ga. galv. steel, except tie angle
Figure 4.106.—Plans for the N-3 Coshohcton-type runoff sampler.
Figure 4.107.—Plans for the vehicle-mounted telescoping crane.
### Parts Schedule

<table>
<thead>
<tr>
<th>Part No.</th>
<th>Quant.</th>
<th>Size</th>
<th>Material</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>5(\times)67/8(\times)1(\frac{1}{4})&quot; thick</td>
<td>Steel plate</td>
<td>Side plates</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>1(\frac{1}{2})(\times)1(\frac{1}{4})(\times)1(\frac{1}{2})&quot; 67/8&quot; long</td>
<td>Angle iron</td>
<td>Rails</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>1(\frac{1}{2})(\times)1(\frac{1}{4})(\times)3(\frac{1}{2}) 38&quot; long</td>
<td>Angle iron</td>
<td>Legs</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>1(\frac{1}{2})(\times)14&quot;</td>
<td>Steel rods</td>
<td>Thread 3&quot; on each end (spacer)</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>1(\frac{1}{2})(\times)11(\frac{1}{4})&quot;</td>
<td>Cold roll</td>
<td>Axles for carriage See Note 7</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>2(\frac{1}{2})&quot; schedule 40 (71&quot; long)</td>
<td>Steel pipe</td>
<td>Stationary boom</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>Extra heavy duty 2&quot; (79&quot; long) (length as needed)</td>
<td>Steel pipe</td>
<td>Boom extension</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>2&quot; Cap</td>
<td>Steel</td>
<td>End of boom extension</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>2(\frac{1}{2})&quot; Cap 2(\frac{1}{4})(\times) hole in center</td>
<td>Steel</td>
<td>End of stationary boom</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>Chain sprocket</td>
<td>See Note 3</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>Heavy duty link chain</td>
<td>See Note 4</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>15(\times)20(\times)1(\frac{1}{4}) Aluminum plate</td>
<td>Carriage platform</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>2</td>
<td>2(\times)2(\times)1(\frac{1}{4}) (15&quot; long)</td>
<td>Angle iron</td>
<td>Carriage platform</td>
</tr>
<tr>
<td>14</td>
<td>1</td>
<td>5&quot; diameter sheave</td>
<td>Brass</td>
<td>See Note 9</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>3&quot; diameter pulley</td>
<td>Aluminum</td>
<td>Rear of boom</td>
</tr>
<tr>
<td>16</td>
<td>4</td>
<td>2(\frac{3}{4}) 1&quot; ID 1(\frac{1}{2})&quot; thick Ballbearing (sealed)</td>
<td>See Note 5</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>1(\frac{1}{2})&quot; dia, 29&quot; long</td>
<td>Steel</td>
<td>Crank handle</td>
</tr>
<tr>
<td>18</td>
<td>1</td>
<td>3(\frac{1}{2})&quot; x 4&quot; x 12&quot;</td>
<td>Steel plate</td>
<td>Boom support</td>
</tr>
<tr>
<td>19</td>
<td>1</td>
<td>1(\frac{1}{4})&quot; x 11(\frac{1}{4})&quot; x 6&quot;</td>
<td>Angle iron</td>
<td>Boom support</td>
</tr>
<tr>
<td>20</td>
<td>2</td>
<td>3(\frac{1}{4})&quot; bolt Steel</td>
<td>See Note 6</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>2</td>
<td>Spacers</td>
<td>Machined to fit pipe</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>1</td>
<td>3(\frac{1}{4})&quot; x4&quot; bolt Steel</td>
<td>Axle for sheave</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>4</td>
<td>1 180° O.D. 0 388° I.D Ballbearing (sealed)</td>
<td>See Note 10</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>4</td>
<td>3(\frac{1}{4})&quot; bolt Steel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>2</td>
<td>3(\frac{1}{4})&quot; x4&quot; (16&quot; long)</td>
<td>Steel</td>
<td>Lateral stabilizer</td>
</tr>
<tr>
<td>26</td>
<td>28</td>
<td>5(\frac{1}{2})&quot; x 1&quot; bolts Steel</td>
<td>Bolts angle to side plate</td>
<td></td>
</tr>
</tbody>
</table>

**Note 1**: The angle iron (4) used as rails are bolted to the side plates (1) every 8" with 3\(\frac{1}{4}\)" bolts (26).

**Note 2**: The distance between the side plates (1) is adjusted with the spacer rods (4).

**Note 3**: Use sprocket by Diamond or equivalent 3\(\frac{1}{4}\)B19 Pitch diameter 3 number teeth 1\(\frac{1}{4}\) bore 1\(\frac{1}{4}\" locked with set screw.

**Note 4**: Use chain by link belt or equivalent RC 40 Chain pitch 1\(\frac{1}{4}\") Avg. 30" 3700 (lbs) length 60.

**Note 5**: New departure 77R16 bearing or equivalent.

**Note 6**: Stationary boom (6) and extension boom (7) can be locked in position every 6" with a bolt through each. Extension boom (7) has holes drilled on 6" centers.

**Note 7**: Axles (5) are 16" centers apart.

**Note 8**: The angle iron under carriage platform is rounded to fit stationary boom (6) and welded. Cut the back angle to fit within the side plate.

**Note 9**: Ballbearing sheave for USOS type A Crane.

**Note 10**: Lateral support bearing MRC 200FS or equivalent.

**Figure 4.107**—Continued
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INTRODUCTION

The purpose of this chapter is to offer a broad range of guidelines to those who may be in the initial stages of developing a program of hydrogeology studies, or interested in expanding or changing directions in an ongoing program. Hydrogeology is defined here as those physical geologic processes which profoundly influence the hydrologic cycle and bring together the two disciplines of hydrology and geology.

The chapter is divided into three sections. The first section covers basic geologic investigations used in gathering preliminary information for a hydrogeology program. Instrumentation, methods, and data-gathering techniques are discussed.

The second section covers ground-water investigations and discusses equipment and installations needed, instrumentation and methods used, and several data processing suggestions.

The third section covers quantitative geomorphology investigations and their relative importance in hydrologic investigations. Installations, measuring techniques, and methods of observation are given in detail for drainage network analyses. Practical illustrations are given or referenced throughout the chapter.

BASIC GEOLOGIC INVESTIGATIONS

The geologic materials underlying a watershed are one of the most salient features influencing the hydrologic flow regime. The rate of flow, of both surface and subsurface water, is dependent upon the nature of the material in the path of flow. Certain basic geologic investigations are needed prior to intensive research. Accurate surficial geologic maps, from which interpreted geologic cross sections can usually be constructed, are important to understanding the origin of soils, stream-drainage patterns, and sediment production. Geologic maps and cross sections are also needed to aid in accurate interpretations of ground water movement and storage, stream transmission losses, infiltration rates, and ground water quality.

Geophysical techniques may be used to help interpret prevailing geologic conditions which influence the hydrologic regime.

Geologic Mapping

Certain basic items of geologic information are required for a geologic map to be useful in the field. For most purposes these items include: (1) Identification and description of rock units, (2) Delineation of rock units, (3) Description of the attitude of the rock units (dip and strike), (4) Measurement of the outcrop thickness and sequence, (5) Identification of all faults, attitude, and amount of displacement, (6) Use of rock unit as an index horizon for correlation purposes, and (7) Location of springs, wells, and water levels for ground-water investigations.

For more detailed needs, joint systems, lineation, and foliation characteristics may be mapped. The field mapping is usually done by experienced geologists because of the technical knowledge required to identify and characterize geologic information. Lahee (53) provides comprehensive coverage on geologic field mapping techniques.

Ground Control

The first step in preparing a geologic map of an area is to establish accurate ground control. This control is usually in the form of maps and aerial photographs to allow the investigator to locate, plot, and delineate the geologic units being investigated. If maps or photos are not
available, base stations and control points must be established and accurately surveyed.

Selection of map and aerial photographic scale is made according to the size of the area to be mapped and the degree of accuracy required. Large-scale maps are ideal for studying small areas in detail. However, if a regional geologic map is to be made, a small scale would be more suitable since time would prohibit detailed observations.

An area should be mapped first at a small scale to satisfy immediate use requirements. Detailed mapping at a larger scale can be done later as the need requires.

**Aerial Photographs**

The use of aerial photographs can reduce cost and field investigation time by improving the plan of study, aiding correlation, and locating geologic structures (66).

Direct interpretation of surficial geology on aerial photographs is often concealed by vegetation. However, vegetation can often be used as an indicator of certain soil and rock associations. Rock identification and vegetative characteristics may be enhanced by the use of infrared and color when mapping geology from aerial photographs (1).

When selecting aerial photographs for geologic field investigations, a scale must be selected that will permit sufficiently accurate mapping, and also be in keeping with the quality and quantity of photographs available. A variety of scales and types of aerial photographs of good quality is usually available to the purchaser from many sources. Such agencies as U.S. Geological Survey, U.S. Army Map Service, U.S. Department of Agriculture Soil Conservation Service, U.S. Department of Agriculture Forest Service, and the U.S. Department of Agriculture Agricultural Stabilization and Conservation Service are good sources. Many private companies are also sources for aerial photographs. A photo-index can usually be purchased at little cost, and a list of the required prints can be selected.

Relief, the difference in elevation between the high and low points of the land surface, is an important feature in geologic mapping from aerial photographs. Distortion of these relief features can occur on aerial photos without adequate stereoscopic overlap. For regional coverage by vertical photographs, a standard side-lap of 30 percent is used on photos of adjacent flight lines. Overlap of 60 percent is standard with photos in individual lines. Figure 5.1 shows flight lines planned for a project area, spaced for 30 percent sidelap and 60 percent overlap. Distortion is kept to a minimum when the central portion of stereo-pairs is used. The ability to obtain adequate stereoscopic overlap should be a factor in purchasing photos.

Convergent photography, twin low-oblique, gives 100 percent stereoscopic overlap if all the photos of a flight line and adjacent flight lines are used. If only plain pictorial coverage (non-stereoscopic) is required, every second photo in a flight line is necessary to give complete coverage. Scale must be considered when using aerial photos because of distortions caused by oblique photography and unintentional tilt. In low oblique photos the scale at the upper edge of the photo may be as much as 75 percent larger due to the camera angle. Uniform scale and rectified prints, which correct for angle and tilt distortions, can be purchased, but these must be specifically requested and usually cost more than standard prints.

Geologic mapping from aerial photographs generally requires an initial field check making ground observations that can be transferred to photos. The work can then continue in the office, using a stereoscope or any other photo interpretive equipment available. Subsequent field checking is often required to produce a final map. The following methods for field mapping from aerial photos are efficient and thorough but not necessarily best suited for all situations.

- Delineate geologic units first using a silver lead pencil.
- Outline units later in ink and color or symbol coding (fig. 5.2).
- Use the same code for each unit being mapped.
- If spot information such as a mine or a well is required, make a notation by placing a pinhole through the photo at that location and describe the location on the reverse side of the photo next to the pinhole.
- Designate structural features such as dip
and strike, faults and folds on the photos and describe briefly on the reverse side.

- Keep complete description of all data, especially measured sections, in a fieldbook.
- In some cases it may be desirable to do some stratigraphic and structural mapping without prior knowledge or field checking of the rock units or structures. However, the geologist must field check this work.

Geologic mapping using aerial photographs enables the geologist to map inaccessible areas, and to obtain a broad all-encompassing view of features that might be obscure and confusing from the ground.

**Topographic Base Maps**

Most topographic maps are derived from aerial photographs. The most useful of these is the topographic map which shows the vertical relief of an area as well as accurate horizontal control. Unlike aerial photographs, these maps are not distorted. However, some information is always lost on such factors as soil tone, vegetation, and small gully delineation.

Topographic maps are constructed and available from such agencies as the U.S. Geological Survey, U.S. Army Map Service, and the U.S. Coast and Geodetic Survey. Areas are usually mapped first at a small scale of 1:250,000 and later remapped at a larger scale according to public demand. Topographic maps are issued in series by degrees and minutes of latitude. A 7.5-minute quadrangle series is usually published at a scale of 1:24,000, a 15-minute quadrangle at 1:62,500, and a 2-degree quadrangle at 1:250,000.

All maps can be reproduced to larger scales by simple photographic methods. A map enlargement by this method, unlike an aerial photograph enlarged from a negative, does not
FIGURE 5.2.—Geologic mapping on aerial photo.
yield any increased detail, only magnification of what is already visible on the original. This magnification is usually accompanied by a loss of quality of sharpness and definition.

Vertical control on topographic maps is presented as contour lines, which connect points of equal elevation. Contour intervals vary according to the scale of the map and the amount of relief represented. Most mapmakers will give areas of low relief a smaller contour interval than areas of high relief. If a single map presents both a low and a high relief area, two contour intervals are generally used.

Depending upon use of the information, selection of map scales for geologic mapping is determined by the detail and accuracy required. Map scale selection depends on the complexity and size of the units to be mapped. For example, if large areas of basin alluvium with sparse, uniform rock outcrops are to be mapped, a small-scale map would give sufficient detail since the area lacks diversity. If, however, a small area containing a variety of stratigraphic units or complex structures is to be mapped, one must select a map scale which adequately describes and depicts the interrelationships of these units—a large-scale map.

Geology can be mapped directly on topographic maps as on aerial photos. The advantages of mapping on topographic maps are that vegetative cover does not obscure the land surface, roads, and landmarks; and relief values are graphically depicted and can be read directly. Topographic maps also offer to the geologist much useful information on such identification points as well sites, elevation benchmark locations, mine sites, names of hills, mountains, valleys, stream channels, and towns.

The topographic expression of many geologic features are often plainly visible on topographic maps. Some disadvantages are that colors and shades that might indicate a rock type are not shown, areas bare of vegetation cannot be distinguished, and minute relief features are not discernible. One can locate oneself more accurately on an aerial photograph than on a topographic map because the surroundings are readily recognized on the photograph. Locations on a topographic map can be found by using any one of several compass-bearing or horizontal-angle measuring devices.

Where geological detail and accuracy is required, or where no topographic map exists, the planetable and alidade may be used to construct a base map. The planetable method of surveying is well suited for construction of a topographic base for a geologic map, detailed geomorphology measurements, and sediment transport studies. Watershed descriptions, such as soil types and vegetative characteristics, may be included on the map.

Accuracy and detail depends on the size of the area, the number of sightings taken from each station, and interpretations by the geologist for planetable survey methods and equipment (22, 61).

General planetable work by the geologist doing field mapping can be done rapidly and requires the help of one technician. When planetable mapping, the geologist acts as rodman calling for distance-elevation readings at points he deems pertinent to the survey. To facilitate the communication between the instrument man and the geologist, two-way radios are ideally suited. In lieu of radios, hand signals are frequently used.

A simple case of planetable work would be the mapping of a small basin. First, the geologist and technician walk the area to examine geologic features and locate visual vantage points. Next, a decision is made concerning what the best instrument locations would be to give the fullest coverage of the area. The instrument location site is preferably a point of mean elevation within the area to be surveyed.

The geologist proceeds to the first point and places the stadia rod on the reference to be described. Both record the reading as Station No. 1, and the geologist describes the geologic significance of the point in a notebook. The geologist then proceeds to all other points required for the survey, recording pertinent facts. The instrument man records distance-elevation points and numbers them consecutively on the planetable sheet.

When the geologist has gathered all the information needed for the area under command of the instrument, a turning point shot is called for by the instrument man. The turning point is a vantage point that has been selected
as the next instrument station. Before moving
the planetable, the geologist and instrument
man review each station reading to make sure
they have the same number of stations and
know their geologic significance. Successive in-
strument stations are occupied until the re-
quired area has been completely covered in
sufficient detail.

During traverses, the geologist has observed,
taken notes, and called for instrument shots on
such things as formation contact, faults, folds,
and topographic highs, lows, and irregularities.
Other features that will assist in preparing a
good map for watershed descriptions should be
noted. These may include soil and vegetative
characteristics and land use.

The topographic information recorded by the
instrument man has been plotted on the plan-
table sheet as the survey proceeds. Remaining
to be added to plotted survey data are contour
lines that will yield a completed geologic map
on a topographic base made entirely in the
field.

Other surveys

A reconnaissance survey can be made of an
area where only a scant amount of information
is required or as a preliminary step toward a
more detailed mapping survey. Such surveys
are usually done in one or two days' time, using
a vehicle and topographic maps, altimeter, com-
pass, sextant, or any other means of control.

Altimeters may be used for preliminary topo-
graphic and delineation of geologic features.
The surveying method may be used for recon-
naisance mapping of ground-water levels, loca-
tion of springs, and seeps, and for a regional
picture of geologic and ground-water trends.
Significant geologic features and other land-
scape characteristics may be located and plot-
ted on any topographic map or aerial photo by
using a compass, sextant, transit, or combina-
tion of these.

Surprising measurement accuracy by on-foot
surveys can be obtained with practice. The
observer must be careful to follow simple rules
of pace and stride calculations as they are
affected by uphill and downhill traverses. All of
these methods are discussed in detail in most
texts on surveying such as Lahee (54) and
Davis and Foote (22).

Identification, Delineation, and
Attitude of Rock Units

Certain rock types and their mode of implace-
ment have a pronounced effect on ground-
water behavior and related hydrologic phenom-
ena, stream patterns, topographic configura-
tions, and other surface features. The identifi-
cation of these rock units is necessary to
determine the subsurface trends, characteris-
tics, and relationship to all local units.

Rock types are divided into three main
groups that are usually distinguishable in the
field. These groups are: (1) sedimentary—those
rocks including alluvium that were deposited in
a fluid environment such as air or water, (2)
igneous—those rocks derived from a molten
liquid environment or magma and intruded
between or into other rocks, therefore crystal-
lizing below the earth's surface, or those rocks
derived from a liquid magma ejected or forced
to flow out of the earth and over the ground,
crystallizing on the earth's surface, and (3)
metamorphic—those igneous or sedimentary
rocks that have undergone recrystallization
and change in texture deep within the earth by
contact with molten igneous rocks, extreme
earth pressures, or hydrothermal action. Ex-
amples of the three rock types are given in
table 5.1.

Further subdivision of these groups requires
specialized training and expert knowledge. Ad-
ditional information can be found in Pirsson
(71), Pettijohn (70), Barth (73), Billings (7), and
Johnson (46).

In geologic mapping, the attitude (dip and
strike) of rock strata is important in determin-
ing relative position of each unit. The strike of
an inclined bed (fig. 5.3) is the compass bearing
of the outcrop as it intersects the horizontal
surface. A bearing taken along a strike line can
be in two directions 180° from each other. Strike
 bearings, if not lying perfectly east and west,
are always referenced to the north direction
(fig. 5.3).

The dip of an inclined bed is taken at right
angles to the strike on the down-sloping side. It
is measured in degrees of maximum inclination
from the horizontal. A horizontal bed has no
dip or strike. Attitude of beds, when plotted on
a map, will indicate the overall structure of the
TABLE 5.1.—Subdivision of the standard rock types

Common sedimentary rocks
- Clastic (derived from mechanical disintegration and deposition)
  - Sandstone
  - Conglomerate
  - Breccia
  - Quartzite (Orthoquartzite)
  - Siltstone
  - Shale
  - Arkose
  - Non-clastic (derived from chemical disintegration and deposition).
    - Limestone
    - Dolomite
    - Gypsum
    - Anhydrite
    - Rock Salt

Common igneous rocks
- Pyroclastic
  - Volcanic tuff
  - Volcanic breccia
- Glassy
  - Obsidian
  - Basalt glass
  - Pumice
- Aphanitic
  - Rhyolite
  - Dacite
- Granular
  - Granite
  - Granodiorite
  - Diorite
  - Gabbro
  - Dolerite

Metamorphic rocks showing sedimentary and igneous origins
- Sedimentary rock
  - granite (related coarse grained igneous rock)
  - Rhyolite (related fine grained igneous rock)
  - Basalt (related iron-magnesian rocks)
  - Peridotite (related igneous rock with iron-magnesium minerals and very little quartz)

- Igneous rock
- Metamorphic derivative
  - Metaquartzite schist
  - Gneiss; schist
  - Slate; phyllite; schist
  - Marble
  - Gneiss; schist; phyllite
  - Schist; phyllite
  - Hornblende schist
  - Serpentine; talk schist

unit or units, such as folds and domes, and will also indicate the direction of continuation if dipping beneath the surface. Some important field observations that can be plotted by symbols on a map are trends of folds, faults, cleavage, foliation, joints, lineation, and schistosity.

The geologist must map rock units as they appear on the surface and attempt to interpret their subsurface continuity. Geologic mapping requires that each rock unit be given a designation, preferably a proper name. For mapping purposes, it is permissible to designate a rock unit by a number if the unit is fully described and clearly distinguishable from other units. Once all rock units that are to be mapped have been differentiated and assigned a name or number, mapping can begin.

Plotting of the attitude of layered rocks is necessary to obtain an overall picture of the geologic structures. The number of plots required to describe an area is proportional to the complexity of the structures being mapped. Reconnaissance surveys, or surveys in areas of little structural variation, require fewer atti-

![Diagram of rock bed: Top surface, dip and strike of inclined bed; side surface, true thickness of bed.](image)
tude measurements to interpret the regional geology.

The purpose of mapping rock types is to identify and describe them and record their location, areal extent, and attitude. The equipment normally used for field mapping is a base map or aerial photographs, magnetic compass with clinometer, 100-foot (30.5 m) tape, rock hammer, notebook, sample bags, and protractor.

A brief reconnaissance, to become familiar with the mapping units, is advisable prior to the start of a detailed survey. The fieldworker then begins mapping in that portion of the area which contains the most completely exposed, stratigraphic section, and follows these units outward, plotting them on the base map or aerial photos. Appropriate notes are taken on thickness, attitude, composition, and textural changes, faults, and other characteristic features. Any index horizon if present should be adequately described (see below).

The final product of field mapping of an area will be a plan view of the geologic units showing their aerial extent, structural trends, and field designation. Since only the uppermost surface of the earth's crust can be shown on a plan view map, underlying geologic units, even though they are exposed on the surface on vertical cliffs, etc., cannot be shown. Stratigraphic sequence and thickness of rock units must be described in report form, using columnar sections and cross sections as an appendix to the plan view map.

Index Horizon

An index horizon is a prominent rock formation, bed, or layer that can be used as a reference to establish the relative position of other rock units. A good index horizon should have some characteristic which makes it readily recognizable and persistent over a large area. It can have a characteristic geologic age determined by fossil dating or simply be an established horizon from which other horizons can be indexed relatively.

Features of a good index horizon may be a persistent layer containing a specific fossil or fossil assemblage, an occurrence of a particular color, or a particular mineral inclusion or bed. A reliable index horizon is an asset to any stratigraphic survey. It is the first item to look for when an outcrop is examined; and, if found, all adjacent beds can be related to it and compared for correlation purposes to other adjacent areas.

Thickness of Rock Units

The thickness of a stratigraphic unit is measured on a line perpendicular to the bedding plane (fig. 5.3). If the erosion face of a rock outcrop happens to be perpendicular to the bedding plane, the thickness can be measured directly with a tape. In all other cases, the outcrop thickness must be measured and, taking the ground slope and dip of the bed into account, the true thickness calculated.

Direct measurement of the thickness of inclined strata can be made in the field by using Jacob's staff method. There are numerous equations for calculating thicknesses of strata under a variety of slope and dip conditions. Graphical representation of dip and slope conditions and graphical thickness computations are simple and adequate if proper scales are used.

The thickness of a single stratigraphic unit may vary. When describing the unit, the maximum thickness is always referred to. Graphical representation of strata by means of geological columns drawn to scale is an excellent method for showing the rock types, thickness, and areal distribution. Correlation of the continuity of stratigraphic units can be done readily using scaled geologic columns.

Location, Displacement, and Trends of Structural Features

Structural geologic features are those that interrupt continuous or flat lying strata, such as faults, folds, joints, cleavage, and the intrusion of magmatic bodies. Rock strata are seldom found in their original position. Repositioning is the result of compressional and tensional forces within or below the earth's crust.

Folds are warped or bent strata resulting from tectonic action and are found in igneous as well as sedimentary rocks. Folds may vary in size from less than an inch to several tens of miles. A fold is described in terms of its atti-
titude, thickness of beds, vertical amplitude, horizontal length, and relationship to adjacent strata. Age dating can be important when determining the relative positions of folded strata. Further information on folds and other structural features can be found in Billings (7).

Faults are earth ruptures that allow movement to take place along adjacent parallel planes. Faults, like folds, may be minute features or many miles long. Fault attitude is described in terms of dip and strike much the same as is bedding attitude. Because of the complexities involved in differential movement along fault planes, describing the displacement may be difficult. Movement along a fault is usually not a single event. It is several events spread over a period of time and not always in the same direction. Faults must be recognized and properly described in order to determine their movement relative to the surrounding strata. It is usually sufficient to describe the fault attitude, net displacement, and resultant direction of movement.

Figure 5.4 shows a simple classification of three major fault movements. The normal, or gravity fault (4A) is one which the hanging wall (the wall above the fault plane) has moved downward in relation to the footwall. The reverse, or thrust fault, (4B) has the hanging wall moving upward in relation to the foot wall. Both 4A and 4B have displacement in the vertical direction. A strike slip fault (4C) has movement of one side of the fault in relation to the other parallel to the strike of the fault and shows only horizontal displacement.

Joints are features that separate rocks, but differ from faults in that there is no displacement along the parting plane. Joints are described by measuring their dip and strike and, when possible, the amount of separation and secondary cementation. Fracture planes are usually not straight. Therefore, dip and strike measurements are not generally used. It is usually possible to measure trends or average attitudes of a series of fractures and joints.

**Hydrologic Characteristics of Rock Types**

Volcanic flows (igneous extrusions) may be thoroughly jointed and fractured and may also contain large voids in the form of chambers and tubes. Chambers may occur any place within the flow and act as a collection place for ground water flowing through fissures, joints, and fractures. Tubes, often large enough to walk through and extending for several miles, usually occur near the lower portion of flows.

---

**Figure 5.4.**—Classification of faults: A, normal fault; B, reverse fault; C, strike slip fault.
and can act as "underground channels" when filled with water.

Field investigations of extruded rocks involve describing the rock type, mapping the areal extent and thickness, noting the structure, and determining the feasibility of transmitting and storing water. If extrusive rocks have been caused to flow or fall into a preexisting surface basin, this basin could become an important ground water aquifer. Such basins may be completely buried, leaving no surface indication of their presence.

Igneous intrusions are rock bodies emplaced by assimilation of the surrounding rock, by forcing surrounding rocks out of the way, or by a combination of both processes. Igneous emplacements may be several thousand square miles in areal extent and exert pressure on surrounding rock, causing them to be folded and faulted. Intrusive rocks are the least permeable rock type when not fractured but may decompose readily by weathering and mechanical breakdown. It is generally considered to be a true basement rock. The structural identification and mapping of these igneous units may be difficult without the aid of drilling or geophysical methods.

Sedimentary rocks are composed of a variety of granular material ranging from clay size to boulders, held together with varying degrees of cementation. Some sedimentary materials contain little or no cementation.

Because of the incompetency of sedimentary rocks, they are more subject to geologic deformation than igneous rocks. Because of their higher porosity and permeability, sedimentary rocks usually form the best aquifer systems of all the consolidated rocks. However, water quality, primarily due to hardness, is not always acceptable. Many of the more favorable aquifers in the world occur in unconsolidated or semiconsolidated alluvial deposits. Shales and unconsolidated clay formations usually operate hydrologically as confining layers and are often associated with artesian aquifers.

Joints and fractures (irregular parting) play an important role in ground-water recharge storage and movement. Areas consisting of consolidated rocks should not be considered to have low permeability until investigation has shown that open fractures and joints are not extensive.

**Mapping Hydrogeologic Units**

Mapping of hydrogeologic units is done from existing geologic maps, providing they are of a suitable scale. The surface extent of the lithologic formations is grouped according to such hydrologic properties as porosity and permeability. If no geologic map is available, the hydrogeologist examines the outcrops in the field, groups the formations into suitable mapable units, and plots their occurrence on maps or photographs of suitable scale. Information for mapping can also be gained from drill logs and geophysical surveys.

Proper attention should be given to structural features which may influence recharge rates and ground-water flow. Fracturing due to tectonic activity may increase permeability of certain formations; or faulting may bring a permeable formation adjacent to one of lower permeability, causing local recharge or a change in the general flow system. Water sampling for chemical analyses and water temperature data from wells can be significant findings when interpreting hydrogeologic units for mapping purposes.

When the hydrogeologic map is completed, it generally will not look like a standard geologic map of the same area. Hydrogeologic boundaries will not necessarily coincide with the lithologic boundaries of the geologic map. However, all structural features, when mapping at the same scale, should be identical on both maps.

Structural contour maps may be developed on certain horizons of interest, such as the surface of a permeable zone at depth, to help plot the flow system or estimate the aquifer thickness. Cross sections drawn from the hydrogeologic map can aid in projecting water gradients and possible areas of discharge.

It may be advantageous to map geomorphic features when applicable, especially in areas of Pleistocene or Recent deposition. Glacial features such as outwash, moraines, eskers, and terraces are often very permeable features and commonly mapped as such. Stream deposits such as sandbars, beach ridges, and alluvium,
and windblow deposits such as loess and sand dunes, should also be mapped.

**Geophysical Investigations**

The proper evaluation of the factors controlling the behavior of ground water movement requires a thorough knowledge of the subsurface geology. Water well records and borehole log information are the best subsurface information obtainable. Drilling to obtain information on the subsurface geology is time consuming and costly. Geophysical methods offer a supplemental means whereby large subsurface areas can be investigated rapidly at a reasonable cost.

In selecting a geophysical method to be applied to an area, the investigator must decide exactly what information is needed and weigh this against the time and cost factors. Each geophysical method has limitations.

**Seismic Methods**

Seismic methods in watershed hydrology are mostly concerned with differentiating between a variety of porous and nonporous rock strata. Ground-water investigations require information on aquifer size, the nature of the rock strata, and water-table elevations. Stream transmission losses in alluvial channels are dependent on the depth and character of the alluvium. Seismic surveying can yield information on all of these.

Seismic theory is based on the fact that all uniform materials have a characteristic shock-wave transmitting velocity depending on their elastic constant and density. Since the seismic velocities of materials vary, the materials can be distinguished.

Seismic surveying determines shock-wave transmission velocities of geological materials in place. Velocity data gathered along survey lines can be interpreted to reveal the sequence, identity, and depth beneath the ground surface of the underlying strata. Subsurface geologic profiles can be constructed along survey lines. It is difficult, however, to identify rock type because characteristic velocities of certain rock types overlap (table 5.2).

Seismic refraction and reflection methods are commonly used for subsurface investigations. In seismic surveying a shock wave is generated on or near the ground surface, resulting in energy waves being radiated in all directions. These seismic waves travel through each geologic material and reflect and refract at the interface of the different materials (fig. 5.5). Depending upon the nature of the underlying material, some will refract or reflect to the surface where their arrival times can be recorded by electromagnetic sensors called geophones. Since the distance between the generated shockpoint and the geophones is known,

**TABLE 5.2.**—*Characteristic seismic velocity ranges*

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<td>Velocity (ft./s)</td>
<td>0</td>
<td>1,000</td>
<td>2,000</td>
<td>3,000</td>
<td>4,000</td>
</tr>
</tbody>
</table>
FIGURE 5.5.—Characteristic reflection velocity wave pattern.
and the time required for the return of the seismic wave is recorded, the velocity can be computed.

Seismic reflection methods record shock waves that are reflected off the various layered materials beneath the earth and, unlike refraction, measure not only first shock-wave arrivals but subsequent arrivals (fig. 5.6). Reflection methods are commonly used for deeper penetrating investigations.

Seismic refraction methods, because of simplicity and low cost, are best suited for hydrologic studies such as construction site investigations, shallow aquifer evaluations, and alluvial investigations. A single geophone with a non-recording oscillograph or digital readout is the standard equipment used for depth penetration to about 100 feet (30.5 m). For depths greater than 100 feet (30.5 m), more complex equipment with multiple geophone sensors is required. Seismic refraction surveys measure the arrival time of a surface generated shock wave that travels through a lower velocity material to a higher velocity material. The wave is refracted at this interface and travels through that higher velocity material, generating shock waves upward to the surface (fig. 5.6).

Since the incident angles of refraction have a large horizontal component, the distance between the point of shock generation and the geophone is proportional to the depth the shock wave reaches. A rule of thumb for estimating the relationship between depth penetration and seismic shock, and geophone spread length, is 3:1; for example, a 900-foot (274 m) spread between shock point and geophone will measure 300-foot (91 m) in depth. Small single geophone units may only require the impact of a sledge hammer on the ground to generate a seismic shock wave, while greater depth shooting with more elaborate equipment may require explosives.

Figure 5.7 is a typical example of data plotted from a dual geophone seismic meter, operated with a large hammer and steel plate as an energy source. The objective of this survey was to determine the depth of soil overlying the first high-velocity layer. The two geophones were placed at 160 feet (49 m) apart. Readings were taken first with the hammer striking the plate at 2.5 feet (0.76 m) away from the first geophone and 157.5 feet (48 m) away from the second. A dual traverse was then achieved, averaging out any errors which may have existed.

The time at each distance was read from the meter in milliseconds and plotted on time-distance curves as in figure 5.7. The slope of the lines were determined by use of an overlay template. The range of velocities generally fell

![Figure 5.6.—Characteristic refraction velocity wave pattern.](image-url)
between 700 and 20,000 ft/s (213 and 6,096 meters/s) so a suitable overlay could be drafted by computing these slopes. The velocity is equal to the reciprocal of the slope and is computed as horizontal distance in feet divided by the vertical distance in milliseconds, giving velocity in thousandths of feet per second.

The points on the plot are joined by best fit and the overlay placed upon the \( V_1, V_2 \) lines to determine the velocities. The average depth to bedrock along the distance \( L \) is computed using the formula:

\[
D = \frac{L \cdot V_2 - V_1}{2 \cdot V_2 + V_1}
\]

where
\( D \) is average depth to bedrock;
\( L \) is critical distance (fig. 5.7);
\( V_1 \) is velocity of first arrival; and
\( V_2 \) is velocity of second arrival.

When using seismic methods for subsurface investigations, one should study the surface outcrops and any drill logs available prior to starting a survey. In addition, when practical, seismic measurements of these outcrops should be made to determine their relative characteristic shock-wave transmission velocities. This preliminary information can be very useful in interpreting the subsurface seismic survey data.

The subsurface characteristics which control the distribution and flow of ground water are of prime interest in watershed investigations. The depth and extent of porous rock or alluvium must be delineated to determine the extent of ground-water storage. Information concerning bedrock characteristics such as confining layers may also be determined.

All existing borehole and geologic information is taken into account when planning the actual seismic work. Seismic shot lines are oriented so that maximum information can be obtained concerning depth to bedrock, confining layers, ground-water levels, suspected faults, scarps, and attitude of rock units. Alluvial fill material characteristically has a low-seismic velocity. Water saturated alluvium substantially increases the velocity so that ground-water levels can often be detected. Bedrock, or confining layers such as clay, have a higher seismic velocity and can be readily distinguished from adjacent alluvial fill.

It is rarely necessary to cover the entire
watershed by seismic line traverses since in-between areas can be interpolated if needed. It is sufficient to make one or two traverses across an aquifer at selected points. Data gathered are examined during the survey to make sure they are yielding the information sought and to help in planning the remainder of the survey.

A seismic survey cannot be expected to yield a complete detailed description of the subsurface geology, but it should be designed so that the information gained, coupled with borehole and known general geologic information, will produce an adequate description of the subsurface conditions controlling the behavior and storage of ground water. An experienced seismic crew of four using a 2,300-foot (701 m), 24-geophone recording unit can shoot three or four lines a day if terrain and vegetation conditions are not too severe. Using a 2-geophone seismic meter for shallow interpretations, two men can complete a 100-foot (30.5 m) spread in 30 minutes using a hammer for impact source. Further information on seismic surveying can be found in Dobrin (25). Examples of shallow seismic work in watershed investigation are reported in Stephenson and Zuzel (82).

Electrical Resistivity

Electrical prospecting started in the early 1800's using natural earth currents. More advanced techniques now use direct current, alternating current, and electromagnetic fields. Interpretation is largely empirical. Wenner, in the early nineteen hundreds, developed the four-electrode measurements theory. The Wenner electrode configuration is given in figure 5.8. Since that time, several additional electrode configurations have been developed.

It is important to realize that resistivity measurements for geologic mapping are apparent resistivity rather than true resistivity. This should be considered when electrode distribution for potential-difference measurement is chosen. Potential difference is merely the line integral of the potential gradient from one electrode to the other. Apparent resistivity is a fluctuation of the average gradient between potential electrodes (98). This averaging of differences indicates differing geologic conditions. Therefore, the best distribution is one where potential electrode (geometric) spacing is the minimum. Possible electrode spacing configurations are as follows:

![Figure 5.8](image-url)
\[
P = \text{apparent resistivity} \quad V = \text{potential difference} \quad I = \text{total current} \\
a = \text{electrode spacing}
\]

\[
P_1 = 4\pi a \frac{V_{10}}{I} \quad \text{and} \quad P_2 = 4\pi a \frac{V_{02}}{I}
\]

1 indicates easternmost (or northernmost)

\[
V = \text{potential difference between } P_1 - P_0 \\
\text{or} \quad P_0 - P_2
\]

\[
P_a = 4\pi a \frac{V}{I}
\]

\[
P_1 = 6\pi a \frac{V_{10}}{I} \quad \text{and} \quad P_2 = 12\pi a \frac{V_{02}}{I}
\]

\[
P_a = \frac{2\pi l^2}{a} \frac{\Delta V}{I}
\]

\[
\Delta V = \text{potential difference between two electrodes}
\]

and \( P_a = \frac{\pi l^2}{P_m P_n} \frac{\Delta V}{I} \)

An example of a field apparent resistivity sheet is given in figure 5.9.

Apparent resistivity can be measured and calculated using any of these electrode spacings. Depending on the geologic conditions (structure, stratigraphy, and topography), the spacing best suited to individual problems should be selected. Van Nostrand and Cook (98) discuss the advantages of each spacing and conditions to which they are best suited. Data taken with a symmetrical configuration can be plotted as a function of distance along the traverse (Wenner configuration equations, figs. 5.9, 5.10).

Asymmetrical configurations have no clear-cut midpoint, and the apparent resistivity is usually plotted at a point midway between the two potential electrodes. Potential electrodes are of two basic types: porous pots with a copper sulfate solution and a metal bar. The porous pot type of electrode is best suited to damp areas where the relative humidity is fairly high. The metal electrode works best in dry-arid areas. The electrode spacing can be plotted as a function of location. Field data can be collected and listed as in figure 5.9 and
plotted on a graph as in figure 5.10 which depicts two methods of plotting and the contacts picked.

It is desirable in horizontal apparent resistivity surveys to have some drill-hole or geologic outcrop information to provide necessary vertical control. In mapping, using resistivity data, one must keep in mind that stratifications are not always horizontal and that they may be disturbed by subsurface structure. It is therefore necessary, in many cases, to run resistivity lines in more than one direction. Consideration must be given to the fact that anomalies are elongated in the direction the traverse is run.

Field Apparent Resistivity Sheet (Wenner spacing)

<table>
<thead>
<tr>
<th>Current direction</th>
<th>Applied voltage, volts</th>
<th>a, spacing ft.</th>
<th>E millivolts</th>
<th>I milliamps</th>
<th>E/I ohms</th>
<th>Mean E/I ohms</th>
<th>2ρa</th>
<th>E/I ohm-feet</th>
<th>ρ ohm-feet</th>
<th>ρ ohm-feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>45</td>
<td>3</td>
<td>8.5</td>
<td>23</td>
<td>.370</td>
<td></td>
<td></td>
<td>6.71</td>
<td>6.33</td>
<td>6.33</td>
</tr>
<tr>
<td>-</td>
<td></td>
<td></td>
<td>8.0</td>
<td>23</td>
<td>.348</td>
<td></td>
<td></td>
<td>18.7</td>
<td>6.33</td>
<td>6.33</td>
</tr>
<tr>
<td>-</td>
<td>67.5</td>
<td></td>
<td>11.7</td>
<td>34</td>
<td>.344</td>
<td></td>
<td></td>
<td>5.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+</td>
<td></td>
<td></td>
<td>10.0</td>
<td>34</td>
<td>.294</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+</td>
<td>45</td>
<td>6</td>
<td>5.0</td>
<td>12.2</td>
<td>.416</td>
<td></td>
<td>.431</td>
<td>16.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-</td>
<td></td>
<td></td>
<td>5.5</td>
<td>12.3</td>
<td>.477</td>
<td></td>
<td>37.4</td>
<td>13.45</td>
<td>19.78</td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>67.5</td>
<td></td>
<td>6.0</td>
<td>20.0</td>
<td>.300</td>
<td></td>
<td>.290</td>
<td>10.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+</td>
<td></td>
<td></td>
<td>5.5</td>
<td>19.9</td>
<td>.278</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FIGURE 5.9.—Field apparent resistivity sheet.
Commercial earth resistivity meters can be obtained that will measure earth resistances to a depth of several thousand feet. They vary in cost from one to several thousand dollars.

Gravimeter Methods

The gravity method utilizes the principle that gravity values vary in relation to the variance of mass and density of geologic materials within the earth. Gravity measurements are simple to make, and equipment is light and portable. A single technician can conduct an entire field survey with little assistance.

Gravimeter surveying is being conducted through the United States by government agencies on a continuing basis. Eventually, if continued, much of the United States will be surveyed by this method and the interpreted subsurface geology of these regions will be available on public file. Gravity meters are mechanical or electrical instruments that directly measure the pull of gravity by measuring the magnified deformation of the pull of gravity on the elastic force of springs and torsion wires. A digital reading of gravity can be made at a measuring site in a matter of a few minutes.

Prime requirements for this type of survey-
ing are accurate vertical and horizontal control. Areas with many well-located elevation bench marks on topographic maps are ideally suited for gravimetric surveying. Gravimeters only measure relative values of gravity; therefore, a base station, where the absolute value of gravity is known, is required. However, gravity base stations may be expanded by making short-time, comparative readings at adjacent sites.

In hydrologic studies, areas having contrasting lithologic densities, such as low-density or alluvium-filled valleys, are best suited to large-scale gravity surveys. Gravity surveys are limited in the amount of information they will yield. They will not discern the lithology of alternating layered materials. Gravimeter data only gives information on gravity gradients which must then be interpreted from what is known from the surface geology and measured rock densities. Several corrections to observed gravity measurements must be made. Some of these are: (1) free-air correction, which is a correction for measuring station altitude, (2) Bouger correction, which is the correction for the amount and density of rock between the measuring station and sea level, and (3) terrain (topographic) correction, which corrects for gravitational influence of nearby hills that rise above the station or depressions extending below it.

Gravity surveys do yield valuable information on the attitude and nature of bedrock beneath alluvial materials and features, such as large igneous dikes and large faults (25).

Magnetometer Methods

The magnetic method of geophysical exploration utilizes a natural and spontaneous field of force, with fields of geologic bodies superimposed upon a normal terrestrial field. Magnetic bodies frequently owe their magnetism to the magnetic field of the earth. Consequently, these anomalies are often subject to change with geographic latitude. Rock bodies may also have their own magnetism, which may or may not coincide with magnetism induced by the terrestrial magnetic field.

In magnetometer methods, total field vector as used in gravitational methods, is rarely used. It is usually resolved into horizontal or vertical components. Vertical component usually exhibits the clearest relation between anomalies and disposition of geologic bodies.

Magnetic anomalies of geologic bodies are dependent on their magnetic susceptibility and remanent magnetism. The largest magnetic anomalies are associated with igneous rocks where magnetite and other magnetic minerals are present. Sedimentary rocks are generally weak in magnetism. Anomalies can also be caused by structural forces which may alter the disposition of magnetic formations in the course of geologic time.

Magnetometer surveys are run either by ground instruments or by airborne magnetometers. The latter is more costly but much faster. Magnetometer surveys are used in ground-water studies to locate such features as buried alluvial valleys, impermeable structural features, including dikes intruding sedimentary rocks, and folds or faults causing alteration in ground-water flow. As in all geophysical methods, a reasonable and accurate knowledge of the local geologic conditions is necessary.

Additional information on magnetometer methods can be found in Heiland (39), Davis and DeWiest (38), and Leroy (60).

GROUND-WATER INVESTIGATIONS

Installations

Preliminary Investigations

Varied descriptive information is needed prior to the initiation of a detailed ground-water research program in watershed hydrology. This information should provide sufficient knowledge to formulate plans for the location of detailed study areas and basic ground-water network design for instrumentation. However, these preliminary investigations should be a part of the basic objectives of the overall research plan.

A few of the more important elements of a
preliminary investigation are hydrogeologic mapping, determining the elements of the flow system, aquifer constants, and the nature of channels as related to base flow conditions. Geophysical investigations, photogeology, and remote sensing techniques can be very beneficial in these preliminary investigations.

In watershed hydrology, all possible attempts should be made to quantify the total hydrologic system which may influence ground water. This is especially important in that, precipitation is the primary input. Streamflow becomes important because it may either recharge the aquifer or receive base flow from it, and vegetative features, such as phreatophytes may serve as withdrawal. Hence, in watershed modeling for prediction or simulation, all segments of the hydrologic cycle and their interrelationships must be described whenever possible.

Hydrogeologic Mapping

The fundamental principles of hydrogeologic mapping are to state the properties of the geology in terms of the hydrologic conditions (fig. 5.11). The subsurface flow system must be defined in terms of properties of porous media, properties of fluids (salinity, temperature), and physical dimensions of the aquifer and associ-

\[ \text{FIGURE 5.11.—An example of hydrogeologic (left) and geologic (right) maps of same area indicating differences in detail and notations (23).} \]
ated transmitting and retarding strata. Techniques and methods for mapping hydrogeologic units are found in the previous section on geophysical investigations.

**Delineating the Flow System**

The ground water flow system is defined by Toth (94) as, "a set of flow lines in which any two flow lines adjacent at one point of the flow region remain adjacent through the whole region, and that can be intersected anywhere by an uninterrupted surface across which flow takes place in one direction only." The major elements of a flow system (fig. 5.12) in a ground-water basin are the recharge and discharge areas, the water table, and the hydraulic head. Recharge areas are those areas in which water percolates through the unsaturated zone to the water table, entering the ground-water flow system. The direction of flow will be away from recharge areas.

Discharge areas are those areas in which the dynamic ground-water flow system loses water. Flow lines will be found to converge at discharge areas. Discharge can occur in the form of base flow, springs, seepage, and evapotranspiration.

The water table is that surface in an unconfined water body at which the pressure is atmospheric. It is defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water. In wells penetrating to greater depths, the water level will stand above or below the water table if an upward or downward component of ground-water flow exists.

The hydraulic head is the sum of the pressure head and elevation head. At any point in a hydraulic potential field, the hydraulic head equals the elevation, above a standard datum, of the liquid level in a piezometer inserted at that point (34).

If sufficient water level information in the area of study is available, the elements of the flow system can be determined. Where little preliminary ground-water information is available, observation of surface conditions can be used to give preliminary determinations concerning the ground-water flow system. Detailed

---

**Figure 5.12.—Idealized flow system (26).**
geologic investigations and reconnaissance of the area will help determine materials through which ground water flows, establish gradients and continuity of flow. Base flow and the presence of phreatophytes along channel segments, springs, and seeps generally indicate discharge areas. Transmission losses along alluvial channels and areas of precipitation excess are often associated with recharge areas.

**Channel Characteristics**

Stream channels can be characterized as intermittent, perennial or ephemeral, depending upon how they flow in relation to their bed material and source of water. Likewise, the characteristics of the channel are often related to the ground-water flow.

A perennial stream during the summer months, where there is no evidence of surface runoff, is being fed by discharge from ground water. This is herein defined as base flow. Ephemeral streams, those which flow only in response to precipitation, usually occur in the more arid environments, have deep alluvial channels, and are rarely associated with base flow. The channels can serve as recharge vessels to local or perched aquifers, or to the regional ground-water system. This is the major source of recharge to many aquifers in the arid environments.

An intermittent stream usually indicates that base flow is occurring or that the stream has alternating segments of deep to shallow alluvial fill. If the latter is true, during low flow conditions the entire flow may pass through the alluvium never reaching the surface until it approaches shallow, impermeable bedrock. When the alluvium becomes saturated, surface flow will occur.

**Geophysical Investigations**

Surface geophysical exploration equipment and methods have been described previously. All of these methods can benefit hydrogeologic exploration by supplementing surface geologic and hydrologic reconnaissance. Geophysical exploration is more costly, but if the conditions are favorable and the situation warrants their use, these methods should not be overlooked. Subsurface geometry, boundary conditions, subsurface stratigraphy and depth to the water table can often be determined with reasonable accuracy by one or all of these methods.

Probably the most accurate and universally applicable geophysical method is seismic refraction (see p. 407). These units are available for a two man operation with use of a sledge hammer as an energy source, with penetration in excess of 100 feet (30.5 m) depending upon the material being explored. Unit costs generally run in excess of $2,000. For information at greater depths, larger and more complex units are available on a contract basis.

**Photogeology**

The use of aerial photographs in geologic mapping is discussed in more detail on page 398. For preliminary ground-water investigations, aerial photographs, when properly interpreted, can be of considerable use.

Interpretation of hydrogeologic features from aerial photographs can be extremely complex. Familiarity with the area is always advisable. One should look first for identifying topographic features, such as prominent ridges, sharp-crested buttes, rolling hills, and valley floors. In many cases, these topographic features reflect the underlying geologic structures which may assist in interpreting ground-water flow systems.

Bedrock identification from aerial photographs may be difficult. However, differential erosion is one method used for bedrock identification. The importance of bedrock identification is that certain rocks such as sandstone, limestone, or certain volcanic rocks have characteristic fracturing which may be related to recharge of the ground-water flow system. Drainage characteristics are often controlled by fracture patterns and structural trends. Stream transmission losses may be directly related to the fracture system of the underlying bedrock.

Most aerial photographs are produced in black and white. As a result, all colors are seen in various shades of gray. Since color variations can only be seen as gray tones, it is imperative that careful attention be given to tonal characteristics.

Tonal differences are often associated with changes in soil, vegetation, and rock outcrops. Darker colors, such as the deeper greens gen-
erally associated with vegetation in wetter areas, will show as a darker gray on the photos. Vegetation density responds to tonal changes. Soil moisture variations are also noticeable as tonal changes. For hydrogeologic investigations, if an area of darker gray is indicated in small topographic depressions, one should look for ground-water discharge areas to occur. Presence of phreatophytic vegetation and damp soil would be the indicators.

Where differences in rock, soil, or vegetation might be recorded on color photographs, but not on black and white, the added cost of color aerial photography might be justified. Color aerial photos, with true color preservation, generally permit additional interpretations to be made.

Infrared photographs are very helpful in locating areas where temperature changes exist. The film is sensitive to the infrared end of the spectrum. It records with good contrast areas where phreatophytes are prevalent and where base flow is a heavy contributor to stream flow.

Network Design

Network design for any ground-water study depends upon the answers sought and the problems involved. In most cases, the need for a network is to discern the elements of the flow system and determine the aquifer characteristics. General knowledge concerning the physical characteristics of the area that should be known includes surface and subsurface lithology, structural features, general trends of the elements of the flow system, landforms channel characteristics, and precipitation variations.

If the area in question has an accurate, detailed geologic map, the lithologic materials and their distribution should be studied first for the possibility of grouping units together which respond alike to the movement and storage of ground water. One such study analyzed a total of 17 lithologic mapping units and grouped these into four hydrologic units (table 5.3). This grouping was based primarily upon transmissibility characteristics. When pumping tests were performed in all these formations, as a check on the validity of the groupings, the transmissibility values overlapped in enough cases to warrant their grouping. In an assemblage of lithologic formations within a watershed, the aquifer characteristics contained within these formations are usually of a range of hydrologic values. These formations, then can often be grouped hydrogeologically so that the total number of network wells may be reduced.

Prior to the final designation of the well network and installation of wells for a ground-water study, an effort should be made to determine what local information is already available in the area. One should not overlook the use of wells already in existence. There are usually domestic wells, irrigation wells, or wells for stock watering purposes located in most areas. Inquiries can usually lead to the well depth, at least, and often to the driller's name.

<table>
<thead>
<tr>
<th>Lithographic units</th>
<th>Hydrologic units</th>
<th>Relative transmissibility values (gal/day/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alluvium</td>
<td>Aquifer</td>
<td></td>
</tr>
<tr>
<td>Lake sediments</td>
<td>Aquiflude-aquifer</td>
<td></td>
</tr>
<tr>
<td>Silicic volcanics (latite welded tuff)</td>
<td>Aquifuge-aquitard</td>
<td></td>
</tr>
<tr>
<td>Basalt</td>
<td>Aquifer</td>
<td></td>
</tr>
<tr>
<td>Granite</td>
<td>Aquifuge-aquitard</td>
<td></td>
</tr>
</tbody>
</table>

1 Aquifer stores and transmits water freely; aquitard stores and transmits water slowly, sufficient for wells; aquiflude stores water but does not transmit significant amounts; aquifuge does not store or transmit water.
and his well logs. Most States now require the filing of all drill records and/or logs if the wells are drilled by a commercial contractor. Most of these wells will have pumping test (well completion, drawdown and recovery) data on file. Unverified information must be carefully selected and evaluated for accuracy.

Cultural and agricultural practices should also be investigated before network design. Irrigation practices, for example, can alter natural flow systems, changing both recharge and discharge areas if on a large enough scale. Various cultivation practices alter soil surface conditions to reduce runoff and increase percolation and recharge. Entrapment of channel flow or spring flow into reservoirs can also alter recharge characteristics.

Soil and vegetation characteristics should be known if possible. The soil may be a dominant factor in percolation and drainage to the water table, and many phreatophytes are responsible for large losses of ground water. Any drastic changes made in soil or vegetation should be noted. A record should also be made of the location and flow of springs, areas directly associated with either regional or local flow systems.

### Drilling Methods

The fundamental unit for ground-water investigations is the well. A well, as used here, is a vertically drilled or dug hole constructed to obtain ground-water information by examination of depth to water, rate of water flow, drill logs, material samples, and water chemistry. It may not be necessary or possible to obtain or use all this information for any one well. Before a well is drilled, it is necessary to decide its purpose. This, in turn, determines the drilling method, logging detail, sampling frequency, and well completion.

There are several methods of drilling wells, with advantages and disadvantages associated with each. The material to be drilled and the economic factors involved usually determine the method used.

#### Augering

Drilling by the auger method consists of two types—the continuous flight and the bucket or Iwan type, both of which can be hand or power operated.

Hand augers (continuous or Iwan) are useful for shallow depths. The material must be loose and unconsolidated, and the hole must stand without caving. The maximum diameter is usually about 3 inches (7.6 cm). Hand augers are especially useful for soils mapping. Several kinds of small motorized hand augers are available, but their limitations are about the same as hand augers. These augers are of limited use in ground-water investigations.

Power augers are those mounted on trucks or jeeps and can be used to drill holes from a few inches to several feet in diameter to depths of 200 feet (61 m), depending on the power of the system and the material drilled. They are also limited by material hardness and stability. Samples are disturbed and are suitable only for disturbed-material laboratory tests. Advantages are: lower operator's costs, ease of operation, and rate of penetration.

#### Jetting

Jetting is a method of drilling a well by forcing water through a pipe. The pipe may be left in the ground to serve as the well casing (fig. 5.13). The jetting may be accompanied by striking or rotating the cutting tools. Water is returned on the outside of the drill stem carrying the drill cuttings to the surface. Jetting is not recommended where accurate drill logs are needed as the samples are generally composite mixtures of materials from various layers encountered. A chisel point bit is used if there is any degree of cementation in the formations. An open end pipe will usually be sufficient if in unconsolidated materials.

The jetting method is not successful in well-cemented, hard material or where boulders are present.

#### Cable Tool

The cable-tool method of drilling wells (fig. 5.14), sometimes referred to as percussion or churn drilling, is the oldest drilling method and still one of the most widely used. In cable-tool drilling, the drilling tools are supported from a cable and are moved up and down in the hole by percussion strokes. The percussion strokes
can vary from less than 1 foot (.3 m) to greater than 3 feet (.9 m), depending upon the formation being drilled, and the weight of the tools can be varied depending upon the material and the hole depth. The reciprocating action of the cutting tools and cable is rendered by a spudding beam which operates off of an eccentric. The bit is worked up and down in the hole until enough cuttings are accumulated to fill the hole to about 5 feet (1.5 m). The bailer is then used to remove the cuttings.

The cable-tool method can be used in any type of material; however, its success will vary depending upon the hardness and consolidation of the material, depth of hole, hole diameter and ability of the driller. In hard crystalline rock, drilling progress is slow because of frequent need to repair the bits. Five to 10 feet (1.5 to 3m) of hole per day is not unusual in these hard-rock formations. Fifty to 100 feet (15 to 30 m) per day can easily be drilled in loosely consolidated sand and silt formations. The experience of the driller in knowing how to handle the various materials usually determines the success of cable-tool drilling.

**Rotary drilling**

Rotary drilling (fig. 5.15) advances the hole by rotating a drill bit which is under pressure. This bit cuts and grinds the material at the bottom of the hole. The drill cuttings are removed by drilling fluid, either water or air. If the cuttings are heavy or from considerable depth, the water can be increased in density by adding special muds to the drilling fluid. (The drill fluid can vary from freshwater or air to muds made up of water, clays, barites, or other thickening or thinning additives to assist in removing the cuttings.) The method used to return the cuttings is determined by how the drilling fluid is forced down the hole. The most common practice is to force the fluid down through the drill stem and return the cuttings.

![Diagram of setup for jetting observation wells](image)

**FIGURE 5.13.—Setup for jetting observation wells, with arrows indicating direction of water movement (46).**

![Diagram of truck-mounted percussion (cable tool) equipment](image)

**FIGURE 5.14.—Truck-mounted percussion (cable tool) equipment for drilling wells. Casing not commonly used for wells drilled in consolidated rock.**
Rotary drilling is well suited to different sampling techniques, such as rotating core barrels, drive samples, and various types of washed samples. In general, rotary drilling is the most versatile and fastest drilling method.

**Examination of Drill Cuttings**

One reason for drilling a well is to obtain an accurate description of the subsurface material by recording the depth and description of the drill cuttings. The description should include identification of the rock and minerals present. The most accurate information is obtained by core drilling. This is usually done by rotary drilling, although under certain conditions solid cores can be obtained by the percussion or driving method.

Rotary drill cores are obtained with less difficulty from consolidated unfractured formations. When taken under these conditions, accurate sample depth can be determined. The softer the formation and more numerous fractures, the greater the chance of compaction or poor recovery of the core.

Drill cuttings taken by the bailer with the cable-tool method of drilling are generally accurate depending upon the experience of the driller. A well experienced cable-tool driller can tell by holding onto the cable when a change in hardness of material is encountered. Accuracy to within several inches to a foot can be obtained with a bailer if the sample is taken at the top of the cuttings.

Rotary drilling, using a roller-cone bit and drilling mud, offers less possibility for obtaining accurate drill cuttings with depth. Samples must be taken from the mud at frequent intervals and inspected for their correlation with previous samples. If the hole is not cased, and most often in rotary drilling it is not to any great depth, contamination from above can easily occur. The time for the sample to reach the surface, which is a function of depth and mud viscosity, must be considered to determine accurate position of each sample.

Air, used as a drilling fluid, can be quite satisfactory for return of good samples provided the compressors are large enough to force the larger cuttings to the surface. Air drilling, however, usually gives fine or powdered sam-

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**Figure 5.15.** Major components of rotary equipment for drilling wells, with arrows indicating direction of mud circulation (23).

Through the annular space. Rotary water drilling is well suited to most types of material, with the exception of loose, hard boulders and very coarse gravels.

Reverse hydraulic rotary drilling is best suited to large diameter holes. The fluid is forced down the annular space and removed by high velocity water through the drill stem. Water must be kept in the hole at all times to prevent caving, and care must be taken to drill at a rate that does not inhibit the water flow.

Compressed air can be used as a drilling fluid. This is especially advantageous when a water shortage exists. A large diameter drill stem is necessary to get a large enough air volume to cool the bit. This method has the advantage that fragmented drill samples obtained from compressed air-drilling are not contaminated with drill mud and water. Cores obtained with air, in most cases, have less contamination than forced-water cores. Rotary air drilling works best in dry conditions and has the same limitations as forced water.
Samples from augering and jetting are less suitable.

A stereoscopic wide-field microscope is generally used in examining the drill cuttings. Although a 10-power magnification is most convenient for general purposes, higher magnification is advantageous if the examiner wishes to identify specific accessory minerals or is estimating the degree of roundness of fine sands.

The type of rock—that is, whether the rock is a conglomerate, sandstone, siltstone, mudstone, limestone, or any other—is recorded first. Then the color of the rock is described, preferably in terms consistent with the Geological Society of America's rock color chart. If the overall color of the rock differs from the color or colors of its component parts, both are recorded.

Except where the sample consists of silt or clay, Wentworth grade scale is used for determination of particle sizes. No attempt is made to differentiate sizes if a sample consists wholly of silt or wholly of clay. The term “mudstone” is applied to a mixture of silt and clay.

The degree of roundness is estimated by comparing a scattering of grains under the microscope with a chart that pictures well-rounded, rounded, subrounded, subangular, and angular grains.

Samples consisting of sandstone are described with respect to the degree of sorting. If 90 percent or more of the grains fall into two adjacent particle-size ranges, the sandstone is described as well sorted. However, if 90 percent of the grains falls into three or four adjacent ranges, it is described as fairly well sorted; and if the grains fall into five or more ranges it is described as poorly sorted. The composition of the grains is also noted. Quartz grains are described as clear, stained, frosted, or amber. Accessory minerals are identified, if possible; but if not identifiable, their color, prevalence, and other readily observable characteristics are described. Because of their possible bearing on the quality of the ground water, sulfides, such as marcasite and pyrite, are of particular interest, as are gypsum, the halide minerals, and carbonaceous material. If ion-exchange minerals can be recognized, their presence in samples should also be recorded.

The presence of fossils when encountered in the drill cuttings should be recorded. If possible they should be identified to class. Cementation is described as hard, firm, or weak, depending upon the extent to which the sediment has been lithified. The type of cement is also recorded. Krumbein and Sloss define cement as a postdepositional chemical precipitate deposited in the interstices among grains to form a lithified sedimentary rock. However, the principal binding material in some sandstone is clay, and the sandstone is described as having an argillaceous cement. Close examination of some such clayey sandstone indicates that the argillaceous material actually is a matrix, not merely an interstitial filling. Ferruginous zones also are recorded. Such zones are of interest because they may indicate former long-time positions of the water table and, if firmly cemented, may hinder free circulation of the ground water in otherwise homogeneous rock. In places, iron-cemented zones are known to be confining layers becoming the artesian conditions.

For design purposes on construction projects such as small dams, engineering properties of drill cuttings must be determined. The description of engineering properties is necessary for evaluation and interpretation for design, construction, and installation purposes. The U.S. Department of Agriculture Soil Conservation Service, Corps of Engineers, the Bureau of Reclamation and others adopted the Unified Soil Classification System in 1952 as a standard method for identification and classification of these materials. This system is used to describe both soils and geologic materials. It provides a simple visual method for field description.

Well Logging

Logging of a well consists of recording information obtained from drilling or by further examination of the well when drilling is completed. The three well-logging methods most frequently used are the driller's log, the geologic log, and the geophysical well log. The geophysical log requires a great deal of expensive equipment and technical ability to accu-
### TABLE 5.4.—Unified soil classification system

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**Key:***
- **CO**: Coarse gravel (greater than 4.76 mm), very coarse sand (greater than 2.00 mm), gravel, or coarse sand.
- **C**: Coarse sand (2.00 mm to 0.075 mm), gravel, or medium sand.
- **S**: Silt (0.075 mm to 0.005 mm), clay, or fine sand.
- **F**: Fine sand (0.005 mm to 0.0002 mm), or silt.
- **CL**: Clay (less than 0.0002 mm), or silt.
- **PL**: Plastic soil, plastic clay, or fine silt.
- **ML**: Mottled soil, mottled plastic, or fine silt.
- **PM**: Peat or other highly organic soil.

**Legend:**
- **Field Identification Procedure:**
  - **Dry Strength (Coefficient of Attraction):**
  - **Plasticity:**
  - **Saturated Surface:**
  - **Physical Properties:**
  - **Soil Structure:**
  - **Particle Size:**
  - **Plasticity:**
  - **Silt and Clay Size:**
  - **Organic Matter:**
  - **Saturated Surface:**

**Laboratory Classification Criteria:**
- **CL**: Clay (less than 0.0002 mm), or silt.
- **ML**: Mottled soil, mottled plastic, or fine silt.
- **PM**: Peat or other highly organic soil.

**Note:**
- This table provides a unified soil classification system based on physical properties, soil structure, particle size, plasticity, and organic matter. It is designed to standardize soil classification for easier comparison and analysis across different regions and projects.

**Further Information:**
- For a comprehensive guide on soil classification, refer to the relevant section in the U.S. Army Corps of Engineers' Manual on Soil Classification and Testing.
rately survey the drilled hole. This work is generally contracted from a geophysical well-logging company.

**Drillers Log**

Most water-well drillers, unless properly trained, have neither the experience nor time to write up a complete and accurate log of the well. However, the driller can contribute very useful information when required to do so. An experienced and skillful driller should record sample information, such as size, hardness, color, and the depth at which these changes occur.

The rate of penetration and any difficulties such as caving of the material being drilled should be recorded. Water loss or gain should be recorded. If the drill is shut down over night or for any length of time, the water level should always be measured before starting again. This can help determine changes in potential levels.

Drillers' descriptions are sometimes vague and ambiguous. Such terms as “blue clay,” “muck,” and “broom sand” should be avoided.

A portion of a driller's log considered to be an excellent example is given in figure 5.16. In contrast, the driller's log in figure 5.17 is far less adequate.

**Geologic Logs**

Geologic logs provide information necessary to interpret and correlate surface and subsurface geologic and ground-water conditions. This information can be critical in predicting major flow zones. For this reason alone, the geologic log is perhaps the most important log of a well. Some of the information used in geologic logs would be descriptions of depth to certain lithologic horizons, thickness, continuity, attitude of strata, unconformities, texture of cuttings, water depth potential changes and rate of entry of water to the hole.

Geologic logs are generally of two types—graphic and written form. A graphic log illustrates lithologic changes with depth and the written log gives these changes in descriptive terms. Figure 5.16 is a good illustration of the written version of the geologic log. An additional column on this log, illustrating the lithologic change, could be used to make it a graphic log as well.

The geologic log should always consider the information given on the driller's log. Changes in drilling rates and water levels, and reaction of equipment to drilling, such as rebound of the cable and tools and chattering of the rotary bit, are generally indications of changes in rock characteristics.

The degree of difficulty in constructing an accurate geologic log depends very much on which drilling methods were used to obtain the cuttings. Cuttings from rotary drilling must be washed to free them of the drilling mud and screened to get rid of material finer than sand. Material finer than sand is usually carried in the drilling mud and can easily be confused as true samples from a particular horizon. For this reason sampling of fine sand and silt formations from rotary drilling is difficult. Percentage logs (fig. 5.18) are common in these situations. Two types of percentage logs are used: the unqualified percentage log where all lithologic information is recorded without considering caving from above, and the qualified percentage log which shows percentages of freshly cut samples only and does not consider the cavings. The qualified percentage log is by far the better of the two. Note in figure 5.18 how abrupt changes in percentages correlate with lithologic changes.

**Geophysical Well Logging**

Geophysical well logging measures *in situ* the physical properties of the earth's strata with instruments operating in a borehole. The result of these operations is a record from these measurements as a function of depth on which interpretations are made.

Geophysical well logging was developed by the petroleum industry in the late 1920's employing two measurements—spontaneous potential and electrical resistivity. As petroleum exploration increased, more elaborate logging methods were developed for interpretation of the more complex stratigraphic conditions. In general, the type of logging equipment used in the petroleum industry is now used for logging water wells.

The cost of geophysical well logging is usually high. The equipment is sophisticated and takes trained personnel to operate and interpret the
data. Most water well contractors do not own this equipment so one generally would contract the work through commercial oil well logging services or enter into cooperative projects with one of several government agencies utilizing these methods (48).

A geophysical well logging unit consists of a truck, with an electrical power plant, and mounted equipment van which houses the upper electronics equipment, hoist unit, radiation sources, and the various downhole sondes (fig. 5.19). The sonde is the encased source sensing and transmitting device, or both, which is lowered down the hole. In electric logging the electrodes are built into the sonde.

To obtain a complete suite of logs, each sonde is lowered individually into the borehole and retrieved while the measurements are being

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<td>Boulders (basalt) w/clay mix. Hard drilling</td>
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<td>Mixture of green, red &amp; black basalt, soft drilling</td>
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<td>20'</td>
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<td>Some reddish basalt, mostly black. Slower drilling</td>
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<td>Very soft, red and brown basalt and green clay</td>
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<td>Broken basalt, red and brown w/yellow clay, fast drilling</td>
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<td>Very tight grey-blue clay-some lignite stringers</td>
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Well Location NW 1/4 SW 1/4 SW 1/4 Sed. 16, T. 5 S N/A, R. 3 W E/W
Size of drilled hole 5 5/8

Total depth of well 640

Give depth to standing water from ground 15, 25

Water temp. ______ F.

On “Pumping Test” delivery was _____ gpm. _____ cfs. Drawdown _____ ft.

Size of pump and meter used to make test

Length of time of test ______ hours ______ minutes.

If flowing well, give flow _____ cfs. or _____ gpm. and of shut off pressure

If flowing well, describe control

Water will be used for test hole

Wt. of casing per lineal foot none

Thickness of casing 1.88

Casing material Steel

Diam., length, and location of casing 5" casing 20' length above ground 19'4" depth (casing -12 in. in diam.
give inside diam.: +12 in. outside diam.)

<table>
<thead>
<tr>
<th>From Feet</th>
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<th>Type of Material</th>
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<th>Casing Perforated Yes/No</th>
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<td>618</td>
<td>640</td>
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water 200 - 205

" 350 - 355

FIGURE 5.17.—Example of poor driller’s log.
The direction of current flow and resulting spontaneous potential in a test hole penetrating the aquifer in which the water in the sandstone is more saline than the drilling mud. The total electrochemical potential is the algebraic sum of the liquid boundary potential and the potential developed across the shale “membrane.”

Potentials of 100 millivolts can be reached between low and high permeability formations such as clay and sand (64). Most potential values, however, are considerably less than 50 millivolts. Potential differences are measured between a surface electrode and a downhole electrode. The differences are measured in a column of conductive mud at a particular depth and are related to an arbitrary constant. Currents occur at contacts of drilling mud and water in the sand or other permeable strata and across clay layers above or below permeable strata. Shallow water wells with fresh water generally show little variations in the SP curve.

**Figure 5.18.** Part of a percentage log of a well penetrating sedimentary rocks (23).

Geophysical well logging can be categorized as electric (including caliper) and radiation.

**Electrical Methods**

The most common geophysical well log is the electric log. However, it is limited to uncased boreholes. An electric log generally consists of at least two curves, spontaneous potential and resistivity.

Spontaneous potential (SP) logging operates on the premise that direct current, electrochemically derived electromotive, forces exist between dissimilar lithologic formations (fig. 5.20).
FIGURE 5.20.—Spontaneous potential log (23).

The SP log is generally flat in front of low permeability zones such as clays or shales and show positive or negative anomalies opposite more permeable zones. It is generally convenient, then, to take the “shale line” as the base line to work from (fig. 5.20).

Salinity of the water in the borehole and resistivity of the drilling mud are several factors affecting spontaneous potential curves. Consequently, the SP logs are rarely significant alone. Quality of water in an aquifer can also be estimated by spontaneous potential logging (23), but this information is only qualitative and used best for determinations of salinity.

There is no quantitative relationship between spontaneous potential and porosity or permeability (60). However, in a particular section of a borehole, marked changes in the magnitude of the spontaneous potential generally are associated with changes in the physical properties of the strata.

Resistivity logging is commonly used to determine strata boundaries, and uses the principle of electrical resistivity, the reciprocal of conductivity. When dry, most rock formations such as sand, shale, or fractured crystalline rock are very poor conductors of electricity. Consequently, they give high resistivity values. Saturating these rocks reduces their resistivity, each to a different degree, depending upon the porosity and the mineralization of the water.

Electrical conductivity of waters varies according to the mineralizations or content of dissolved solids. Distilled water is a poor conductor, but saline water is a good conductor with low resistivity. Clay formations, because of the multitude of fine particles and dissolved minerals, show relatively low resistivity. In contrast, saturated sand formations contain less mineralization and give higher relative resistivity readings. Complications exist when brackish water occurs in sand formations, making it difficult to distinguish between sand and clay formations by the resistivity method alone. Resistivity and SP curves, consequently, should always be interpreted together (fig. 5.21). Single electrode configuration is usually employed with water well contractors, while multiple configurations are used in the petroleum industry (fig. 5.22).

Electric current is produced in the instrument truck and transmitted to the subsurface strata via the electrodes. One potential electrode is grounded at the surface and the remaining potential and two current electrodes are enclosed in the sonde. The positions of the electrodes can be changed within the sonde as it is lowered to various positions within the borehole. The pattern of electrode arrangement, as many as three or four, within the sonde determines the depth of current penetration. The curves recorded are termed normal or lateral depending upon the electrode arrangement. The normal curve is generated when one current and one potential electrode are lowest in the borehole, and a lateral curve is generated when the two current electrodes are lowest in the borehole (fig. 5.22).

The recorded curve will have distinctive configurations for all lithologic units. The multiple-electrode method provides a variety of resistivity curves (fig. 5.23) which may be compared
among themselves as well as with the spontaneous potential curves. The combined use of these two electrical logs provides a suitable means for strata correlation.

The resistivity logging method minimizes the effect of the drilling mud and well bore diameter, while maintaining the advantage of direct comparison of several recorded resistivity curves. Spontaneous potential logs are influenced by the hole diameter and the electrolysis of the drilling mud which must be taken into consideration when interpreting SP logs.

Radiation Methods

Radiation logging is an important aspect of geophysical well logging in hydrogeology. Although radiation measurements are affected by casing, cementing, gravel packing, and other borehole characteristics, these logs are useful because of the penetrating nature of the radioactivity. These are the only logging methods which give lithologic information from a cased hole. Natural gamma, neutron, and induced gamma are the principal methods used.

![Descriptive Log](image)

**FIGURE 5.21.—Typical electric log of sandstone beds separated by clay beds, showing trace of spontaneous potential and resistivity logs (46).**
Natural gamma, sometimes referred to as gamma-ray logging, is a borehole geophysical method used to measure the natural gamma radiation of subsurface formations. Natural gamma logs are used for correlation purposes between wells and also for lithologic interpretations. They are especially useful in determining strata of high clay content. Certain unstable isotopes of elements such as thorium, uranium, and potassium-40, while decaying to a more stable element, give off alpha, beta, and gamma particles. Alpha and beta particles are easily stopped, but gamma particles are very penetrating. It is this gamma radiation that is logged.

The natural gamma log is a trace plotting the relative emission of gamma radiation in counts-per-second against depth below the surface (fig. 5.24). The radiation is measured by slowly lowering a sonde containing a detector—either a Geiger-Mueller tube or a scintillometer as the counter. The scintillation counter is the more sensitive of the two. The counting pulses are converted in the recording instruments at

![Diagram of electrode arrangements and electrical circuits for three electric logging procedures producing different resistivity curves](image)

**Figure 5.22**—Schematic diagrams of electrode arrangements and electrical circuits for three electric logging procedures producing different resistivity curves (46).
the surface into electrical pulses as voltages and are continuously recorded on strip chart, tape, or film. The curve obtained is similar in appearance to the resistivity curve of the electric log (fig. 5.25).

Some geologic formations contain higher concentrations of radioactive elements than others. Clay and shale generally contain more radioactive trace metals than sand, sandstone or limestone. Organic shale generally has the highest gamma activity. Certain volcanic rocks such as welded tuffs are characteristically high. Figure 5.26 shows a list of rocks and their relative gamma activities.

The neutron method of logging uses a fast neutron source which emits neutrons into the surrounding environment of the borehole. The fast neutrons are slowed until they become of lower energy (thermal) and can be eventually captured. The sonde lowered into the borehole contains a detector and a source of artificial neutrons, usually beryllium, and an active alpha emitter which is usually plutonium or radium. During the interaction that ensues, the beryllium absorbs alpha particles, giving off fast neutrons. Hydrogen nuclei that are in water, minerals, and hydrocarbons, most effectively slow the neutrons. A high concentration of hydrogen near the source will increase neutron capture and reduce the number detected by the counter.

The response at the detector, then, is a measurement of the hydrogen content of the surrounding media. If the hydrogen content is
low, the counter measures increased activity. If the hydrogen content is high, lower counts are recorded. The activity registered on the log is inversely proportional to water content and saturated porosity in the vicinity of the probe. The resulting log (fig. 5.24) of a water well gives a continuous reading in counts per second, with depth, of the medium energy, thermal neutrons.

In induced gamma logging, a source for gamma radiation, usually Cobalt-60 is placed in the sonde and shielded from the detector. The surrounding rock at the borehole is bombarded with gamma rays from the source. As the gamma particles pass into the wall rock, some are absorbed and some are back-scattered to the detector and counted. The amount of particles detected at any one level of strata is a function of the density of that strata. The higher densities of strata result in lower detector response.

The log obtained from induced gamma logging is referred to as the density log. The log provides a record of the relative bulk densities of the media which is related to porosity. Information from the gamma logs can be used to compute total porosity of strata with reasonable accuracy as the fluid density and grain density of the media are generally known. Other methods: Several other geophysical well-logging techniques exist. Of these the caliper log (fig. 5.27) and the temperature logs are the most familiar and universally beneficial.

The borehole caliper is used to measure variations in borehole diameter. Borehole size varies due to changes in the material being drilled. Information on borehole configuration can be very useful when interpreting logs. Caving of

![Figure 5.24.—Typical gamma curve and neutron curve.](image-url)
Gamma-ray — Counts per second

FIGURE 5.25.—Comparison of resistivity curve with gamma-ray curve obtained in logging uncased well (46).

certain strata such as loosely consolidated sands or well jointed crystalline formations will cause a widening of the borehole where this occurs. This can often be related to high porosity formations.

The borehole caliper consists of a sonde equipped with a motorcontrolled spring loaded device that, when triggered, releases three to four arms which remain in contact with the sides of the borehole (fig. 5.28). As the configuration of the borehole changes, the arms move accordingly. Movement of the arms controls the resistance of a potentiometer which is monitored by a recorder. The log (fig. 5.27) is a trace of the average diameter of the hole with depth recorded by a borehole caliper.

Temperature logs help interpret SP and resistivity logs. A thermistor, electronically controlled and placed in the same sonde as the resistivity equipment, is used to determine temperature variations with depth. Temperature changes can occur in zones where water is rapidly entering the borehole or can be related to changes in water quality.

Well Completion and Development

Completion of a well does not usually end with drilling. Future use of the well will determine what kind of completion and development is necessary. The kind of casing and screen, and length and perforation of each, will be determined by the use of the well, drilling method and the geologic formations in which the well was drilled. Johnson (46) presents an excellent discussion on well screens.

Well development is any one of several methods used to stabilize the drill hole. Proper well development brings the well to its maximum capacity for production. Development of a well in a sand and gravel aquifer results in a naturally developed zone of uniformly graded particles of high porosity and permeability surrounding a well screen. In hard rock formations, where the well is often unscreened or uncased, proper development removes the finely textured cuttings and mud commonly forced into the rock wall fractures.

Surging

This is one of the most common and effective methods used for well development in sand and gravel formations. The method consists of working a plunger, commonly called a surge block (fig. 5.29), up and down in a well, forcing the water into and out of the surrounding material. Care must be taken to start slowly in order to stabilize the surrounding material. Over-activity before stabilization may result in extraneous material from above or below the pumped zone being introduced into the desired pumping formation. The action brought on by surging loosens and removes fine-grained particles of sand, silt and clay near the perforations of the casing or screen. These particles

FIGURE 5.26.—Relative gamma-ray activity.
are brought into the well where they can be removed by pump or boiler.

**Backwashing**

This method also consists of a reversal of flow similar to surging. The water level is raised and lowered as rapidly as possible by turning the submerged pump on and off. As soon as the water rises in the columns to the ground surface, the pump is shut off. This produces inflow and outflow through the well screen, loosening fine material. The pump should remain on long enough to remove the fines from the bottom of the well. An air lift or a deep well turbine without a foot valve are the only pumps which can be used practically for this purpose. Backwashing is not as vigorous a surging action as with the surge block and is generally not as effective.

**Jetting**

High-velocity water jetting provides a very effective method of developing a well. This method consists of treating the well screen or perforated casing with horizontal jetting actions. The energy is concentrated on a small area and every part of the screen can be treated separately.

The jetting tool (fig. 5.30) consists of a pipe lowered to the prescribed depth and fitted with two or four nozzles of small diameter, working no more than an inch away from the screen. The forceful action of the jetted water working through the screen openings agitates, removes and rearranges the particles adjacent to the outside of the screen. If possible, the well should be pumped simultaneously to remove the fine particles. The wall cake deposited by rotary drilling will also be broken down so that the drilling mud can be pumped out. Jetting is far less effective for wells with perforated casing than for those with continuous-slot well screens.

**Overpumping**

This is one of the simplest methods for developing a well to remove the fines. This method consists of pumping at a greater rate than the well would be pumped when put into service. Overpumping should start slowly so that a slow and steady withdrawal of material will proceed.

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**Figure 5.27**—Caliper log, showing variation in hole size with depth (60).
A rapid withdrawal of water could cause bridging of sand grains, reducing flow and restricting removal of the fines.

In large production wells it may be difficult to pump at a high enough rate to remove sufficient fines to stabilize the material. In most cases, over-pumping alone seldom brings a well to full development. The backwashing method is sometimes used concurrently.

Other methods of well development include air, dry ice, acid, dispersing agents and explosives. These latter methods are generally restricted to special cases. Additional information on these methods can be found in Johnson (46).

**Well Site Completion**

After a well has been drilled and fully developed for production or testing purposes, the location of the site should be accurately recorded. Most states that require a driller's log to be filed also require an approximate location by section, township and range, and the approximate elevation. This information is sufficient for domestic wells, but for research purposes, accurate locations and elevations must be established.

**Surveying Needs**

An engineering level or transit is generally used to determine precise location and elevation of the well site. Most well sites can be located on USGS, 7 1/2- or 15-minute quadrangle maps if available. Aerial photos may be used to determine location of the site with greater accuracy.

The ground surface elevation of the well site

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**FIGURE 5.28.—Sketch of sonde for caliper logging: Left, closed position; right, open position (60).**
For use on drill stem, surge block can be welded to a good pin cut from an old bit or other tool.

Same general design may be used for larger or smaller casing by using different size nipple and coupling as a base, and proportionate size changes in other elements of the block.

For larger sizes, use 4" standard pipe base.

**Notes**

**Vented Surge Block**

For Use in 8" Diameter Casing

**Solid Surge Block**

For Use in 8" Diameter Casing

**FIGURE 5.29.—Surge block for surging water well (97).**
should be tied to a common benchmark elevation or mean sea level (MSL) elevation. When this is determined, the casing top and the ground-water level can be established. Most water-level readings are made from the top of the casing. Static water levels at a particular time can be measured by sounding (several methods) and referred to the casing or ground-level datum. This ground-water level can then be used to set a recorder to read directly MSL or assumed benchmark ground-water elevation. If periodic measurements at the well site are necessary rather than continuous records, ground-water depth measurement can be made at selected time intervals.

**Instrument House**

Conditions at most well sites are generally such that any recording device on the well should be protected. The design, size, and material of an instrument house will depend on many factors (fig. 5.31 and 5.32). A few of the more important factors are: (1) location - topography, vegetation, aspect, land use, and future changes, (2) type of instrumentation - size, shape, and manufacturer's instrument specifications, (3) climatic conditions, both inside and outside gage house, ventilation, temperature, and humidity, (4) permanency of house - construction materials, moving house to new location, (5) servicing instrument - possible future instrument changes, or well maintenance, (6) size of well casing, and (7) cost.

**Observations**

**Water Level Fluctuations**

Water level fluctuations of aquifer systems are caused primarily by recharge and discharge, and generally involve a change in total storage. Water level fluctuations which do not involve an appreciable change in storage may be caused by wind, earthquakes, earth tides, and loading by vehicles.

Water level fluctuations can be caused by high velocity winds passing over the open mouth of a well. The result is a drop in pressure in the well causing the water to rise. As the wind subsides the water-level drops.
Earthquakes can cause very sudden changes in water levels. The degree of change is dependent on intensity of the quake, proximity to the epicenter and the aquifer materials. The elastic energy waves caused by the shock pass through the earth causing deformation by compression and expansion of the aquifer materials. This deformation is reflected in changes of water level in wells tapping these aquifers. Following strong quakes, unconsolidated aquifer materials in close proximity to the epicenters often compact and deform, expelling water from the land surface.

Earth tides, caused by the attraction exerted on the earth's crust by the moon and sometimes the sun, can cause fluctuation in groundwater levels. These tides can cause minor changes in water levels of confined aquifer. The net change rarely exceeds 0.1 foot (0.3 m). Fluctuations caused by earth tides show two minima each day which correspond with the moon's upper and lower culminations. The attraction causes slight dilation of the aquifer giving pressure changes which bring fluctuations in the water level.

The application of a heavy load over a confined aquifer body compresses the aquifer and increases the hydrostatic pressure. Wells in close proximity to railroad tracks often show this effect of loading. Soon after application of the load, the pressure decreases and the water flows radially away from where the load was applied. Initially the load is shared by the confined water and the aquifer material. However, as the water flows outward more of the load is borne by the aquifer materials. Changes in water levels under these conditions are dependent on the elasticity of the aquifer and the load, but rarely exceed 1 foot (0.3 m).

More significant fluctuations in water levels in confined aquifers are caused by ocean tides and barometric effects. Quite often fluctuations due to these conditions need to be determined and removed from the normal trend of the hydrograph. Water levels in wells tapping aquifers in close proximity to oceans respond with changes in ocean tides. In wells tapping water table aquifers, or confined aquifers which are
ON  OFF
DATE 8-4-69

TIME 12:30 p.m.
DEPTH TO WATER 22.90 ft.
INITIALS JZ

REMARKS

Windy

FIGURE 5.33.—Water level fluctuations due to wind and daily barometric changes.
in contact with the ocean, the water level response is due to the actual movements of water into or out of the aquifer body. In confined aquifers which extend beneath the ocean floor, tidal fluctuations cause pressure changes within the aquifer body. This relationship can be expressed as follows:

\[ \Delta pt = \Delta pw + \Delta ps \]  

(5-8)

where

\[ \Delta pt = \text{the change in pressure caused by changes in the ocean level}; \]
\[ \Delta pw = \text{the change in pressure of the water in the aquifer}; \]
\[ \Delta ps = \text{the reactive pressure of the solid grains in the aquifer}. \]

The rise of water, \( h \), in a piezometer is then expressed as:

\[ \Delta h \gamma = \Delta pw \]  

(5-9)

where

\( \gamma = \text{the specific weight of water}. \)

The value of \( pw \) will vary with the aquifer material. The more flexible the aquifer the greater the value of \( pw \).

Todd (93) also gives expression for water level changes in confined and unconfined aquifers which occur in submarine outcrop.

Changes in atmospheric pressure have little effect on water table situations but can be pronounced in confined conditions as it decreases the water levels. This is the reverse of loading over coastal aquifers due to change in ocean tides which cause a rise in piezometric level.

Fluctuations caused by changes in barometric pressure (fig. 5.33) can be removed from a well hydrography by determining the barometric efficiency of the aquifer. This may be expressed as:

\[ BE = \frac{Sw}{Sb} \]  

(5-10)

where

\( Sw = \text{the net change in water level}; \) and
\( Sb = \text{the net change in barometric pressure}. \)

Both terms are expressed in feet of water. In determining barometric efficiency, water level changes can be plotted as the ordinate and the corresponding changes in atmospheric pressure as the abscissa on rectangular coordinate paper. The slope of the straight line drawn through the points is the barometric efficiency. Barometric efficiency is directly proportional to aquifer rigidity.

The tidal efficiency of an aquifer, a measure of aquifer flexibility, may be expressed as:

\[ TE = \frac{Sw}{St} \]  

(5-11)

where

\( Sw = \text{the range of water-level fluctuation, in feet, in a well tapping the aquifer}; \) and
\( St = \text{the range of tide in feet corrected for density when necessary}. \)

A confined aquifer which responds to tidal fluctuations should also respond to changes in atmospheric pressure because the same mechanism in the aquifer produces both types of response.

Jacob (44) expressed the relationship between tidal and barometric efficiency as follows:

\[ BE = \frac{\Delta h \gamma}{\Delta pa} \]  

(5-12)

and

\[ TE = \frac{\Delta h \gamma}{\Delta pt} \]  

(5-13)

The sum of these expressions is unity, that is:

\[ BE + TE = 1 \]  

(5-14)

when \( BE \) is the barometric efficiency at the coast and \( TE \) is the tidal efficiency at the coast.

Further discussion on short term water-level fluctuations can be found in Ferris and others (29), Todd (93), and Davis and DiWiest (23).

Water level fluctuations due to changes in aquifer storage are due to recharge to the aquifer from precipitation or streamflow and to discharge by springs, baseflow, evapotranspiration, or pumping. These fluctuations are generally large and give rise to gradual changes in water levels.
Water Level Measurements

Accurate information regarding the position of the water table or potential surface is essential in any ground-water study. In the case of multiple aquifer systems, care must be taken when observations are made that the observer is aware of which ground-water zone is being observed. One should also be aware of whether the aquifer under study is confined or of the water table case.

Field observations of ground water are the basis for ground-water contour maps just as descriptions of surface exposures are for geologic maps. A ground-water contour map is simply a configuration of the water surface, from which hydraulic gradient and ground-water divides may be determined. Flow lines constructed normal to the contour (equipotential) lines can also be constructed to indicate direction of flow as well as areas of concentrated or converging flow. This will help determine the major elements of the flow system. As water tables are generally in a state of flux, a contour map on the water surface represents the condition only for a short time period.

The method of observation for water level measurements will normally be determined by site conditions, geologic factors, type and depth of aquifers, effect of surface water, and rate and direction of ground-water movement.

Two basic methods for observing ground water are used: nonrecording (periodic) and recording (continuous). After determining the method and frequency of measurement, it must be determined if an observation well or piezometer is to be used. Piezometers are used to determine hydrostatic pressure at a particular point while wells measure the integrated pressure of the saturated zone (fig. 5.34). Piezometers are useful to determine direction of water movement, particularly in areas where the aquifer is confined or semiconfined. Results may be plotted in plan and section and equipotential lines drawn on the pressure surface indicated by the piezometer readings. Flow lines can be drawn to show the direction of movement. Hydraulic gradient and areas of flow convergence can then be determined.

Nonrecording Methods

Water level observations must be referred to a surface reference point, such as mean-sea-level (MSL), before comparison between different observation points can be made. When a MSL reference point is not available, an assumed bench mark can be established. However, MSL should be used whenever possible.

Periodic measurement can be made as frequently as the study warrants. For example, periodic measurements of a cone of depression in a draw-down test would require more frequent measurements than water-table observation on a regional basis. Shallow water-table observations, because of their more rapid fluctuations, would require more frequent observations than deep measurements when pumping is not involved.

Measurements (fig. 5.35) can be made by (1) air line with pressure gage which indicates pressure necessary to counter-balance depth of water outside the air line, (2) tape and inverted cup sounding “popper”, (3) steel tape with carpenter’s chalk, (4) tape and float, and (5) electrical sounder.

Depth to the water table is subtracted from the surface reference elevation in order to determine the elevation of the water table.

When using the air line method, depth to water is calculated by:

\[ d = L - 1. \]  \hspace{1cm} (5-15)

where

- \( d \) = depth of water (ft)
- \( L \) = depth to bottom of air line (ft) and
- \( l \) = is pressure head (ft) represented by column of water of height equal to the subsurface length of the air line.

Figure 5.35 (a) shows air line installation with \( d, L, 1 \) indicated.

Of all methods for measuring water levels the wetted tape method, (fig. 5.35) has the best accuracy. Approximate depth to water from previous reading date should be known first to prevent the necessity of seeking and rechalking the tape.
**Recoding Methods**

A number of commercial water-level recorders are available. There are two types (fig. 5.36): chart and digital tape. Data collected on graphic charts (fig. 5.33) has the advantage of availability of a plotted picture of the water level. Machine digitization of these graphic charts reduces labor costs of data processing. The rise and fall of the float with changing water levels turns the drum proportionally, as the clock-controlled pen moves across the chart at a constant rate. The resulting graph shows water levels against a record of time. The range in stage is limited only by length of float line, since the chart drum may make any number of revolutions.

Chart scale factor and time factor vary widely and can be changed to obtain the necessary accuracy. Time scales commonly used are 4, 8, 12, 24 hours and 2, 4, 8, 16, and 32 days. Commonly used chart scales are 1:1, 1:2, 1:5, 1:10, and 1:20 (ft-English decimal); 10:12, 5:12, 16, 1:12, and 1:24 (ft-English duo-decimal); and 1:1, 1:2, 1:5, 1:10, and 1:20 (metric). The rate, magnitude, and frequency of water-table response and the reason for the observations determine the combination of scale-time factor.

Digital water level recorders (fig. 5.37) mechanically convert angular position of a rotating shaft into a coded digital output at selected intervals. The shaft, as in chart recorders, is connected to a cable, drum, and float. Hence, the only difference between the two methods is the recording technique. The advantage of binary-digital data system is that a large amount of data can be collected and analyzed with a minimum of labor, and the data can be translated directly by machine. Digital scale and time factors can be varied depending on watertable movement and observation frequency. Commonly used time factors are 5, 6, 15, 30, and 60 minutes. Scale factors are tenth, hundredth, and thousandth of a foot with a maximum of four digits.

Binary tape ground-water elevations as shown in figure 5.37 can be used for any depth. The depths shown on figure 5.37 read 0.77 foot (23 cm) at 1100 hours, 1-7-69. A correction, 300 feet (91 m), for example could be added to make the tape read 300.77 feet (91 m) MSL. This tape is punched at 5-minute intervals.
In addition to float recorders, water-level sensing devices are available which operate in conjunction with the float recording mechanism. The sensing device operates on an electrical circuit with the circuit being closed by contact with the water. The sensing device, such as the Keck, SD-62B in figure 5.36 enables continuous hydrographs to be obtained in wells or pipes with diameters as small as 5/8 inch (1.59 cm). They are also advantageous for deep wells. The record obtained is nonstopping and accurate to 0.01 foot (0.3 cm).

**FIGURE 5.35.—Methods of measuring water levels (46).**
FIGURE 5.36.—Water level recorders: *Top left,* typical recorder with pen trace; *top right,* water level sensing device attached to pen-trace recorder; *bottom,* typical digital recorder with punch tape.
The sensing device is fully transistorized. The sensing element, which goes into the well, is a solid brass bob, insulated except for the end that contacts the water surface. A ground wire attaches to the casing or ground rod. The unit contains two motors which drive the sensing bob up or down depending upon the bob’s location in respect to the water surface.

These units generally operate on two, 6-volt dry cell or chargeable batteries. Care must be taken to insure proper grounding and to prevent plating on the sensing bob due to electrolysis in certain waters. A small piece of emery cloth can be used periodically to clean the brass tip of the bob. For smaller diameter wells, these sensing devices in conjunction with Stevens Type F recorders (fig. 5.38) give excellent response to very small water level changes.

Determining Aquifer Properties

Pumping Tests

The pumping test is one of the most useful tools available for evaluating the hydraulic properties of an aquifer. When pumping water from a well, the piezometric surface (a free water surface) around the well is lowered and a cone of depression is created. Hydraulic characteristics of the aquifer are determined by measuring time and water level change. Water-level measurements are obtained from the pumped well and/or observation wells.

The “draw-down” data are then evaluated by means of various formulas to determine the hydraulic characteristics of the aquifer. The hydraulic properties of an aquifer are the coefficients of permeability, storage, and transmissibility. Because of the wide range of variability of the physical materials composing an aquifer it must be recognized that one pumping test will rarely determine the hydraulic characteristics throughout the aquifer system. Usually a number of tests are run, depending upon the variation of the results, and the mean values used as the coefficient.

The results from pumping tests must be in accord with the geology of the area when interpreting a ground-water flow system. Driller’s logs, geologic logs, geologic maps, well depth and water level records should be consulted when available prior to interpreting the results of pumping tests for determining the hydraulic characteristics of an aquifer.

There are no specific rules which hold true for performing all pumping tests. However, all data that can be economically collected should be recorded neatly and legibly, and all measure-
ments should be made with precision consistent with the required accuracy of results for each specific test.

Several types of pumping tests are used (13): The “constant-rate” test is usually used when observation wells are available. The purpose of the test is to determine the aquifer characteristics. In this case, the well is pumped at a constant rate for the entire period of the test. The “step draw-down” test is usually conducted to determine the characteristics of the well itself. Pumping is started at a low rate and increased at regular intervals until the desired capacity or the maximum capacity of the maximum capacity of the well is obtained. These tests will be described later.

The necessary length of time for the “constant-rate” test and the necessary pumping period at each rate of the “step draw-down” test will vary from case to case. A competent person experienced in pumping-test work can usually estimate the necessary length of time needed for the test from an examination of the preliminary drilling and water level data. However, this would be only an estimate, and events which take place during the test itself may make it highly desirable to extend, shorten, or entirely change the whole test procedure.

Installations and Data Acquisition

In order to obtain the most reliable data, the water-producing formation should be hydraulically stable prior to the test (for example, water levels should not be changing). This condition can usually be approached by discontinuing all pumping from the water-producing formation for at least 24 hours prior to the test, but may vary considerably with different formations. After pumping is stopped (in preparation for the test) water levels should be measured periodically. Not until constancy has been observed should the test be started.

Where it is impractical to stop all pumping from other wells in the vicinity, these wells should be kept pumping at constant rates for the period prior to and during the test. It is not always possible to meet these conditions, but every effort should be made to adhere to them as nearly as possible; otherwise, the reliability of the data will suffer.

When the purpose of the pumping test is to evaluate well interference or the characteristics of the water-producing formation, it is necessary to have one or more observation wells. The observation wells should be located in the vicinity of, and at various distances from, the pumped well. The tops of the observation wells should be accessible so that water-level recorders or other measuring equipment may be installed.

If wells are drilled to be used only as observation wells they should be at least 1¼ inches (3.2 cm) in diameter when water-level measurements are to be made with a tape or electric dropline. If float-actuated water-level recorders are to be used, it is desirable to have observation wells at least 6 inches (15.2 cm) in diameter. The distances between all wells should be carefully measured and reference elevations determined. Whenever possible, the logs of all wells should be reviewed prior to the test.

When the observation well is a well with a permanent pump installed, the well must be equipped with an air line of known length. Several different types of pumps can be used. A turbine-type pump is preferable. The pump should have sufficient capacity to pump at least the maximum desired rate in the case of a finished well. Either an electric motor or some type of internal combustion engine may be used to run the pump. More precise data can be obtained when an electric motor is used. The pumping equipment should be capable of oper-
ating continuously for the entire period of the test.

The pump discharge line should be equipped with a valve so that the rate of discharge may be accurately controlled. Provision must be made for the installation of orifice plates and piezometer tube, meter, or other acceptable equipment to measure the pumping rate. At the beginning of the test the valve should be partially closed to enable adjustment in the rate as the test progresses.

If the well to be tested produces water from sand and gravel, the screen should be of maximum practicable length and diameter. It should be selected with care to fit the graduation of sand and gravel encountered. Unless the well is of the gravel-pack type, the finer material surrounding the well should be loosened, drawn through the screen by surging and removed from the well before the test pump is installed.

The pump should be installed and a preliminary test run to see whether the formation is worthy of a more detailed and prolonged production test. The preliminary production test will reveal whether or not the pump is set deep enough. Any necessary changes can be made before the date of the test.

An air line of known length constructed of some suitable material should be installed in the pumped well with the lower end near the top of the pump-bowl section or a foot or two above the lower end of the pump-section pipe. The upper end of the air line should be equipped with a 1/4-inch (0.64 cm) pipe tee. An ordinary tire-valve stem equipped with a valve core should be installed in the tee. The air gage should be connected to the other opening of the pipe tee. The air-line system should be entirely free of air leaks except for the open end at the bottom. An ordinary tire pump should also be available.

When an air line is not available, provision must be made for lowering an electric dropline or other water-level measuring devices into the well. This requires a free passageway into the annular space between the well casing or hole and the pump column pipe. The annular space between the well casing and pump column pipe must be of sufficient dimension to allow free passage of the water-level measuring device up and down the well. Figure 5.38 shows several devices now used to measure water levels manually.

Figure 5.39 is a sketch of a typical test “set-up” on the pumped well. During the early part of a pumping test the water level in the pumped well lowers rapidly. This increases the net pumping head and will usually cause the pumping rate to decrease appreciably. The pumping rate should be checked continuously during this part of the test and the discharge valve manipulated to keep the pumping rate as nearly constant as possible.

As the test progresses, the rate of lowering of the water level ordinarily decreases, and it is not necessary to check the pumping rate quite so closely. However, the importance of keeping the pumping rate under close control throughout the test cannot be over emphasized. Any appreciable variations in pumping rate should always be recorded and the cause noted when it can be determined.

Changes in barometric pressure may cause the water levels to fluctuate in some artesian wells. A rise in barometric pressure would cause a lowering of water level. It is very seldom that barometric pressure changes during a pumping test would cause water-level variations of more than one foot, and the change is usually much less.

The frequency of observations and the amount of data recorded will vary with the accuracy desired, available personnel, and the particular well and water-bearing formation being tested. Figure 5.40 shows pumping test data, giving a general guide for frequency of observation.

Ordinarily it is desirable to make observations more frequently during the earlier part of the test and to increase the period between observations as the test progresses. After pumping has been stopped, measurements of the water-level recovery should be made quite frequently during the earlier part of the recovery period.

In general, when the water level is changing rapidly, readings should be taken as often as they can be recorded. As the water level becomes more steady, sufficient readings should be taken to facilitate a well-defined curve on a graph of water levels versus elapsed time.
Computing Aquifer Properties

Pumping test analyses first require the definition of the following basic terms:

- Permeability (P)—the capacity of a porous medium for transmitting fluid. The coefficient of permeability is the quantity of fluid that will flow through a unit cross-sectional area of a porous material per unit of time under a hydraulic gradient of 100 percent at 60°F (16°C).

- Transmissibility (T)—the same basic definition as permeability. However, the coefficient of transmissibility (T) as defined by Theis (9.2) is the rate of flow in gallons per day per foot through a vertical section of an aquifer whose height is the thickness of the aquifer and whose width is one foot under a gradient of 100 percent. Temperature is the field temperature of the ground water. This, when introduced into the simplified form of the Darcy equation, gives a useful form for computing flow through any vertical section of an aquifer as follows:

\[ Q = TIW \]  

(5-16)

where
\[ I = \text{hydraulic gradient} \]
\[ W = \text{width of vertical section} \]
\[ T = \text{transmissibility} \]
\[ Q = \text{flow} \]

Therefore, the ground-water outflow or inflow to any area (watershed, valley alluvium, and aquifer) can be computed.

- Coefficient of storage (S)—the volume of water released from storage or taken into storage, per unit of surface area of aquifer per unit change in head. For a phreatic ground-water body, S is the same as specific yield of the material dewatered during pumping. Changes in storage within a basin can only be determined from an adequate knowledge of the occurrence of ground-water in the basin; antecedent information on water levels, pumping records, and pumping tests; specific yields of unconfined aquifers and storage coefficients of confined aquifers; and adequate knowledge of geologic conditions.

- Radius of influence (R)—the distance from the center of the well to the limit of the cone of depression.

- Specific yield (Sy)—the ratio of the volume of water that a saturated rock or soil will yield by gravity to the total volume of the rock or soil. This definition implies complete gravity drainage and is equal to porosity minus specific...
Test conducted by: Alabama Engineering Co. and State Water Survey
Well Owner: City of Doeville Address: Doeville, Illinois
Pumped Well No: 2 Location: Approx. 1000' N & 2000' W of SE Cor. of Sec: 10 Twp. 1N Range 3E County Doe
Observation Well Locations: No. 1 - 1270' due west of Well No. 2
Airline Lengths: Pumped Well 97.3' Observation Wells
Remarks: Elevation of top Casing Well No. 2 - 704.08' MSL
Elevation of top of Casing Well No. 1 - 705.72' MSL
Test observed by R.T.S., G.H.N. Pumping rate measured with 8" x 10" orifice. Water levels measured with airline in well No. 2 and recorder in Well No. 1.

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Figure 5.40.—Actual pumping test.
retention. It is usually expressed as a percent and depends on duration of drainage, temperature, water quality, and physical condition of material under consideration.

- Specific retention (Sr)—the ratio of the volume of water a saturated rock or soil will retain after complete gravity drainage to the total volume of rock or soil.

Using these basic definitions and a definition of the boundary conditions of the aquifer, a pump test can be designed to measure aquifer constants. The following equations are those most generally applied to pumping tests.

There are two basic equations for equilibrium well equations (46). These equations are for water table conditions equation 5-17, and artesian conditions given in equation 5-18.

\[ Q = \frac{P(H^2 - h^2)}{1055 \log (R/r)} \quad (5-17) \]

where
- \( Q \) = pumping rate (gal/min);
- \( P \) = permeability (gal per d per ft\(^2\));
- \( H \) = saturated thickness before test (ft);
- \( h \) = depth of water in the well while pumping (ft);
- \( R \) = radius of cone of depression (ft); and
- \( r \) = radius of well (ft).

\[ Q = \frac{P m (H - h)}{528 \log R/r} \quad (5-18) \]

where
- \( m \) = aquifer thickness (ft);
- \( H \) = static head at bottom aquifer (ft); and
- \( P, h, R, \) and \( r \) = see equation (5-17).

Figure 5.41 shows a set-up for each test and an explanation of terms. Before these equilibrium formulas can be used, it is necessary that certain assumptions be made: (1) uniform permeability in the radius of influence, (2) no stratification in the aquifer, (3) for phreatic aquifer a constant \( (H) \) before the test and a constant \( (m) \) for artesian aquifers, (4) one hundred percent efficient pumping well, (5) equilibrium conditions are reached, (6) laminar flow throughout the aquifer, (7) horizontal surfaces for the water table and piezometric surface, (8) total penetration of the well, (9) no vertical leakage, (10) aquifer infinite in area, (11) small drawdown for a thickness "m".

These assumptions limit the use of an equilibrium test. However, with a certain amount of judgment and experience, these assumptions may not be too critical.

Equations 5-17 and 5-18 can be used to calculate well yield. Permeability \( (P) \) must be determined from laboratory or field tests; \( (H) \) and \( (m) \) are obtained from the driller's or geologic log, and \( (R) \) is usually estimated.

For the water table aquifer, \( (P) \) is calculated as follows:

\[ P = \frac{1055 Q \log r_2/r_1}{(h_2^2 - h_1^2)} \quad (5-19) \]

where
- \( P \) = permeability (in gal per day per ft\(^2\))
- \( Q \) = pumping rate (gal/min);
- \( r_1 \) = distance to nearest observation well (ft);
- \( r_2 \) = distance to furthest observation well (ft);
- \( h_2 \) = saturated thickness at the site of the furthest observation well (ft); and
- \( h_1 \) = saturated thickness at the site of the nearest observation.

For artesian conditions the following formula is used to determine permeability (46):

\[ P = \frac{528 Q \log r_2/r_1}{m(h_2 - h_1)} \quad (5-20) \]

where
- \( m \) = thickness of aquifer (ft);
- \( h_2 \) = head at site of furthest observation well measured from bottom of aquifer (ft);
- \( h_1 \) = head at site of nearest observation well measured from bottom of aquifer (ft);

and other terms defined as in equation 5-20.

Besides giving methods for determining permeability, the above formulas are useful in studying well yield. Other things being equal, well yield is directly proportional to permeability for water table conditions. For artesian
conditions, yield is directly proportional to aquifer thickness, all other things being equal (46). The above formulas are standard and commonly used. However, other formulas are available and may be equally adaptable to a particular situation.

Theis (92) was the first to take into account the effect of time of pumping on well yield in his nonequilibrium formula. This approach to well hydraulics permits the prediction of drawdown at any time. Transmissibility and average permeability can be determined in the early stages of a pumping test. A single observation well is all that is required for observation of water levels. The same assumptions as for the equilibrium well equation are applicable to the Theis equation, with the exception that equilibrium is not necessary.

The Theis equation in its simplest form is:

\[
s = \frac{114.6 \ Q \ W(u)}{T}
\]

(5-21)

where

- \( s \) = drawdown (ft) in observation well
- \( Q \) = constant pumping rate (gal/min)
- \( T \) = transmissibility (gal\·d\·ft) and
- \( W(u) \) = well function of \( u \)

The value of \( W(u) \) corresponding to \( u \) is given on table 5.5.

Direct calculation of the coefficients of transmissibility \( T \) and permeability \( P \) is not possible using equation 5-21. However, Cooper (20) worked out a graphical solution which makes it possible to find \( T \) and \( S \) providing values of other terms are known. This method involves matching a curve plotted from specific pumping test data with what is called a type curve. The type curve is prepared by plotting values of \( W(u) \) against 1/u on graph paper with logarithmic scales, are shown in figure 5.42. Values from table 5.5 are used. Data from a pumping test are plotted on similar graph paper with logarithmic scales and cycles identical to those of the type curve.

The following gives an illustration of data
from a standard pumping test. Drawdown was measured at frequent intervals in an observation well 400 feet (122 m) from a well that was pumped at a constant rate of 500 gal per min (2m³/min) (46).

<table>
<thead>
<tr>
<th>Time since pump started in minutes</th>
<th>Drawdown, seconds/foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.16</td>
</tr>
<tr>
<td>1.5</td>
<td>0.27</td>
</tr>
<tr>
<td>2.0</td>
<td>0.38</td>
</tr>
<tr>
<td>2.5</td>
<td>0.46</td>
</tr>
<tr>
<td>3.0</td>
<td>0.53</td>
</tr>
<tr>
<td>4.0</td>
<td>0.67</td>
</tr>
<tr>
<td>5.0</td>
<td>0.77</td>
</tr>
<tr>
<td>6</td>
<td>0.87</td>
</tr>
<tr>
<td>8</td>
<td>0.99</td>
</tr>
<tr>
<td>10</td>
<td>1.12</td>
</tr>
<tr>
<td>12</td>
<td>1.21</td>
</tr>
<tr>
<td>14</td>
<td>1.30</td>
</tr>
<tr>
<td>18</td>
<td>1.43</td>
</tr>
<tr>
<td>24</td>
<td>1.58</td>
</tr>
<tr>
<td>30</td>
<td>1.70</td>
</tr>
<tr>
<td>40</td>
<td>1.88</td>
</tr>
<tr>
<td>50</td>
<td>2.00</td>
</tr>
<tr>
<td>60</td>
<td>2.11</td>
</tr>
<tr>
<td>80</td>
<td>2.24</td>
</tr>
<tr>
<td>100</td>
<td>2.38</td>
</tr>
<tr>
<td>120</td>
<td>2.49</td>
</tr>
<tr>
<td>150</td>
<td>2.62</td>
</tr>
<tr>
<td>180</td>
<td>2.72</td>
</tr>
<tr>
<td>210</td>
<td>2.81</td>
</tr>
<tr>
<td>240</td>
<td>2.88</td>
</tr>
</tbody>
</table>

Figure 5.43 shows these data plotted on regular graph paper. The curve shows how drawdown increased rapidly at first with its rate of increase diminishing as time progresses so that the water level would appear to stabilize eventually if pumping were continued long enough. Since the measurements show that the water level is still dropping after 240 minutes of pumping, the equilibrium formula cannot be applied. Proper analysis of the test data in this case requires use of the Theis nonequilibrium concept.

For solving by the nonequilibrium formula, the data are plotted on logarithmic graph paper as shown in figure 5.44. This graph is then superimposed on the type-curve sheet so that the plotted points fall on or fit some portion of the type curve. In finding the position of best fit, the axes of both graphs must be kept parallel.

Once a good matching position is found, a match point is selected. The match point can be any point in the overlap area of the curve sheets. It is most convenient to select a match point where the coordinates on the type curve are known in advance. This simplifies the computations.

In figure 5.45 the match point is shown as the point on the type curve where \( u \) equals 100, and \( W(u) \) equals 4.038. At the corresponding point on the time-drawdown diagram, \( s \) equals 2.3 feet (70 cm) and \( t \) equals 83 minutes or 83/1440 seconds (s)/day.

Substituting in equation 5-21:

\[
T = \frac{114.6Q}{W(u)} = \frac{114.6 \times 500}{2.3} \times 4.038 = 100,000 \text{ gal/d/ft}
\]

After determining \( T \), \( S \) may be calculated from the following relationship:

\[
S = \frac{UTt}{1.87 r^2}
\] (5-22)

The value of \( r \) in this example is 400 feet, (122 m), the distance from the pumped well to the observation well. Thus,

\[
S = \frac{1 \times 100,000}{100 \times 1.87 \times 400^2} \times \frac{83}{1440} = 1.9 \times 10^{-1}
\]

Brown (12) presents detailed explanations of other ways of solving the non-equilibrium formula by means of the matching-curve technique.

It has been found that when the value of \( u \) is sufficiently small (less than 0.05), equation 5–20 can be modified to:

\[
s = \frac{264Q}{T} \log \frac{0.3 Tt}{r^2 S}
\] (5-23)

where
| N | N \times 10^{-6} | \nabla | \nabla \times 10^{-6} | \nabla \times 10^{-6} | \nabla \times 10^{-6} | \nabla \times 10^{-6} | \nabla \times 10^{-6} | \nabla \times 10^{-6} | \nabla \times 10^{-6} | \nabla | \nabla \times 10^{-6} |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.0 | 33.9616 | 31.6580 | 29.3584 | 27.0583 | 24.7582 | 22.4581 | 20.1580 | 17.8579 | 15.5578 | 13.2576 | 10.9575 |

TABLE 5.5—Values of W(\alpha) and \alpha for nonequilibrium formula

\[ W(\alpha) = \frac{1}{2} \int_{0}^{1} (1 - \alpha) \, d\alpha + \frac{1}{2} \int_{1}^{2} \alpha \, d\alpha + \frac{1}{2} \int_{2}^{3} (3 - 2\alpha) \, d\alpha \]
Symbols ($s$, $Q$, and $T$) as previously defined; and

$t$ = time since pumping started (d);

$r$ = distance from the pumped well to the point of observation (ft); and

$S$ = storage coefficient (dimensionless)

The value of $u$ becomes small as $t$ increases and as $r$ decreases.

A time-drawdown graph (fig. 5.46), when plotted on semilog graph paper with time horizontally (log) against drawdown vertically (normal), will have most of the points falling in a straight line. Using this plot the coefficient of transmissibility can be calculated as:

$$ T = \frac{2640}{\Delta s} \quad (5-24) $$

A direct calculation of transmissibility can be made if a constant pumping rate is maintained. In figure 5.45, the value for $\Delta s$ is the slope of time-drawdown graph over one log cycle. The storage coefficient ($S$) can also be calculated directly using the time-drawdown curve by the formula:

$$ S = \frac{0.3 \, T t_{u}}{r^2} \quad (5-25) $$

where

$t_u$ = intercept of the straight line at zero drawdown (days).

Care must be taken, when using the time-drawdown curve, that pumping is continued over a sufficiently long period to be able to define the slope and position of the line. Care must also be taken in precise graphing of
points. Also, an accurate description of the aquifer boundary conditions is necessary.

Transmissibility \( T \) can also be computed when a distance-drawdown graph is plotted on ordinary graph paper as in figure 5.47.

When plotted on a semilog diagram as in figure 5.48 this plot will form a straight line.

It is necessary to have at least three observation wells and a constant \( Q \). The formula is:

\[
T = \frac{5280}{\Delta s} \tag{5-26}
\]

where

\[ \Delta s = \text{slope of the distance-drawdown graph}, \]

and the formula for storage coefficient is:

\[
S = \frac{0.3 \ T t_w}{r_o^2} \tag{5-27}
\]

\[
T = \frac{264Q}{\Delta s} \tag{5-30}
\]

where

\[ r_o = \text{intercept at zero drawdown of extended straight line (ft).} \]

The above discussion assumes that the test wells were total penetrating. The solution for partial penetrating wells is considerably more complicated and the accuracy is not nearly as great. A detailed review of the method and techniques for partial penetrating tests is given by Todd (97).

This formula shows that when \( s' \) is plotted against \( t/t' \), a straight-line relation is attained on semi-log paper. Values of \( s' \) are plotted on the vertical arithmetic scale, and \( t/t' \) values are plotted on the horizontal log scale. A value for \( \Delta s' \) or the residual drawdown for one cycle on the \( t/t' \) scale can be obtained. This then can be substituted in the formula:

\[
S = \frac{0.3 \ T t_w}{r_o^2}
\]

\[
T = \frac{264Q}{\Delta s}
\]

\[
T = \frac{5280}{\Delta s}
\]

**Figure 5.43.—Variation on ordinary graph paper of drawdown with time of pumping (46).**
and a transmissibility value obtained. Storage coefficient can also be determined by:

\[ S = \frac{0.3 \cdot T \cdot t_o}{r^2} \]  \hspace{1cm} (5-31)

where

- \( t_o \) = the time intercept where the plotted straight line intersects the zero-drawdown axis (days) and
- \( r \) = distance of observation well from the pumping well (ft).

A check on time-drawdown measurements of \( T \) and \( S \) can be made using water-level recovery data. When pumping is stopped, recovery measurements in one or two observation wells should be made (fig. 5.49). Equation 5.23 can be used. First, it is necessary to plot time (minutes) horizontally (log) against recovery (feet) \((s-s')\) vertically (fig. 5.50). Theoretically, the time-drawdown and recovery curves should be identical if the aquifer conditions conform to the Theis assumptions.

Transmissibility is calculated as follows:

\[ T = \frac{264Q}{\Delta (s-s')} \]  \hspace{1cm} (5-28)

where

\( \Delta s - s' \) = change in water-level recovery per log cycle.

Another method of calculating \( T \) is by residual drawdown (fig. 5.51) rather than the recovery curve. By extension of the time-drawdown curve, it can be shown that residual drawdown is related to the log of the ratio \( t/t' \) (\( t \) is time since pumping started and \( t' \) is time since pumping stopped):
where

\[ s' = \frac{264Q}{T} \log \frac{t}{t'} \]  

(5–29)

The well should be fully developed and open to the full thickness of the aquifer. The test involves instantaneous injection of a slug of water into the well. One must be cautious in use of the resulting data because this method of testing generally applies only to material close to the well. The test is best suited for aquifers with transmissibility coefficient of low value, not to exceed 25,000–35,000 gal/day/ft because the injected water will dissipate so rapidly that it cannot be measured accurately enough for straight line plotting.

The apparatus used for injecting the slug involves only a vessel such as a 50-gal (189 l) oil drum with a trapdoor in the bottom and an outlet nipple to guide the water into the well.

![Diagram of plotted points representing pumping test data superimposed on type curve in position where points fall on type curve. Match point for \( \frac{1}{u} \approx 100 \).](image)
**FIGURE 5.46.**—Drawdown versus time of pumping on semilogarithmic scales (Gh).

- **Pumping rate,** $Q = 500$ gpm
- **Distance of well from pumped well,** $r = 400$ ft
- **Predicted drawdown after 720 minutes of continuous pumping,** $3.5$ ft
- **Time since pump started,** in minutes
- **Drawdown, in feet**
- **$t_0 = 1.44$ min
- **$\Delta s = 1.30$ ft**
Figure 5.52 shows the arrangement and sketch of the equipment used in a particular series of testing.

Usually, only a small quantity ("slug") of water can be injected into a well and can rarely be measured far enough beyond the injected well to warrant construction of observation wells. Therefore, water level measurements are made only in the injection well.

When performing the test, the "slug" of water must be administered instantaneously, and the water-holding container should be placed over the casing in such a way as to permit air to escape from the casing.

The equation used to compute $T$, is written as

$$T = \frac{114.6q (1/t_m)}{s}$$

where

- $T$ = coefficient of transmissibility (gal d ft)
- $q$ = volume of the slug (gal)
- $t_m$ = time in minutes measured from the average of the times marking the beginning and cessation of the injection
- $s$ = the residual head after injection of the slug in feet

Steps for performing a slug injection test are outlined as follows (28):

- Before injecting the slug of water into the well, define the existing water-level trend by making water-level measurements at frequent intervals.
- By means of a suitable apparatus, instantaneously (or nearly so) inject a known volume, $q$, of water into the well.
- Remove the injection apparatus from the well and resume water-level measurements.
Ground-Water Quality

Water is a universal solvent, is always in motion, and is always striving for chemical equilibrium with its surroundings. Ground water, in its slow movement through the aquifer materials, is constantly dissolving or precipitating material and leaving a record of its chemical history.

Because of this chemical record, water chemistry analyses, together with flow system analyses, can offer far-reaching explanations about many of the unknowns in the ground-water phase of the total hydrologic cycle for a watershed. Problems amenable to improved solution include: (1) age, amount, and residence time of ground water, (2) mixing of water from different sources, (3) an aid in defining areas of recharge, lateral flow, and discharge, (4) amount and location of recharge and discharge, and (5) sources of pollution. Water quality investigation, where the quality of ground water is desired as it moves through a system, is a good example of ground-water chemistry analyses.

A starting point for chemical analyses in groundwater investigations is the precipitation
Pumping started (500 gpm)

Static water level

Drawdown 16 ft

Residual drawdown

Pumping stopped

Recovery 16 ft

FIGURE 5.49.—Typical drawdown and recovery curves for well pumped for 48 hours at constant rate of 500 gallons per minute, followed by idle period for water level recovery (46).

Sample. Precipitation is relatively pure water but can contain tritium and carbon 14, both of which can be useful in tracing ground-water movement. Chemical loss of various kinds and amounts may occur in precipitation, depending on the atmospheric sources and conditions. Special precipitation gages can be constructed so that the receptacle will be open only as long as it is raining to prevent contamination of the receptacle before the catch or of the sample after the catch (6).

After sampling precipitation, the next step would be to obtain a sample of the soil water, if possible. This may be very difficult to do in areas of rocky soil, shallow soil, and soils of low infiltration rates. Suction instrumentation is often necessary. Installations are made in previously determined areas of recharge if known. A network of wells is laid out so that the water in areas of lateral flow and in areas of discharge is sampled. All springs in the area of interest should also be sampled.

FIGURE 5.50.—Time-recovery curve for observation well A as straight line when plotted on semilog diagram (46).
FIGURE 5.51.—Residual drawdown plotted against ratio, $t$ (time since pumping started)/$t'$ (time since pumping started) (46).

FIGURE 5.52.—Apparatus for performing “slug” test.
Precipitation moving into aquifer materials of low solubility may take some time to approach equilibrium. Many minerals in aquifer materials have the capacity to exchange one ion for another, especially the cations of calcium, magnesium and sodium. The exchange occurs between the mineral grains and the water in solution and will continue until equilibrium is reached. Time in residence and temperature of the water are important factors in the rate of exchange.

Samples are usually collected on a regular schedule. The schedule will in part be determined by the rate at which the water moves and the consistency of recharge events.

Samples are taken in polyethylene or glass bottles which have been thoroughly rinsed with distilled water just before sampling. Usually a 1-gallon (3.8 l) sample should be taken to provide sufficient amount for any number of analyses. The testing laboratory will usually determine the sampling amounts and the schedule.

Analyses can be run at most any university or can be contracted through private companies. The expense of equipping a laboratory capable of complete water analyses is generally too great for a single investigation. Portable kits for rather thorough water chemistry analyses are available but are of a preliminary nature and generally do not give the thorough and accurate analyses required.

The previous example of ground-water quality analyses was applied to natural systems. However, an investigation of ground-water pollution studies from manmade inputs would be handled the same way. Sampling frequency may vary according to the needs of the investigations.

Recently efforts in ground-water quality investigations have involved modeling the transport of chemical constituents in ground-water flow systems to determine pollution from point sources. This combination to water chemistry ground-water hydrology and computer simulation models will undoubtedly find its place in pollution investigations.

Additional information on ground-water quality investigations can be found in Davis and DeWiest (23), Todd (93), and Walton (99).

**Ground-Water System Analysis**

Ground-water movement and storage may be quantitatively evaluated by analyses of flow nets. These analyses provide the basis for understanding ground-water systems. When the system is understood, it is then possible to develop prediction and simulation models of ground-water flow. These models can be used by analysts to assess the impact of chemical movement and evaluate future water quality and quantity.

**Flow Nets**

Factors that need to be considered and analyzed before a flow net is constructed for a watershed are: (1) surface runoff from adjacent watersheds to determine if interbasin flow occurs, (2) surface runoff from subwatersheds to determine intrabasin flow, (3) geological conditions within the watershed (structure, stratigraphy, and lithology), (4) ground-water characteristics within the area (water table, flow direction and gradient, number of aquifers, aquifer boundaries, and permeability), and (5) variations in ground-water elevation within the watershed area with time.

After these factors are considered and boundary conditions established, flow nets can be drawn for the watershed area. They will permit analysis of ground-water movement from, or into, the area, assuming that reasonably accurate values of transmissibility and aquifer thickness are known.

Flow nets are graphical representations of flow patterns. They offer reliable assistance, and often provide a graphical solution when mathematical solutions are not practical. A flow net is composed of two families of lines or curves: (1) Streamlines, or flow lines indicating the path followed by water as it moves in the direction of decreasing head. (2) Equipotential lines which intersect streamlines at right angles and represent contours of equal pressure head in the aquifer.

Theoretically, flow patterns contain an infinite number of flow lines and equipotential lines. Flow net construction, however, makes use of only a few of the lines. Equipotential lines are selected so that the total drop in head across the system is evenly divided between
adjacent pairs of potential lines. Similarly, the flow lines, normal to the equipotential lines, are selected so that the total quantity of flow is divided equally between adjacent pairs of line.

The hydraulic gradient is determined by the drop in head between two equipotential lines in an aquifer, divided by the distance traversed by water moving from a higher to a lower potential line. This assumes that the water moves in a straight line, which is often not the case under natural-geological conditions; some error may, therefore, be introduced into the analysis.

In general, the water will follow the path of least resistance, or the shortest path between equipotential lines. Thus, it follows that the direction of water movement is everywhere analogous with paths that are normal to the equipotential lines.

A flow net constructed on the above principles is assumed to be rectangular, and the ratio of the mean dimensions of each rectangle is constant. This must be kept in mind at all times during construction of the net. The net becomes a system of squares if the sides of the rectangles are equal. Flow nets, however, involve curved flow paths, and the geometric form is somewhat curvilinear, and true squares or rectangles are seldom attained.

Flow net construction of the ground-water surface is difficult. It requires a thorough knowledge of the geological conditions and experience in construction of nets. Casagrande (16) listed the following points, which are helpful in flow net sketching:

- Study the appearance of well-constructed flow nets and try to duplicate them by independently reanalyzing the problem they represent.
- In the first attempts at sketching, use only four or five flow channels.
- Observe the appearance of the entire flow net; do not try to adjust details until the entire net is approximately correct.
- Frequently, parts of a flow net consist of straight and parallel lines, which result in uniformly sized true squares. By starting the sketching in such areas, the solution can be obtained more readily.
- In flow systems having symmetry (for example, nets depicting radial flow into a well), only a section of the net need be constructed, as the other part or parts are images of that section.

- During the sketching of the net, keep in mind that the size of the square changes gradually; all transitions are smooth and, where the paths are curved, are of elliptical or parabolic shape.

Taylor (91) suggests a somewhat different technique. He recommends that a trial flow line be drawn and that the entire system be completed as if the trial line was correct. If the completed system is not correct, then the initial line is corrected and the entire system re-sketch. This method permits a more accurate analysis, in that the whole picture of the flow net is reviewed and analyzed as one.

Before attempting to construct a flow net, it is necessary to establish the boundary conditions and describe them. For steady flow, with particular boundary conditions, only one flow net exists. However, flow nets in nature are constantly changing as a function of time.

Therefore, to obtain accurate directions of subsurface flow, computations must be made whenever an appreciable change is noted in streamlines, or equipotential lines. These changes can be measured in observation wells and determined from ground-water control maps drawn when a predetermined elevation change is monitored. This variation is defined as any change affecting the ground-water flow.

After these changes are considered and boundary conditions established and described, a flow net can be drawn for the basin for a specific time. This flow net, as constructed, will permit the analysis of subsurface water movement assuming that reasonably accurate values for permeability and aquifer thickness are known. Therefore, water balance studies of a watershed can be made if, in addition, accurate surface hydrologic information is available (47).

The following is an example of flow-net construction, using the flow-net equations:

\[
\frac{dq}{ds} = \frac{K dh}{dm} \text{ (rectangles) for unit thickness of aquifer (93)}
\]

(5-33)
Assume $ds = dm$, the equation reduces to

$$dq = Kdh$$ (squares) for unit thickness of aquifer;

$dm$ = distance between flow lines;

$ds$ = distance between equipotential lines in direction of flow;

$K$ = coefficient of permeability;

$dh$ = head loss between flow lines;

$dq$ = constant flow between two adjacent flow lines;

$T = 180\, \text{ft thickness of aquifer (Meridian Sand)}$—Pigeon Roost Creek, Miss.; and

$K = 50\, \text{ft/d (Meridian Sand)}$—Pigeon Roost Creek, Miss.

Total flow per day through the Meridian formation

$$dq = K \frac{dh}{ds} dm T \text{ (rectangle)}$$

$$dq = K \frac{dh}{ds} T \text{ (square)}$$

Using the equipotential ground-water map, flow lines were drawn for the watershed, culminating in a series of squares or rectangles (flow net) around the watershed boundary.

Flow directions were determined for each bounding rectangle to permit analysis of subsurface flow. An identifying number was assigned to each square or rectangle along the boundary. The distance between the equipotential and streamlines was measured (scaled), and the flow was computed through each area (fig. 5.53), using equation [5.33]. Computations are simplified when the bounding areas are squares.

The following computations use the flow-net equations:

Assumptions:

1. Uniform permeability, both horizontally and vertically (homogenous material)

2. Uniform thickness of aquifer

Outflow from the watershed (rectangles)

$$dq = 50 \left( \frac{10}{78} \right) 45 \times 180 = 51.8 \times 10^4 \, \text{ft}^3/\text{d}$$

$$dq = \frac{\text{ft}}{\text{d}} \left( \frac{\text{ft}}{\text{ft}} \text{ or unity} \right) (\text{ft})(\text{ft}) = \text{ft}^3/\text{d}$$

**Figure 5.53.**—Ground water flow net, Pigeon Roost Creek Watershed.
Outflow from watershed (square)
\[ dq = 50(10) \times (10) = 90 \times 10^9 \text{ ft}^3/\text{d} \]
\[ dq = \frac{\text{ft}}{\text{ft}} \times (\text{ft}) = \text{ft}^3/\text{d} \]

Summation of all ground-water outflow areas from the watershed

\[ = 2150 \times 10^9 \text{ ft}^3/\text{d} \]
\[ 2150 \times 10^9 \text{ ft}^3/\text{d} \times 365 \text{ d/year} \]
\[ = 784.6 \times 10^9 \text{ ft}^3/\text{year} \]

(Watershed area) = 117 miles^2

\[ = 3,261 \times 10^6 \text{ ft}^2 \]
\[ \frac{784.6 \times 10^9 \text{ ft}^3/\text{year}}{3,261 \times 10^6 \text{ ft}^2} = 0.2405 \text{ ft/year} \]

= 2.886 area in/year

Summation of all ground-water inflow areas to the watershed = 438 \times 10^4 \text{ ft}^3/day

\[ 438 \times 10^4 \text{ ft}^3/\text{year} \times 365 \text{ d/year} \]
\[ = 160 \times 10^4 \text{ ft}^3/\text{year} \]
\[ \frac{160 \times 10^4 \text{ ft}^3/\text{year}}{3,261 \times 10^6 \text{ ft}^2} = 0.049 \text{ ft/year} \]

= 0.588 area in/year

(Outflow) − (Inflow) = Water loss

2.886 area inches/year minus 0.588 area in/year = 2.298 area in/year water loss

These computations assume that the reference flow net represented the mean condition during the year, which may or may not be precisely the case. However, they provide a usable estimated ground-water loss. This analysis assumes a homogeneous and isotropic medium.

For aquifers that are partially homogeneous, a single system of squares cannot be used. A net can be constructed in which length of the sides of the rectangle is proportional to differences in transmissibility. The flow lines in this case would be refracted, according to the tangent law, when flow from one subarea enters another. An analysis of this type is extremely difficult and requires a measure of the transmissibility in each subarea. Bennett and Meyer (4) used such a system to determine the quantity of flow from an area using pumping tests in each subarea. This method provides a more realistic value of the flow from a watershed area than pumping tests alone, which represent only a small area of the aquifer. This type of analysis is expensive and time consuming, but will give more precise correlation between isolated pump tests and the total flow net analysis.

**Ground-Water Models**

The physical laws governing steady-state ground-water flow were first presented in the correct mathematical structure in 1940 by M. King Hubbert (42). Transient (unsteady) ground-water movements were being studied at the same time by other hydrologists and applied mathematicians.

As indicated by Freeze (30), researchers studying unsteady ground-water movement during the period 1935–60 used the individual well as a unit of study, whereas Hubbert analyzed large-scale regional effects. The ground-water basin was finally established as an acceptable study unit in the 1960’s. Toth (94) expanded Hubbert’s work by establishing that exact ground-water flow patterns could be derived as solutions to boundary value problems. Toth’s method was reasonably general, but the solutions were applicable only to homogenous media and to the special cases considered.

Freeze (30) extended available solutions of ground-water flow to more general cases. His objectives were to obtain with a mathematical model the flow patterns for a general three-dimensional, nonhomogeneous ground-water basin having any water-table configuration and to investigate the effects of the water-table configuration and geologic boundaries on the flow system (33, 34, 35).

Finite difference solutions to the partial differential equation of ground-water flow:

\[
\frac{\partial}{\partial x} \left[ \rho K(x, y, z) \frac{\partial \Phi}{\partial x} \right] + \frac{\partial}{\partial y} \left[ \rho K(x, y, z) \frac{\partial \Phi}{\partial y} \right] + \frac{\partial}{\partial z} \left[ \rho K(x, y, z) \frac{\partial \Phi}{\partial z} \right] = \frac{\partial \rho}{\partial t} + \rho \frac{\partial \theta}{\partial t}
\]

(5–34)
where
\[ \rho \quad \text{is the mass density of the fluid} \]
\[ K \quad \text{is the permeability of the aquifer} \]
\[ x, y \quad \text{are the horizontal coordinate directions} \]
\[ z \quad \text{is the vertical coordinate direction or elevation head} \]
\[ \theta \quad \text{is the volumetric saturated moisture content or the porosity of the medium} \]
\[ t \quad \text{is time, and} \]
\[ \Phi \quad \text{is the hydraulic potential energy per unit weight} \]

With the right-hand side equal to zero (steady state) comprised Freeze's mathematical model.

For the boundary conditions Freeze assumed that the groundwater basin was bounded on the bottom by a horizontal, impermeable layer, on the top by the water table, and on all sides by vertical impermeable boundaries (ground water divides).

Freeze and Harlan (32) indicated that an average water-table position should be an adequate steady-state boundary condition to simulate the ground-water component of a hydrologic response model, providing that the zone of fluctuation is small and the relative configuration of the water table remains constant. An unsteady state or transient mathematical model will be necessary if these two conditions are not satisfied. Finite difference solution models for the two dimensional horizontal unsteady case have been developed (8, 96).

Recent developments in three-dimensional transient models for basin-wide ground water have provided new insights to ground-water flow systems (31, 81).

A numerical approach for solving transient fluid flow problems in complex systems is reported by Javendel and Witherspoon (45) and Witherspoon and others (101). This approach is called the finite element method and is adaptable to digital computers. The partial differential equation and the initial and boundary conditions are replaced by a corresponding calculus of variations problem. A finite number of subregions replaces the continuum, and the variational principle is expressed as a summation of functionals.

The solution to the original boundary value problem is obtained by minimizing the resulting functional with direct methods of the calculus of variations. This method was verified by comparing results to published analytical solutions, but no field applications were given. Kealy (47) has developed a finite element model to locate the phreatic surface within tailings pond embankments. This work is currently being applied to typical ground-water flow systems in several Idaho basins.

**Data Reduction and Processing**

Chart annotations on either digital or analog charts for continuous recordings should include station location, time on, time off, date on, date off, depth to water or water level elevation at time on and time off, and any information concerning recorder malfunction, recorder adjustment, or unusual occurrences (fig. 5.54).

Tabulation of continuous recording data may be accomplished for selected time intervals either manually or with the use of automatic chart readers. The advantage of chart reader equipment is that data tabulation can be automatically recorded on punchcards and mag-tape. Computer programs may then be developed to accomplish almost any type of well hydrograph analysis, including determination of aquifer constants from continuous recordings taken during pump tests and barometric efficiency of wells by combining barograph data with water level changes.

Ground-water data collected on a daily, weekly or monthly basis can be recorded on prepared field sheets (fig. 5.55). Information on the field sheet should include such items as station location or well number, date last checked, depth to water on this date. Columns for present date checked and present depth to water should be provided. Space should also be provided for remarks such as a change in reference points or an obstruction in a well.

Since ground-water data must be reduced to a common datum, elevation above mean sea level should be used. Reduction of field data may be accomplished manually if the number of sites is not too great and data collection is less frequent than once a day.

The processing of large volumes of ground-water data is usually accomplished by use of a
**SUMMIT #1**

- **ON**
- **OFF**

- **DATE**: 3-2-77
- **TIME**: 10:45 a.m.
- **DEPTH TO WATER**: 27.98 ft.
- **INITIALS**: DC
- **REMARKS**

---

- **ON**
- **OFF**

- **DATE**: 3-8-77
- **TIME**: 12:05 p.m.
- **DEPTH TO WATER**: 28.40 ft.
- **INITIALS**: RM & ST
- **REMARKS**

*Figure 5.54.—Example of well chart annotations.*
computer. Data from field sheets may be punched into cards (fig. 5.56) immediately and processed by computer at any time. Desired outputs may be in the form of printouts (fig. 5.57), punched cards, plotted, or all of these. Additional manipulation of data within the program can be accomplished rather easily to obtain outputs such as water level change between successive measurements or total change over a specified time period or precipitation event.
GEOMORPHOLOGY INVESTIGATIONS

Geomorphology took its present course under the leadership of William M. Davis (24) in his publication on the genetic system of land-form description.

The modern phase of quantitative expressions of geomorphology and channel morphology began with Horton (40, 41). He defined various measurable basin parameters while describing the erosional development of streams and drainage basins. He found relationships and developed laws between stream channel order numbers, lengths, watershed areas, and slopes. Horton's work also provided the lead for some of the present-day infiltration theories and laws of overland flow. He, in addition, explained surface erosion by overland flow, attempted to evaluate erosional forces, and explained development of stream valleys. Since this time, many workers have modified, refined, and added to Horton's list of definable and measurable watershed properties (18). They also developed and applied statistical techniques to these quantitative landform and channel morphological descriptions.

More recent quantitative geomorphology has been done by Strahler (84, 85, 86, 90) who has developed a system of stream ordering, hypsometric analysis, statistical techniques, and other geomorphic properties. These properties may be grouped into four broad classes describing the drainage basin: Length, shape, drainage net, and relief.

Morphometry, or morphometric analysis, occurs frequently in the literature, especially by English and European physiographers. The term morphometry means the use of measurement and mathematical analysis of the earth's surface, and the shape and dimensions of its landforms. This is no different than quantitative geomorphic analysis as used in the U.S. guidelines in geomorphic studies referred to in this chapter deal with the more quantitative aspects of the subject. The classical theories of Davis are mentioned principally for the reader's interest (74).

Recent quantification of earlier qualitative concepts is given in figure 5.58, which illustrates the main branches of geomorphic studies with those aspects depending on quantitative data specially outlined.
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Figure 5.57.—Example of printed computer output of ground-water data.
**Installations**

Mass movement, channel erosion, and periglacial effects are the most common geomorphic processes encountered in landform investigations. Installations for measurement of these processes are described below.

**Mass Movement**

Mass movement includes all forms of gravity movements of soil, earth, and rock, except those moved by some media other than gravity. Landslides, frost heaving, and soil and rock creep are examples of mass movement or mass wasting (15). Several methods are used to measure mass movement under various conditions.

A strain gage is a small sensitive electric resistor that changes resistance when it is subjected to external strain or compression. By passing an electric current through a strain gage, with proper instrumentation, the change in potential across the strain gage can be observed and calibrated to read in microinches of strain which, in turn, can be converted to pounds strain or compression. Strain gage readings are subject to the incidental effects of temperature changes and hysteresis for which compensation must be made.

Strain gages can be affixed to any member or substance where it is wished to measure amounts of strain or pressure. Strain gages are often affixed to an elastic strength member such as a steel or aluminum rod, bar, or strip which is then mechanically connected in the strain or compression-measuring system.

Strain gage measurement of mass movement phenomenon is ideally suited for short-term observations. The chief advantage in the use of strain gages is that very minute amounts of movement can be detected readily. This allows the investigator to get immediate indications as to the direction and amount of gravity movement. Longer term observation methods can be used in conjunction with strain gage measurements, or strain gage methods can guide the planning of longer term studies.

Strain gage methods require that the moving material be referenced to a nonmoving point or object such as a stake or anchor. The strain gage device is placed between the two and movement measured in relation to the fixed object.

On large slopes, it is difficult to establish a

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**Examples of Geomorphic Studies**

1. **Field Observations**
   - Numerical measurements (e.g., stream discharge, valley-side slope angle, etc.)
   - Qualitative observations

2. **Laboratory Observations**
   - Numerical measurements conducted on field samples (e.g., properties of soil samples)

3. **Office Observations**
   - Measurements arising from controlled experiments (e.g., rate of nickpoint recession—Brush and Welman (15)).

4. **Theoretical Work**
   - Extraction of the maximum amount of information from data collected by field, laboratory, or map work (e.g., the "sorting out" of geological variables—Krumbein (50)).

   a. Statements ultimately possible of numerical expression (e.g., relative becomes absolute age).
   b. Statements that may (and should?) remain qualitative (see Krumbein (51)).
   c. Quantitative measurements (e.g., leading to calculation of drainage density).
   d. Subjective analysis of attributes (e.g., delimitation of erosion surfaces).

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**Figure 5.58.** Example of the main branches of geomorphic studies.
fixed point for reference since every part of the slope may be moving. For shallow soil movement studies steel piling may be driven or drilled into bedrock for reference and attached, by the strain gage device, to a steel plate driven into the ground on the downslope side. A similar installation for observing subsidence can be used whereby a piling or stake is driven vertically to bedrock and the strain gage device connected between the emerging piling and an anchor buried near the land surface.

**Reference Rods, Pins, and Stakes**

Reference rods can be used for observing mass movement, but are best suited to long duration studies.

Soil creep is generally accompanied by subsurface drag; that is, the upper soil horizons move downslope at a faster rate than do the lower horizons. This is readily observed by the tilting of telephone poles and fence posts. If a reference rod can be stabilized in bedrock, then a rod or pin can be placed in the moving horizon and indexed to the stable rod for net movement measurements.

It is often necessary to establish reference stakes in stable ground on the flanks, above, or below the area being studied. It often is possible to measure the amount of movement of slope slip and creep by simply observing the amount of deflection of what was a straight fence line. Farmers and ranchers can usually date the installation of fences fairly closely. Rotational slippage and landslide phenomena can usually be measured in the field by survey methods and observation of surrounding reference points such as geologic strata or rock types.

Mass transport on slope studies are readily observed by using erosion pins and stakes. Erosion pins are spikes driven into the ground through a steel washer to a depth of about 12 inches (30 cm). Lines of spikes are set out along slopes leaving a portion of the spike protruding out for relocation. As erosion takes place, the washer on the spike follows the ground surface downward. If subsequent deposition takes place, the washer is covered and the depth of covering can also be measured. Premarked objects can be used to observe downslope movement if the objects are imbedded in the slope material.

Mass transport studies on hillslopes are facilitated by using premarked objects such as numbered or painted rocks and sand grains tagged radioactively or by using naturally fluorescent quartz grains. Tagged objects are placed on slopes in lines that have stakes at their end points, and later observations measure the amount of downslope travel gained by the objects.

Slopes can be surveyed accurately enough by transit or plane-table methods to be able to detect periodic changes due to mass movement or mass transport. Surveying will detect changes in the topography, but will not keep track of individual particles or objects. If a surveyed slope is being eroded and at the same time is receiving new sediment at the same rate, it cannot be detected. Only net losses or gains can be observed.

**Channel Measurements**

Stream-channel measurements are important in determining sediment movement and predicting what trends are developing that may affect later flood, erosion, and deposition control.

Surveyed cross sections along stream channels will only detect net gains or losses of channelbed materials between individual flows. Surveying is done by placing stakes on the banks at selected cross sections from where leveling is done, using a tape for distance and a transit or level for leveling. Anchored chains or ropes can be buried to depth in stream-channel materials to measure scour and fill taking place during flows at one or more selected sites.

A hole is dug in the channel material to a depth below which scouring is expected to occur. A chain or rope with an anchor attached at the lower end is then placed in the hole and backfilled so the chain or rope remains vertical and has a measured length remaining on the surface trailing out of the hole. As the channel material scour downward, the chain or rope is excavated and caused to trail out of the hole by the current. If the site is later buried or filled, the chain or rope will remain trailing out and buried at the lowest scour level. Subsequent excavation of the marker will reveal the depth.
of scour and also the depth of fill above the lowest scour level.

Measurement of the movement of channel material can also be done with premarked material such as painted boulders or other smaller rocks. Glass marbles, fluorescent dyed sand or gravel, and radioactively tagged material are also used. Accurately locating these objects prior to storm flow and locating them accurately at end of test will help determine channel degradation characteristics.

Periglacial Effects

Periglacial conditions include the effects of snowpack, frost action, and avalanches as erosion agents. Measuring the effects of periglacial conditions involves installations similar to those described in the Mass Movement subsection. Some record of initial position of material must be made as a reference at the beginning. Instrumentation for this purpose is covered in the following section.

A close and accurate record of climatic conditions must be kept which include recording rain gages, snow depth measurements, anemometers, temperature recordings of the soil mantle, temperatures of the air, and temperature of the snowpack when present. Depth of freezing in the soil mantle should be noted, as well as the percentage and aspect of the slope.

Observations

Observing geomorphic features is often difficult at the ground surface. A reconnaissance is generally made first by reviewing aerial photos and maps, or by making a brief overflight of the study area. From this overview more detailed studies in the field can be made.

Mass Movement

The elements of mass movement discussed are slides (landslides and slumping), flows (soil flow, mud flow, and debris avalanches), and creep.

Slides are shear failures with complex movement characteristics. An equation describing the equilibrium of forces has been described by Leopold, and others (59) as

\[
\text{Driving movement} = \text{resisting movement} \\
W_1 x_1 = W_2 x_2 + s r l 
\]

where

\[
W_1 = \text{the weight of the portion of the soil tending to produce failure and} \]

\[
W_2 = \text{the weight of soil tending to resist it} \]

Flows occur when water saturates the soil or debris. Mudflow is the most common of the flow phenomena of mass movement. Creep is the slow movement of the soil and rock downslope under the influence of gravity only. Creep occurs in all climatic environments with slopes usually greater than 5°.

Measurements of mass movement include rate, differential velocities at various depths, vegetation characteristics, slope and aspect, precipitation and temperature measurements. Movement rates are most often made by placing rods, pins or other markers on or in the slopes as references and making periodic recordings of their movement. Williams (100) has used the strain measurements from strain gages to determine the amount of downslope movement. Maps or surveying equipment, or both, should be used to determine slump volume measurements.

Channel Morphology

The importance of understanding the principles of channel morphology in hydrologic studies cannot be overemphasized. An understanding of these techniques may help to describe and correlate hydrologic and sediment characteristics within watersheds, as well as to predict performance of ungaged areas. Langbein (54) has shown a mathematical relationship between drainage area and discharge. Potter (72) used length and slope of stream channels in multiple regressions on peak flow. Stream channel dimensions, stream velocity, and sediment load were shown to vary as the power function of discharge both at a point and along
the length of the channel by Leopold and Maddock (57). Morisawa (67) has since studied morphometry and lithology in relation to discharge characteristics of watersheds in the Appalachian Plateau.

Results showed quantitative relationships on a regional basis but also indicated that laws of drainage composition do not hold for basins that differ in geologic structure, lithology, or both. Basins in this case would be expected to have differing hydrogeomorphology. Carlston (17) showed that runoff and drainage density are related to transmissibility of the watershed rocks and soil cover. In other words, drainage density, discharge and ground water are parts of a single hydrologic system.

Carlston’s Model stated:

\[ T = \frac{WD^2}{8h_o} \]  

where

- \( T \) = transmissibility;
- \( W \) = recharge;
- \( D \) = drainage density, and
- \( h_o \) = the height of the water table at the water-table divide.

He also reported that ground-water discharge into streams, or baseflow \( Q_{b} \), is dependent upon and varies directly with transmissibility of the terrain. If \( W \) and \( H_o \) are constant:

\[ Q_{b} \propto D^{-2} \]  

These and many other research workers have pointed to the importance of channel morphology in the understanding of the hydrological, erosional, and sedimentation processes operating within watersheds. They have also pointed the way to an understanding and methods for predicting performance within and between watersheds.

**Cross Section Geometry**

According to Horton (47), “The average slopes of streams of each of the different orders tend closely to approximate an inverse of geometric series in which the first term is the average slope of streams of the first-order.” Morisawa (67), in using stream segments, noted that “... most Appalachian Plateau watersheds do not conform to this law.” This is very much the same as in the case of stream length. Broscoe (17) restated Horton’s law for use with Strahler’s segment-slope data by using cumulative value \( H'/L' \) for Horton’s average slope:

\[ H'/L' = \sum_{u=1}^{n} H_u \sum_{u=1}^{L_u} \]  

where

- \( H'/L' \) = cumulative mean slope;
- \( H_u \) = mean elevation difference observed for segments of order \( u \); and
- \( L_u \) = length under stream length (59).

Channel profiles can be measured on aerial photos, maps from aerial photos, or surveyed in the field. The latter is more accurate and is usually preferred. Field surveys also permit the establishment of movements to relate to future surveys. However, in many cases this may be impractical, and one of the other methods used. Channel cross section can be measured during the profile survey or can be measured from maps or photos, depending upon the accuracy desired.

In making natural channel flow computations, average slope, or slope-segment, and average cross-sections are used. Figure 5.59 shows a sketch plan, cross section, and profile of a typical channel section. In this case, the average slope can be computed for the first and second order streams and average cross-section area for any study reach.

**Channel Roughness**

Channel roughness is considered in this section to refer to the bed materials. Bed-material characteristics that have the greatest effect on flow within the channel are size, sorting, and shape of the particles. For example, median-particle size does not indicate the range. Therefore, a measure of size dispersion is necessary. This dispersion is the sorting, or particle-size distribution.

Particle-size description provides a physical description of the materials of which a streambed is composed. Leopold and Wolman (58) suggested that particle size determines the characteristics of the longitudinal profile.
FIGURE 5.59.—Sketch plan, cross section, profile of channel.
Therefore, plots of mean particle size against slope or length should show a significant correlation (log-log distribution). Particle size should be related to stream order number by log-normal distribution.

Distribution, in addition to mean particle size, and others can be described by dispersion and skewness. Dispersion in the form of phi standard deviation ($\sigma_\phi$) can be measured from the probability plots and calculated by:

$$\sigma_\phi = \frac{\phi_{84} - \phi_{16}}{2} \quad (5-39)$$

in which subscripts denote the percentage of material coarseness. Another measure of dispersion is Trask's (95) sorting coefficient ($S_o$):

$$S_o = \frac{\sqrt{Q_3}}{Q_1} \quad (5-40)$$

where

- $Q_3 = $ diameter in millimeters, of which 75 percent of the material is finer
- $Q_1 = $ diameter in millimeters, of which 25 percent of the material is finer.

Skewness ($a_\phi$) may be defined by:

$$a_\phi = \frac{\frac{1}{2}(\phi_{84} + \phi_{16}) - \phi_{50}}{\sigma_\phi} \quad (5-41)$$

where

- $\phi_{84}, \phi_{50}, \phi_{16}$ are values of phi which are larger than 84, 50, and 16 percent of the total range.

Brush (14) reported in Pennsylvania that sorting and skewness do not have a definite trend. However, they may be related to other geomorphic parameters and do provide a physical description of the channel roughness and define resistance to flow.

Particle shape is usually measured in terms of sphericity (closeness to a sphere), roughness, and surface texture. The most common measure is Krumbein's (49) intercept sphericity ($\psi$). This is determined by taking the ratio of the volume of an ellipsoid, defined by the dimensions of the axes of the particle, to the volume of a circumscribing sphere, which has a diameter equal to the longest axis of the particle:

$$\psi = \frac{3}{\sigma_\phi} \quad (5-42)$$

where

- $a, b, c =$ long, intermediate, and short axes.

**Sinuosity**

Channel sinuosity of a reach, or sinuosity index (S.I.) can be defined as the ratio of length of channel to length of meander-belt axis (10). In cases where the meander belt cannot be defined, S.I. is defined as the ratio of length of channel to length of valley axis. The sinuosity of a meander belt may be determined from the ratio of length of meander-belt axis to length of valley axis. In a discussion of S.I., meandering must be defined. This, as mentioned by Brice (10), in many cases is very difficult to do. Langbein and Leopold (55) discuss bend radius and meander length, which are factors for consideration when conducting watershed hydrologic studies and hydraulic studies of channels.

**Flood Plain**

A river or stream flood plain can be defined as that portion of a river valley adjacent to the river channel which is built of sediments during the present regimen of the stream and which is covered with water when the river overflows its banks at flood stages. During the stream's cutting into the parent geologic material, deposition of the valley alluvium occurs.

These materials provide the hydrologic connection between the stream and the parent formation through which subsurface water movement (gain or loss) can occur. This potential subsurface storage reservoir in a watershed hydrologic study can be very significant. Therefore, quantitative measurements of the valley alluvium are desirable.

Two types of flood plain deposition are described in the literature: the point bar and the overbank deposit. These are hard to distinguish in the field after deposition. However, a distinction can be made during the actual deposition. Generally, it is acknowledged that the amount of overbank deposition is small in comparison
to point-bar type of deposition. The point-bar sediments are generally more uniform in size.

The valley alluvial materials are available to transmit ground water. They permit streams to gain or lose water at a rate dependent upon the alluvium and parent material. Therefore, before the hydrologic characteristics of a watershed can be understood, and the data used to predict performance of other areas, the movement of water in the alluvium must be understood.

The water movement past any measurement point can be divided into surface and subsurface. The surface flow can be measured by standard surface techniques. Measurement of the subsurface alluvial flow necessitates information regarding the hydraulic characteristics, such as transmissibility, permeability, and hydraulic gradient of the zone transmitting the flow. It is then possible to estimate total subsurface flow through a particular cross-sectional area by the following equation:

\[ Q = T I W \]

where:
- \( T \) = transmissibility;
- \( I \) = gradient (watertable); and
- \( W \) = width of vertical section.

When runoff information, surface and subsurface, is available on successive measurement points on a channel, the channel loss and gain between points can be computed.

Stream Ordering

Stream ordering provides a basis by which drainage-net characteristics could be related to each other and to hydrologic and erosional processes. Horton’s (47) method of stream ordering states “that higher-order streams extend headward to include one unbranched tributary” (fig. 5.60). This method is hard to duplicate and necessitates a certain amount of personal judgment.

Strahler (85) suggested that streams be drawn wherever V-shaped contour inflections occur. He redefined streams of any given order to include only segments formed by the merger of two channels of the next lower order and ending when the segments merge with chan-
frequency depends on scale of the base map. Horton’s first law of stream numbers states, “The number of streams of different orders in a given drainage basin tend closely to approximate an inverse geometric series in which the first term is unity, and the ratio is the bifurcation ratio.” A geometric series would then form a straight-line of points when the numbers of streams of each order are plotted on a logarithmic scale on the ordinate against order numbers on an arithmetic scale on the abscissa.

Figure 5.62 shows several subwatersheds within the Little River Watershed, Tifton, Ga. The regression equation of these lines indicates that the subwatersheds are similar in stream frequency, even though they differ in size. The drainage density, or frequency of stream per square mile, is 13.9, 12.0, 12.1, and 11.2 for Watershed A, G, I, and J, respectively.

**Stream Length**

Horton’s (41) second law of channel description states, that “the average lengths of streams of each of the different orders tend closely to approximate a direct geometric series in which the first term is the average length of stream of the first order.” This relation was questioned by Strahler (87), who found that in several basins the relationship is better described by a power function than by the exponential function of Horton’s geometric progression. Broscoe (77) restated Horton’s law of average stream lengths for use with segment-length data by substituting cumulative mean-segment length \( L' \) for Horton’s average lengths:

\[
L' = \sum_{u=1}^{n} L_u \quad (5-44)
\]

where
- \( U \) = segment order;
- \( L_u \) = observed mean length for segments of order \( u \); and
- \( n \) = order under investigation.

Figure 5.63 shows Broscoe’s cumulative method in comparison to the plot of average stream lengths. Bowden and Wallis (9) found this method worked on 66 watersheds in eight physiographic regions. Shumm (76) used frequency distribution analysis to study stream lengths (fig. 5.64).

**Stream Azimuth**

Stream azimuth may be defined as the number of degrees of arc in a horizontal angle measured clockwise from the direction of geographic north.

The inflection angle (\( \psi \)) (figure 5.65) of contour lines is the angle which a contour line makes with itself crossing a stream channel. Usually the size of the inflection angle decreases as the stream order increases. In any study of channel morphology, one of the most difficult questions is “What is a stream channel?” Therefore, it is necessary in all cases to define the criteria, map scale, channel location techniques, and photo size used to locate the channels.

The stream axial (\( \xi \)) is the angle formed between two stream channels (fig. 5.65). Horton (41) found the valley side slope (\( \theta \)), axial angle, and channel gradient (\( \gamma \)) to be related by:

\[
\cos \xi = \frac{\tan \gamma}{\tan \theta} \quad (5-45)
\]

**Basin-Shape Parameters**

Quantitative descriptions of drainage basins are associated with the hydraulic geometry of the channel network. Consequently, the basin is described by channel characteristics. The methods of stream ordering by Horton (41) and Strahler (87) (89) make it possible to express quantitatively the general channel geometry, drainage area, and drainage density within and between drainage basins.

**Bifurcation Ratio**

Horton (41) used this parameter to express the ratio of the number of streams of any given order to the number in the next lower order. When plotted, it becomes the slope of the line relating number of streams to stream order. The bifurcation ratio is inversely proportional to flood discharges. If the ratio is very high the discharges are lower but with extended peaks.
FIGURE 5.62.—Channel frequency, Litter River Watershed, Tifton, Ga.
FIGURE 5.63.—Plot of average stream length contrasting the random shape (left) resulting from segment ordering and the linearity (right) from Broscoe's method, Little River Watershed, Tifton, Ga.
If the ratio is low the discharges are higher with sharp peaks. Except where strong geologic controls dominate, the bifurcation ratio is highly stable and shows a small range of variation from region to region or environment to environment.

**Elongation Ratio**

Schumm (76) defines this parameter as the ratio between the diameter of a circle with the same area on the basin and the maximum length of the basin as measured for the relief ratio (see page 485). The ratio approaches 1 as the shape of the basin approaches a circle. Numerical values for basin shape are given.

**Circularity Ratio**

Miller (65) used this parameter, which is very similar to elongation ratio. It is defined as the ratio of circumference of a circle of same area as the basin to the basin perimeter.

**Basin Length**

This parameter is generally measured from the mouth of basin to its drainage divide. However, using the basin length parameter as a dimensional property it can be used to reveal the scale of units comprising the drainage network. One method of length analysis is the measurement of length of each segment of channel of a given stream order.

Maxwell (62) applied the following criteria to basin diameter studies: The diameter must be a straight line and (1) be essentially parallel to the longest drainage line, (2) divide the main channel into segments such that the sums of segment lengths on opposite sides of the diameter are approximately equal, (3) be parallel to the line which separates opposite-facing valley slopes (4) bisect the basin area, (5) and be the longest diameter. If the channel is weighted highest to lowest the following criteria should be used: *straight and longer* than one-half of diameter—criteria 1, 2, & 3; *straight and shorter* than one-half of diameter—criteria 1, 3, & 4; *curved and longer* than one-half of diameter—criteria 5, 3, & 2; *curved and shorter* than one-half of diameter—criteria 3, 4, & 5.

\[ Q = bA^r \]  \hspace{1cm} (5-46)
where
\[ Q = \text{some measure of discharge:} \]
\[ b \text{ and } c \text{ are constants} \]
and \( A \) is area of basin.

Hack (37) found that the average annual discharge in cubic feet per second equals the drainage area measured in square miles on the Potomac River Basin above Washington, D.C.

**Drainage Texture Parameters**

The texture of a drainage basin is determined by the complexity, number, and length of the stream network within the area of a basin. Textural features are related to runoff and infiltration characteristics.

**Drainage Density**

This parameter is defined by Horton (41) as the sum of the stream lengths divided by the area of the basin. It is a measure of the efficiency with which a stream collects and discharges available water. In general, as the drainage density number increases, the size of individual drainage units, such as the first-order drainage basin, decreases proportionately.

**Texture Ratio**

Smith (77) defines texture ratio as the ratio between the number of contour crenulations and the length of the perimeter. Because the contour inflections on a good topographic map indicate the existence of channels too small to be shown by stream symbols, their frequency is a measure of the closeness of channel spacing and hence also correlates with drainage density. Figure 5.66 shows the relationship between drainage density and texture ratio. Variations in drainage density under a variety of bedrock conditions are also noticeable in figure 5.64.

**Constance of Channel Maintenance**

Schumm (76) defines constance of channel maintenance as the reciprocal of drainage density. This value is the number of square feet of watershed required to sustain 1 foot (30.5 cm) of channel and is dependent on relative relief, lithology, and climate of the area.

The significance of the ratio is that it represents in square feet the area required to maintain 1 foot of drainage channel. It is the quantitative expression of one of the most important numerical values characteristic of a drainage system: the minimum limiting area required for the development of a drainage channel. Along with drainage density this constant is of value as a means of comparing the surface erodibility or other factors affecting surface erosion and drainage-network development.

**Length of Overland Flow**

A related texture measure is Horton's (41) length of overland flow, the distance over which runoff will flow before concentrating into permanent drainage channels. The length of overland flow equals the reciprocal of twice the drainage density.

**Relief Features**

Relief features are beneficial in determining the potential energy or erosion potential of a drainage basin.

**Relief Ratio**

Schumm (76) defined relief ratio as the total basin relief divided by the maximum basin length. Previous work by Schumm (75) has shown sediment yield related to relief ratio. More positive relationships may be developed if the characteristic regression for the climatic conditions at a particular basin are established.

**Relative Relief**

Melton (63) defined relative relief as the ratio of the maximum basin relief to the perimeter length.

**Ruggedness Number**

Strahler (90) defined ruggedness number as drainage density times relief. Any change in either value is important to slope length and steepness, and, ultimately, erosion factors.

**Slope Measurement**

Slope of the ground surface may be described in several different ways. Cumulative curves, changes in slope, and tangent or sine values are commonly used. The importance of slope measurement is that it in part is a function of erosion and sediment production.
Strahler (89) points out the importance of assessing slope properties and discusses procedures for measurement.

**Maximum Valley Slopes.**—One significant indicator of the overall steepness of slopes in a watershed is the maximum valley side slope which is measured at intervals along the valley walls on the steepest part of the contour orthogonals running from divides to adjacent stream channels. Maximum valley side slope has been sampled by several investigators (Coates, 19, Melton, 63, Miller, 65; Schumm, 76, 78; and Strahler, 84) in a wide variety of geological and climatic environments. Within-area variance is relatively small compared with between-area differences. This slope statistic

![Diagram of drainage density and texture ratio](image)

**Figure 5.66.**—Definitions of drainage density and texture ratio (87).
would therefore seem to be a valuable one which might relate closely to sediment production.

**Mean Slope Curve.**—Another means of assessing the slope properties of a drainage basin is through the mean slope curve (85). This requires the use of a good contour topographic map. The problem is to estimate the average or mean slope of the belt of ground surface lying between successive contours. This may be done by measuring the area of each contour belt with a planimeter and dividing this area by the length of the contour belt to yield a mean width. The mean slope will then be that angle whose tangent is the contour interval divided by the mean belt width.

Mean slope of each contour interval is plotted from summit point to basin mouth. Curves of this type will differ from region to region depending upon geologic structure and the stage of development of the drainage system. If the mean slope for each contour belt is weighted for percent of total basin surface area, it is possible to arrive at a mean slope value for the surface of the watershed as a whole.

**Slope Maps.**—Another means of determining slope conditions over an entire ground surface of a watershed is through the slope map (88). These maps are constructed by using a good topographic base. On this map a short segment of slope normal to the trend of the contour's is determined at a large number of points. These may be recorded as tangents or sines, depending upon the kind of map desired. These readings are contoured with lines of equal slope, here called isotangents.

The areas between successive isotangents are measured with a planimeter and the areas summed for each slope class. This yields a slope frequency percentage distribution. Because the entire ground surface has been analyzed, the mean, standard deviation, and variance are treated as population parameters, at least for purposes of comparison with small samples taken at random from the same area.

Lines of equal sine of slope, or isosines, may also be drawn. The interval between isosines on the map becomes the statistical class on the histogram. Sine values are designated as g values because the sine of slope represents that proportion of the acceleration of gravity acting in a downslope direction parallel with the ground surface.

**Rapid Slope Sampling.**—The construction of slope maps and their areal measurements is extremely time consuming. Experiments have shown that essentially the same information can be achieved by random point sampling (34). Both random coordinate sampling and grid sampling have been tried. In the random-coordinate method, a sample square is scaled in 100 length units per side. From a table of random numbers the coordinates of sample points are drawn for whatever sample size is desired. The grid method does much the same thing but is not flexible as to sample size.

Point samples which are easy to take were compared with the frequency distribution measured from a slope map. Close agreement occurs between means and variances and in the form of the frequency distributions, including a marked skewness. Tests of sample variance and mean are discussed by Strahler (88).

**Hypsometric Analysis**

This procedure is best used to determine the geomorphic stage of development of a drainage basin. Hypsometric analysis, or the relation of horizontal cross-sectional drainage basin area to elevation, was developed in its modern dimensionless form by Langbein (54). Whereas he applied it to rather large watersheds, it has since been applied to small drainage basins of low order to determine how the mass is distributed within a basin from base to top (89).

Figure 5.67 illustrates the definition of the two dimensionless variables involved. Taking the drainage basin to be bounded by vertical sides and a horizontal base plane passing through the mouth, the relative height is the ratio of height of a given contour (h) to total basin height (H). Relative area is the ratio of horizontal cross-sectional area (a) to entire basin area (A). The percentage hypsometric curve is a plot of the continuous function relating relative height (y) to relative area (x).

As the lower right-hand diagram of figure 5.67 shows, the shape of the hypsometric curve varies in early geologic stages of development of the drainage basin but once having attained
Model Hypsometric Function:

\[ \frac{d-x}{x} \frac{a}{d-a} \]

Characteristic Curves of Erosion Cycle:

Inequilibrium (young) Stage

Equilibrium (mature) Stage

Monadnock Phase

FIGURE 5.67.—Method of hypsometric analysis (87).
an equilibrium or mature stage (middle curve on graph), tends to vary little thereafter. Several dimensionless attributes of the hypsometric curve are measurable and can be used for comparative purposes. These include the integral or relative area lying below the curve, the slope of the curve at its inflection point, and the degree of sinuosity of the curve. Many hypsometric curves seem to be closely fitted by the model function shown in the lower left corner of figure 5.67 although no rational or mechanical basis is known for the function.

Hypsometric curves have been plotted for hundreds of small basins in a wide variety of regions and conditions, and it is possible to observe the extent to which variation occurs. Generally, the curve properties tend to be stable in homogeneous rock masses and to adhere generally to the same curve family for a given geologic and climatic combination.

Data Reduction

Field Notes and Measurements

The emphasis on clear, thorough, and concise field notes cannot be overemphasized. This particularly is true when a number of field measurements are taken. It is quite often not feasible, or totally impossible, to return to a study site to repeat a measurement.

Field notes and measurements should be taken with the thought in mind as to how they are going to be processed and analyzed. Many quantitative geomorphology measurements which are taken either in the field or from maps or aerial photos, are used in standard statistical computer programs. One should be familiar with the needs of the automatic data processing and computer facilities available prior to the start of a study. It is possible that this familiarity may alter to some extent the field methods of data collection.

Map Data and Scale

Map scales used in geologic, geomorphic, and ground-water studies vary widely. Maps are usually made using aerial photographs or field surveys such as hand-level and plane table. These maps may show only boundaries and major surface physical features. However, it is desirable, regardless of the use of the map, that topography (ground-surface contours) be shown. One of the most important things to remember in any data reduction is to list the scale of the map. For example, a first-order stream on a 1:2,400 map may not be shown on a 1:24,000 map. Therefore, when comparing variables measured on a map between watersheds, the scale must be the same.

Commonly used map scales are shown in table 5.6. The selection of scale for data reduction must consider the use that will be made of the data and the size of the study area. The scale that the data is to be reduced by must also be taken into account when data is collected. If, for example, measurements are needed to the nearest foot, this could not be determined when the data is plotted to a scale of 1:12,000 (2.5cm:30,000cm). Hence, both the accuracy of the collected data and the scale must be considered.

Organization of Data

In most geomorphic studies correlation analyses are made. This is usually done statistically from a number of variables such as climate, vegetation, soil, and geologic, ecologic, geomorphic conditions. If these data are removed from maps or aerial photos, it can be done
mechanically and put directly on punch cards by the combined use of the Kelsh plotter, coordinatograph, and digitizer. An example of this procedure is given by Stephenson and England (80), where actual calculations were processed by the computer directly from the cards punched by the digitizing equipment.

Grouping of data for correlation and regression analysis is a common procedure and one should familiarize himself with procedures such as these before starting a quantitative geomorphic study.

Strahler (87) gives an excellent review of sampling techniques and statistical analysis as applied to geomorphic studies. Dury (77) gives a more recent and thorough review of the application of statistical methods to geomorphology.

When most field observations are made, the data are usually put into tabulated form for future reduction and processing. Fluvial studies such as bedload analysis, hillslope processes, and channel changes are examples. Laboratory observations, office observations, and theoretical work that involves data reduction may not always require the intermediate steps of tabulation before processing. Quantitative measurements from maps and aerial photographs and mathematical models fall in this category.

Reduction of tabulated geomorphic data is easily done by the standard desk calculator, minicomputer, or other data processing equipment. This procedure renders the data readily available for statistical analyses.

### Data Processing

Geomorphic data are generally represented graphically or statistically. The use of computers has made both processes, especially the latter, much easier.

#### Graphical Representation

Figure 5.68 is a graphical representation of the size distribution of river-bed sediments. On this graph, seven streams are represented with particle size distribution for each. This graph illustrates how a variety and distribution of data can be represented. Figure 5.69 is a graphical representation of the relationship of channel width and drainage area to channel length.

![Figure 5.68](image)

**Figure 5.68.—Samples of size distribution of bed material, Yellowstone Missouri-Mississippi River System (87).**
It illustrates three ways of representing several relationships.

**Statistical Representation**

Much of the quantitative geomorphic data collected is represented statistically. Several samples are given which illustrate the use of statistical representation. Figure 5.70 shows frequency distribution histograms of slope sines. The data were tabulated into classes, and the desired statistical method applied. The results, illustrated graphically, show the statistical analysis. Each bar in the histogram represents a class; the height of each bar represents the number of readings falling within that class.

Quite often it is difficult to determine whether the population from which the investigator has drawn his sample follows any particular form of distribution (57). Too often the investigator has little time in the field and cannot afford to return for additional data to improve his sample size.

A quick method to ascertain whether a distribution is normal or log normal is given for general guidance (87). The grouped data are plotted on probability paper (fig. 5.71). First the percentage of variates in the classes of the frequency distribution are set down in cumulative form. These data are next plotted on the probability paper—cumulative percentage frequency on the ordinate, class midvalues on the abscissa.

By adjusting the spacing on the ordinate of the probability paper, any normal probability distribution yields a straight, sloping line of points on this paper. As shown in figure 5.69, the cumulative slope data taken at Bernalillo, N. Mex., fall close to a straight line (line C), whereas those of stream lengths (line A) form a
broadly curved trend. It is evident that the slope data may well represent a normally distributed population, but the stream-length data are not likely to represent a normal distribution.

**Computer Usage**

The use of the computer has enabled investigators in geomorphological studies to expand their investigations tremendously. Tracer-digitizers and digital plotting systems are used for graphic outputs of terrain analyses in both 2 and 3 dimensions. Computer simulation methods are being used to develop deterministic and stochastic models of drainage basin development (68) and other landscape features.

Stone and Dugundji (83) have developed a system for quantifying microrelief features for landscapes in California by means of Fourier analysis. The digital computer was used to process the terrain profiles.

Krumbein (56) has used trend surface analysis of contour-type maps for separating regional trends from local features. Polynomial analysis was used with the polynomial equations solved by use of the computer.

Multifactor computer programs (73) have been used in terrain analysis to test variables related to surface geometry. The computer programs in this study were used to solve factor analysis equations developed for comparisons of different landscapes. Drainage basin parameters such as channel segment length, basin perimeter, basin area, basin diameter, and drainage density were used along with geologic structural features such as fracture patterns.

This is only a brief review of the sum of the computer in quantitative geomorphic investigations. Many programs for normal statistical and mathematical analyses are available at computer centers.
Illustrated Uses of Quantitative Geomorphology

Block diagrams are three-dimensional representations of a particular landscape characteristic. They also illustrate the volumetric expression of subsurface conditions.

Watershed characteristics that affect the water regime inherently involve geology, geomorphology, climate, vegetation, and soils. The interdependence of these parameters characteristics requires an analysis of these factors using a common technique. Quantitative geomorphology offers a technique whereby mathematical expressions may be assigned to watershed physical conditions and the interdependence of these conditions assessed.

Therefore, it follows that quantitative geomorphic expressions should be used for expressing ground-water conditions, such as available and actual storage volumes, distribution, seasonal or individual storm effects on recharge, seepage losses and gains, and availability for surface storage facilities. The development of numerical expressions of a watershed for both surface and subsurface features is necessary to define the hydrologic prediction equation.

Watersheds should be considered as a three-dimensional unit. A watershed, as shown schematically in figure 5.72 has descriptive volumetric characteristics. First, it is necessary to select a datum plane above which the description is to be made. Hypsometric descriptions of the watershed can then be made and volume distribution histograms prepared. Total comparisons are possible; however, a comparison of volumes between specific contours cannot be made due to differing surface, subsurface, and water-table configurations.

The watershed can be divided by a grid system to study the hydrologic properties of individual subareas within the watershed. This procedure overcomes limitations imposed by using area measurements between contours to compute volumes. For example, Grid A-B-C-D

---

**Figure 5.72.**—Block diagram of theoretical watershed with subsurface boundaries and phreatic water table.
(fig. 5.70) has elevations at each corner on the ground surface, water-table surface, and aquiclude surface. These elevations can be substituted in the equation:

\[ V = LWF \left( \frac{A + B + C + D}{4} \right) \]  

(5-47)

Where

\[
\begin{align*}
V & = \text{volume of material (L^3)}; \\
L & = \text{length of grid (L)}; \\
W & = \text{width of grid (L)}; \\
F & = \text{correction factor (for border grids only)—percentage of area lying within the watershed boundary for subject grid (dimensionless); and} \\
A, B, C, D & = \text{differences in elevation of the surface being considered and the base plane.}
\end{align*}
\]

Equation 5.47 is used to compute directly or by differences:

\[
\begin{align*}
V_T & = \text{total watershed volume above datum plane;} \\
V_{aq} & = \text{volume below aquiclude surface above datum plane;} \\
V_{aq} & = \text{volume of aquifer;} \\
V_{wT} & = \text{volume below water-table surface for time (t) and above datum plane for the same time;} \\
V_{SAT} & = \text{volume of saturated material at time (t); and} \\
V_{ISAT} & = \text{volume of aquifer not saturated at time (t).}
\end{align*}
\]

\[ V_{aq} - V_{SAT} = V_{ISAT} \]  

(5-48)

The maximum available ground-water storage is computed using a representative porosity value.

\[ V_{ISAT} \times \text{Porosity} \]  

(5-49)

The amount of water movement from each area can be computed if a representative transmissibility value is known. Hence, ground-water movement within and between grids can be followed and traced through the system.

Volumetric quantitative descriptions in the past have described watersheds by measuring area between contours and multiplying by height above a datum. These descriptions can also be used to describe ground water, aquifer, and aquiclude conditions. For example, if a three-dimensional description of a watershed is available (fig. 5.72), areas between contours of the ground surface, aquiclude, and ground water can be planimetered. Percentage hypsometric curves can be drawn and the three separate areas under the curves determined (fig. 5.73). Volumes can be obtained using the percentage hypsometric curves as shown below:

\[
\text{Area} \times \text{Difference} \times \text{Integral} = \text{Volume (acres) in height (feet) above base plane (feet)}
\]

\[
72 \times (149-87) \times .5746 = 2,565.0
\]

These values compare favorably with the values obtained by computing volumes between each contour, above the base plane, and summing to obtain the total volumes (table 5.7, col. 2). The method of multiplying area under the

\[ \text{FIGURE 5.73.—Percentage hypsometric curves.} \]
Integral by the total volume is faster and easier.

Absolute hypsometric curves (fig. 5.75) can be drawn and average slope of the land surface and lower boundary of the aquifer computed. The values (3.14 percent surface and 3.23 percent subsurface) indicate the overall land configuration and slope within the watershed.

Volumes of the total watershed and aquiclude are shown in figure 5.75. These volumes were obtained by the planimeter method. The aquifer volume is the difference between the histograms. This is the case for the total volumes. However, the volume between contours is not truly representative due to the differing configurations of the aquiclude surface and land surface. This method, therefore is limited and gives only a general picture of the overall watershed configuration, both surface and subsurface.

Saturated aquifer volume and phreatic ground-water distribution can be analyzed using these techniques. For example, ground-water conditions on two dates (February 16, 1968 and March 22, 1968) were appreciably different. Phreatic ground water was present under the entire watershed March 22, and only under the central portion February 16.

Saturated area, total aquifer and saturated volume, and aquiclude volumes can be computed. The volume of the aquiclude above the datum plane is subtracted from this total volume to obtain the saturated volume—444.8 acre-feet (.36 m³) (table 5.6, column 2). This same procedure was used for February 16; however, a saturated volume for this date could not be obtained. A common area (total watershed and saturated area) is necessary for the above method to work.

The hypsometric method previously described can also be used to measure aquifer conditions. The results are shown in table 5.6, column 3. This method is inadequate for computing saturated ground water volumes for February 16, 1968.

Another method of subdividing the watershed into subareas or grids can be used in conjunction with flow net analysis. This technique makes possible comparison of the saturated volumes, ground-water-table slope, ground-surface slope, and aquiclude-surface slope. Figure 5.71 shows a sample grid, no. 302, for one date for Walker Pond Watershed, Tifton, Ga. The corner elevations of the surface for which the volume is to be computed are read and punched on IBM cards. Corner elevations are determined by overlaying a contour map on a grid map. The volume of saturated material

### Table 5.7.—Walker Pond Watershed volume measurements by 3 methods

<table>
<thead>
<tr>
<th>Item</th>
<th>Grid</th>
<th>Planimeter</th>
<th>Hypsometric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total watershed †</td>
<td>2,538.9</td>
<td>2,536.7</td>
<td>2,565.0</td>
</tr>
<tr>
<td>Aquiclude †</td>
<td>1,791.8</td>
<td>1,775.3</td>
<td>1,799.4</td>
</tr>
<tr>
<td>Aquifer †</td>
<td>747.1</td>
<td>761.4</td>
<td>765.6</td>
</tr>
<tr>
<td>Saturated zone (3-22-68)</td>
<td>437.1</td>
<td>444.8</td>
<td>435.2</td>
</tr>
<tr>
<td>Saturated zone (2-16-68)</td>
<td>140.0</td>
<td>(2)</td>
<td>(2)</td>
</tr>
</tbody>
</table>

† Plane passed below watershed at 87.0 ft, assumed bench mark 100 ft.

* By difference (total watershed less aquiclude).

* This value cannot be measured due to differing watershed area.
within each grid can be computed and summed for the total watershed by a computer (table 5.6, column 1).

Advantages of the grid method are that any portion or all of the watershed can be analyzed at any time. These individual grids also make it possible to determine the direction and slope of the water table, therefore, tracing the groundwater flow through the watershed. The seasonal and individual storm effects on the ground water can be studied, and the rate of delivery to the storage facility can be computed, if the transmissibility for the aquifer is known.

Quantitative geomorphic methods permit the assignment of numerical values to watershed physical conditions whereby analyses of watershed hydrologic performance can be made. With these geomorphic techniques, landforms, geology, ground water and soil characteristics can be expressed in similar terms. The integration of individual areas or units within the watershed is therefore possible, and the surface, and subsurface hydrologic performance for the entire watershed can be analyzed.

These techniques can be used to develop quantitative aquifer descriptions such as available aquifer for water storage, saturated volume, and aquifer distribution. Planimeter and hypsometric volumetric measurements of the aquifer, aquiclude, and different water tables were made, and it was determined that these methods are not applicable to all cases. However, a grid technique was developed, tested, and worked in all cases. The grid method permitted the description of the total watershed and aquifer volumes, saturated volumes, and stored ground water. Therefore, a three-dimensional picture of the watershed was obtainable.
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CHAPTER 6

INTRODUCTION

Of the many processes affecting the rainfall-streamflow relationship within agricultural watersheds, one of the most significant is the storage of water in the soil mantle. In terms of total volume, soil moisture accretion is often the largest abstraction from rainfall, and thus it becomes an important factor in the performance of the watershed.

Determinations of soil moisture are made at selected soil depths within sites chosen to represent soil conditions over the watershed. Site and depth selections are based upon soil surveys and on morphology of the soil profile.

Moisture determinations should be made on as many sites as can be adequately maintained, and measurements should be taken on a regular schedule as often as feasible. Supplementary readings should be taken where possible before and after storm events and consecutively on days during periods of drainage and evapotranspiration.

From such records it is possible to estimate soil moisture recharge due to infiltration of rainfall and losses due to drainage and evaporation. Records taken before and after rain storms are especially useful in explaining watershed performance under different antecedent moisture conditions.

SOIL CONDITIONS

Soil Moisture

Soil Moisture Determination

Soil moisture determination is the direct or indirect determination of soil moisture content or of soil moisture potential or energy status. There are numerous procedures and types of equipment for the determination of each. Since each method has its advantages and limitations, it is well to consider both the purpose for which determinations are to be made and the features of each possible method including the cost of buying equipment and operating and maintenance costs.

Soil moisture content is expressed either in percent by weight or percent by volume. Moisture percent by weight is based on dry weight of the soil and is expressed as follows:

\[
P_w = \frac{W_w - W_d}{W_d} \times 100
\]  

(6-1)

where \(W_w\) is equal to wet weight of soil, \(W_d\) is equal to dry weight of soil, and the value of the numerator represents the weight of the water that was contained in the soil sample. If this determination is carried out, the data will be obtained from soil samples taken in the field and the method will be discussed in detail in the subsection on gravimetric sampling (p. 507).

In many cases it is more useful to express soil moisture percentage by the volumetric moisture percent, \(P_v\), expressed as follows:

\[
P_v = \frac{V_w}{V_s} \times 100
\]  

(6-2)

where \(V_w\) equals volume of water in the sample, and \(V_s\) is equal to the bulk volume of the sample. The volumetric moisture percent is usually not determined directly because of the difficulties involved in determining both the volume of the water and the volume of the soil. Since it is impossible to extract all the water from the soil sample by any method except drying, the only practical way of determining the volume of water in a given soil sample would be by determining the weight change of the soil sample upon drying and assuming that the specific gravity of the water in the soil was
1.0, thus equating weight of water with volume of water.

This assumption is adequate for field determination of soil moisture. The real difficulty comes with the determination of the soil volume. At best this is laborious and is described in detail in the section dealing with bulk density of soil. In addition to the time and labor involved, the main difficulty is that there is no good method available for determining the volume of a large number of soil samples on a routine basis.

The moisture percent by weight and moisture percent by volume are related by the following equation:

\[ P_v = P_w (\rho) \]  \hspace{1cm} (6–3)

where

- \( P_v \) is moisture percent by volume,
- \( P_w \) equals moisture percent by weight, and
- \( \rho \) is the bulk density of the soil.

Another method of determining the volumetric moisture content of the soil is the neutron scatter method which is discussed in the subsection on radiological methods (p. 513).

The usefulness of the moisture percent by volume lies in the fact that it can be converted easily into surface units of water, therefore being compatible with quantities of rainfall or irrigation water applied. All calculations involving the water balance of the soil, including calculation of irrigation deficits, water application efficiency, and recharge of the soil moisture reservoir by rainfall, involve the use of the volumetric moisture percentage.

A number of devices available for field use measure components of the thermodynamic energy status of the soil moisture, or the soil moisture potential. There is much confusion about the terminology used to describe soil moisture potential mainly because these concepts were developed independently by soil physicists, engineers, plant physiologists and climatologists. There have been efforts to unify both the terminology and units that describe the energy status of water in the soil-plant-atmosphere continuum. Literature in the field uses such terms as soil moisture potential, stress, suction, matric suction, capillary suction, and total soil moisture stress. The units for expressing these may be atmospheres, bars, dynes per square centimeter, ergs per gram, pounds per square inch, centimeters of water, centimeters of mercury, and pF. In the absence of an agreed terminology, soil moisture potential expressed in units of bars (1 bar = 10^6 dynes cm\(^{-2}\)) will be used.

The total soil moisture potential is the total thermodynamic potential of the soil water. This includes three main components as follows:

- Potential energy due to elevation above some arbitrary reference plane. This is an expression of the driving force acting on the soil water due to the force of gravity.
- Osmotic potential. This is the potential energy of the soil water due to dissolved solutes. It represents the driving force which would be applied to the water across an appropriate, semipermeable membrane with distilled water on the other side of it.
- Capillary potential. This is the physical force by which water is held in soil pores by forces of capillarity, adhesion, and cohesion. The capillary potential is the component of the total soil moisture potential that is most easily measured with commercially available equipment.

It is often assumed that the capillary potential is equal to the total soil moisture potential because (1) A knowledge of soil moisture potential is important both in relation to the availability of soil moisture to plants and to problems of soil moisture movement in the unsaturated state; and (2) The measurement of the capillary potential is more easily carried out under field conditions than measurement of the other potentials or total potential.

Potential energy due to elevation does not play a large role from the point of view of water uptake by plants, and in the case of unsaturated soil moisture flow, it is a minor component of the total driving force. Furthermore, in nonsaline and well-leached soils the osmotic component is very often also minor compared to the capillary potential.

Since many situations arise where only one measurement is available, either the soil moisture content or the capillary suction, obtaining the value of the other parameter from a known
relation between soil moisture content and soil moisture potential is desirable. A unique and single-valued relationship between soil moisture content and capillary potential would be required to do this. Since such a unique relationship does not exist for most soils, it is markedly affected by hysteresis. Thus, the soil moisture content at a given capillary potential is a function not only of the capillary potential but also of the history of the soil volume under consideration.

There is a main hysteresis loop with one branch applicable to dewatering of the soil, and the other branch to rewetting. There are also an infinite number of secondary scanning curves between the two main branches. In many situations it is enough to refer only to the soil moisture desorption curve (determined under drying conditions). The desorption curve is in very many cases a unique curve for a particular soil. The curve is applicable in numerous situations where it is known that the observation took place during the drying process. In certain soils the spread between the two branches of the hysteresis loop is relatively small. Therefore, assumption of the existence of one unique soil moisture retention curve may be justified for practical purposes.

With the significant exception of the neutron meter, most of the commercial devices available for field installation consist of a porous material which attains equilibrium with soil moisture. These devices measure the soil capillary potential and not the soil moisture content. Since some of the equipment was originally developed with the aim of measuring soil moisture content and marketed as such, descriptive literature often contains instructions for calibrating these devices against soil moisture content.

In light of the hysteresis problem, care must be exercised in the use of this equipment since errors caused by hysteresis are appreciable. In principle it is always preferable to use direct measurements. For example, instruments which essentially measure capillary potential should be used for measuring capillary potential rather than measuring soil moisture content. A detailed discussion of available equipment and related measurements follows.

Selection of Site for Moisture Measurements

Soil moisture is subject to so many modifying factors that the area represented by a particular site is often extremely limited. The slope of the land affects soil moisture by the extent to which excess rainfall is removed. The depth and duration of overland flow and subsequently the opportunity for infiltration vary with position on the slope. Lateral transmission is also a function of slope and position. Other factors which affect soil moisture are: Profile characteristics, land use, and treatment and exposure.

The area of homogeneity with respect to these characteristics is often quite small. Consequently, aerial representation is usually obtained by selecting several sites for moisture determination. The number of sampling sites to be chosen within each homogeneous area as well as in the entire study area will depend both on the accuracy and the precision of measurement required. In fact, the way in which “homogeneous area” is defined will also vary from location to location.

The purpose to which the measurements are put as well as the variability of the soil in the area will affect the sampling site chosen. Therefore, no one standard can be followed. However, the variability of the area should be determined by simple soil survey techniques before decisions on sampling sites are made.

Where feasible the best guide for designing a sampling program is a preliminary statistical survey which gives the coefficient of variability with respect to soil moisture properties that may be expected in areas of different sizes. In view of the limited information on proper techniques for selecting moisture-station sites, analyses of the data should be kept current so that the adequacy of the sampling procedure can be determined.

Gravimetric Determination of Field Samples

Standard Method

Samples are taken in the field with convenient tools such as shovels, spiral hand augers, bucket augers, power driven augers, and power driven or hand driven soil sampling tools like
the Veihmeyer tube. The best procedure is to place the soil sample immediately in a leak-proof tare-weighted can suitable for transporting to the laboratory for drying in an electrically heated oven. The size of the sample should be consistent with the required precision and type of balance used for weighing the sample.

It is convenient for most soils laboratories to weigh samples on automatic balances that read to the nearest 0.1 gram and that often have a taring adjustment to allow direct determination of net weight. If automatic balances are to be used it is advisable to use sample cans tared to the same weight, and to take soil samples that weigh at least 3.5 ounce (100 g), preferably between 3.5 and 7.1 ounce (100 and 200 g). A 100-gram sample may characteristically contain about 0.71 ounce (20 g) of water, and an error in weighing of 0.0004 ounce (0.1 g) will represent a measurement error of 0.5 moisture percent.

The most convenient sample can is aluminum, having an approximate capacity of 79 inches (200 cm). This type of can may be embossed with a serial number on both the body and the lid and can be easily brought to a uniform tare weight. The best material to use for embossing is one of the several kinds of epoxy resins available on the market, preferably one "filled" with aluminum powder. Since epoxy adhesives do not change weight upon setting, it is possible to apply the precise amount needed to the inside of the can lid. If the epoxy mixture is prepared to a consistency similar to that of honey, it is easy to drip a thin thread of the mixture from the tip of a spatula onto the can lid which should rest on the top of the can body on the balance pan.

If cans are to be transported for a considerable distance from the field to the laboratory, care must be taken both to avoid opening of the can and spilling and to avoid moisture loss from the cans. The cans may be effectively sealed against evaporation by placing a wide rubber band over the joint between the can lid and the can body. For transport it has been found convenient to construct a thin plywood suitcase with internal partitions about the general shape of an attache case. A convenient arrangement is to place 24 sample cans in one of these suitcases in six compartments of four cans each.

The gravimetric method of moisture determination is the standard method to which all other methods are compared. It consists of drying a sample at 221°F (105°C) to a constant weight (usually 16 to 24 h). If a sample is dried at a lower temperature, all the water may not be removed, and if it is dried at a higher temperature, other volatile matter may be driven off in addition to the water. The minimum time required to bring soil samples to a constant weight will depend on sample size, number of samples placed in the oven, moisture content of the samples, and type of oven. It is best determined by trial and error under typical operating conditions. The moisture content is calculated by the following formula: $P = \frac{\text{loss of weight on drying}}{\text{weight of the oven-dry soil}} \times 100$.

Nonstandard Methods

Methods other than standard are available for gravimetric soil moisture determination, but these are generally to be used only for special purposes or in emergencies. In one method, it is possible to dry soil more rapidly at temperatures higher than 221°F (105°C). However, there is the danger of losing some volatile components of the soil in addition to the water, which could cause considerable error in determining moisture. On the other hand with sandy-textured soils this method may be justified if rapid results are required.

Another method is to place the soil sample in a tared, perforated bottom container, pour methanol onto the soil until an appreciable amount drips through into a lower metal saucer and to ignite the methanol. After all this alcohol has burned out, more methanol is poured over the soil and again ignited. The methanol, being miscible with water, removes some water from the soil by mass flow and provides heat for water evaporation. The amount of alcohol required will vary with size of soil sample, texture, and moisture content. Here again there is a danger of losing an appreciable amount of volatile components from the soil due either to excessive heating or to actual combustion. However, this method
may be useful in the field under certain conditions.

Measurement of acetylene in carline bombs is also a method for determining soil moisture content. In various commercially available carline bombs, a moist soil sample is mixed in a closed chamber with calcium carbide which reacts with the water in the soil to form acetylene. Automatic weighing arrangements which read the pressure of the acetylene built up in the bomb make it possible to get a fairly rough estimate of soil moisture content. This method has the advantage of making the results immediately available in the field.

Various pycnometer methods determine soil moisture content by adding measured amounts of polar or nonpolar liquids to the soil sample in the pycnometer. This method is rarely used since it is not particularly convenient under field conditions and too inefficient for the processing of large numbers of samples in the laboratory.

Other methods use various commercial moisture balances or moisture meters. These methods are based on the principle of rapid drying of a small soil sample placed in a permanent or disposable aluminum dish under an infrared heating lamp. The time of heating required to completely dry a sample usually has to be determined by trial and error for the particular soil being tested. While the equipment is small and fairly portable, it does require electricity and is thus not strictly a field method. Although it has the advantage of giving almost immediate results, the method is too slow and cumbersome to be used for processing large numbers of samples, and therefore its use is limited in a regular soil moisture sampling program.

Other improvised methods have been tried under particularly difficult conditions such as drying soil samples in the baking portion of an ordinary kitchen range or on a camp stove. However, none of the alternative methods are adequate substitutes for the standard method. They have been described only because of their possible usefulness for reconnaissance in remote locations and in emergencies. No well-ordered research program should rely on these methods.

**Limitations of Gravimetric Sampling**

While it is always good practice to backfill a hole from which a sample was removed, repeated sampling should not be done in the same spot during a sampling program. Therefore, when a small area is to be used for a long-term study, a considerable portion of the area would be disturbed by sampling holes. In spite of the backfilling, a large number of holes in a small area could certainly affect such hydrologic properties as the gross infiltration rate of the soil. Furthermore, the inability to return to the same sampling site inevitably introduces sampling error due to soil heterogeneity. In addition, appreciable labor and time are required to obtain soil samples, and the results of the moisture determination are not available until the following day.

**Measurement of Soil Moisture Potential**

Instruments have been devised which will measure the total soil moisture potential, the osmotic potential, and the capillary potential. To date, only instruments designed for the measurement of the capillary potential are sufficiently reliable and cheap to be used in a fairly large-scale field sampling program. These instruments will be described below. In some cases it is impossible to obtain the measurement of the capillary potential because of the nature of the instrument. Care must be taken to use instruments measuring capillary potential under conditions where osmotic potential can play an appreciable role.

**Soil Moisture Tensiometers**

The essential part of a soil moisture tensiometer is a porous membrane, usually made of ceramic, having a pore size that can withstand the maximum capillary suction likely to be exerted. The pore size distribution of the ceramic should be as uniform as possible, and the average pore size should be as large as possible so that rapid changes in soil moisture conditions can be detected. Porous membranes of various dimensions and shapes made of ceramic, sintered stainless steel, sintered glass, or various plastics are commercially available.

Complete soil moisture tensiometers are also available from several manufacturers. The po-
rous sensing element is attached to a holder which is designed (1) to facilitate insertion of the tensiometer into the soil, (2) to provide a rigid and sealed chamber which will be filled with water, and (3) to provide a place for connection of a pressure measuring device. The pressure measuring device may be a liquid manometer of the U-tube type which uses either a water column or a multiple liquid column such as water and mercury. The multiple liquid column is the most common type used. Bourdon-type dial gage manometers are commonly used for field installation.

Recently several types of tensiometers have been designed which use a strain gage transducer with an electrical output leading directly to a recorder. One general type consists of a number of tensiometers being connected through a hydraulic transmission to a scanning valve which is activated by means of a timer and solenoid, thus enabling one fairly expensive transducer to read several tensiometers in turn. While this approach is attractive because of the savings possible, the system is extremely vulnerable to leakage at a number of points, and the plumbing problems have so far been insurmountable in allowing field use.

The other system features a pressure transducer built into the tensiometer holder itself, with the transducer membrane forming the upper part of the water chamber behind the porous membrane. This system is expensive because each tensiometer has to have its own individual transducer. This type of tensiometer is characterized by a small water volume in the chamber which makes it less susceptible to leakage. Neither tensiometer system has been sufficiently tested for definite recommendations.

Installation of Tensiometers—The porous membrane of the soil moisture tensiometer must be saturated with water so that it can function properly. Since the water in the instrument will be subjected to negative pressures, which can cause dissolved gases to come out of solution and form bubbles in the system, degassed water should be used for initial charging of the tensiometer. The system may be degassed for initial installation either by boiling the ceramic head of the tensiometer and filling the instrument with boiled water, or by degassing under vacuum.

However, since the tensiometer is in contact with soil water which is aerated, the water inside the tensiometer will not remain gas-free indefinitely. Where the physical design of the tensiometer permits, the instrument may be degassed while installed in the soil by the application of vacuum. Tensiometers should be prepared in the laboratory and transported to the field with the ceramic element wrapped in a wet rag or inserted in a container of water. In the field, a hole of appropriate depth and diameter is prepared, usually with an auger or soil sampling tube. Since the functioning of a tensiometer depends on good contact between the ceramic element and the soil, it is good practice to prepare a thin slurry or mud from the excavated soil, to pour it into the hole, and to seat the ceramic element of the tensiometer in this slurry. The rest of the hole is then backfilled with the excavated soil.

When the tensiometer construction has a casing that extends as a straight tube and protrudes through the surface of the soil, there is a danger that surface runoff will collect in a small depression around the tensiometer shaft and leak along the walls of the tube down to the tensiometer. This would, of course, produce unrepresentative conditions at the sampling site. Therefore, careful backfilling is necessary. It may also be desirable to place an impermeable barrier around the tensiometer tube some small distance below the soil surface.

The barrier may consist of a large washer cut from a sheet of rubber, asphalt or bitumen, a layer of clay, caulking compound, or various chemical grouts. Due to the insertion of the tensiometer in a wet slurry, considerable time may elapse before the installation comes to equilibrium with the surrounding soil moisture. When the tensiometer is installed below the plant root zone, installation may take as long as several weeks. Tensiometers measure only the soil capillary potential because solutes are free to move through the permeable membrane. Some tensiometers, which feature electrodes either within the ceramic or in the water chamber above the ceramic, allow determination of the electrical conductivity of the solution within the tensiometer. An indication of soil
solution salinity or its osmotic potential can be obtained from this.

**Limitations of tensiometers**—A perfect hydraulic system subjected to an absolute vacuum would register one atmosphere of negative pressure, which is the theoretical limit of the range of operation of any hydraulic tensiometer. However, the tensiometer is in contact with and tends to establish equilibrium with soil moisture which is at times held by forces far exceeding one atmosphere. The hydraulic tensiometer is therefore limited to the measurement of soil capillary potentials not exceeding the equivalent of one atmosphere of negative pressure. At this pressure, water will boil at ambient temperature and water vapor bubbles will break the liquid column leading from the ceramic element to the manometer. In practice, the conventional tensiometers usually break down in the vicinity of 0.85 atmosphere.

The manometer portion of the conventional hydraulic tensiometer, the only part of the system that is not rigid, allows for appreciable change of volume of the system. This is true regardless of whether the measuring device is a liquid manometer type or a Bourdon gage. As a consequence, an appreciable volume of water may flow out of the tensiometer cup into the surrounding soil, especially under arid conditions. Thus, the tensiometer may also act as an autoirrigator. When this happens the measuring instrument begins to affect the condition which is to be measured, and in many cases concentrations of plant roots have been found wrapped around the tensiometer cup upon excavation. The insertion of a tensiometer into the area to be described may therefore alter the conditions which are to be measured.

The hydraulic tensiometer is very sensitive to the thermal conditions of the environment. Due to differential expansion and contraction of the aboveground parts and due to temperature gradients between the soil surface and the depth at which the sensing element is located, tensiometer readings are known to undergo diurnal fluctuations even when moisture conditions in the soil remain constant. Tensiometers, with casings constructed of relatively nonconducting materials are best. Readings should be taken at the same time each day, preferably in early morning.

The transducerized tensiometer can be built as one small compact unit which is buried entirely in the soil. The water chamber between the transducer and the ceramic membrane may also be quite small. This tensiometer design therefore eliminates problems due to temperature dependence and due to the autoirrigator effect. The tensiometer also responds very quickly. However, the equipment is still in the developing stage and is beset by other problems such as the inability to purge the chamber of accumulated air. This problem, for example, can cause a considerable increase in the reaction time of the instrument and eventual operating failure. Other problems encountered with this type of tensiometer are short circuits due to water leakage into the electrical system and grounding problems. When functioning properly, these tensiometers allow a continuous record of capillary potential changes, making them highly useful instruments for studies of soil moisture movement.

**Electrical Resistance Methods**

The electrical resistance of a nonconducting porous matrix is a function of its moisture content and of the electrolyte concentration of the solution. If the latter remains constant, it should be possible to determine soil moisture content as a function of the electrical resistance between two electrodes. This measurement was originally attempted by inserting bare electrodes into the soil and by applying an electrical potential across the electrodes. This method has proved impractical and in most instances unworkable. The only exception to this is the use of four electrode system which has not been used in the field.

All practical electrical resistance methods have electrodes encased in some porous medium which in turn is in contact with the soil. The most common encasing materials in use are gypsum, nylon fabric, and fiberglass fabric. Since the pore distribution of the porous medium of the resistance unit will not be the same as that of the soil, what is being directly measured by the electrodes is the moisture content of the porous casing and not the moisture content of the soil. The water in the porous casing of the electrodes will tend towards a potential equilibrium with the soil moisture.
While most electrical resistance methods were originally developed with the aim of measuring soil moisture content, they are actually best measured by tensiometers. When tensiometers are intended for soil moisture content measurements, one must not only take hysteresis into consideration, but also the units must be calibrated with the same soil in which the units are to be installed in the field.

**Calibration**

Calibration is best carried out in the laboratory and two general approaches are possible. One is to place the resistance unit in a small container surrounded by initially saturated soil and allow the soil to dry out gradually to various levels of moisture content (determined by weighing of the system) accompanied by readings of the electrical resistance of the unit. When calibrated in this manner, the problems of hysteresis must be taken into account.

A preferable method of calibration is to place the electrical resistance unit in a pad of soil resting on a membrane in a pressure plate or pressure membrane extraction apparatus. Special electrical lead-through plugs, which may be screwed into the wall of the pressure apparatus, are available, allowing continuous calibration of the units without requiring the chamber to be opened for resistance measurements. The soil is initially saturated and is again brought step-wise to various levels of capillary potential. When equilibrium is reached, as indicated by cessation of outflow from the apparatus, a resistance measurement is taken and the soil is then brought to the next step on the desorption curve. Since the electrodes do measure the moisture content of their porous casing, they may also be subject to hysteresis. Where high precision of measurement is required, it may be advisable to calibrate these units both on the wetting and drying branches of the retention curve.

All electrical resistance units are affected to a greater or lesser degree by the electrolyte concentration of the soil solution, and this should be borne in mind when the units are to be used in saline soils. The units are also all subject to problems of polarization and electrolysis at the electrode interface. It is therefore considered good practice to measure the resistance with an AC resistance bridge.

**Gypsum Resistance Blocks**

Several types of gypsum blocks are in use which may be either purchased commercially or made in the laboratory. The units are generally either brick shaped or cylindrical, and the electrodes may either be two bare exposed wires cast into the gypsum, two screen electrodes, or, in the case of cylindrical blocks, they may consist of a cylindrical screen electrode and a coaxial bare wire electrode at the axis of the cylinder. Since gypsum is slightly soluble in water, the solution inside a gypsum block tends to be saturated with calcium sulfate. As a consequence, the gypsum blocks are fairly well buffered and relatively unaffected by soil salinity.

On the other hand, the blocks are relatively less sensitive to moisture changes at high moisture content than are some of the other resistance units. Gypsum blocks are also vulnerable to chemical attack under certain conditions and may deteriorate within a period of a few months. It is often difficult to detect when a unit has deteriorated by the resistance readings, which may nevertheless be in considerable error. An improved version of the gypsum block, coated with a porous plastic, is available. This alleviates, to some extent, the problem of deterioration, but, on the other hand, the plastic may impair the sensitivity and speed of response of the block.

**Fabric Resistance Blocks**

These blocks are usually much smaller than the gypsum blocks and consist of electrodes placed in a sandwich of fiberglass or nylon fabric. The entire unit is usually encased in a perforated stainless steel case. One type of unit is available either with or without a thermistor placed in the stainless steel case allowing the simultaneous determination of the unit resistance and of soil temperature. The resistance units using fabric as a porous medium are relatively more sensitive than gypsum blocks to moisture changes in the high moisture content range, and they are also much more sensitive to electrolytes in the soil solution. It is there-
fore impossible to separate the osmotic component from the capillary potential component of the soil moisture potential. The addition of salts to the soil solution decreases the total potential, making it more difficult for the plant to take up water from the soil. The salt addition decreases the soil moisture resistance, thus producing a reading from the electrical resistance units that indicates a wetter soil.

Before installation, the resistance units should be saturated with distilled water and checked for uniformity. The saturated resistance reading should be recorded. The installation procedure in the field is identical to that of installing tensiometers. In order to avoid possible leakage of water along the wire leads, it is advisable to dig a short, shallow horizontal trench near the soil surface in which the leads will be laid with a slope away from the vertical hole, and only then brought to the soil surface. Each set of leads should be numbered for identification and tied to an easily visible stake. Like the hydraulic tensiometer, sufficient time should be allowed for the units to come into equilibrium with the surrounding soil before measurements are taken.

The main limitation of electrical resistance units is their relative lack of sensitivity in the high moisture content range. The second important technical limitation is the sensitivity to soil salinity of all electrical resistance units except for gypsum blocks. Other limitations are as follows:

- Gypsum blocks may deteriorate rapidly in certain soils, and it is often difficult to detect this deterioration from the resistance readings alone.
- Commercially manufactured resistance units are fairly expensive and must be excavated from the soil at the end of the study so they can be reused.
- As is the case with any permanent installation, the sampling site must be protected against damage by cattle or farm machinery. The sampling site may also interfere with normal farming operations. Where crops are grown in rotation, it will be necessary to either remove all the units before the land can be plowed or to bury the wire leads below plow depth.
- The calibration curves of some electrical resistance units tend to drift with time even when no obvious physical deterioration of the unit has taken place.

**Radiological Methods**

Two general radiological methods are available for the measurement of soil moisture content. One is based on the interaction between high energy neutrons (fast neutrons) and the nuclei of hydrogen atoms in the soil. The other method is based on the attenuation or backscattering of gamma rays as they pass through the soil. Both methods use portable equipment for taking measurements at permanent observation sites. These methods are therefore nondestructive and have the additional advantage of yielding data from the same location at each observation. Both methods require careful calibration, preferably with the soil in which the equipment is to be used.

However, the radiological methods have several common drawbacks. The equipment is expensive, and currently available equipment may require considerable maintenance. In addition, it is necessary to train the operator not only to produce satisfactory results but also to observe necessary safety precautions. While equipment currently on the market is safe to use on a continuing basis, improper use in handling the equipment might involve radiation hazards. The equipment must therefore be operated in accordance with safety rules established by the U.S. Atomic Energy Commission and by the U.S. Department of Agriculture. Regulations are covered in section on "Safety" (p. 521).

Much work has been and is being done on the neutron method of measuring soil moisture. Other nuclear procedures such as gamma ray attenuation are also being developed. Without a doubt nuclear techniques are superior to other methods (gravimetric, conductometric, or thermal) in general use. Because of the relative newness of nuclear methods for soil moisture measurements, new and improved instrumentation and techniques are constantly being developed. Since the field of nuclear instrumentation is growing rapidly, new applications to soil moisture or soil density measurements will continue.
Neutron Scatter Method

The operating principle behind the neutron scatter probe is subsequently described. If a radioactive source emitting high energy of fast neutrons is placed in the soil, the neutrons will travel away from the source at high speed, colliding on their way with nuclei of various elements found in the soil. When a fast neutron collides with a heavy nucleus, its direction will be changed but its energy will be relatively unaffected. However, when the fast neutron collides with a light nucleus, an appreciable part of its energy will be transmitted to this nucleus and the neutron will continue as a slow or thermal neutron characterized by a lower speed and energy.

In the soil, hydrogen is the most common atom with a light nucleus. Most of the hydrogen found in the soil is a component of water. The majority of neutron-moderating collisions that take place occur between the fast neutrons and hydrogen atoms associated with water. The fast neutron source in the soil will therefore be surrounded by a cloud of slow or thermal neutrons whose density and radius will be a function of both the rate of fast neutron emission by the source and of the volumetric moisture content of the soil. Excluding the presence in the soil of hydrogen atoms not due to water and of other atoms with light nuclei which may also participate in fast neutron moderation, it can be concluded that the higher volumetric moisture content of the soil the greater the likelihood that any single fast neutron will collide with the hydrogen atom and become moderated within a given distance from the source.

Conversely, the lower the soil moisture the greater the likelihood that a fast neutron will traverse a certain distance without colliding with a hydrogen atom. At a given uniform soil moisture content, the number of unmoderated or fast neutrons per unit volume of soil decreases with distance form the source. From this it is seen that the radius of the volume of soil which effectively participates in neutron moderation is itself a function of soil moisture content.

After a fast neutron has been converted to a slow or thermal neutron it will continue to travel through the soil colliding with additional atoms and having a generally random path. A certain statistical percentage of all the slow neutrons in the soil may be expected to traverse any given sampling plane. If a detector unit is placed in such a sampling plane, it will measure the flux rate of slow neutrons which will be a function of source strength, soil moisture content, and the geometry of the system. Due to the radial geometry of this system, the density of the fast neutrons and slow neutrons will obviously be the greatest in the vicinity of the source. For this reason it is desirable to place the slow neutron detector near the fast neutron source. This configuration is also desirable from the point of view of probe construction.

The neutron moisture generally consists of a metal cylinder 1 1/2 to 2 inches (3.8 to 5.1 cm) in diameter and about 14 inches (35.6 cm) long containing a source of fast neutrons, a detector, and a preamplifier. Older neutron probes contained radium-beryllium sources which were limited to a strength of 1 to 5 millicuries due to the fact that they emitted an appreciable amount of hazardous gamma rays in addition to neutrons. Currently the most common and the most efficient source available for general soil moisture work is a 100-millicurie americium-beryllium source which is an almost pure emitter of neutrons.

Most slow neutron detection systems consist of a tube filled with boron trifluoride enriched with boron-10 to increase efficiency. Slow neutrons react with atoms of boron which emit positively charged alpha particles that are detected electronically. The amplified signal is transmitted through a cable from which the probe is suspended in the soil to a scaler or rate meter. This portable device usually contains an amplifier, a counting circuit, and a power supply. The most useful power supply is the type which may be recharged periodically. A chart recorder output may also be incorporated in the instrument.

Installation for depth measurements—In order to insure the permanence of the observation site, observation holes are usually cases with thin-walled access tubing. Access tubes may be made of any material suitable for the
purpose including aluminum, steel, copper, or even plastic. Aluminum tubing is preferred for several reasons. Of all the common materials available, aluminum is most nearly transparent to neutrons, giving the highest counting efficiency of any material. Its common availability in the desired dimensions is an important practical consideration.

Neutron moisture probes are commonly manufactured with nominal diameters of 1 1/2 inches and 2 inches (3.3 and 5.1 cm). The latter is made to fit inside 2-inch (5.1 cm) diameter seamless irrigation tubing which is almost universally available. If soil conditions allow the use of aluminum tubing, it is therefore preferable to purchase a 2-inch (5.1 cm) diameter probe for which access tubing can be purchased from any supplier of irrigation equipment. Access tubing of other diameters would have to be purchased through a special order.

Since air gaps between the probe and the access tube as well as between access tube and the surrounding soil affect both the average count rate and its consistency, it is necessary not only to install the access tube properly in the soil but also to use a combination of probe diameter and access tube diameter that will have the smallest possible air gap.

It is recommended that the radial air gap should not exceed 0.02 inch (0.5mm). Access tubes may be installed in such a way that their upper end protrudes from the soil or, when special conditions demand, a sectional telescoping access tube may be used whose top end is pulled up to protrude over the soil surface for measurement and is inserted into a recessed well when not in use.

The commonly used one-piece access tube which protrudes over the soil surface should have the top opening covered to prevent rain, water, and dirt from falling into the tube. Metal cans from frozen fruit juice make a good snug cover over 2-inch aluminum tubing. In conjunction with this, rubber stoppers should also be inserted into the top of the tube. Since condensed moisture on the walls of an access tube will lead to false readings, it is advisable to hang small sacks of drying material from the cover of the tube where condensation is a problem.

A number of procedures have been recommended for installing access tubes. Both hand and machine drilling of bore holes have been used, as well as drilling within a removable casing, drilling without a casing, and drilling with the access tube itself. The criterion for effectiveness is the closeness of fit of the access tube within the bore hole. In homogeneous material, this requirement is normally met. In rocky or shaly soils considerable difficulty may be encountered. The removal of materials such as rocks and pebbles often produces voids considerably in excess of the planned hole diameter.

Some workers have drilled oversized bore holes and backfilled the space between the access tube and the soil with fine material. The ingenuity of the individual research worker must be used in solving this particular problem. Where soil conditions and length of access tubes permit, the access tube should be installed, by hand, augering soil from within the access tube at about 6-inch (15.2 cm) depth intervals and advancing the tube within the bore hole. The augering of an undersized hole and shaving off the excess soil material with the forward edge of the access tube assures the best fit between tube and soil. With this method it is also possible to collect the excavated material and use it for calibration purposes.

Various recommendations may be found in the literature as to the need for sealing the bottom of the access tube. While the neutron probe itself is reasonably well sealed against moisture, it is definitely not advisable to dip the probe in water. This can be effectively guaranteed only by a tube which is well sealed at the bottom as well as at the top. If the access tube is to be inserted into a predrilled hole, it may be sealed by cementing in a rubber stopper or by welding it shut before installation.

Various methods have also been described for sealing the bottom of the tube after installation. In some cases an open ended access tube may function as a ground water well and a piezometer as well as a soil moisture access tube. In this case the observer should first measure the elevation of water in the access tube, thus eliminating any danger of dipping the probe into water.

Calibration of neutron depth probe.—Calibration curves for neutron moisture meters are
usually constructed from laboratory standards of known equivalent moisture content. Since actual soils are seldom used, the calibration supplied will usually not be acceptable for use in a particular soil. However, the calibration curve is useful for checking the efficiency and reliability of the neutron moisture meter's performance.

Various field and laboratory calibrations have been described in the literature and the procedure adopted will depend largely on local conditions. Field calibration of the moisture meter would be ideal. However, soil variability and the lack of sufficient moisture range in a given soil at a given time may make field calibration difficult. If a number of bore holes are excavated around the access tube for the taking of gravimetric samples, an accurate calibration curve will be obtained, but the site can no longer be used because the natural soil moisture regime has been disturbed.

Where soil conditions permit, a good method of calibrating the moisture meter is to simultaneously insert access tubes and remove gravimetric samples. Soil is excavated from within the access tube at 6-inch (15.2 cm) depth increments, and the access tube is advanced after the excavation of each such increment. The excavated samples are placed into sample containers, and their moisture content is determined gravimetrically. After completion of excavation and insertion of access tube, a complete count rate profile is carried out with the probe.

Since the precision of measurement is a function of the total number of counts, the statistics of measurement should be considered. A sufficiently long count should be taken at each measurement depth. Since the count rate is usually interpreted as volumetric moisture content, a knowledge of the soil bulk density is required for calibration. This is probably the largest single source of error in the calibration procedure.

As discussed, the effective diameter of measurement or what is called “the sphere of influence” extends for some distance around the source. The volume of influence is roughly in the shape of a flattened sphere, and its effective diameter has been reported to be anywhere between 2 to 10 inches (5 and 25 cm). In connection with this, it must be pointed out that depth moisture probe readings are not consistent near the soil surface when compared to readings taken deeper in the soil. This is due to the fact that when the sphere of influence intersects the soil surface some neutrons escape into the air. When the effective center of the probe is at a depth less than about 6 inches, (15 cm), neutrons are likely to escape through the soil surface, and count rates will be lower than would be expected for that particular soil moisture content. Therefore, the overall calibration curve cannot be used for shallow readings.

This difficulty has been overcome in several ways. Some workers do not take any readings in the top foot of soil and supplement the neutron probe readings by gravimetric samples, electrical units, or tensiometer measurements. Others have constructed a special calibration curve for the top layer of soil, usually 6 to 12 inches (15 to 31 cm) in depth. It is also possible to determine the moisture content of the top soil with a neutron surface probe. If the neutron depth probe is to be used for shallow readings, the operator must take particular care to stay about 3 feet (1 m) away from the access tube during this measurement since there is a danger of exposure to excessive radiation due to escaping neutrons.

Various laboratory calibration methods have been proposed using either excavated field soil or synthetic media. Various plastics, paraffin, chemical solution, or barrels filled with sand and wetted either with water or chemical solutions have been proposed. Laboratory calibration of a particular soil is tedious since a large volume of soil of known and uniform density and moisture content is required for each measurement. The main difficulty lies in the fact that field calibration of a uniform and homogeneous soil is relatively easy, not requiring laboratory calibration. On the other hand, stony and nonuniform soils are difficult to calibrate in the field, but it is also difficult and in some situations impossible to duplicate in a container the heterogenous arrangement of a field soil, particularly of a stony soil. Each researcher will have to decide on the best method.

Well-designed laboratory calibration methods obviously tend to have a better precision than
field calibration methods leaving some doubt, however, concerning the accuracy. On the other hand, while field calibration is representative of the conditions of use, the tediousness of the method and technical difficulties may make it difficult to carry out the field calibration with sufficient replications to assure a satisfactory precision. In some situations a combination of field and laboratory calibration might provide the most satisfactory solution.

Use of the neutron depth probe.—Several routine preparatory steps should be taken before actual depth moisture determinations are made with the neutron probe.

The optimum high voltage setting of the scaler must be found by the determining count rate as opposed to a high voltage plateau as described in the operator’s manual. This plateau usually does not change appreciably with time, and once determined, the same high voltage setting can be used for a considerable time. It is good practice to check the plateau at least once a year if the instrument has not been sent for repair and after any repairs have been made.

The moisture probe usually comes equipped with a carrying case filled with paraffin or plastic which serves as a radiation shield. The shield also serves as a standard. While a standard count reading is not a substitute for calibration, standard count readings with the probe contained completely in the shield should be taken periodically. It is good practice to check the standard count reading at the beginning of a day’s work, in the middle, and at the end.

The average standard count reading decreases very gradually with time due to decay of the radioactive source. This is usually a very minor effect and may influence the relation between count rate and moisture content over periods of several years only. However, the count rate may also vary randomly due to such factors as electronic malfunctions of the system, temperature effects, and aging of batteries. The determination of a standard count is a good check on the proper functioning of the system. If on a given day the average standard count rate differs appreciably from normal, the cause of this should be investigated before further use is made of the equipment.

The cable leading from the neutron probe to the scaler or rate meter is probably the single most vulnerable component of the entire system. In addition to transmitting the signal, the cable also serves to support the weight of the probe in the access tube and it is therefore particularly vulnerable to mechanical damage. It is thus advisable to keep a spare cable on hand at all times.

Because of the vulnerability of the cable, it is absolutely essential that the probe be free to travel within the access tube. If a probe gets lodged in a bent or damaged tube it usually cannot be removed by pulling on the cable, and it may be necessary to remove the entire tube from the soil, sometimes by excavation. This can be avoided by always testing the access tube by inserting a dummy probe supplied by the manufacturer of the equipment. The probe is made of solid stainless steel and is tapered in such a manner that it is easy to pull out even when it becomes lodged in a constriction. It is suspended from a chain, thus making it possible to exert considerable force, if necessary, for removing a lodged dummy probe.

The neutron surface probe.—In order to obviate the difficulties associated with measurement of moisture in the surface 6 inches (15 cm) of soil, a special surface probe has been developed. Various configurations are available, including a completely self-contained unit as well as units where either the radioactive source only or an entire portion of the depth is transferred to a special holder. Where surface moisture measurements are to be carried out in conjunction with depth measurements, the self-contained surface probe is the safest and most practical, but it represents an appreciable investment, costing about as much as the depth probe.

The surface probe works on the same principle as the depth probe and requires separate calibration. Since the bottom surface of the probe must be exposed, the entire probe cannot be stored in a shield and standard. More care must therefore be exercised in using the probe to avoid an overdose of radiation. Like the depth probe, the surface probe senses the moisture content of an indefinite and changing volume of soil. However, moisture variability at a given site can be expected to be greater
vertically than horizontally, making it more difficult to assign a reading from the surface probe to a distinct depth layer.

**Gamma Attenuation**

Gamma rays, as well as other electromagnetic radiations, are attenuated on passing through matter. This attenuation can be expressed as:

\[ I = I_0 e^{-\mu \rho x} \]  \hspace{1cm} (6-4)

where
- \( I \) = measured intensity of attenuated beam;
- \( I_0 \) = intensity of nonattenuated beam;
- \( \mu \) = mass absorption coefficient which is characteristic for the absorbing material;
- \( x \) = Thickness of absorber; and
- \( \rho \) = density of absorber.

There are two methods for measuring the attenuation of gamma rays—transmission and reflection. The above equation can be used to estimate the attenuation of transmitted gamma rays. Two probes are necessary for measuring attenuation—one contains the radioactive source and the second the detector. A schematic diagram of a dual probe used to measure the density of underwater sediments by the attenuation of transmitted gamma rays is shown in figure 6.1.

The measurement of gamma-ray attenuation by reflection uses one probe, similar in appearance to the neutron depth probe, which contains a radioactive source and the detector. A lead shield is placed between the source and detector so direct transmission is impossible. All gamma rays beamed into the surrounding material are subject to scatter and absorption. Some gamma photons will be backscattered to the detector. The intensity of these backscattered, attenuated gamma rays can be measured. An empirically determined calibration curve relating reflected gamma-ray intensity to density of the surrounding medium can be prepared.

The changes in attenuation of transmitted gamma rays, for a given value of \( x \) and \( \mu \), can be related to changes in total density. In a soil system, the attenuation of gamma rays can be used to determine soil density and soil moisture. The attenuation of gamma rays is due to mass; hence, one cannot distinguish attenuation due to water and attenuation due to dry soil in a moist soil unless other information is available. One can determine readily changes in soil moisture content by measuring changes in the attenuation of gamma rays in a moist soil. The dry bulk density of the soil must remain unchanged. If the dry bulk density of a given soil is known, the absolute soil moisture can be found from the difference between the total and the dry density values.

**Equipment.**—The equipment used in measuring soil moisture and soil density by the attenuation of transmitted gamma rays consists of a scaler ratemeter, a pulse height analyzer, a dual probe assembly with the detector in one probe and the radioactive source in the other, an aluminum calibration bar, and an umbrella to provide shade. Glow tubes on the scaler are
difficult to read in full sunlight. Electronic instruments perform better when protected from the summer sun. Two access tubes are necessary to accommodate the two probes.

The detector used in the dual probe consists of a sodium iodide scintillation crystal and a photomultiplier tube. The necessary power supply and read-out units are in the scaler. The pulse height analyzer is used to restrict the measurement of gamma rays to those emitted from the source and only those that are unscattered or unabsorbed. All units are transistorized and powered by rechargeable dry cells.

Equipment used in measuring soil density by backscatter of gamma rays by a single probe is illustrated in figure 6.2.

Installation.—The access tubes used for measurement of soil density and moisture by attenuation of transmitted gamma rays and for measurement of soil density by gamma backscatter may be installed by the same methods used in neutron scatter technique. In the case of the dual probe, it is convenient to use two access tubes of the same size and material.

The two access tubes should be parallel. Install one tube by the usual methods. A jig is recommended to insure that the second tube will be installed parallel to the first. The spacing between access tubes is not critical but must be constant—12 inches (30.5 cm), center-to-center, is a useful spacing for cesium-137 sources of 5 to 10 millicuries.

Operation.—The dual probe detection system consists of sodium iodide crystal, photomultiplier tube, preamplifier, pulse height analyzer (PHA), amplifier, and scaler rate meter. This is a gamma scintillation spectrometer. The system is to be operated in the differential mode so it is a gamma differential scintillation spectrometer. As such, the system discriminates, or rejects, all gamma photons except those of acceptable energy level. For cesium-137, the characteristic peak energy is at 611 kev. The pulse height analyzer permits selection of the energy peak to be measured as well as the width of the spectrum band included.

The probes are placed in the access tubes; the equipment is turned on and the necessary adjustments made. In operating differentially, a maximum reading is wanted. If the baseline setting is 661 and the window setting at 2 (v), adjustment of the calibration setting at 2.(v), adjustment of the calibration control to give maximum intensity is needed. Normally this is done with a standard aluminum bar in position. The calibration control on the PHA meter (fig. 6.1) is adjusted to give maximum deflection. Then the probes are lowered into the soil and measurements are made.

Each reading is considered as a ratio to the aluminum bar reading. The original calibration curve is based on a known reading for the aluminum bar. Each experimental measurement is corrected by the ratio of the given aluminum bar reading to the standard aluminum bar reading. The density corresponding to the corrected reading in counts per minute is read from the calibration curve.

Calibration.—The calibration of the dual probe is best performed in the laboratory under controlled conditions and with the soil to be used. Experimental work has verified that differing soils will produce slightly differing attenuation of gamma rays. For most soils, wet or dry, this difference is not sufficiently large to require the use of more than one standard calibration curve. It will be necessary, however, to calibrate each system in the exact geometry of the field setup and with samples of the field soil.

To calibrate a dual probe, the attenuation of gamma rays must be measured in several media of known density. The density of water is \( p = 0.0056 \) pounds per inch or 1 gram per centimeter. Aluminum and magnesium metal have been used for standards, but the mass absorption coefficient of aluminum and magnesium are sufficiently different than that found for most soils so that these metals should not be used for calibration.

Standard aluminum and magnesium bars can be successfully used as standards to check the day-to-day and hour-to-hour operation of the detector.

Laboratory calibration of a dual probe must duplicate the geometry of the proposed field installation. Access tube size, material, and spacing must be duplicated. As the transmitted gamma rays are confined to a straight line beam between source and detector (an elongated pyramid or wedge shape), a small container is adequate for calibration. This con-
FIGURE 6.2.—Measurement of soil density by the gamma-ray attenuation method: Top, basic equipment; bottom, set-up of equipment in the field.
tainer has the access tubes in place at the proper distance and the desired soil, at known density and moisture content, can be placed in the container. A calibration curve is obtained from a series of measurements over the selected range of variation of density or moisture content.

Replicated readings should agree within the square root of the mean count. Any drift in instrument performance should be observed by frequent aluminum bar readings. Should the aluminum bar readings change by more than the square root of the observed initial reading, adjustment of the PHA meter by calibration control is required. Density measurements accurate to 0.12 lb/ft³ (0.002 g/cm³) are obtainable. Variations of 0.31 lb/ft³ (0.005 g/cm³) are acceptable. Moisture contents are obtained on a volume basis. The dry density of any horizon should be measured to report moisture content by weight.

Advantages of the method.—Measurements of density by gamma-ray attenuation provides a nondestructive method of determining soil moisture and soil density. The site sampling can be repeated as often as desired. The measurements can be made vertically as close as one inch. Measurements made at one inch from an interface (surface) are valid. The precision is high and accuracy of the results is excellent. Errors in measurement can usually be detected and corrected at time of measurement. No particular health hazard is involved in this type of measurement provided simple safety precautions are observed and the radioactive source is shielded when out of the access tube.

When measuring soil moisture, it is assumed that the changes in density are due to changes in water content. The bulk (dry) density of the soil is assumed constant. Valid measurements cannot be made in recently tilled soil, or soils that exhibit considerable swelling and shrinkage during a wetting-drying cycle.

Safety.—The source material used in the probe for the production of gamma rays is cesium-137 of about 3 millicuries specific activity. This material is radioactive and should be treated with caution. The amount of activity present is harmless to the operator if certain precautions are taken. The manufacturer provides a lead carrying shield. The probe should be kept in this shield at all times. Only when the probe is lowered into the access tube is its removal from the shield necessary. The shielding provides ample protection for the operator during the working day. Whenever the probe is not in use, it should be stored under lock in a relatively unfrequented area. In transporting the probe to the field and while using it in the field, the operator should use the shield and keep as much distance between himself and the probe as possible.

All operators should wear some type of film badge in order to provide data regarding exposure levels. The operator who places the probe in the access tube should wear one badge on the ankle. For example, calculated time limits for a soil density probe based on an allowable exposure of 50 milliroentgens per day would be 2 ½ hours per day at closest approach to the probes in the carrying shield and 20 minutes per day at closest approach to the bare probe. Keep probe in shield at all times except when making measurements. Store probe in shield and carrying box under lock in an area not continuously occupied.

Data Collection

Gravimetric Methods

Since the standard gravimetric determination is not completed in the field and since manual weighing is usually involved, data collection is usually manual as well. A field data sheet should be designed in one of two ways. One alternative is to make a form complete enough to provide room for recording sample weights in the laboratory, calculating soil moisture content, and in cases where this is needed, the volumetric soil moisture deficit from field capacity and other information, such as moisture depletion rate or design irrigation application. Such a form should also include headings for data, field or experiment, plot, site, crop condition, and observer’s name.

Since different situations call for different forms, it is probably best to design forms locally and make copies than attempt to design a universally applicable form. The complete form must necessarily be fairly large and may become crowded even on an 8½ × 11 inch (2.16 cm × 27.9 cm) sheet. The other alternative is to
have separate field and laboratory forms. The field form in this case can be quite small, and it has been found convenient to make up small blocks similar in construction to a checkbook. Field identification is then entered both on the main part of the sheet and on the stub—the main sheet is transported to the laboratory with the samples and the stub retained in the observer’s notebook. This makes it possible to transfer samples from the field crew to the laboratory technician without fear of losing a data sheet or sample identification. The compact form of the pad also makes the field operation more convenient, and the laboratory data can be stored on clean and less crowded data forms.

**Tensiometer Methods**

The readout of a conventional hydraulic tensiometer is generally obtained manually with a mercury manometer or a Bourdon-gage manometer. In this case, choice and design of data sheets is best left to the individual scientist’s judgement. Hydraulic tensiometers can be modified to transmit their readout to a strip chart recorder, and transducer-tensiometers are designed to operate with a recorder. Data collection is automatic, and raw data are stored on the strip charts.

All tensiometers must be checked for zero reading before installation since both the hydraulic and the transducer models may give a reading other than zero when moisture tension at the point of measurement is zero. The zero reading of a hydraulic tensiometer depends on the depth of installation and the length of the transmission line from the sensor to the soil surface. The transducer instrument has a zero reading which is a function of the electrical properties of the individual transducer. Over a period of time, transducers are known to exhibit zero-drift which is difficult to detect without removing the instrument from the soil.

**Electrical Resistance Units**

These units are read in the field with a portable alternating current resistance bridge. Readings are generally taken manually and recorded on field forms. It would be technically possible to have a central switchboard with a scanning switch and a recorder for automatic reading. The electrical resistance readings must be converted to soil moisture tension or moisture content with the aid of the calibration curve. Electrical resistance units are temperature sensitive, and the field observation must include a temperature reading. Some resistance bridges have an adjustment knob to compensate for temperature differences. It is best to convert the raw data to moisture content or tension before storing. Electrical resistance units also suffer from zero drift and from deterioration, both of which are difficult to detect in the field.

**Radiological Methods**

The two radiological methods used for determining soil moisture are neutron scattering and gamma-ray attenuation. It is not possible to automatically operate these methods in the field. The readout of either the scaler or ratemeter is in counts per minute and is recorded either manually by observation of decade glow tubes or digital indicators, or it may be recorded by a strip chart recorder. Counts per minute are converted to volumetric moisture content with the aid of the calibration curve, and in this case, too, it is preferable to convert the raw data to moisture content values before storing.

**Data Storage**

Raw field data are seldom usable in their original form. Often it is even difficult to discern signs of malfunctioning equipment or undesirable features of management from the field sheets. It is thus good practice to do immediate primary data reduction to a form that is capable of interpretation before storing the data for eventual analysis. The original data sheets should be stored at least long enough to enable checking for errors at the time a study or experiment is summarized. If the destruction of data would have serious consequences, it is good to keep a copy in a separate location or to separate the original sheets from the reduced data. Due to the bulkiness of field records, the
transfer of data to punchcards and to magnetic tape in the primary data reduction step is worth considering. Computer programs are available for the primary reduction of various kinds of soil moisture data.

**Data Processing**

To date no instruments are available that measure soil moisture properties and give a digital output. It is therefore necessary to transfer data from field sheets by manual punching onto cards. Analog records from a recorder can be transferred directly to computer punchcards with the aid of a chart reader coupled to a card punch machine. This operation only requires the operator to place a target on the point on the chart to be recorded and to press a foot pedal. The chart automatically translates the analog coordinates into digital coordinates and punches them onto the card. Modern computers cannot only perform calculations but also can print out both intermediate and final results in either digital or graphical form.

**Gravimetric Soil Moisture Data Processing**

The first result that can be obtained from gravimetric samples is the soil moisture content on a dry weight basis, in percent, for each sample. After averaging replicate samples, the moisture percent of each layer becomes known. These results may be summarized graphically in two ways:

- The graph may be constructed to show moisture content as a function of time, with time being the abscissa and moisture percent the ordinate. A separate graph must then be drawn for each depth layer to be depicted.
- Soil moisture profiles may be drawn, with moisture percent being the abscissa and depth the ordinate of the graph. A separate graph must then be drawn for each time of observation. For some studies analyzing results on the basis of moisture percent is adequate, but these represent the minority of cases.

In most instances relating soil moisture percentage to actual volumes of water is required. This is best accomplished by converting all quantities of water to be handled into depth units in the metric system for using soil moisture data in a water balance.

**Problem:** In a watershed investigation calculating the water balance change resulting from a particular storm is desired. Precipitation, runoff, and soil moisture content data are being collected. The ground-water table is too deep to play an active role in the balance.

**Given:**

<table>
<thead>
<tr>
<th>Depth</th>
<th>Before storm</th>
<th>After storm</th>
<th>Accretion or depletion</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-30</td>
<td>8.9</td>
<td>14.3</td>
<td>+ 5.4</td>
</tr>
<tr>
<td>30-60</td>
<td>10.2</td>
<td>15.8</td>
<td>+ 5.6</td>
</tr>
<tr>
<td>60-90</td>
<td>14.9</td>
<td>16.2</td>
<td>+ 1.3</td>
</tr>
<tr>
<td>90-120</td>
<td>15.3</td>
<td>15.5</td>
<td>+ 0.2</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>+ 12.5</td>
</tr>
</tbody>
</table>

Watershed area = 15 ha
Rainfall, \( P = 75 \text{ mm} \)
Runoff, \( Q = 3,560 \text{ m}^3 \)
Average bulk density of soil, \( S_a = 1.30 \)

**Solution:**

Let \( D \) = depth of sampling layer, cm
\( d \) = depth of water applied, or in soil, mm;
\( P_w \) = soil moisture content on dry weight basis, percent; and
\( P_r \) = soil moisture content on volume basis, percent.

For any one layer, \( d = \frac{D(\Delta P_w)(S_a)}{10} \).

Since \( D \) is the same for all layers, it can be factored out, and the total moisture change in percent is used. Therefore, for the entire profile, for a 30 cubic meter sampling increment and a bulk density of 1.3:

\[
d = \frac{30(\Sigma \Delta P_w)(1.3)}{10}
\]

\[
d = 3.9 (\Sigma \Delta P_w)
\]

\[
d = 48.75 \text{ mm soil moisture accretion converted to units of surface mm of water}
\]
Runoff is calculated as follows:

\[
P = 75.0 \text{ mm} \\
\text{Recharge} = 48.8 \text{ mm} \\
Q = 25.2 \text{ mm}
\]

Measured runoff = 3,560 m$^3$

\[
1 \text{ mm} = 10 \text{ m}^3/\text{ha}
\]

\[
\frac{3,560 \text{ m}^3}{15 \text{ ha}} \times \frac{1 \text{ mm}}{10 \text{ m}^3/\text{ha}} = 23.7 \text{ mm}
\]

Useful conversion factors:
1 ha = 10,000 m$^2$
1 mm precipitation = 10 m$^3$/ha

**Tensiometer Data Reduction**

Tensiometer data are usually read directly unless transducer tensiometers are used. In this case millivolt values have to be converted to appropriate units of tension. This can be done either manually, or by reading a calibration curve table and the raw data into a computer and converting with the aid of a suitable program.

**Electrical Resistance Unit Data Reduction**

Electrical resistance values are converted to either moisture content or moisture tension values with the aid of a calibration curve, as in tensiometer data reduction.

**Neutron Probe Data Reduction**

Neutron probes are calibrated in moisture percent by volume, and therefore the same equation as was used for reduction of gravimetric samples can be used after conversion of counts per minute to volumetric moisture content with the aid of the calibration curve.

**Soil Temperature, Soil Heat Flux, and Frost**

Soil temperature, soil heat flux, and frost vary with such site factors as elevation, exposure, soil characteristics, soil moisture content, vegetal cover, and land use. All of these factors must be considered in selecting the location or network of measurement sites. The use for which the data are intended usually dictates the extent of consideration to be given each factor. The interpretation and use of data obtained are limited to the site conditions actually sampled.

**Measurement of Soil Temperatures**

Instruments commonly used for sensing soil temperatures are mercury or liquid in glass thermometers, bimetallic thermometers, electrical resistance thermometers, and thermocouples. Continuous records of soil temperature are usually made with mechanical soil thermographs, thermocouple activated recorders, or electrical resistance thermometer systems.

The soil thermograph has an advantage for remote field measurements because it is inexpensive and completely mechanical. The measuring unit consists of a Bourdon tube attached to a pen recording on a chart. Most Bourdon tube units are accurate to within $\pm 2^\circ\text{F}$. The sensing units have the disadvantage of being large. Since the capillary tube is relatively sensitive to changes in temperature, it is very important that during installation the Bourdon element be protected from direct radiation and that at least 3 ft. (0.93 m) of the protected capillary tube be buried at the same depth as the bulb.

**Shape**

Describe briefly using such characteristics as "roughly rectangular," "round," or "fan-shaped." Give approximate average width and length (width first) and give the length in relation to the direction of the principal drainageway. Give maximum and minimum watershed elevations in Mean Sea Level (MSL). In cases where other dimensions will be more descriptive of the shape, the other dimension should be used, such as fan-shaped, 350 feet (107 m) radius; length of arc, 450 feet (137 m), or equilateral triangle 550 feet (168 m) each side. Give width and length in feet and meters if the area is less than 640 acres (259 ha) and in miles and meters if the area is more than 640 acres (259 ha); in either case, carry to no more than two significant figures.
Slopes

Give the slope in terms of the ranges commonly used in soil survey work in the area. Give the aspect (direction of exposure) of the watershed. If possible, list valley side slopes separately from the overall slope figures. If slope-aspect relationships seem to vary in a systematic manner, (for example, east-facing slopes steeper than west-facing slopes) detail these variations.

The most popular electrical method of measuring field temperature is by thermistor. Thermistors are a thermally sensitive resistor of semiconductor material which has a high negative temperature coefficient of resistance. Thermistors are well suited for field measurement because of their high resistance values. Cable lengths between the probe and recorder are not critical and may vary in length. In addition, thermistors are small, have low heat capacity, a strong signal and no requirement for reference temperature. Using current field equipment and techniques, accuracy of temperature measurements made with carefully calibrated, systematically culled thermistors is better than ± 0.04 °F (0.02 °C). Probes and recording systems are commercially available. Several homemade, DC-powered multipoint units have been built and successfully utilized by various field researchers.

For special studies where continuous records are not necessary, spot readings may be taken by a bimetallic or mercury thermometer. Soil moisture sensing units are also commercially available that include an imbedded thermistor for temperature measurements.

Installation

Soil temperature measurements should be made at the same depths so that data from place to place can be directly compared. Common depths for profile measurements are 4, 8, 20, 39, 59, and 118 in (10, 20, 50, 100, 15 and 300 cm). Temperature measurements made nearer to the surface than 4 inches (10 cm) may be in error because of radiative heating. This heating is controlled by the density of vegetable cover or presence of snow, if any.

Proper installation of the sensing elements and leads is necessary to reduce field-induced errors. When installing sensors in the soil, it may be necessary to insert a sharp-pointed object in the soil first to provide a pilot hole. Care must be taken not to make this hole too large so that thermal contact with the soil will be lost. Sensors installed horizontally should have 2 or 3 feet (0.61 to 0.92 m) of leads (wires or capillaries) buried at the same depth as the sensing elements. This reduces the effect of thermal conductivity of the lead wires that are exposed to different temperatures. Sensing elements placed vertically will give some average temperature over the depth of the soil in which the unit is buried.

It is essential that the experimental area where the sensors are installed should be protected from trampling especially when an observation is being made. The natural state of the surface must be preserved and not disturbed in any way. Sensors should be inserted in the soil at least a week before beginning measurements.

Calibration

Temperature data collected in the field are only as good as the accuracy of the total recording system. This accuracy can only be determined through proper calibration of the total recording system, sensors, and recorders. Each system should be calibrated just prior to installation. The calibration of the system should be checked periodically in the field.

Always check the calibration of new instruments prior to installation. The complexity of the calibration is determined by the sophistication of the recording system and research plan for the data collected. Therefore, any calibration needs to be only as accurate as the levels of experimental error encountered in the field measurements. Materials needed for calibrating temperature measuring systems are (1) primary standard platinum resistance thermometer or a secondary standard thermometer, (2) Dewar flask, thermos bottle or a temperature-controlled water bath, and (3) stirrer.

In working with most soils, a mercury-in-glass thermometer may be calibrated to be used as a secondary standard thermometer. The calibration is then carried out by filling the
Dewar flask with crushed ice made from distilled water and then adding water and stirring until all the air in the ice is displaced. This is the first point on the calibration curve, the ice point 0°C (32°F). Then gradually add warm distilled water until the ice melts.

Always stir vigorously after adding the warm water until the water temperature in the flask becomes stable. Compare the reading of the standard thermometer to the sensor being calibrated after each stable reading. Continue to add warm water and stir until a satisfactory curve has been developed over the desired temperature range. Be sure the thermometer or sensors being calibrated are immersed into the water bath to the proper depth. If more precise calibration is desired, a primary standard should be used along with a very accurate water bath or triple-point apparatus.

Measurement of Frost

The depth of frozen soil is determined at sites representing bare soil, grass, and woods. The line of demarcation between unfrozen soil and the ice crystals in frozen soil is frost depth. Frozen soil is sampled with a pick or mattock, and the depth is determined by the presence of macroscopic ice crystals and the disruption of normal soil structure. When frost is 6 to 12 inches (15.2 to 30.5 cm) deep, a twist drill may be used. Measurements should be taken at the same time daily, preferably in the morning. Four replicates should be sampled for each observation area if the frost depth variation is no more than one-half inch (1.3 cm). If the variation is greater than a half inch (1.3 cm), six replications are needed.

After the frost is determined, the loose soil is replaced in the holes to produce as little disturbance of the site as possible. Disturbance of the measured area is kept at a minimum by starting measurements at one end of the field and gradually working into the undisturbed area. This avoids compaction, which favors greater frost penetration.

Measurement of Soil Heat Flux

The soil heat flux density can be a major term of the energy balance equation of soils. It is usually only considered in watershed studies where detailed energy balance studies are conducted. Heat flux plates are used to measure the sensible heat as it moves past the plate by means of the temperature gradient which exists across the plate. Similar to soil temperature measurements, the heterogeneity of vegetative cover and soil requires that heat flux be measured at several places in order to obtain a representative sample.

The magnitude of the soil heat flux of the surface is usually more affected by the type and amount of cover than by other soil characteristics. It is generally recommended that the heat flux plates be placed at depths between 2 and 4 inches (5 and 10 cm). Careful calibration must be carried out prior to installation. The calibration of the soil heat flux plates and the collection of field data require special instruments that are only available on the most detailed energy balance studies. Therefore, the kind of recording system used would be dictated by the type of study being carried out.

Data Collection

Soil Temperature

Continuous soil temperature data are normally obtained by chart recording instruments. Clearly identify the chart, giving station name, chart number, data and time of placement, and removal of chart, field calibration checks, and existing soil surface conditions. If DC powered recorders are being used, it is also helpful to indicate on the chart the date of the last battery change.

Frost

Soil temperatures have not been found to be reliable indicators of frost. Therefore, a physical depth measurement must be obtained. When the depth measurement is made, then the type of frost is noted. Sometimes two or three types are found together. The terms “concrete,” “honeycomb,” and “Stalactite” are used to classify frost types, described as follows:

- Concrete frost is characterized by many very thin ice lenses, small crystals, and an extremely dense complex. It usually occurs in soils previously frozen and thawed or in soils settled by a heavy rain. It is more prevalent on bare soils or those with sparse vegetal cover.
When soil freezing is greater than 3 inches, (7.6 cm) concrete-type frost generally prevails. Permeability is extremely low.

- Honeycomb frost has a loose, porous structure and is easily broken into pieces. It is generally associated with shallow freezing conditions and with pasture or meadow soils full of grass roots or where soils are highly aggregated. Permeability of honeycomb frost is likely to be higher than that of the concrete type.

- Stalactite frost is characterized by many small icicles connecting the heaved surface to the soil below. It is often found associated with honeycomb structure in pasture and meadow soils. Stalactite frost is sometimes formed during a refreeze of a partially thawed honeycomb structure. Permeability is likely to be higher in stalactite frost than in the concrete type.

**Soil Heat Flux**

Procedures for collecting soil heat flux data would be dictated by the type of specialized recording equipment used.

**Data Processing**

It is imperative that all field data be processed as soon as possible after collection. Keeping current on data processing is important for locating defective equipment and maintaining proper calibration. Chart notations made during data collection are much more meaningful if reviewed with as little delay as possible.

**Soil Temperature**

Data from recorder charts and field notes are tabulated and dated to show daily maximum, minimum, and means for the various depths measured. Daily values are summarized for the month, and the monthly averages are determined. Soil temperatures are usually tabulated to the nearest whole degree. Soil temperature data may also be summarized graphically on a temperature vs. time relationship for the various depths. The time base may vary depending on the research plan.

More detailed studies on large watersheds usually require a computer to process the large volume of data collected. Many recording systems do not read directly in degrees temperature but require a resistance-temperature conversion. A computer is helpful for making this conversion and at the same time can be further used to make corrections for nonlinearities of the recording system.

**Frost**

Data on frost depth and type of frost are usually incorporated with precipitation measurements as a possible explanation of precipitation runoff relationship during the winter months.

**Soil Heat Flux**

Data processing procedure for soil heat flux data would be dictated by the research plan for energy balance studies.

**Soil Density**

The weight per unit volume of soil is defined as soil bulk density or volume weight. Determinations are usually made by weighing oven-dry samples of known volume but may be made on samples containing soil moisture if there is allowance for water content. Samples for density measurements are generally of two types, core samples and fragment or “clod” samples. Core samplers take relatively undisturbed cores of known volume usually at least 12 in³ (200 cc) in size. Care must be exercised in extracting core samples to prevent either compaction or fragmentation of the core. Samples should not be taken when the soil is either too wet or too dry.

Fragment samples consist of blocks of soil carefully extracted by manually cutting or breaking pieces of soil along natural cleavage planes. Fragments can be of any size, the larger the better, within practical handling limits. “Fist-size” fragments are commonly obtained. Fragments are usually coated by dipping in either wax or plastic resin to prevent disruption and drying during handling. The protective coating also serves to waterproof the fragment for subsequent volume determination by liquid displacement during which the sample is immersed in water. The coating can easily be removed or perforated during oven drying.

When the weight of the soil core or fragment corrected for water content and the weight of coating is known, and the volume of the sample has been determined, bulk density is calculated by dividing the oven-dry weight of the sample
by its volume. The result is expressed as grams per cubic centimeter or pounds per cubic foot.

To detect density changes in the upper soil layers over large areas, nuclear surface probes are very useful. Measurements are obtained rapidly with minimal surface disturbance. Another appropriate technique, especially useful in rocky soils, is excavation, whereby a quantity of soil is removed dried, and weighed. The volume of the hole from which the soil was excavated is determined by filling with a measured quantity of sand which the volume weight is known. The volume may also be measured by filling the excavation with water after first rendering the bottom and sides of the hole impermeable. This can be done with plastic spray coatings, by membranous linings of plastic, or rubber. A convenient method is to allow the water to inflate a rubber balloon to exactly fill the hole.

Bulk density determinations are useful in detecting changes in soil structure due to land use and treatment. These changes are reflected in soil porosity changes which affect the infiltration, storage, and distribution of rainfall. Major changes in density occur in the uppermost layers of soil as a result of plowing or compaction by animal traffic. Sampling should thus be concentrated in the upper few inches to detect these changes. Since most soils are highly variable in their physical properties, a sampling program should be designed to provide enough replicate samples to define central tendencies in bulk density values.

**WATERSHED CHARACTERISTICS**

Each watershed should have a complete description to aid in the interpretation and extension of its hydrologic evaluation. The reliability and potential for use of a comparison between significant characteristics of different watersheds of the same type and between watersheds of different types has long been a source of argument between researchers in fields where such comparisons are needed. Words alone fail to give data which will permit analyses between watersheds. To permit such analyses, watershed characteristics must be expressed numerically whenever practical and possible.

**Watershed Description**

The data needed for preparing watershed descriptions are subsequently outlined.

**Location**

Show county and State, distance and direction to nearest town, and the river basin in which the watershed lies; the river basin should be large enough to show up as a named tributary on a U.S. Geological Survey (USGS) State base, or comparable map. Include latitude, longitude, section, township, range, USGS quad sheet(s), name(s), and other descriptions where possible.

**Area**

Give total area, channel area, and flood plain area in English and SI units to three significant figures. Give English units in acres if watershed is less than 640 acres (259 ha). Give in acres and in square miles if more than 640 acres (259 ha).

**Soils**

Soil descriptions should include data on texture, structure, permeability and internal soil drainage. Use descriptions, such as those in USDA Agriculture Handbook (AH) 18 (4), AH-436 (5).

**Soil Texture**

Soil texture refers to the relative proportions of the various size groups (or separates) of individual soil grains. Specifically, it refers to the proportions of clay (less than 2 mm), silt (greater than 2, but less than 50 mm), and sand (greater than 50 millimeters, but less than 2 mm in diameter). The various classes of texture from coarsest to finest are (1) sands, (2) loamy sands, (3) sandy loams, (4) loam, (5) silt loam, (6) silt, (7) sandy clay loam, (8) clay loam, (9) silty
clay loam, (10) sandy clay, (11) silty clay, and (12) clay. In some of the descriptions the broader classification of coarse, moderately coarse, medium, moderately fine, and fine has been used—the coarse soils are the sands and the fine soils the clays.

**Soil Structure**

Soil structure refers to the aggregation of primary soil particles into compound particles, or clusters of primary particles, which are separated from adjoining aggregates by surfaces of weakness. Structure grade or the durability of the aggregates when subjected to disturbance, is described as structureless, weak, moderate, or strong. The size of the aggregates is described as very fine, fine, medium, coarse, and very coarse. Structure shape is described as being platy, prismatic, columnar, angular blocky, subangular blocky, granular, or crumb.

**Permeability**

Permeability is the quality of soil that enables it to transmit water or air. This quality is described by the term very slow, slow, moderately slow, moderate, moderately rapid, rapid, and very rapid.

**Internal Soil Drainage**

Internal soil drainage is the quality of a soil that permits the downward flow of excess water. Internal drainage is reflected in the frequency and duration of periods of saturation with water. It is determined by the texture, structure, and other characteristics of the soil profiles and of underlying layers and by the height of the water table, either permanent or perched, in relation to the water added to the soil. Internal soil drainage is described as none, very slow, slow, medium, rapid, and very rapid.

**Erosion**

Soil erosion conditions are described in USDA Agriculture Handbook 18(4). The major classes of soil erosion are:

- **Class 1:** The soil has few rills or places with thin horizons that give evidence of erosion which has accelerated but not to a degree that would greatly alter the thickness and character of the A horizon. Except for soils having very thin A horizons (less than 8 in or 20 cm) the surface soil consists entirely of A horizon throughout nearly all of the delineated areas. Up to about 25 percent of the original A horizon (or original plowed layer in soils with thin A horizon) has been removed from most of the area. This class also includes the areas of no erosion.

- **Class 2:** The soil has been eroded to the extent that ordinary tillage implements reach through the remaining A horizon or well below the depth of the original plowed layer in soils with thin A horizons. Generally, the plow layer consists of a mixture of the original A horizon and the underlying horizons. Mapped areas of eroded soil usually have patches in which the plow layer consists wholly of the original A horizon and others in which it consists wholly of underlying horizons. Shallow gullies may be present. Approximately 25 to 75 percent of the original A horizon or surface soil may have been lost from most of the area.

- **Class 3:** The soil has been eroded to the extent that all or practically all of the original surface soil, or A horizon, has been removed. The plow layer consists essentially of materials from the B or other underlying horizons. Patches in which the plow layer is a mixture of the original A horizon and the B horizon or other underlying horizons may be included within mapped areas. Shallow gullies, or a few deep ones, are common in some soil types. More than about 75 percent of the original surface soil, or A horizon, and commonly part of all of the B horizon or other underlying horizons have been lost from most of the area.

- **Class 4:** The land has been eroded until it has an intricate pattern of moderately deep or deep gullies. Soil profiles have been destroyed except in small areas between the gullies. Such land is not useful for crops in its present condition. Reclamation for crop production or for improved pasture is difficult but may be practicable if other characteristics of the soil are favorable and erosion can be controlled.

**Land Capability**

Land capability as classified by Klingebiel and Montgomery (1) expresses the suitability of land for use without damage. The eight land-capability classes, distinguished according to
the risk of land, damage or difficulty of land use, are classes I to IV, suitable for cultivation and other uses, and classes V to VIII, not suitable for cultivation.

- Class I: Very good land for cultivation; nearly level and productive; not subject to erosion; needs only ordinary good farming methods.
- Class II: Good land for cultivation; mostly gently sloping, not more than moderately subject to erosion; some land rather wet; can be farmed safely with easily applied practices.
- Class III: Moderately good land for cultivation; mostly moderately sloping; some areas too wet or too dry; can be farmed safely with practical conservation measures, carefully applied; usually a combination of two or more measures is needed.
- Class IV: Fairly good land, suitable for occasional cultivation; generally strongly sloping; often shallow or very sandy; often found in dry climate.
- Class V: Land very well suited for grazing or forestry; requires good range or woodland management.
- Class VI: Land well suited for grazing or forestry; steeply sloping land, droughty land, or wet land; requires careful management.
- Class VII: Land fairly well suited for grazing or forestry; severely limited in use by such factors as very steep slope, shallow or droughty soil, wetness, severe erosion, or excessive salinity; requires careful management.
- Class VIII: Land not suitable for cultivation, grazing, or forestry; may be useful for wildlife, recreation, or protection of water supplies.

Surface Drainage

Surface drainage refers to the ease with which excess water flows from the watershed area. Give the length of principal waterway as the distance from the gage station to the most remote point on the watershed boundary, measured along the flood plain of the watercourse.

Give typical cross sections as necessary for flood routing. Describe soils, alluvial or geologic material, and vegetation in waterway.

Include type of drainage patterns such as dendritic, rectangular, trellis, annular, parallel, radial, centripetal, or otherwise. In some small watersheds, pattern determination is not possible due to lack of full development of a drainage net.

Character of Flow

Describe the flow of the stream, or reach or stretch of a stream, in respect to permanence and space. The following definitions are from the U.S. Geological Survey (2).

With respect to permanence, streams may be divided into perennial streams, intermittent streams, and ephemeral streams.

A perennial stream, or stretch of a stream, is one which flows continuously. Perennial streams are generally fed in part by springs, and their upper surfaces generally lower than the water table in the localities through which they flow.

Intermittent streams may be divided, with respect to the source of their water, into spring-fed intermittent streams and surface-fed intermittent streams.

A spring-fed intermittent stream, or stretch of a stream, is one that flows only at certain times when it receives water from springs. The intermittent character of streams of this type is generally due to fluctuations of the water table whereby the stream channels stand a part of the time below and a part of the time above the water table. This is the ordinary type of intermittent stream.

A surface-fed intermittent stream, or stretch of a stream, is one that flows during protracted periods when it receives water from some surface source, generally the gradual and long-continued melting of snow in a mountainous or other cold tributary area.

The term may be arbitrarily restricted to streams or stretches of streams that flow continuously during periods of at least one month.

An ephemeral stream or stretch of a stream, is one that flows only in direct response to precipitation. It receives no water from springs and no long-continued supply from melting snow or other surface source. Its stream channel is at all times above the water table. The term may be arbitrarily restricted to streams or stretches of streams that do not flow continuously during periods of as much as one month.

A continuous stream is one that does not have interruptions in space. It may be perennial, intermittent, or ephemeral, but it does not habitually have wet and dry stretches.
Instrumentation

Describe and locate hydrologic instruments on the watershed.

Watershed Conditions

Avoid giving exhaustive detail on watershed conditions unless specifically required for the experiment. Summarize the general land use including farm, forest, or range practices prior to the period of record and the conservation measures, crops, yields, and general cultural operations and practices during the period of record. When describing rotations, list the crops in the order that they were grown, for example, if a rotation of corn, oats, and winter wheat was planned but the experiment actually started in the year that oats were planted, the rotation would be oats, winter wheat, corn.

General Problem Areas Represented

Give general problem area in terms used by the Soil Conservation Service. Regional and State maps give refinements of this general problem area map, but the names of the areas and subareas are the same. The area name should be accompanied by qualifying factors as interior and surface drainage, land use, erosion.

Watershed Documentation

Land Characteristics

An example of the type of formation required to portray watershed characteristics is given in the following description of land characteristics of Watershed No. 177.

- Location: Coshocton County, Ohio; 10 miles NE. of Coshocton; Walhonding River, Muskingum River Basin, Longitude 81° 50’ W., Latitude 40° 20’ N. Area: 75.6 acres total (3.06 x 10^5 m^2), <1 acre in channel, no floodplain.
- Shape: Roughly triangular; base-1,900 feet (580 m), height-2,700 feet (820 m); mean standard elevation 1040 feet to 1280 feet (317 m to 390 m).
- Slopes: 3 percent of the watershed land slopes 2- to 6-percent; 20 percent slopes 6- to 12-percent; 55 percent slopes 12- to 18-percent; 17 percent slopes 18- to 25-percent, and 5 percent slopes 25- to 35-percent. Sixty percent of area has an aspect E. and SE.
- Soils: Residual, developed from shale and sandstone; topsoil, silt loam to loam texture, moderately fine crumb structure, 6 to 8 in (15 to 20 cm) deep; subsoil, moderate permeability, medium internal drainage, no impeding layer. Muskingum silt loam, 35 percent; Keene silt loam, 24 percent; Muskingum loam, 20 percent; Keene silt loam, shallow phase, 16 percent; mixed silt loam, 5 percent.
- Erosion: Class 2, 73 percent; class 3, 27 percent.
- Land Capability: Class III, 78 percent; class IV, 17 percent; class VI, 5 percent.
- Surface Drainage: Good, length of principal waterway-2,800 feet (853 m); a natural watershed with surface flow to one main channel, with no major division or tributaries, and with natural boundary.
- Character of Flow: Ephemeral, continuous.
- Instrumentation: Runoff: concrete dual Parshall flume, 8 feet (2.5 m) wide; supplemental sheet metal-type H flume, 1.5 feet (45.7 cm) deep; 2 FW-1 recorders (runoff gage 177). Precipitation: recording gages numbers 103, 100, and Y102 from W. to E. across N. third of watershed and number 107, 200 feet SE. of southern divide.
- Watershed Conditions: Mixed cover: Woods, 11 percent; grassland, 36 percent; cultivated, 42 percent; miscellaneous, 11 percent. After 1943, cultivated area, all in contour strips, reduced to 20 percent with increase in woods and grassland. Watersheds 129, 130 and 135 lie within the north and west boundary of this watershed.
- General Problem Areas Represented: Conservation practices on mixed cover areas of Muskingum, Keene, and associated silt loams and loams with medium internal drainage, good surface drainage, moderate to severe erosion found on rolling to steep topography in the Allegheny-Cumberland Plateau.

Watershed Maps

Watershed features and conditions, recorded graphically on maps and photographs, are useful as working tools in the field and for illustrations in publications. Map formats, scales and symbols should be selected to meet mapping objectives. Figure 6.3 illustrates some useful
SOIL CONSERVATION SERVICE
STANDARD MAPPING SYMBOLS FOR FARM CONSERVATION
PLANNING MAPS AND ENGINEERING DRAWINGS

**BOUNDARY LINES**
- Watershed or Area
- Section Line
- Farm Boundary No Fence
- Permanent Fence
- New Fence
- Crop Boundary No Fence
- Field Boundary No Fence

**HIGHPWAYS & RAILROADS**
- All Weather Road
- Dirt Road
- Private or Field Road
- Bridge
- Single Track Railroad
- Double Track Railroad

**LAND USE SYMBOLS FOR SMALL AREAS ONLY**
- Cultivated Land
- Woodland
- Permanent Pasture
- Idle Land
- Buildings and Lots
- Orchards
- Permanent Hay (Grass and Legume)
- Wildlife
- Unclassified

**DRAINAGE**
- Continuous Stream, Large
- Continuous Stream, Small
- Intermittent Stream
- Stream Disappears on Flat
- Stream Disappears in Sink
- Large Deep Gully
- (Gully, Cannot Cross with Farm Implements)
- (Gully, Can Cross with Farm Implements)

**DRAINAGE (Continued)**
- Levee
- Spring
- Lake or Pond
- Intermittent Lake or Pond
- Marsh
- Terrace
- Diversion
- Grassed Watercourse
- Terrace Outlet
- Permanent Structure

**MISCELLANEOUS SYMBOLS**
- Mine, Quarry, Gravel Pit
- Cemetery
- Church
- School House
- Occupied Residence, Store

**ADDITIONAL SYMBOLS TO BE USED TO SHOW ENGINEERING WORK ON AGREEMENT MAPS OR ENGINEERING DRAWINGS**
- North Arrow
- Section Center
- Section Corner
- Existing Tile
- Proposed Tile
- Break in Tile Size
- Break in Grade
- Relief Well
- Breather
- (Existing Open Ditch)
  (Less than 4' Deep)
- (Proposed Open Ditch)
  (Less than 4' Deep)
- (Existing Open Ditch)
  (4' Deep or Over)
- (Proposed Open Ditch)
  (4' Deep or Over)

Figure 6.3.—Symbols to be used for planning maps and engineering drawings.
and commonly used map symbols. Special symbols for instruments and conservation measures can be shown in the map legend.

Since most maps are reduced photographically, a graphic scale should be used and lettering should be planned so that the map remains legible after reduction. Most will be reduced to fit an 8 x 10 1/2 inch (21.6 x 27 cm) sheet. For maximum clarity and longevity of originals, ink the drawings on tracing linen or make polyester film photocopies of originals while they are still in good condition. The following are descriptions of various maps which should be kept.

- Road Map: Prepare road map similar to the one on figure 6.4. Some municipality should appear on the map if possible. Otherwise, show direction and distance to the nearest town.

- Topographic Map: Prepare drawing similar to the one in figure 6.5, using proper size lettering to allow photographic enlargement or reduction for publication purposes. Elevations are expressed as mean sea level (MSL) values whenever practical; otherwise, use an assumed datum and describe same.

The contour interval should be small enough to define the watershed topographic features. Too many contour lines make a map illegible. Too few reduce its usefulness. Engineering surveys should include a traverse around the watershed for watersheds under 20 acres (8 ha). For resurvey purposes, at least two transit angle points should be permanently set protected sites. Drainage areas of larger watersheds may be obtained by planimeter on topographic maps. In some cases aerial photographs and photogrammetric processes can be used to develop topographic maps of large areas at less cost than conventional surveys.

Scale should not be less than 1 inch = 50 feet (2.54 cm = 15.3 m), and the scale shall not be more than that required to place the watershed on the maximum size sheet 24 x 30 inches (61 x 76 cm). Scale should be designated graphically (not numerically). As mentioned above, size of lettering should be chosen on a basis of degree of photographic enlargement or reduction anticipated. Planimetric features such as gages, buildings, roads, buried utility lines, and similar items should be shown. Show magnetic and true north direction arrows, date map was prepared, and yearly declination charge.

Pondage Topographic Map

A topographic survey of the area upstream from the weir, flume or other flow measuring device is needed when pondage corrections to the gage record are required. Close contour intervals are usually needed for this map. Mean sea level elevations should be in this survey. Contours should extend at least 1 ft above stage of estimated maximum flood peak (fig. 6.6). Supplemental contours are usually required for the zero flow and controlled crest elevations.

Land Capability Map

Land capability maps should conform to the latest standards of the Soil Conservation Service (3). Land capability is the product of the combination of slope, soils, and erosion. Criteria have been established by soil scientists for rather broad groups of soils, which give the capability for various combinations of slope and erosion. Classifications in table 6.1 are for deep, well- to moderately well-drained loams and silt loams developed in less than 42 inches (107 cm) of silty material having permeable profiles. The scales for all watershed maps should be the same as those used for the topographic map.

A slope class map (fig. 6.7) is prepared from a study of the topographic map. The soils and erosion maps (figs. 6.8 and 6.9) are prepared from a detailed soil survey (1). Transportation of the three maps (slope, soil, and erosion) are

| Table 6.1. — Factors for determining land capability of moderately permeable silt loams |
|----------------------------------|----------------|----------------|----------------|----------------|----------------|
| Factor                          | Capability class | I   | II  | III | IV  | VI  | VIII |
| Slope                           | 0-2              | 2-5 | 6-11| 12-19| 20-29| 30+ |
| Erosion class                   | 1,2              | 1,2,3| 1,2,3| 1,2,3| 1,2,3| 1,2,3|

1 Capability classes are defined in subsection on Land Capability (p. 529). Data for class VIII are not available. Erosion classes are defined in subsection on Erosion (p. 529). Data on class 4 are not available.
FIGURE 6.4.—Road map to Edwardsville, Ill., Project Watershed.
superimposed one over the other and the capability classes thus determined are shown in figure 6.10. Where only one soil group is involved, only the slope and erosion maps are needed to develop the capability map.

**Cover and Tillage Map**

A cover and tillage map similar to that shown in Figure 6.11 is necessary when the watershed is comprised of more than one field. Sites such as fences, buildings, roads, field numbers and woodlots are shown on this map. Contours are helpful but not necessary. Cover and tillage records for each year are noted chronologically in the tabular form on this map. It is important that all farming operations that may affect the watershed hydrology be given on this form.

**Drainage Map**

A drainage map, similar to the one shown in figure 6.12 is required when a quantitative geomorphic analysis of the drainage system is planned (see ch. 5, Geology, Geomorphological Investigations). This map can be prepared by field survey, or taken from USGS or U.S. Army Map Service quadrangle sheets or from aerial photographs, depending upon the size of the watershed, the accuracy desired, and the budget allowed. For a drainage map to be

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**FIGURE 6.5.—Topographic map of Fennimore, Wis., Watershed IV.**
Estimated maximum stage or line of maximum temporary pondage.

Notes
All elevations are mean sea level datum.
Elev. weir crest = 1158.98
Weir has 3:1 side slopes

FIGURE 6.6.—Contour map of pond area.
SLOPE CLASS MAP
WATERSHED W-IV
PROJECT WIS 2 FENNIMORE WIS.
US DEPARTMENT OF AGRICULTURE
AGRICULTURAL RESEARCH SERVICE

FIGURE 6.7.—Slope class map, Fennimore, Wis., Watershed IV.
useful the researcher must (1) precisely define first order stream selection criteria, and (2) give the scale and other map factors of the base map upon which the drainage map was prepared. Knowing what measurement techniques are used and the relative accuracy of the base map is helpful.

A drainage map should show which reaches of the stream flow perennially, intermittently, or ephemerally. It should show locations of channel grade controls such as weirs, culverts, bedrock outcrops, or drop structures, and should also show locations of headcuts, ponds, gully plugs, debris basins, flood control reservoirs, ground-water recharge areas, and so forth. Any drainage feature that does or can alter the hydrologic behavior of the watershed should be shown.

If an evaluation of the effect of man's activities on the development of the drainage net is desired, it will be necessary to prepare maps of continuous and discontinuous drainage before and after controls were installed. If a total water budget for the watershed is needed, a ground-water map showing permanent and perched water table elevations, direction(s) of ground-water flow, aquicludes, and well locations with average withdrawal figures will also be needed. (See ch. 5, Geology, Geomorphological Investigations.)

Photographs

Photographs of initial watershed conditions should be followed periodically by other photographs to show important changes. Photographs of runoff measuring stations, including upstream and downstream channel and other instrumentation may be required. Give any explanation necessary to clarify any questionable aspects of a photograph, such as overexposure or underexposure, camera and film used, shutter speeds, type of lens used. Where aerial photographs are filed, attached page listing source of duplicates and dates and locations of other flights known to be available in the area.

Number the photographs and negatives consecutively by date. Most factory and bulk developed film and prints are now numbered consecutively and have the development dates stamped or printed on them. However, since many people often leave film in their cameras for long periods of time, this does not preclude the necessity of careful dating of each photograph or slide with regard to the time and date taken not developed, especially where time-lapse sequences are planned. Also, many local cut-rate film processors do not number or date photographs or transparencies so reliance on the developer for numbering is inadvisable.

Keep notes on each picture taken and there will be little trouble in identifying dates and sites. As soon as the roll is returned from the developer, label and date all slides and prints, while memory is fresh. For quickness and legibility use an adjustable-date rubber stamp. To protect photographs when labeling, turn the print face down on a smooth hard surface such as glass before writing anything on the backside, especially if a ballpoint pen is used. A ballpoint pen is probably the best type to use since pencil can smear, and the ink from fountain pens will often soak through the print.

After labeling individual photographs, file them in properly labeled jackets and set up a card index file. These precautions are needed because there is usually only one negative although there may be more than one print on a given subject. If this negative is lost or ruined, the remaining prints should be in the best reproducible condition, and this usually calls for a glossy print with a perfectly flat surface.

Instrument Installation History

In addition to the watershed characteristics previously outlined (p. 528), additional information should be recorded and kept in a separate file entitled "Instrumentation of Experimental Watershed Number." This file should contain a brief history of each installation including dates of construction of installation. For runoff stations, give such additional items as description of type of control, size and maximum flow expected, type of stilling well, Gage Datum Elevation and other features of the station, make, model, and serial number of recorder if one is used, rating table(s), date record began, dates that levels and gages are checked, dates silting occurred (good records of silting dates can be obtained by merely observing deflection
Black to very dark brown friable silt loam of heavy compact structure.

Dark brown friable silt loam of medium crumb structure.

Medium to light brown silt loam becoming lighter in color when rubbed. Very heavy angular fragmented structure.

Yellowish brown silt loam mottled with gray material on the surface of the structure. Soil becomes lighter when rubbed.

LEGEND

Soil type boundary
Watershed boundary
Soil boring
Soil column location
Depth to impervious strata exceeds 48 inches
Impervious material.

SOILS MAP
WATERSHED W-IV
PROJECT WIS 2 FENNIMORE WIS
U.S. DEPARTMENT OF AGRICULTURE
AGRICULTURAL RESEARCH SERVICE

FIGURE 6.8.—Soils map, Fennimore, Wis., Watershed IV.
Figure 6.9.—Soil erosion map, Fennimore, Wis., Watershed IV.
points on chart recession curves), extent of silting, approach channel alterations such as brush clearance or grading, realignment, or bank lining, distance upstream and data of installment of grade controls, stilling well and intake pipe cleanout dates, and other important adjustments and changes.

Rainfall gage description should give type, make, serial number, time scale of chart drive (if recording), date of installation, date record began, height of catchment lip above ground, and the exposure (percent, slope aspect, obstacles) of the gage site. Maximum and minimum thermometer installations should be described as to type of shelter, direction of exposure, and height above ground. For other types of instrument installation, give details which might alter or affect data collected.

Field Observations

Conditions on a watershed at the start of a storm significantly influence the amount and distribution of runoff. Soil moisture, land use and treatment measures, stage of growth, tillage operations, frost, and a snow blanket are some of the more commonly recognized conditions that affect runoff.

Keep records of the conservation measures, crops, yields, and general cultural operations and practices during the period of record. Give areas in terms of percent of watershed area involved. When preparing these records, keep in mind that their purpose is to record existing conditions of a watershed which significantly influence the amount and distribution of storm runoff. When possible, watershed conditions should be expressed numerically to facilitate data analysis.

Crop Cover and Tillage

Notes on vegetal type, density, and height are helpful in the analysis of watershed hydrologic data. A record of the cover and tillage conditions of the watershed should be kept in map or tabular form, according to outlined instructions (p. 544).

When describing rotations, list the crops in the order that they were grown; for example, if a rotation of corn, oats, and wheat was planned, but the experiment actually started in the year that oats were planted, the rotation would be oats, wheat, corn. Record fertilizer applications and harvesting operations at the time they are initiated. This record will suffice for a summary of the general status of land management. However, if the investigator feels the need for more exact information, a supplement should be prepared for this map and its tables. The descriptive text that follows gives an example of information required.

Crop Year 1938. Watershed W—IV Fennimore, Wis.

Field 1: Hay; type, Ladino cover; planting drill width, 4 inches; density of cover 90 percent; yield 2.61 tons per acre.
Field 2: Pasture; type, sweetclover, medium red clover, and Kentucky bluegrass; density of cover, 95 percent; yield average, 3,210 pounds per acre.
Field 3: Buildings and Garden; roofed and/or paved area, 0.22 acres.
Field 4: Strip crop, 22 planted x 2 fallow, corn; type Dekalb 149; contour plowed to 44' rows; drill planted 1 kernel per hill every 18 inches; yield, 50.57 bushels grain per acre.
Field 5: Small grain, oats; type, Victoria; planting drill width, 3 inches; yield 79.0 bushels per acre.
Field 6: Corn, solid planting; type, Pioneer 206: contour plowed to 44' rows; drill planted 2 kernels per hill per 24 inches; yield, 46.28 bushels grain per acre.
Field 7: Roads; gravel, 20-foot width; shoulders ditched, surface planted in Timothy, Smooth bromegrass, and Reed canary grass; yield, 1,630 pounds per planted acre.
Field 8: Strip crop, oats and hay; strip widths 163 feet; type, Richland oats, and Ladak Alfalfa; planting method for both; surface, 3-inch drill width; Alfalfa; cover density, 100 percent; hay yield, 2.79 tons per acre; oats cover density, 95 percent; oats yield, 83 bu per acre.
Field 9: Pasture; type, Alsike clover, Timothy, Reed canary grass; density of of cover, 98 percent; yield average, 2,320 pounds per acre.
Field 10: Strip crop, corn and oats; strip widths 168 ft; corn, DeKalb 149, in 42' rows;
A daily diary is kept of all farm operations by field or watershed number. Operations such as plowing, disk ing, harrowing, cultivating, planting, liming, manure spreading, hay cutting, hay removal, combining, and other practices are recorded. Yields are recorded at the harvest date.

**Vegetative and Ground Conditions**

Watershed observations of vegetative and ground conditions should be taken at regular intervals. At some locations these observations should be taken once a month in April, May, September, and October and twice a month in June, July, and August, and supplemented at times when these conditions are changed. This schedule may vary according to the crop season and the particular needs at each station. Note ground characteristics such as soil moisture, erosion, rock cover, and structure and litter. Divide plant growth into dominant and subdominant species and type. Percentage of coverage, stage of growth, and average height should also be noted. In addition, such damage as hail, wind, insects, fire, flood, or drought should be evaluated for each plant growth area. Also record total vegetal density coverage of the soil for the entire watershed area.

Because of the wide variation that exists in root patterns, litter production, and soil knitting capabilities of different species of plants, it is desirable to give the vegetative cover percentage in each category (woods, brush, grassland, and cultivated crops). With the exception of cultivated croplands, which can be calculated with relative ease, the lists of the percentage and densities of the species of trees, and grasses do not have to include the names of more than the dominant and subdominant species in each category, if the effect of the remaining plant population on watershed runoff control is minimal. These field observations are recorded on a form similar to that shown in figure 6.13. Summaries, along with cultural practice records for each year, should be made separately for each watershed.

**Historical Land Use**

Give a brief resume of as much about the history of the land as can be determined. If possible, tell what conditions of vegetative cover existed before the advent of modern man, what changes man exerted on the land after his arrival, and what land management practices have been employed prior to the beginning of the period of record established by the present research project. This historical background often will explain the cause of various problems or unusual conditions within an area.

An example of one problem would be the high salt content of some of the potentially arable land of the Gila and Santa Cruz River Valleys in Arizona. Rather than being natural salt deposits, they were caused by over 200 years of irrigation of crops by the Indian tribes around Casa Grande. Another example of a culturally oriented problem would be the drastic erosion of the sandy hill country of the southeastern States. Except for the clearing of the hilly woodland and the tillage of the steep slopes during the cotton boom of the 1840's, much acreage, now useless, would still be excellent pasturage or timber farm.

The evolution of the dust bowl of the Great Plains is attributed to manmade and climatic factors. During the periods between 1880 and 1900 and between 1920 and 1940 a series of rainy years preceded a drought. Both wet periods occurred when there was great pressure for more farmland and rapid immigration that led to extension of the cultivated area and to overgrazing. Each drought period set an immigration in motion. In both periods the series of rainy years have been mistaken for normal climate, with disastrous results.

Overgrazing in some Southwestern States has eradicated lush stands of black grama grass established during cycles of wet years and caused its replacement with whitethorn or creosotebush shrubs which require less water but are useless for grazing. Quick historical resumes as described above often explain conditions far better than field surveys can.

The histories of general areas are usually obtainable from public records. Developing historical backgrounds for a specific watershed area may be more difficult. One of the easiest
Figure 6.10.—Land capability map, Fennimore, Wis., Watershed IV.
and most enjoyable methods of research is interviewing "old timers" in the area. However, with this approach, care must be taken to separate fact from fiction.

The next most expedient method is searching county archives. Excellent written records often exist. Within limited geographical areas, farmers usually tend to grow the same crops. The discovery of one pioneer family's farm journal will therefore usually be generally indicative for the area if the area was settled at the same time. Many records exist in the form of epitaphs on tombstones, but they may have to be deciphered.

More difficult background research involves dendrochronology. The records left in tree rings tell not only when the tree sprouted or was planted, but they can often provide records of wet years, drought, cold winters, fires, floods, and so on. If one really wants to dig deeply archaeologists can usually uncover cultural practices prior to the coming of "civilized" man. Carbon 14 and other dating methods are becoming common tools of archaeologists and geologists. Old lakebeds, prehistorical forests, peat bogs, cooking fires, and the like can be dated with relative precision.
Data Reduction and Processing

Data Gathering, Assembling, and Preparation

For purposes of comparison between similar studies, mapping techniques and map factors pertinent to the investigation should be described by the individual doing the field surveys. Watershed conditions should be expressed numerically, where practicable.

Certain analyses require that each condition factor be expressed as a watershed average. The area of representation must be determined or estimated for each site of sampling or measurement. The criteria of homogeneity for estimating area of representation vary with the condition factor under consideration. A practical procedure is sometimes adopted in which readily discernible characteristics such as soil, slope group aspect, elevation, and land use and treatment are indicated on a watershed map, and from these characteristics the worker may derive subareas of homogeneity. Expressed as percentages of the watersheds, these areas are used to weight site observation of each condition factor in computing the watershed average.

If a legend system other than a widely used and easily accessible one is to be used, it should be presented with or cross-referenced on the map in question. Data should include the name or initials of each member of the survey party and their capacity. All maps should have the proper type and amount of information shown for location and filing, for example, type of map (soils, erosion, or slope), watershed name or number, project number, station location and agency name. Department (USDA), service (SEA) should be shown in the lower right-hand corner of the map.

Formats for maps and tabulations have been given in the foregoing instructions.

Data Analysis and Interpretation

Little can be said in a manual of instruction of this nature with regard to how data should be analyzed or interpreted. The degree of analysis and interpretation to be carried out will depend largely on the knowledge and experience of the researcher working with the data and on what the particular goals of the research project might be. Most of the information involved requires no further effort than that expended in gathering the facts and preparing a written summary. The "analysis" comes later when the data above have been used as a tool, a reference bank of knowledge describing the watershed, to aid in the ensuing decision making processes.

Data Storage and Retrieval—(Archive Filing)

The completed watershed description should be typed on $8 \times 10^{1/2} (20.3 \times 26.7 \text{ cm})$ paper, and original maps should be drawn on tracing linen with black India ink. Duplicate copies should be made using a reproducing process such as typing carbons, multilith, photostat, Xerox or photo-offset which are permanent and will not fade if exposed to light or temperature changes (as opposed to Ozalid "blue-line" or Thermofax copies which will fade). A copy of the completed report or description should be kept in the investigators files, or remain in the station’s office files, and a copy should be sent to the archiving station. Index cards should be prepared in duplicate for the field station or laboratory, (possibly for the Area and Regional offices), and for archiving card catalog files.

A brief summary of the data involved should be given for any associated publications. Using the same data description on each card, cross-referenced index cards should be prepared for each field or subject matter involved. The index card should also contain the watershed’s location by State and county, the ARS or any other organizational watershed number, size, and the dates of record. The card should also give the name of the investigator(s) and the sponsoring agency or agencies.

Various forms of watershed summaries of runoff, rainfall, and other related information are compiled and distributed by USDA research agencies. At present, summaries of data and simple initial analyses of a backlog of many years of data for agricultural research watersheds are being compiled and distributed by the Science and Education Administration.
These summaries include separate reports on (1) monthly precipitation and runoff for small agricultural watersheds in the United States, (2) annual maximum flows from small agricultural watersheds in the United States, (3) hydrologic data for selected runoff events for small agricultural watersheds, and (4) periodic supplements of reports.

If the material in question is stored on punched cards or on magnetic tape, the print commands for the memory banks should be noted. Record size, block size, and data format for data stored should be given. Presently IBM has a "Data-Text" system for storage of printed material only. As computer sciences progress, maps, graphs, and tables will also be stored on tapes, disks, or cards.

REFERENCES

(1) Klingebiel, A. A., and Montgomery, P. H.

(2) Meinzer, O. E.

(3) U.S. Department of Agriculture, Soil Conservation Service.
1950. PROBLEM AREAS IN SOIL CONSERVATION. (Map)

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