Chapter 4
Rainfall Analysis

4-1. General

a. The use of rainfall data is essential and fundamental to the rainfall-runoff process. The rainfall data are the driving force in the relationship. The accuracy of the rainfall data at a point (i.e., at the rain gauge) is extremely significant to all the remaining use of the data.

b. This chapter describes the significance of rainfall data to the rainfall-runoff process. The relationship between point rainfall at a rain gauge and the temporal and spatial distribution of rainfall over the watershed of interest is discussed. Limitations and inaccuracies inherent in these processes are also defined.

4-2. Point Rainfall Data

a. Rainfall measured at a rain gauge is called point rainfall. The rain is captured in a container. The standard rain gauge, shown in Figure 4-1, is an 8-in.-diam metal can. A smaller metal tube may be located in this larger overflow can. An 8-in.-diam receiver cap may be on top of the overflow can and is used to funnel the rain into the smaller tube until it overflows. The receiver cap has a knife edge to catch rain falling precisely in the surface area of an 8-in.-diam opening.

b. Measurements are made using a special measuring stick with graduations devised to account for the 8-in. receiver cap opening, funneling water into the smaller tube. When the volume of the smaller tube is exceeded, the volume from the smaller tube is dumped into the larger overflow can.

c. Other types of rain gauges are also available. In contrast to the nonrecording gauge which requires an observer to manually measure the rain at regular intervals (i.e. every 24 hours), Figure 4-2 shows a weighing-type recording gauge which does not require constant observation. The rain is caught in a standard 8-in. opening but stored in a large bucket that sits on a scale. The weight of the water caught during a short time interval is recorded on a chart graduated to units of linear distance (inches or millimeters) versus time.

d. Other variations of these two gauges exist and perform similarly. Although essentially all United States gauges have exactly an 8-in. opening and have been carefully calibrated for exact measurement with an appropriately graduated stick or chart, several other conditions affect the exact amount of rain caught in the gauge.

e. The gauges are affected by wind, exposure, and height of gauge. Researchers have tried to establish correction charts for windspeed effect on the catch, but since exposure (including gauge height) has such significant impacts on the catch, these charts must be viewed with suspicion. The effect of height has been standardized in the United States at 31 in. Windshields, Figure 4-2, have been used at some locations to minimize the inaccuracy of measurement due to windspeed.

f. Other errors are associated with the volume of water displaced by the measuring stick (a constant of 2 percent) or the inherent errors associated with the mechanical aspects of some other types of gauges (i.e., tipping bucket), which are variable as a function of rain intensity. Variable error associated with mechanical gauges should be evaluated by comparing recorder data against standard gauge data and correction relationships determined for future use.

4-3. Rainfall Data From Remote Sensors

a. Rain gauges measure the amount of rain that has fallen at a specific point. However, hydrologists and hydrologic models typically need the amount of rain that has fallen over an area, which may be different than what was measured at a few points. A better estimate of rainfall may be achieved by installing more rain gauges (a dense gauge network), but such a network is very expensive. Alternatively, weather radar, when adjusted with rain gauge data, may provide a relatively accurate measurement of the spatial distribution of rainfall. If the area is in a remote region, where there are few or no rain gauges and weather radar is not available, environmental satellite data may provide rough estimates of rainfall amounts.

b. Radar (*Ra*dio *D*etecting *A*nd *R*anging) operates on the principle that an electromagnetic wave will be partially reflected by objects or particles encountered by the wave. Generally, a radar system consists of a transmitter, which generates electromagnetic pulses; a movable dish-shaped antenna, which serves both to transmit the electromagnetic pulses and receive reflected signals; a receiver that detects and amplifies the reflected signals; and a device to process and display these signals. The radar antenna transmits electromagnetic pulses into the atmosphere slightly above horizontal. These pulses travel at the

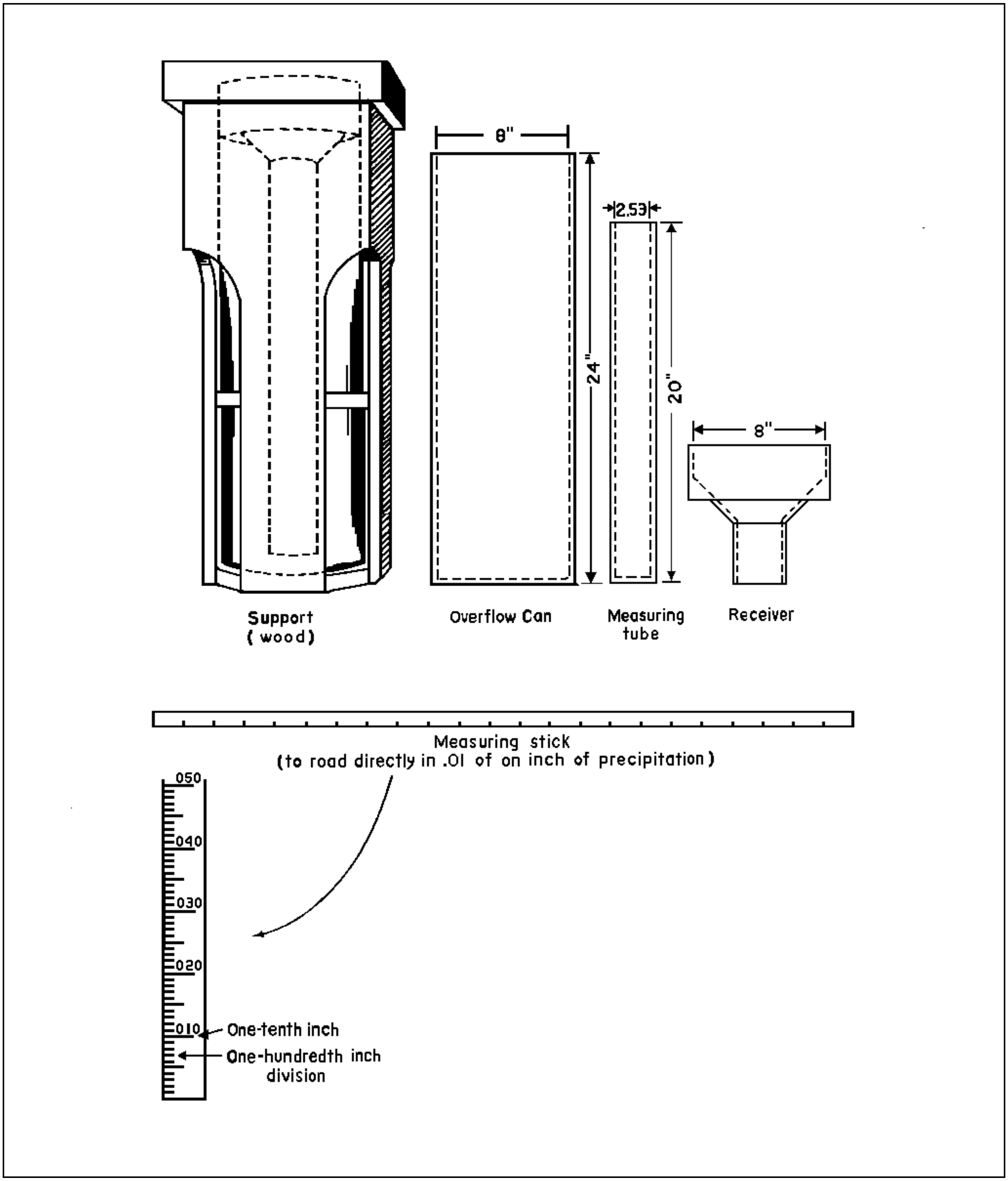


Figure 4-1. Nonrecording gauge, 8-in. opening (U.S. Weather Bureau standard rain gauge)

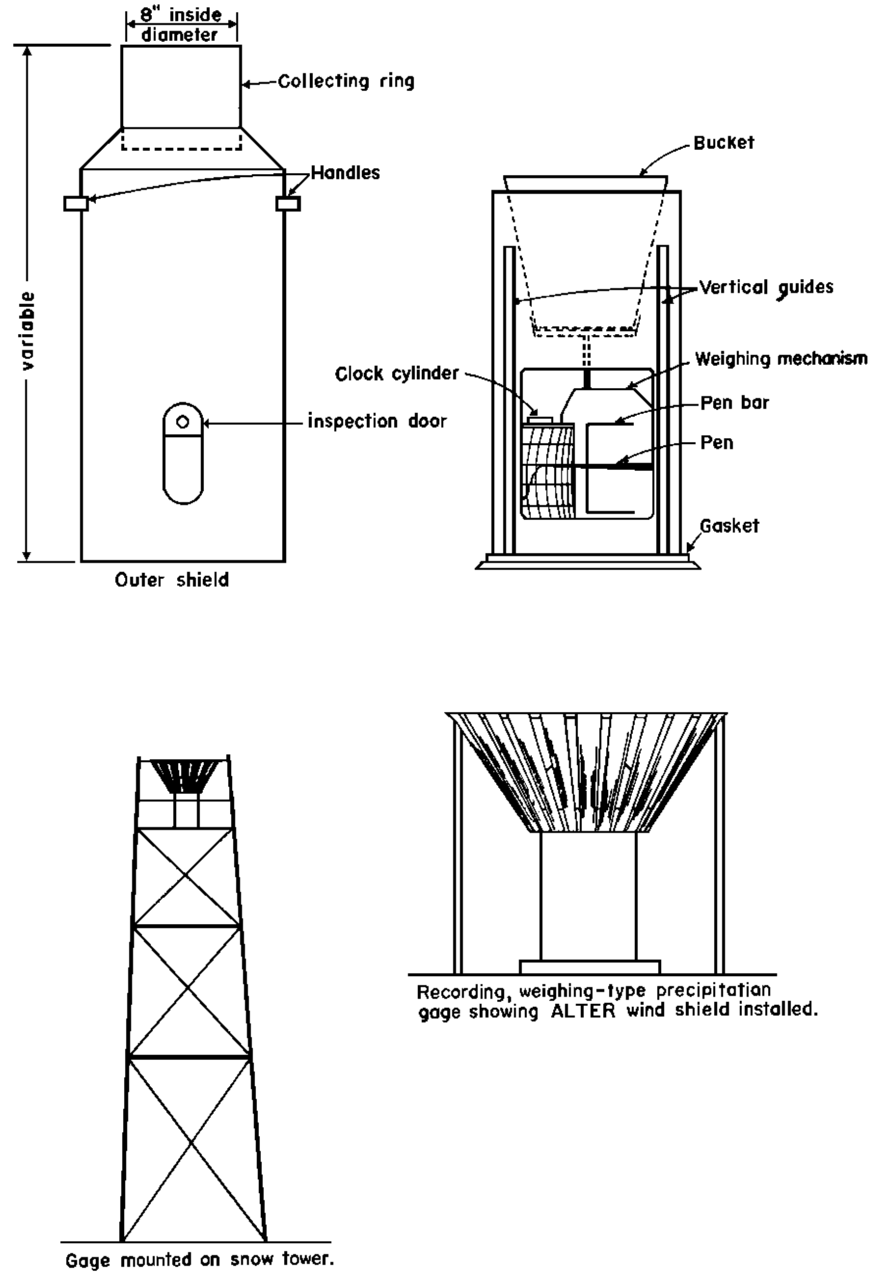


Figure 4-2. Weighing type recording rain gauge (from U.S. Weather Bureau source)

speed of light. As the pulses encounter raindrops (or other objects), the signal is partially reflected towards the antenna. The power and timing of the received signal (or echo), relative to the transmitted signal, are related to the intensity and location of rainfall.

c. Weather radars generally employ electromagnetic pulses with a fixed wavelength of between 3 and 20 cm. A radar with a shorter wavelength is capable of detecting fine rain particles, but the signals will be absorbed or attenuated when they encounter larger storms. A longer wavelength radar will have little signal attenuation, but it cannot detect low-intensity rain.

d. Doppler radars can detect a "phase shift" (a slightly different frequency of the pulse than when transmitted) of a returned pulse. The velocity of the atmospheric particles which reflected the pulse can be calculated from this phase shift. This information is very important in detecting and predicting severe storm phenomena such as tornados but is not generally useful in computing rainfall intensity.

e. The rainfall rate "R," can usually be computed from the reflectivity "Z," which is related to the amount of power in the returned pulse, using the formula:

$$Z = 200 * R^{1.6}$$

where

Z = reflectivity, measured in units of mm^6/m^3

R = rainfall rate, given in mm/hr

The constant (200) and the exponent (1.6) vary depending on the size and type of precipitation encountered. If hail or snow are encountered by the pulse, the reflectivity will be much higher than that for rain.

f. There are several factors which can cause erroneous rainfall rates to be computed from radar data. The more prevalent problems are:

(1) Anomalous propagation, where atmospheric conditions cause the radar beam to bend toward the earth. The beam may be reflected by the ground or objects near the ground, producing false echoes and indicating rainfall (usually heavy) where there are none. Anomalous propagation can be screened by using cloud cover information from satellites or from a knowledge of the atmospheric conditions in the area.

(2) Incorrect parameters in the reflectivity-rainfall rate formula (or "Z-R relation"). The parameters given have been determined for "typical" rainfall drop size distributions, and may vary considerably, depending on the storm. Also, if the beam encounters other types of precipitation, such as snow or hail, these parameters would greatly overestimate the rainfall amount if not modified to match the precipitation type.

(3) Attenuation is the reduction in power of the radar pulse as it travels from the antenna to the target and back and is caused by the absorption and the scattering of power from the beam. Attenuation from precipitation usually appears as a "V" shaped indentation on the far side of a heavy cell and causes the rainfall to be underestimated in this region.

(4) Evaporation and air currents that cause the rainfall rate in the atmosphere, measured by the radar are different than the rate at ground level. Evaporation is the most prominent at the leading edge of a storm, when the air mass near the surface is relatively dry.

(5) Hills and buildings near the radar site can reflect the beam and cause ground clutter. This clutter may also reduce the effectiveness of the radar for areas beyond these objects. Typically, a weather radar is ineffective within a 15- to 20-mile radius.

g. The effect of these factors is that rainfall amounts computed for an area with radar data will typically be inaccurate. However, rain gauge data can be combined with the radar data to estimate rainfall amounts that are superior to either radar or rain gauge data alone. It should be noted that a correct method must be applied when combining the two data sets, or the combined set may be more erroneous than either set alone.

h. In a joint effort of the Department of Commerce, the Department of Defense, and the Department of Transportation, NEXRAD (Next Generation Weather Radar) was developed. The NEXRAD system will incorporate approximately 175 10-cm Doppler radars across the United States. NEXRAD will provide many meteorological products, including several precipitation products. One of the main graphical products is a 1- or 3-hour accumulation of rainfall, displayed on a 2- by 2-km grid to a range of 230 km from the radar site. An important hydrological product is the digital array of hourly accumulations. This product gives rain gauge adjusted rainfall amounts for a 4- by 4-km grid for the area covered by a single NEXRAD radar. Another product "mosaics" the digital products from different NEXRAD sites together, to produce a single-digital rainfall array over a watershed. These digital products can be used as input to rainfall-runoff models for improved results in forecasting or in traditional hydrologic studies.

i. Environmental satellites, such as the GOES system, can provide rough estimates of precipitation over a region. Such satellites cannot measure precipitation directly, but can measure spatial cloud cover and cloud temperature. The approximate height of the top of clouds can be calculated from the temperatures measured by the satellite. The colder a cloud is, the higher the top of the cloud is. In general, clouds with higher tops will yield more precipitation than those with lower tops. If the cloud temperature satellite image is correlated with a rain gauge on the ground, an approximate spatial distribution of the rainfall amounts in that area can be estimated. However, rain gauge data alone provide a more accurate measurement of rainfall over an area than that which is estimated with satellite and gauge data.

j. Satellites can be useful in estimating rainfall amounts in regions where little or no rain gauge data are available, such as areas in Africa. In these regions, estimates of rainfall may be calculated for hydrologic studies, such as sizing a dam, using satellite data (which may have many years of data recorded) when there are no rain gauge data available.

4-4. Areal and Temporal Distribution of Rainfall Data

a. Network density and accuracy. For the application of point rainfall data to a rainfall-runoff calculation, a basin average rainfall must first be determined.

(1) This need raises the question about a proper density of rain gauges (recording and/or nonrecording gauges per square mile of drainage area.) No definite answer exists for this question. Adequate coverage is related to the normal variation in rainfall for a specific region. If thunderstorms account for a major source of rainfall in the specific area, an even denser network of rain gauges is needed.

(2) Average density in the United States is about one gauge for every 250 to 300 square miles. Studies have shown that with this density, a standard error of about 20 percent for a 1,000-square-mile basin is expected if thunderstorms are the major source of precipitation. As shown in Figure 4-3, four times the average density of gauges is required to reduce the error of measurement by 10 percent. These results are derived from data in the Muskingum River basin in Ohio. Mountainous terrain requires a denser network for the same level of error, and plains require a less dense network. If the major source of rainfall is the frontal-type storm pattern, rainfall variations are less than from thunderstorms and less dense gauge networks will suffice.

b. Areal distribution. Several methods are available and routinely used to calculate basin average rainfall from an assumption of areal (i.e., spatial) distribution using point rainfall from a gauge network. The most common, useful method is the Thiessen Polygon.

(1) The Thiessen method weighs each gauge in direct proportion to the area it represents of the total basin without consideration of topography or other basin physical characteristics. The area represented by each gauge is assumed to be that which is closer to it than to any other gauge. The area of influence of each gauge is obtained by constructing polygons determined by drawing perpendicular bisectors to lines connecting the gauges as shown in Figure 4-4a.

(2) The bisectors are the boundaries of the effective area for each gauge. The enclosed area is measured and converted to percent of total basin area. The polygon weighted rainfall is the product of gauge rainfall and the associated polygon area in percent. The sum of these products is the basin average rainfall.

(3) The Thiessen method is usually the best choice for prairie states during thunderstorms, since elevation differences (topographic) are insignificant and gauge density is inadequate to use other methods to define the areal pattern of the thunderstorm cells. When analyzing several storm events having different gauges reporting for each event, the Thiessen method becomes more time-consuming than other techniques to be discussed.

(4) Another popular method is the Isohyetal method, which provides for consideration of topographic effects and other subjective information about the meteorological patterns in the region. A rainfall-depth contour map is determined by tabulating gauge rainfall on a map of the region and constructing lines of equal rainfall called isohyets as shown in Figure 4-4b. Average depths are obtained by measuring the areas between adjacent isohyets (zones). Each increment of area in percent of total basin area is multiplied by the estimated rainfall depth for that area. This product for each zone is summed to obtain the basin average rainfall.

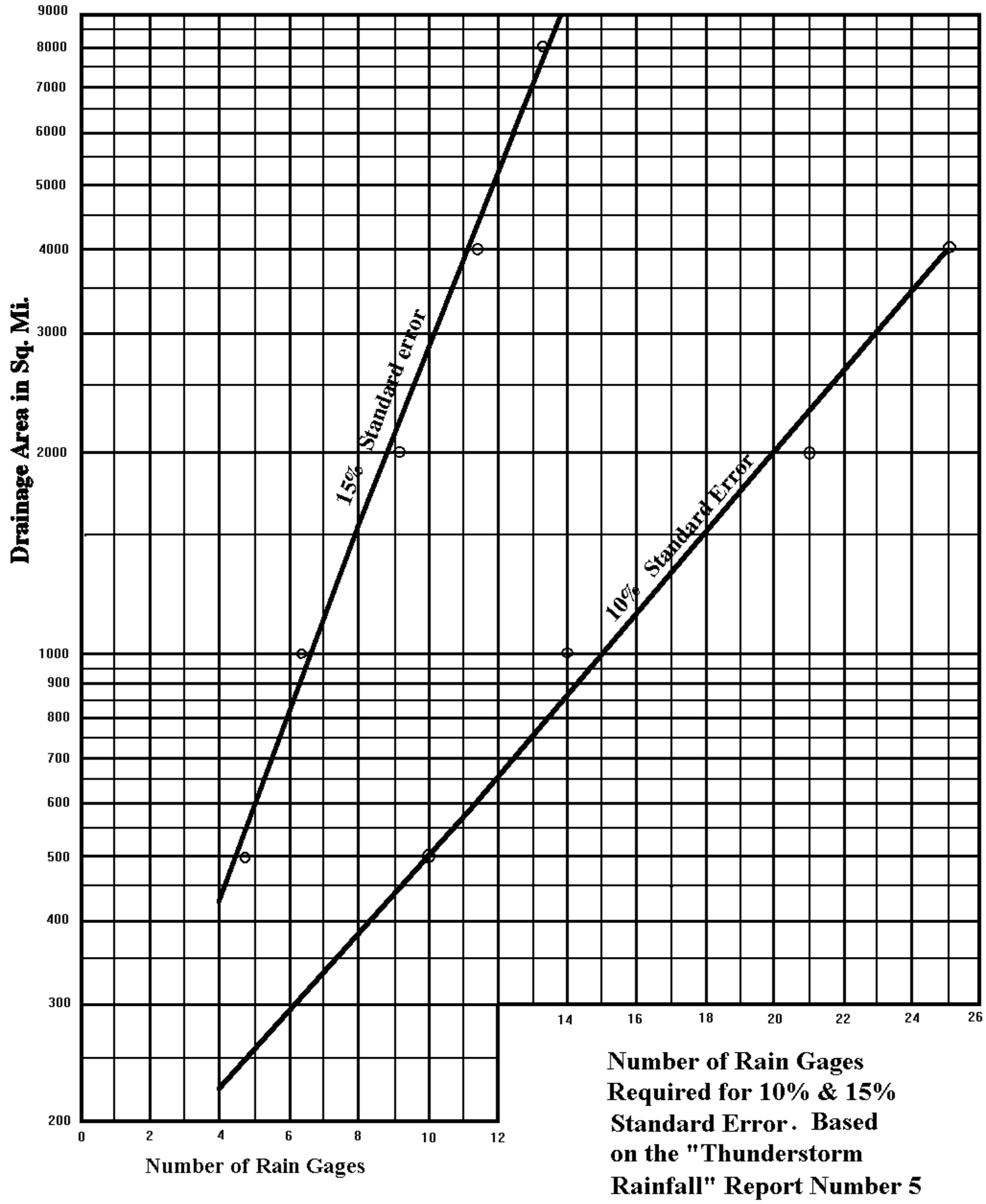
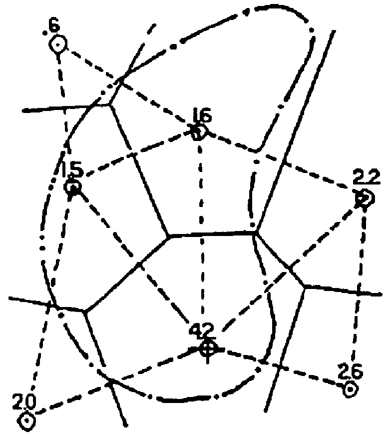
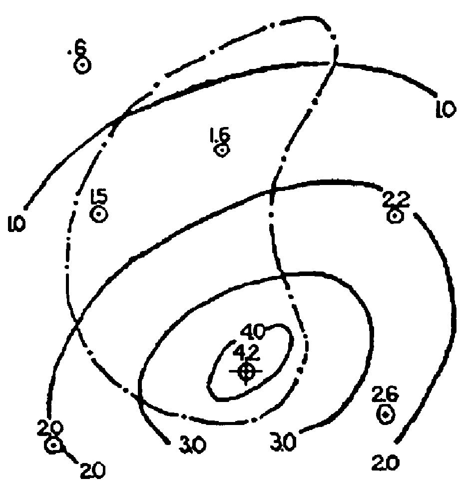


Figure 4-3. Number of rain gauges required for 10 and 15 percent error (U.S. Department of Commerce 1947)



Observed Rainfall (inches)	Polygon (units)	Area (%)	Weighted Rainfall (inches)
.6	2	1	.0
1.5	77	24	.4
1.6	132	40	.6
2.0	4	1	.0
4.2	112	34	1.4
	327	100	2.4

a. THIESSEN POLYGON METHOD



Isohyet Zones	Enclosed (units)	Area (%)	Average Zone Rainfall (inches)	Weighted Rainfall (inches)
>4.0	19	6	4.2	.2
3.0-4.0	60	18	3.5	.6
2.0-3.0	87	27	2.5	.7
1.0-2.0	139	42	1.5	.6
<1.0	22	7	.9	.1
	327	100		2.2

b. ISOHYETAL METHOD

Figure 4-4. Basin average rainfall analysis techniques

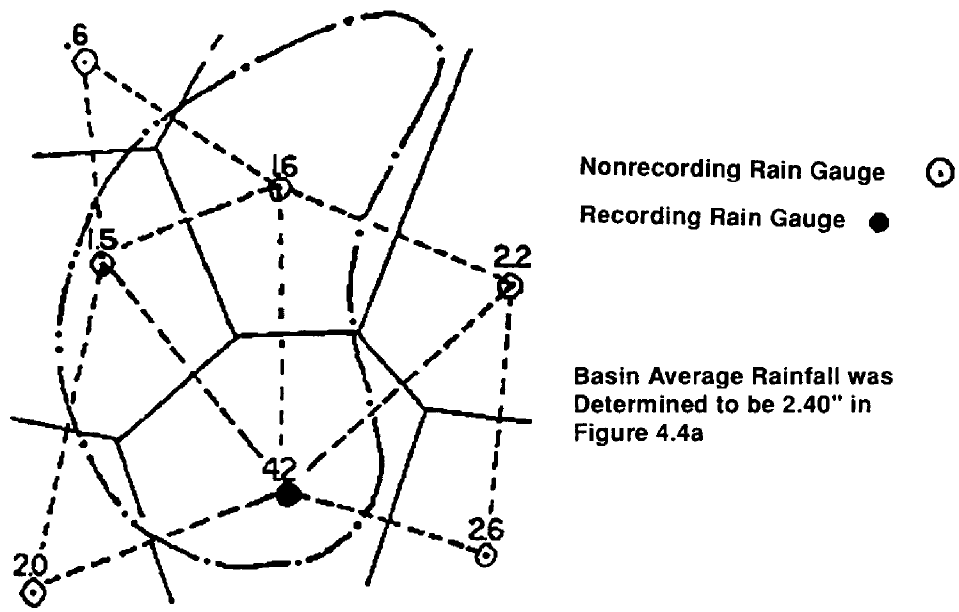
(a) The Isohyetal method allows the use of judgment and experience in drawing the contour map. The accuracy is largely dependent on the skill of the person performing the analysis and the number of gauges. If simple linear interpolation between stations is used for drawing the contours, the results will be essentially the same as those obtained by the Thiessen method.

(b) The advantages of both the Thiessen and Isohyetal methods can be combined where the area closes to the gauge is defined by the polygons but the rainfall over that area is defined by the contours from the Isohyetal method. This combination also eliminates the disadvantage of having to draw different polygon patterns when analyzing several different storm events with a variety of reporting gauges. Regardless of the technique selected for analysis of basin average rainfall, a regional map of areal distribution for the total storm event is also produced.

c. Temporal distribution. Having already determined basin average rainfall, one or more recording gauges in or near the watershed of interest must be located and used as a pattern to estimate the temporal (i.e., time) distribution of the basin average rainfall.

(1) If only one recording gauge is available, it must be assumed that the temporal distribution of the total storm rainfall at the recording gauge is proportional to the basin average rainfall distribution. The calculations necessary to perform this evaluation are shown in Figure 4-5.

(2) If more than one recording gauge is available, a weighted average combination distribution can be tabulated and used in the same manner as the distribution at a single gauge. Caution should be used when utilizing more than one recording gauge to develop the temporal distribution of a storm event. If the event is a short-duration, high-intensity storm and the timing of the center of mass of the rainfall is different between the gauges, traditional averaging can often result in a storm of longer duration and much lower intensities than what was recorded at each of the gauges. If this is the case, it is often better to use the recording gauge that is closest to the center of mass of the subbasin as the temporal distribution, and only utilize the other gauges in estimating the average depth of rainfall over the subbasin.



Time (hrs)	Recorded Rainfall (inches)	Incremental Rainfall (%)	Time Distribution of Basin Average Rainfall (2.4")*
0700	0.0	0	.0
0800	0.4	10	0.2
0900	1.0	24	0.6
1000	0.8	19	0.5
1100	1.4	33	0.8
1200	0.6	14	0.3
TOTALS	4.2	100	2.4

* Developed by multiplying the percent of rainfall (divided by 100) occurring at each time period at the recording gauge by the basin average rainfall (i.e., 2.4 in.).

Figure 4-5. Time distribution of basin average rainfall