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3

Precipitation

Precipitation describes all forms of liquid and solid water that falls from the atmosphere and reaches the earth's surface. Familiar examples such as rain, snow, sleet, and hail make precipitation one of the most recognized portions of the hydrologic cycle. Identification and or prediction of the intensity, duration, and frequency of precipitation events are important aspects of most environmental engineering applications.

Description

3.1 Formation of Precipitation

Condensation is the conversion of water from a vapor into a liquid. For condensation to occur, air must be cooled to the dew point temperature. The primary means of cooling for precipitation events is vertical uplift, which includes a drop in temperature and pressure. As air rises, it is cooled at the dry adiabatic lapse rate of 1°C/100 m. Once condensation begins, latent heat is produced and the temperature will decrease at the moist adiabatic lapse rate, which varies with temperature, vapor pressure, and elevation, but is approximately one-half of the dry rate (0.5 to 0.7°C/100 m). The cooling can also occur by mixing with a cooler body of air, conduction to a cool surface, or a lowering of atmospheric pressure.

Typically, warm moist air rises in the atmosphere and is cooled. As the air is cooled, its capacity to hold water vapor decreases (see Chapter 4 concerning saturation vapor pressure). After sufficient cooling, the air mass becomes saturated, but raindrops may not form. In order for raindrops to form, water molecules must be attracted to and condense onto particles called cloud condensation nuclei (CCN) (Dingman, 1994). Natural sources of CCN are windblown clay and silt particles, smoke from fires, volcanic materials, and sea salt. Cloud seeding is sometimes used during a drought to add CCN to the atmosphere to promote condensation.

The final component of the precipitation event is a lateral supply of moist air to the storm center. If all of the moisture in the earth's atmosphere were to condense and fall, a depth of about 25 mm of water would be added to the earth's surface (Dingman, 1994). For storms to produce significant amounts of precipitation, it is necessary for lateral flow to occur, which supplies much of the water for a rainfall event. One of the primary limitations to cloud seeding is the lack of a lateral source of moist air to sustain the precipitation event.

Warm air can rise as a result of convection, convergence, and topography. When the soil surface warms up very rapidly, the temperature of the adjacent air layer is increased and the density is decreased making the air lighter. The lighter air can rise to great heights to form billowing thunder clouds. Precipitation from clouds formed by this process is called convective precipitation. Intensities can range from low to very high, even within a single rainfall event.

Uneven heating or cooling of the earth's surface causes air masses to move. The movement is usually associated with the mixing of low pressure and high pressure air masses (Figure 3.1). The convergence of these air masses causes significant mixing of the air fronts (boundaries between air masses). The convergence can occur either with cold fronts, warm fronts, or stationary fronts. A cold front (cooler and denser air) lifts the warm moist air ahead of it. When the air rises, it condenses, and forms showers and thunderstorms. When a warm front (warmer and less dense air) encounters colder air, it moves up and over the colder air ahead of the front. Since the warm front movement is generally slower than a cold front, when condensation takes place, preci-

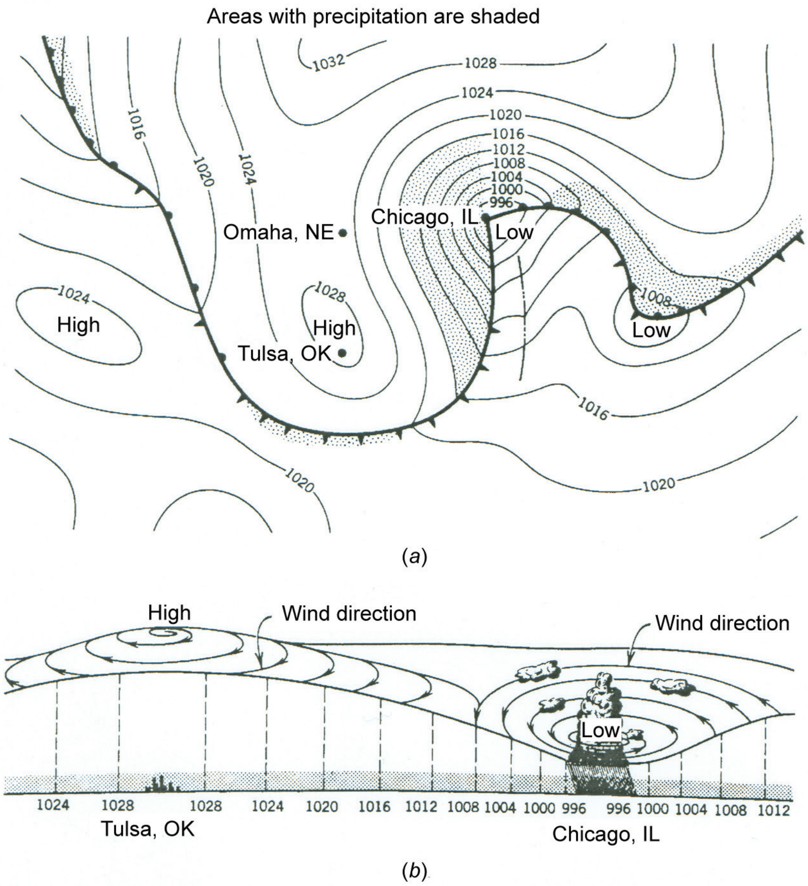


Figure 3.1–(a) Portion of a weather map in April showing cloudy weather in the East, rain in Chicago, and clear skies in the Southwest. (b) Wind circulation around the high pressure center (clockwise) at Tulsa and a low pressure center (counter-clockwise) at Chicago.

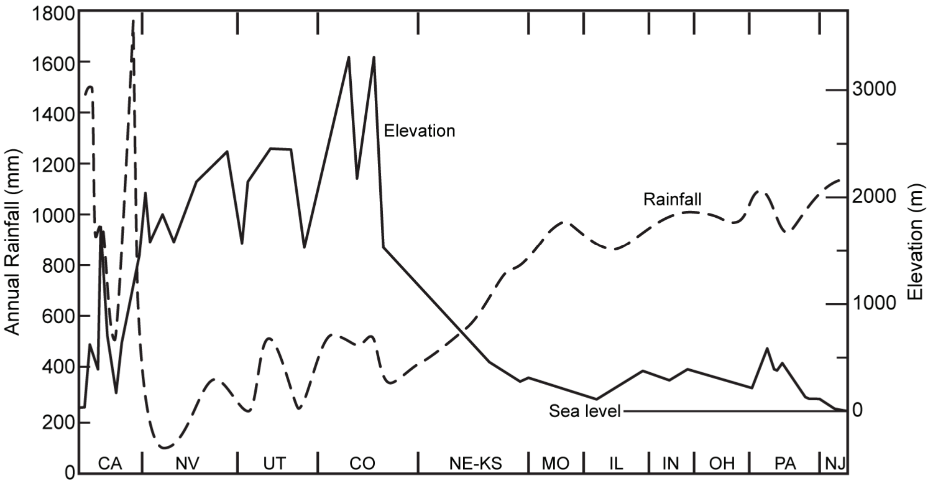


Figure 3.2–Average annual rainfall and elevation across the United States along the 40th parallel of latitude.

pitation is typically steady and widespread. Sometimes, a stationary front can form with little movement of the air masses. Instabilities near the front cause vertical uplift, cooling, and precipitation. Precipitation events caused by the convergence of fronts is called cyclonic or frontal precipitation.

Warm air may also be lifted up when it encounters and moves over high topographic surfaces such as mountain ranges. The air is lifted and cooled as it moves. In the United States, this process contributes to precipitation mostly on the western side of the mountain ranges (Figure 3.2), because the prevailing wind direction is generally from west to east. Precipitation caused by the uplift over topographic surfaces is called orographic precipitation. Once the air mass has moved over the mountains, it will be very dry, causing arid conditions to prevail on the downwind side.

3.2 Characteristics of Precipitation

The largest portion of precipitation occurs as rain, and because rainfall directly affects soil erosion, the characteristics of raindrops are of interest. Raindrops include water particles as large as 7 mm in diameter. The size distribution in any one storm covers a considerable range and varies with the rainfall intensity. Storms with higher rainfall intensity produce large-diameter raindrops and a wider range of raindrop diameters.

Raindrops are not necessarily spherical in shape. Falling raindrops can be deformed from a spherical shape because of pressure difference and air resistance. Large raindrops (>5 mm in diameter) are generally unstable and split in the air.

The velocity of fall for raindrops depends on their sizes, with larger drops falling more rapidly. As the height of fall increases to about 11 m, the velocity also increases ; the drops then approach a terminal velocity, which varies from about 5 m/s for a 1-mm drop to about 9 m/s for a 5-mm drop.

Precipitation may also occur as frozen water particles, including snow, sleet, and hail. Snow is a grouping of ice crystals. Sleet forms when raindrops fall through air having a temperature below freezing. A hailstone is an accumulation of many thin layers of ice over a snow pellet. Of the forms of precipitation, rain and snow make the greatest contribution to our water supply.

Direct condensation from the atmosphere near the earth surface, commonly referred to as dew, can also contribute to water at the soil surface. Studies of dew formation show that about 30 mm per year condenses on bare soil, 25 mm on a grass cover, 15 mm on corn leaves during the summer, and 33 mm on soybean leaves. Although dew is normally evaporated by noon, it helps to reduce the rate of soil water depletion. An important contribution to the hydrologic budget of western forests is fog drip, which is the result of fog condensing on the leaves and branches of trees overnight and dripping to the ground. In some places, such as the coastal forests of California, more than 50% of the annual water budget is produced from fog drip. Orographic cooling can also result in fog drip as the clouds contact the trees in higher elevations.

3.3 Time Distribution

The time of day at which precipitation may be expected to occur depends on the type of precipitation. Frontal and orographic storms are not influenced by diurnal effects. Since storms of the convective type are caused by surface heating, these storms are more likely to occur in the afternoon and early evening.

Rainfall distribution at any location varies greatly with the season. A considerable difference in the seasonal distribution of precipitation throughout the United States is shown in Figure 3.3. On the West Coast, where annual precipitation is high, summertime precipitation is generally very low, making irrigation necessary. In the Midwest and the South, the monthly precipitation in summer is generally somewhat higher than in the other seasons. On the East Coast, there is little difference between summer and winter precipitation.

The annual rainfall distribution over the United States is shown in Figure 3.4. Annual rainfall amounts vary from less than 100 mm in some southwestern areas to over 2500 mm in some mountainous areas. Annual precipitation is not in itself a good index of the amount of water available for plant growth because evaporation, seasonal distribution, and water-holding capacity of the soil vary with geographical location. The PRISM Climate Group at Oregon State University provides access to a wide range of climate parameters (see Internet Resources).

There are some indications that precipitation occurs in cycles; however, relationships between such cycles and other natural phenomena are yet to be established. The effects of natural phenomena such as the El Niño Southern Oscillation and potential global warming on precipitation cycles are being investigated. Some evidence exists that sunspot activity is related to summer temperature and severe droughts. Thompson (1973) showed that average July-August temperatures in the Corn Belt of the United States since 1900 follow about a 20-year cycle of sunspot numbers. Similar observations have been made in other countries at the same latitudes.

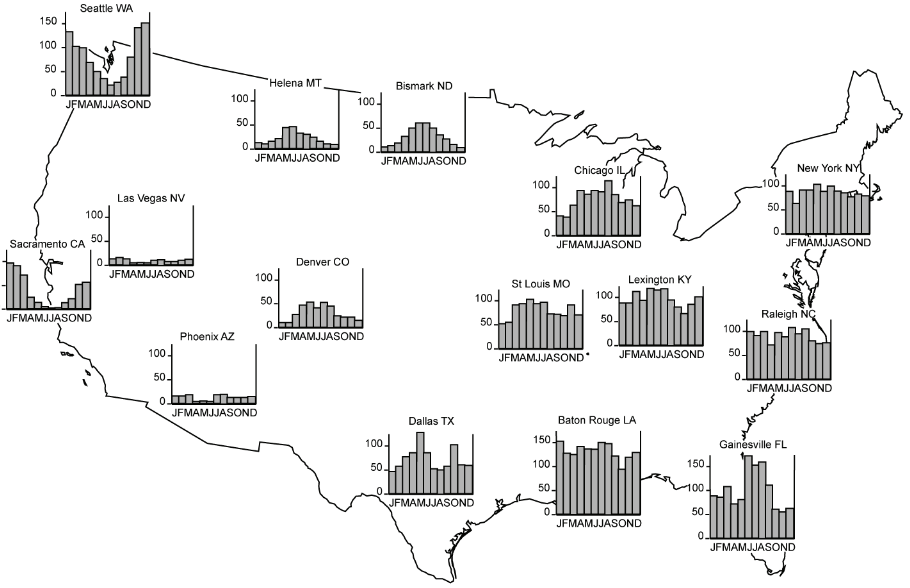


Figure 3.3–Mean (1971-2000) monthly precipitation (mm) for selected locations in the United States.

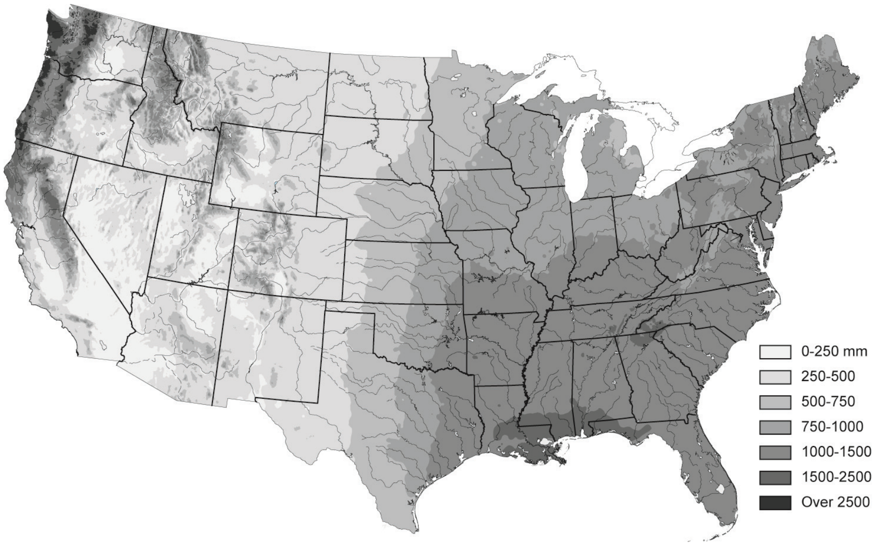


Figure 3.4–Average annual precipitation in the United States in mm, 1961-1990. (Adapted from nationalatlas.gov, 2011.)

3.4 Geographic Distribution

The geographical distribution of rainfall is largely influenced by the location of large bodies of water, movement of the major air masses, and changes in elevation. Figure 3.2 illustrates the effects of elevation and air-mass movement on annual rainfall across the United States along the 40th parallel of latitude. Moving from west to east in Figure 3.2, one can notice that the highest rainfall occurs as the air initially rises over the western mountains (orographic precipitation). The dry air provides some additional precipitation as the air masses rise to higher elevations near the Rocky Mountains. As the air moves down the mountain slopes, lower annual rainfall is generally observed. The rainfall does not increase until the effects of the maritime tropical air moving up from the Gulf of Mexico become apparent. Then the rainfall gradually increases toward the eastern boundary of the United States because of the orographic effects of the Appalachian Mountains and the increased moisture along the Atlantic Ocean.

Measurement of Precipitation

Since most estimates of runoff rates are based on precipitation data, information regarding the timing and quantity of precipitation is of great importance.

3.5 Measuring Rainfall

Rain gauges are used to measure the depth and intensity of rain falling on a flat surface. Rain gauges generally used in the United States are vertical, cylindrical containers with top openings 203 mm in diameter. A funnel-shaped hood is inserted to minimize evaporation losses. Problems associated with rainfall measurements with gauges include effects of topography and nearby vegetation, buildings, and other structures.

Rain gauges may be classified as recording or nonrecording. Nonrecording rain gauges are economical, requiring service only after a rainy day, and are relatively free of maintenance. The gauges are generally read on a daily basis to obtain daily rainfall; however, they do not provide rainfall intensity data or the exact time of rainfall.

Recording rain gauges may be of several types. The weighing type accumulates water in a container placed above the recording mechanism. The weight of the water creates tension on the spring. The amount of displacement is recorded electronically or through an appropriate linkage to a chart placed on a clock-driven drum. Another commonly used recording type of rain gauge is the tipping bucket instrument. In this rain gauge, precipitation is funneled to a tipping bucket assembly. The assembly has two rain collection compartments balanced on a fulcrum, each of which can hold a known increment of precipitation. Precipitation is directed to one of the compartments. When that compartment is filled to capacity, it tips to the opposite position bringing the other compartment in place to collect the precipitation. The movement momentarily activates a magnetic switch and sends a signal to a data logger.

Radar measurement of cloud density and rainfall rate is now common. NEXRAD (Next Generation Radar) or Doppler radar works by sending out a pulse of energy and measuring the portion of emitted energy that is reflected back to the radar after striking the raindrops in its path. Computers analyze the strength of the returned pulse and the phase shift of the pulse to determine the direction and magnitude of the storm. A network of ground-based radars and weather surveillance satellites covers most parts of the continental United States. The National Weather Service (NWS) makes these data available to the public in both image (weather maps) and original coded forms. Weather maps and other information on satellite rainfall data can be obtained from the NWS via the Internet.

3.6 Measuring Snowfall

Since the water content of freshly fallen snow varies from less than 40 mm to over 400 mm of water per meter of snow, snowfall is much more difficult to measure than rainfall. Although this wide variation in density makes it difficult to indicate the amount of snow by simple depth measurements, a water equivalent depth of 10% of snow depth is commonly accepted. Water content of compacted snow, however, is often 30 to 50% of snow depth.

Snowfall measurements are often made with regular rain gauges, the evaporation hood having been removed. A measured quantity of some noncorrosive, nonevaporative, environmentally benign, antifreeze material is generally placed in the rain gauge to cause the snow to melt upon entrance. Errors caused by wind are more serious in measuring snowfall than in measuring rain. Snow may also be measured by sampling the depth on a level surface with a metal sampling tube or with the top of the rain gauge.

Another method of measuring snowfall is by determining the depth of snow by a snow survey. Such surveys are particularly useful in mountainous areas. These snow courses consist of ranges that are sampled at specified intervals. The sampling equipment consists of specially designed tubes that take a sample of the complete depth of the snow pack. The sample is then weighed and the equivalent depth of water recorded.

By measuring the snow courses for a period of years and comparing the equivalent water depth with the observed runoff from the snowfield, watershed managers can make predictions of the amount of runoff. Aerial snow surveys can be made by photographing depth gauges or by picking up radio-transmitted signals from depth-measuring equipment. Such devices are set up on snow ranges at suitable locations. These predictions are of particular value in planning for irrigation needs and forecasting the probability of spring floods.

3.7 Errors in Rain Gauge Measurement

Many errors in precipitation measurement result from carelessness in handling the equipment and in analyzing data. Errors characteristic of the nonrecording rain gauges include water creeping up on the measuring stick, evaporation, leaks in the funnel or can, and denting of the cans. The volume of water displaced by the measuring stick is about 2% and may be taken as the correction for evaporation.

Another type of error is caused by obstructions such as trees, buildings, and uneven topography. These errors can be minimized by proper location of the rain gauge. The gauges are normally placed with the opening about 760 mm above the soil surface. The location should have minimum turbulence of the wind passing across the gauge. The NOAA standard requires that the distance from the obstruction to the gauge be at least twice the height of the obstruction (U.S. Dept. of Commerce, 1994).

The wind velocity also affects the amount of water caught in a rain gauge. A wind velocity of 16 km/h would cause a deficit catch of about 17%, but at 48 km/h the deficit is increased to about 60%. Whenever possible, the gauge should be located on level ground as the upward or downward wind movement may easily affect the amount of precipitation caught.

3.8 The Gauging Network in the United States

Precipitation records have been kept in the United States ever since it was settled; the recording rain gauges that provide the intensity of precipitation have been used since about 1890. Rain gauges have steadily increased in number since then; the gauging network in the United States now consists of about 11 000 nonrecording and 3500 recording instruments. Volunteers service many of the nonrecording gauges; most of the recording equipment is connected with local, state, or federal installations. The results of these extensive gauging activities are published online by the National Oceanic and Atmospheric Administration (NOAA).

Effective Rainfall Depth for a Watershed

Many instances require the rainfall depth over a large watershed to be computed. The watershed may include several rain gauges that are unevenly distributed over the area. A simple arithmetic mean of the precipitation totals can be used to represent the precipitation for the watershed, but methods that account for the area represented by each rain gauge will generally provide a better estimate of the precipitation. Two of the most widely accepted techniques to compute average precipitation depth are the Thiessen Polygon method and the Isohyetal method.

3.9 The Thiessen Polygon Method

The Thiessen method is illustrated in Figure 3.5. For this method, the locations of the rain gauges are plotted on a map of the watershed and connected with straight lines. Perpendicular bisectors are then drawn on each of the straight lines and extended in such a way that the bisectors enclose areas referred to as Thiessen polygons. All points within one polygon will be closer to its rain gauge than to any of the others. The rain recorded from the rain gauge within a polygon is considered to represent the precipitation within the polygon area.

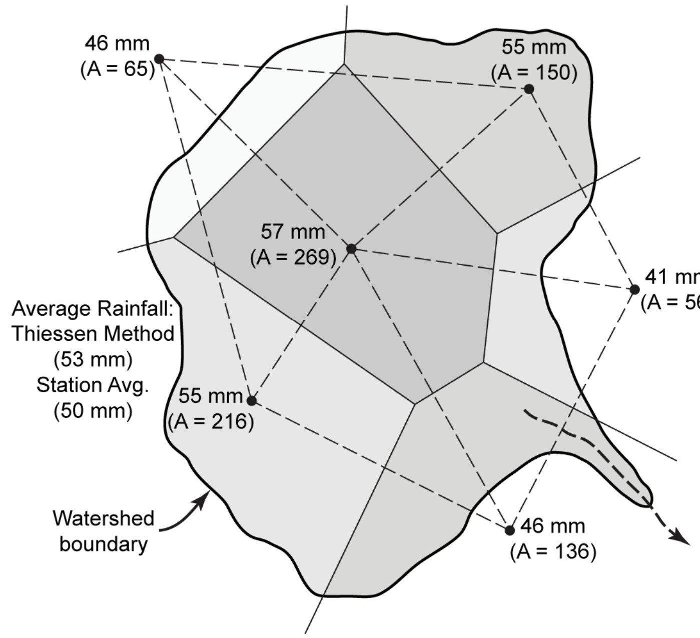


Figure 3.5–Theissen network for computing average rainfall depth over a watershed.

Some difficulty may be encountered in determining which connecting lines to construct in forming the sides of the polygon. Since only one set of Thiessen polygons generally needs to be drawn for a given watershed and a set of rain gauge locations, this procedure does not present a serious limitation. The mean precipitation over a watershed can be determined by using the equation

$$P = \frac{A_1 P_1 + A_2 P_2 + \cdots + A_n P_n}{A} \tag{3.1}$$

where P represents the average depth of rainfall in a watershed of area A, and P_1, P_2, …, P_n represent the rainfall depths from rain gauges within the polygon having areas A_1, A_2, …, A_n within the watershed. The areas A_1, A_2, …, A_n can be determined by using a digitizer or a planimeter.

Example 3.1

A storm on the watershed illustrated in Figure 3.5 produces rainfall at the various gauge locations as indicated. Compare the mean precipitation as determined by the arithmetic mean and the Thiessen polygon methods.

Solution. By the arithmetic mean method, the mean precipitation depth is

$$\frac{(46+55+57+41+55+46)}{6} = 50 \text{ mm}$$

By the Thiessen polygon method, the areas represented by the polygons surrounding each rain gauge are determined and substituted in Equation 3.1.

$$P = \frac{(65\times46)+(150\times55)+(269\times57)+(216\times55)+(56\times41)+(136\times46)}{892} = 52.7\text{ mm}$$

3.10 Isohyetal Method

The isohyetal method consists of recording the depths of rainfall at the locations of the various rain gauges and plotting isohyets (lines of equal rainfall) by the same methods used for locating contour lines on topographic maps. The areas between isohyets may then be measured with a digitizer or a planimeter, and the average rainfall determined by using Equation 3.1. The choice of analysis method depends partly on the area of the watershed, the number of rain gauges, the distribution of the rain gauges, and in some situations, the characteristic of the rainstorm.

Design Storms

Historical precipitation data can be used to estimate the likelihood of future storm events. The rainfall intensity i (L/T) or rainfall depth are characteristics of the rainfall event that are generally required for design purposes. Storms of high intensity generally have fairly short durations and cover small areas. Storms covering large areas are seldom of high intensity but may last several days. The infrequent combination of relatively high intensity and long duration storms produces large total amounts of rainfall. These rainfalls are generally associated with a slow moving warm front or the development of a stationary front and can cause significant erosion damage and devastating floods.

Statistical methods are used to analyze the rainfall records to determine the magnitude of storm events for specific return periods (Haan et al., 1994)). The return period is sometimes called recurrence interval or frequency of the rainfall event. The relationship between return period T in years and probability of occurrence P can be expressed by:

$$T = 100/P \tag{3.2}$$

The probability of occurrence is the probability in percent that an event equaling or exceeding a given event will occur in a given year.

3.11 Frequency Analysis

If long term precipitation data are available, a frequency analysis can be conducted to quantify precipitation uncertainty. A rainfall record of at least 20 years is recommended for a statistically representative sample (Serrano, 1997). For best results, the length of record should be greater than the design life of the structure (Serrano, 1997).

Data for hydrologic frequency analysis can be selected by two methods: the annual series and the partial-duration series methods. In the annual series method, only the largest single storm event for each year is selected for the analysis. Thus, for 20 years of record, only 20 values would be analyzed, regardless of whether multiple large events occurred during a particular year. With the partial-duration series method, all values above a given base value are chosen regardless of the number of events within a given period, or the largest *N* events in *N* years are selected. The partial-duration series method is applicable when the second-largest event value of the year would affect the design. An example is the design of drainage channels where significant damage may result from flooding caused by flows lower than the annual peak flow rate. The annual and partial duration series methods give essentially identical results for return periods greater than 10 to 25 years. For shorter return periods, the partial duration series method gives a larger value.

Regardless of the method of selecting the data, the values must satisfy two important criteria: (1) each event is independent of a previous or subsequent event, and (2) the data for the period of record for analysis is representative of the long term record. The first criterion is necessary for statistical analysis, and the second criterion ensures that the predicted values will reflect the pattern of occurrences from the period of record. When the data are obtained from the highest annual values, the number of observations during the year should be large. Selection of a water year, such as October 1 to September 30, rather than the calendar year has proved beneficial for some types of applications.

Although it is possible to extend the analysis to predict return periods greater than the length of record, the selection of an appropriate probability distribution function becomes important (Haan et al., 1994). One of the most versatile probability distributions is the Weibull distribution because it can be used to approximate exponential, normal, or skewed distributions (Weibull, 1951).

The Weibull cumulative distribution function *P(x)* is:

$$P(x) = e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \tag{3.3}$$

where *P(x)* = Weibull cumulative distribution function,
x = rainfall depth (L),
α = characteristic depth (L),
β = shape parameter.

The parameters α and β can be determined by linear regression. Equation 3.3 can be algebraically manipulated to:

$$\log_e\left[\log_e\left(\frac{1}{P(x)}\right)\right] = \beta \log_e x - \beta \log_e \alpha \tag{3.4}$$

Although it may not be obvious, Equation 3.4 has the familiar form of a line ($y = mx + b$) where the large term on the left side of the equation is y and the natural logarithm of rainfall depth is x. A regression of these will allow the Weibull parameters to be determined.

The first step in the analysis is to rearrange the data in decreasing order of magnitude. The data are assigned a rank m from 1 to N where N is the number of observations. From the ranking, a plotting position (frequency) can be determined by:

$$P = \frac{m - a}{N + 1 - 2a} \tag{3.5}$$

where a is a parameter that depends on the distribution (Bediant and Huber, 2002). The parameter a varies from 0 for the original Weibull formula to 0.375 for normal or lognormal distributions, 0.3 for median ranks, and 0.44 for the Gumbel distribution. Bediant and Huber (2002) recommend 0.4 for a when the distribution is unknown. Once the plotting position P has been determined, the left side of Equation 3.4 can be computed. A linear regression of the left side and the natural logarithm of precipitation produces the slope, which is equivalent to β. The characteristic depth α can be computed from the intercept b of the regression line and slope β as:

$$\alpha = e^{-b/\beta} \tag{3.6}$$

Example 3.2

Determine the Weibull cumulative distribution function for the 20 years of 24-hr rainfall data presented below for Lexington, Kentucky. Estimate the 24-h 10-yr, 25-yr, and 100-yr storms using the distribution.

Year	24-h rainfall (mm)	Year	24-h rainfall (mm)
1984	49.28	1994	60.20
1985	45.47	1995	107.95
1986	38.10	1996	61.72
1987	59.69	1997	141.22
1988	85.85	1998	128.02
1989	78.74	1999	44.20
1990	67.06	2000	55.37
1991	84.33	2001	55.37
1992	126.75	2002	57.15
1993	66.04	2003	52.58

Solution. The rainfall data are rearranged in decreasing order and assigned a rank m in the table below. The rank $m = 1$ is assigned to the largest 24-h rainfall over the 20-year period. Rank $m = 2$ is given to the second highest rainfall, etc. This proceeds until the last rainfall total is given the rank $m = N$, where N is the number of years of record.

The return period is estimated by the plotting position of the ranked series. For $a = 0.4$ in Equation 3.5, the plotting position P is:

$$P = \frac{m - 0.4}{N + 0.2}$$

I (mm)	Rank m	Plotting Position P	$1/P$	$\log_e[\log_e(1/P)]$	$\log_e(I)$
141.22	1	0.029703	33.66667	1.257469	4.950347
128.02	2	0.079208	12.62500	0.930461	4.852155
126.75	3	0.128713	7.769231	0.717923	4.842185
107.95	4	0.178218	5.611111	0.545081	4.681668
85.85	5	0.227723	4.391304	0.391790	4.452625
84.33	6	0.277228	3.607143	0.249136	4.434714
78.74	7	0.326733	3.060606	0.112089	4.366151
67.06	8	0.376238	2.657895	-0.02272	4.205528
66.04	9	0.425743	2.348837	-0.15792	4.190261
61.72	10	0.475248	2.104167	-0.29582	4.122640
60.20	11	0.524752	1.905660	-0.43877	4.097639
59.69	12	0.574257	1.741379	-0.58937	4.089165
57.15	13	0.623762	1.603175	-0.75081	4.045679
55.37	14	0.673267	1.485294	-0.92732	4.014074
55.37	15	0.722772	1.383562	-1.12497	4.014074
52.58	16	0.772277	1.294872	-1.35320	3.962298
49.28	17	0.821782	1.216867	-1.62821	3.897437
45.47	18	0.871287	1.147727	-1.98207	3.816965
44.20	19	0.920792	1.086022	-2.49470	3.788634
38.10	20	0.970297	1.030612	-3.50147	3.640214

A linear regression of the last two columns gives estimates for the slope (2.961) and intercept (-13.058). The slope is β or 2.961, and α can be computed from Equation 3.6 as:

$$\alpha = e^{-b/\beta} = e^{-(-13.058/2.961)} = 82.27$$

Equation 3.3 can be used to determine rainfall values for various return intervals. The frequency for a 10-yr storm can be computed from Equation 3.2:

$$P = \frac{1}{T} = \frac{1}{10} = 0.1$$

Similarly, the frequency for 25- and 100-yr storms is 0.04 and 0.01, respectively. Solving Equation 3.3 for x and substitution of $P = 0.1$ gives the 24-h 10-yr storm depth:

$$x = \alpha\left[-\log_e(P)\right]^{1/\beta} = 82.27\left[-\log_e(0.1)\right]^{1/2.961} = 109 \text{ mm}$$

Likewise, the 24-h 25-yr rainfall is 122 mm and the 24-hr 100-yr rainfall is 138 mm.

3.12 Intensity-Duration-Frequency (IDF) Curves

The design of most hydrologic structures requires knowledge of how frequently storms of specific intensities and durations occur at a particular location. Return periods or frequencies are usually reported as storm events that are expected to occur on average once in 2, 5, 10, 25, 50, or 100 years. Storm duration can be as small as 5, 10, or 15 minutes or for longer periods such as 24 hours, 2 days, or more. A general expression for the relationship between rainfall intensity i for a given duration t and return period T is given by

$$i = \frac{KT^x}{(t+b)^n} \tag{3.7}$$

where K, x, b and n are constants for a given geographic location, and can be determined statistically from rainfall data analyses. Plots of rainfall intensity and storm durations are often constructed for various return periods and are called intensity-duration-frequency (IDF) curves (Figure 3.6). Since rainfall depth is simply the intensity times the duration, depth-duration-frequency (DDF) curves are sometimes plotted. Current estimates of IDF and DDF curves indicate they are not the smooth functions that Equation 3.7 might indicate.

The National Weather Service Hydrometeorological Design Studies Center has developed an interactive Internet site based on the NOAA Atlas 14 publications for producing IDF and DDF data (Bonnin et al., 2003). The site is called the Precipitation Frequency Data Server (PFDS) and allows the user to select a location in the United States for retrieval of either IDF or DDF data. Once a site is selected (from the map, by station, or coordinates) a table of IDF or DDF data is produced (Table 3.1). In addi-

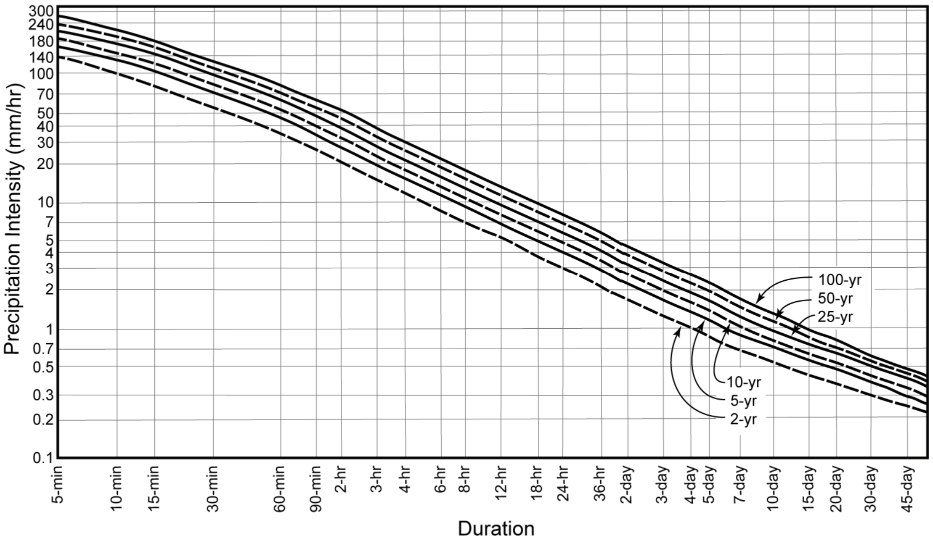


Figure 3.6–Rainfall intensity-duration-frequency data near St. Louis, Missouri.

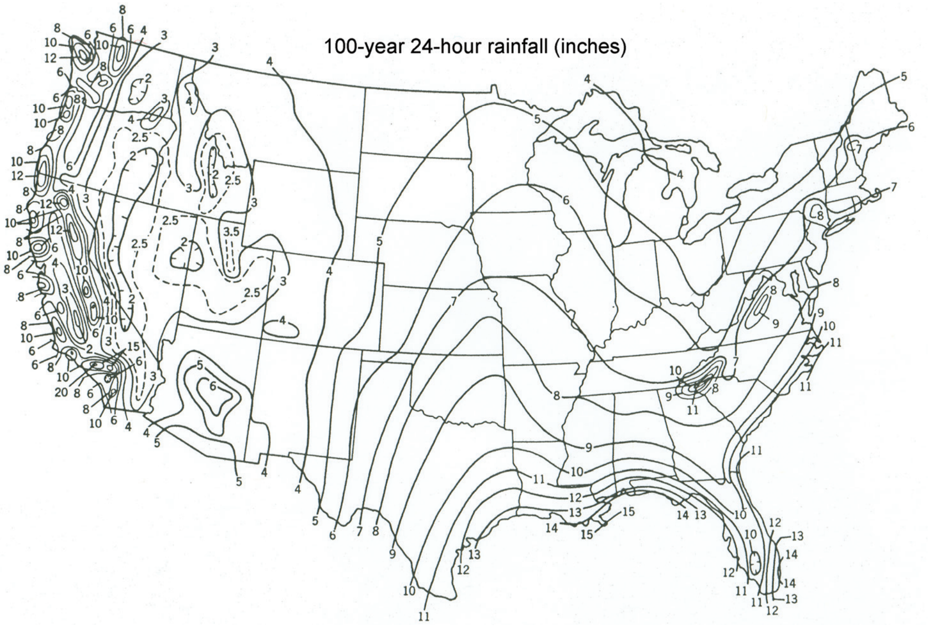


Figure 3.7–TP-40 data for 24-h 100-yr return period storm. (Source: Herschfield, 1961.)

Table 3.1 Typical Depth-Duration-Frequency Table Produced at the Atlas 14 Interactive Internet Site for an Area near St. Louis, Missouri (rainfall depths in mm)

	Average Recurrence Interval (years)								
Duration	2	5	10	25	50	100	200	500	1000
5-min	11	14	16	18	20	22	24	27	30
10-min	17	22	25	28	31	33	36	40	43
15-min	21	27	30	35	38	42	45	50	54
30-min	28	36	42	49	54	60	66	74	81
60-min	35	46	53	64	72	80	89	103	114
120-min	41	54	64	78	90	104	119	144	166
3-hr	43	57	68	84	97	113	130	159	184
6-hr	51	68	81	99	115	134	155	189	220
12-hr	61	81	95	116	135	156	180	218	253
24-hr	72	95	112	139	164	193	228	285	339
48-hr	83	110	130	161	189	223	262	327	388
4-day	95	125	148	183	214	251	294	364	429
7-day	112	145	170	206	237	272	313	377	436
10-day	127	164	191	231	265	304	348	417	479
20-day	173	219	252	296	334	375	420	488	546
30-day	211	265	301	351	391	435	483	553	613
45-day	263	328	371	430	477	528	583	662	728
60-day	307	380	429	494	546	602	663	750	823

tion to the table of data, tables are produced indicating the upper and lower 90% confidence limits of the data. The data are displayed graphically (Figure 3.6).

Prior to the Atlas 14 publications, Hershfield (1961) completed an analysis of rainfall frequency data and provided isohyetal maps (maps showing lines of equal rainfall depths) for the United States (Figure 3.7). These maps were often referred to as TP-40 maps (available at the PFDS Internet site). Weiss (1962) developed a procedure for using the TP-40 maps to obtain IDF data for any location.

Example 3.3

Determine the rainfall depths for 10-min and 6-h storms that might be expected to occur once in 5 years and 50 years at O'Hare International Airport near Chicago, Illinois.

Solution. Access the Precipitation Frequency Data Server and select the state of Illinois. By either selecting a rainfall station near Chicago or by identifying Chicago in the pull-down list, obtain the estimates from the NOAA Atlas 14. The 10-min and 6-h storms can be determined for both return periods from the table produced at the PFDS.

	10-min	6-h
5-yr	21.7	71.6
50-yr	30.4	122.3

3.13 Average Depth of Precipitation over an Area

Precipitation gauges and DDF data represent information at a point in the watershed. If the point data are to represent a much larger area, corrections are required to adjust (reduce) the point data and account for uneven distribution of the storm over the watershed. Figure 3.8 provides adjustment factors for converting point rainfall over an area for storms of various durations. The design point rainfall may be considered as the maximum for the storm, and thus the average rainfall over a watershed will be less than that of the maximum. As part of the development of the NOAA Atlas 14 project the depth area reduction factors are being statistically analyzed and updated. These data will be available on the PFDS.

Example 3.4

Determine the rainfall amount and intensity for a 6-h storm that will occur once in 50 years over an area of 400 km^2 in Chicago, Illinois.

Solution. The 6-h 50-yr rainfall in Chicago (from Example 3.3) was 122.3 mm. From Figure 3.8, for a 6-h storm over a 400-km^2 area, read the percent of point rainfall as 87%. Therefore, the 6-h 50-yr rainfall over an area of 400 km^2 in Chicago can be approximated by $0.87 \times 122.3 = 106.4$ mm, and the intensity is (106.4 mm)/(6 h) = 17.7 mm/h.

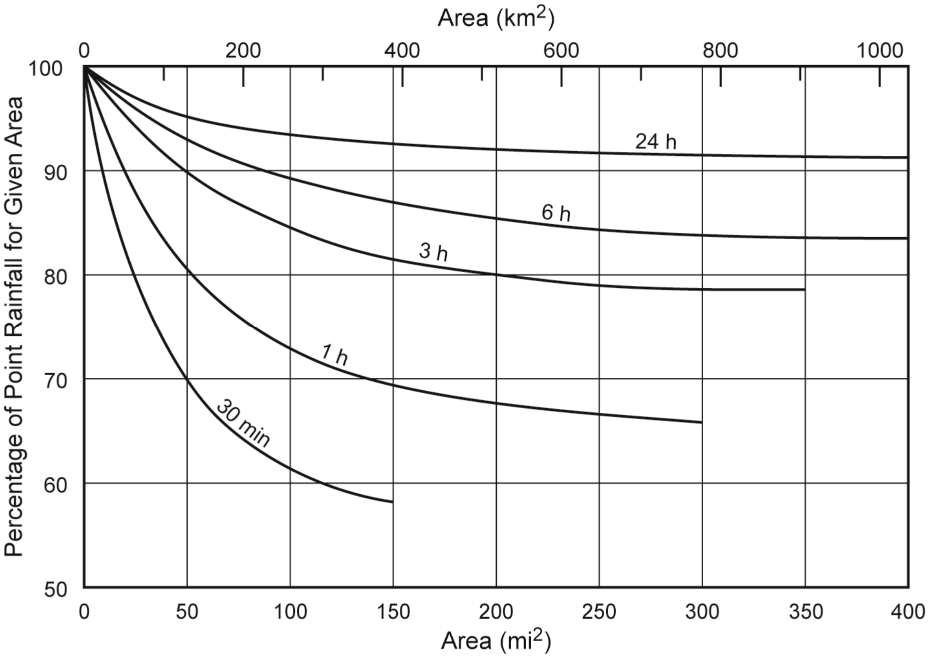


Figure 3.8–Area-depth curves in relation to point rainfall. (Redrawn from Hershfield, 1961.)

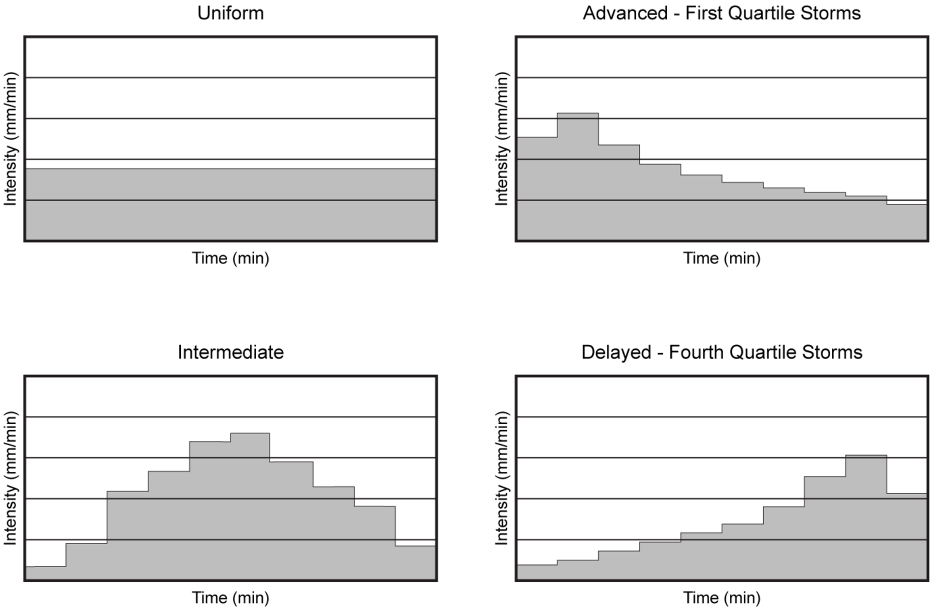


Figure 3.9–Rainfall intensity patterns.

3.14 Storm Synthesis

Most storm events represent a combination of rainfall intensity patterns (Figure 3.9). As the storm event moves across the area, the rainfall intensity fluctuates. The event may include short duration, high intensity precipitation in combination with low intensity precipitation or short periods of no precipitation. To determine maximum rainfall intensity for a particular duration, the time period must be selected from the most intense portion of the storm. The return period of any rainfall intensity for a particular duration can be obtained from the IDF curves for any specific location, similar to Figure 3.6 for St. Louis, Missouri.

Example 3.5

Determine the return period for the maximum rainfall intensity occurring for any 20-min period and for the first 140 min (2.33 h) during the storm shown below for St. Louis, Missouri.

Time (a.m.)	Time Interval (min)	Cumulative Time (min)	Rainfall during Interval[a] (mm)	Cumulative Rainfall (mm)	Rainfall Intensity for Interval (mm/h)
6:50					
7:00	10	10	1	1	6
7:10	10	20	10	11	60
7:15	5	25	11	22	132
7:35	20	45	46	68	138
7:45	10	55	19	87	114
8:25	40	95	31	118	47
9:10	45	140	6	124	8
10:50	100	240	6	130	4

[a] Corrected rainfall based on nonrecording gauge depth.

Solution. The maximum rainfall intensity for 20 min is 138 mm/h. Interpolating from Figure 3.6, read a return period of 20 years. For the first 140-min storm, the average rainfall intensity is 124/2.33 = 53 mm/h, for which Figure 3.6 indicates a return period of over 100 years.

The rainfall intensity pattern with time is of particular interest in hydrologic studies. The storm patterns can be used as input to hydrologic models to predict runoff. In some cases, historical storm patterns that have caused significant damage are selected and used as input. In most cases, a synthetic storm is derived.

During the development of the PFDS, an intensive statistical analysis was performed on the precipitation records to produce temporal estimates of rainfall during a storm event. Figure 3.10 illustrates the temporal distribution of 6-, 12-, 24-, and 96-h storms in the Ohio River basin. Each of these temporal distributions can be further divided into storms where the bulk of the precipitation occurred in the first, second, third, or fourth quartile of the storm duration (Figure 3.11 for 6-h storms). Of the 17 000 storms that occurred in the Ohio River Basin lasting up to 6 hours, most were either first or second quartile storms meaning that most of the rainfall fell during the early stages of the event. Example 3.6 illustrates the use of the temporal storm distributions and the PFDS to develop a synthetic storm.

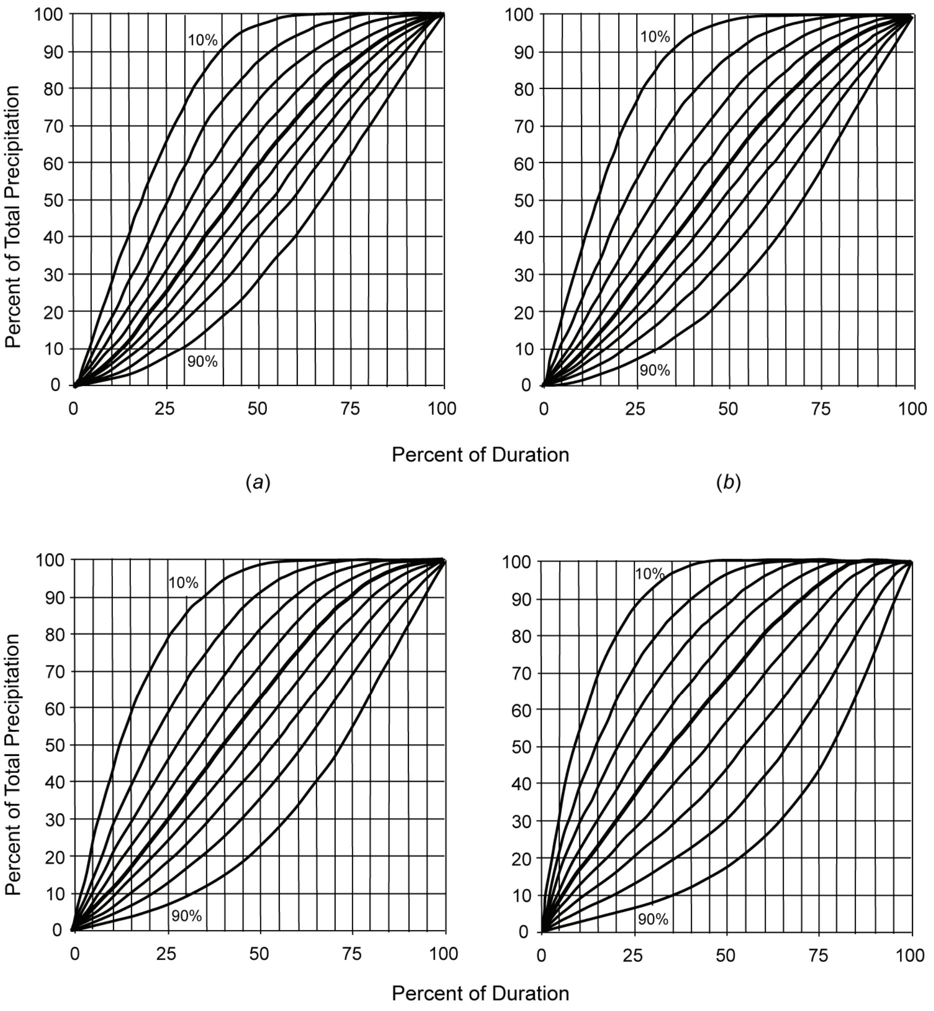
Example 3.6

Develop a 6-h, 25-yr synthetic storm for Lexington, Kentucky, that represents lower and upper 90% confidence limits of the storm total. The design storm is classified as a second quartile storm indicating that the rainfall is temporally distributed such that the bulk of the rainfall occurs during the second quarter of the event.

Solution. From the PFDS site, determine that the precipitation estimate is 93.1 mm for a 6-h, 25-yr storm in Lexington, Kentucky. The lower-bound confidence interval is 85.05 mm and the upper-bound confidence interval for the estimate is 101.0 mm. Construct a table to calculate the rainfall depths with time, according to Figure 3.11b. Obtain the storm duration and total precipitation percentages from Figure 3.11b. The accumulated storm depth is the design rainfall depth (93.1 mm) times the total precipitation percentage (Figure 3.12). The depth increment is the difference in storm depth at successive time increments. The storm depth and depth increment can be computed for the upper and lower confidence intervals.

Storm duration		Total Precipitation	Design Rainfall		Confidence Interval			
					Upper 90%		Lower 90%	
(%)	(min)	(%)	Storm depth (mm)	Depth increment (mm)	Storm depth (mm)	Depth increment (mm)	Storm depth (mm)	Depth increment (mm)
0	0	0	0	0	0	0	0	0
10	36	5	4.65	4.65	5.05	5.05	4.25	4.25
20	72	15	13.96	9.31	15.15	10.10	12.76	8.51
30	108	32	29.79	15.83	32.32	17.17	27.22	14.46
40	144	50	46.55	16.76	50.50	18.18	42.53	15.31
50	180	67	62.38	15.83	67.67	17.17	56.98	14.46
60	216	80	74.48	12.10	80.80	13.13	68.04	11.06
70	252	88	81.93	7.45	88.88	8.08	74.84	6.80
80	288	93	86.58	4.66	93.93	5.05	79.10	4.25
90	324	97	90.31	3.72	97.97	4.04	82.50	3.40
100	360	100	93.10	2.79	101.00	3.03	85.05	2.55

The SCS developed a method of storm synthesis based on rainfall patterns called *type curves* for the United States (SCS, 1986). The 24-hr rainfall depth for a desired storm frequency can be distributed over a 24-hr period based on the type curve. Type II and type III curves represent all but the extreme western portions of the contiguous United States. Although a rainfall depth is distributed over a 24-h period in the SCS method, approximately 50% of the rainfall is projected to fall during the one hour period from 11:30 a.m. to 12:30 p.m.



(*a*) (*b*) (*c*) (*d*)

Figure 3.10–Temporal distribution of rainfall for the Ohio River Basin and surrounding states for (a) 6-h duration, (b) 12-h duration, (c) 24-h duration and (d) 96-h duration.

Haan et al. (1994) described a method of using the IDF curve to develop a synthetic storm, which produces similar results to the SCS method. A design storm of a specific duration and frequency is chosen. The storm duration is broken up into equal portions (e.g., 15-min increments). Equation 3.7 or an IDF curve is used to determine the average rainfall intensity for each duration increment of the storm. For example, if a 3-h, 25-yr storm was to be developed with 15-minute increments, the first increment would represent a 15-min, 25-yr storm; the second increment would represent a 30-min, 25-

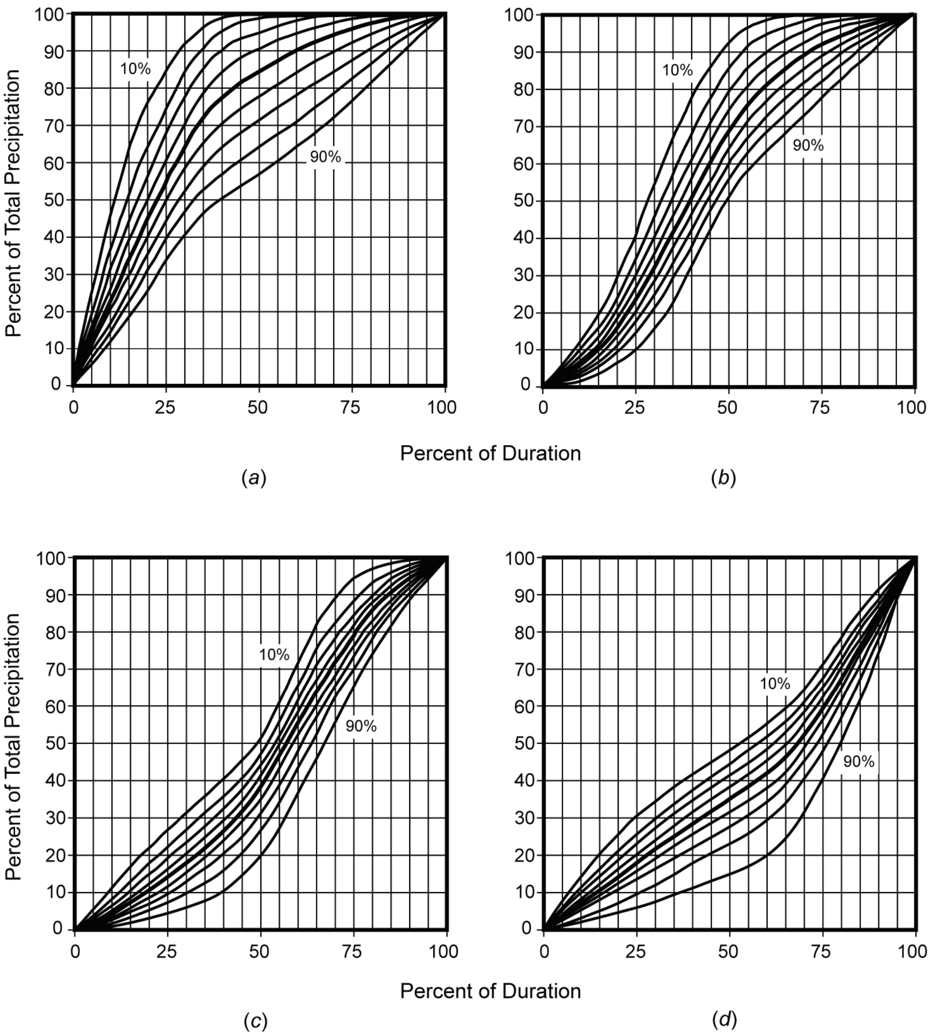


Figure 3.11–Temporal distribution of 6-h duration storms for the Ohio River Basin and surrounding states with (a) first quartile storms, (b) second quartile storms, (c) third quartile storms, and (d) fourth quartile storms.

yr storm; and proceed until the final increment, which would represent a 3-h, 25-yr storm. Rainfall depth is determined by multiplying the duration times the intensity. The incremental depth is the difference between the computed rainfall depths at each time increment. The incremental depths are then rearranged into the storm pattern of choice. If the depths are arranged in a symmetrical (intermediate) pattern, the resulting storm is very similar to the SCS Type II storm (Haan et al., 1994).

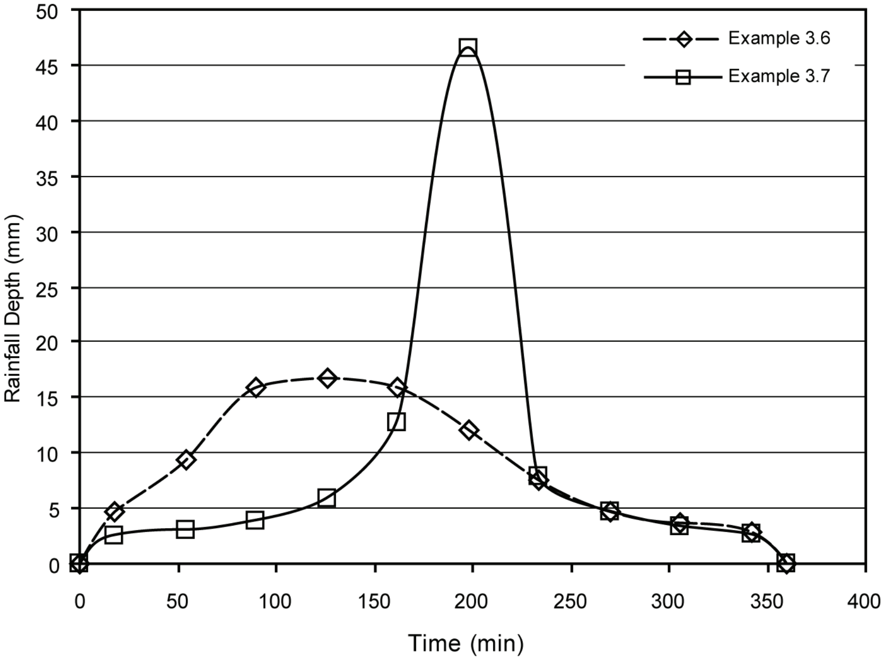


Figure 3.12–Time distribution of rainfall predicted for Examples 3.6 and 3.7.

Example 3.7

Construct a 6-h, 25-yr storm for Lexington, Kentucky. The parameters for Equation 3.7 are $K = 8.21$, $x = 1.593$, $n = 0.76$, and $b = 8.44$. Use a time increment of 36 min.

Solution. Construct a table of time increments and determine the associated rainfall intensity and depth for each increment.

The rainfall intensity for the 36-min increment is:

$$i = \frac{8.21(25)^{1.593}}{(36+8.44)^{0..76}} = 77.4\,\text{mm/h}$$

The rainfall intensity for a 72-min increment is:

$$i = \frac{8.21(25)^{1.593}}{(72+8.44)^{0.76}} = 49.3\,\text{mm/h}$$

The rainfall depth that occurs over the first 36 min is 77.4(36/60) = 46.5 mm.

The rainfall depth that occurs over the first 72 min is 49.3(72/60) = 59.2 mm.

The incremental depth is 59.2 – 46.5 = 12.7 mm.

Once the incremental depths are determined, the synthetic storm can be assembled

(Figure 3.12). An intermediate storm is shown where the maximum intensity occurred between 180 and 216 min (46.5 mm rainfall), the second greatest intensity preceded it from 144 to 180 min (12.7 mm) and the third largest intensity occurred from 216 to 252 min (7.8 mm), etc. The intermediate storm pattern is similar to that produced by the SCS Type II curve. An advanced or delayed storm could have been developed by arranging the 36-minute incremental depths differently. Note that the total storm depth is the same as the 6-h 25-yr storm.

Duration (min)	Intensity (mm/h)	Depth (mm)	Incremental Depth (mm)	Synthetic Storm (mm)
0		0	0	0
36	77.4	46.5	46.5	2.5
72	49.3	59.2	12.7	3.0
108	37.2	67.0	7.8	3.9
144	30.3	72.8	5.8	5.8
180	25.8	77.5	4.7	12.7
216	22.6	81.4	3.9	46.5
252	20.2	84.8	3.4	7.8
288	18.3	87.9	3.0	4.6
324	16.8	90.6	2.7	3.4
360	15.5	93.1	2.5	2.7
Total			93.1	93.1

3.15 Probable Maximum Precipitation

In cases where failure of a hydraulic structure has the potential to cause massive economic damage or loss of lives, an analysis based on the probable maximum precipitation (PMP) is required. The PMP is the "theoretical greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year" (Dingman, 1994). The storm area is taken as the area of the drainage basin of interest and the duration is the time of concentration of the basin (Chapter 5).

In application, the PMP value is input into a hydrologic model to predict the largest flood that might be expected to ever occur in the drainage basin, the probable maximum flood (PMF). The flood value is used in design of the hydraulic structures such as channels (Chapter 6) and emergency spillways (Chapter 9).

Internet Resources

Precipitation Frequency Data Server:
hdsc.nws.noaa.gov/hdsc/pfds/
Internet weather source:
weather.noaa.gov
Climate analysis site:
www.prism.oregonstate.edu

References

Bedient, P. B., and W. C. Huber. 2002. *Hydrology and Floodplain Analysis*. Prentice Hall: Upper Saddle River, New Jersey. 763 pp.

Bonnin, G. M., D. Todd, B. Lin, T. Parzybok, M. Yekta, and D. Riley. 2003. *Precipitation Frequency Atlas of the United States: NOAA Atlas 14 Volume I, Version 2*. NOAA, National Weather Service: Silver Spring, Maryland.

Dingman, S. L. 1994. *Physical Hydrology*. Prentice Hall: Englewood Cliffs, New Jersey. 575 pp.

Haan, C. T., B. J. Barfield, and J. C. Hayes. 1994. *Design Hydrology and Sedimentology for Small Catchments*. Academic Press, Inc.: San Diego, California. 588 pp.

Hershfield, D. N. 1961. Rainfall Frequency Atlas of the United States. *U.S. Weather Bureau Tech. Paper* 40: May. Washington, D.C.

nationalatlas.gov. 2011. Precipitation. U.S. Dept. Interior, U.S. Geological Survey. Available at: www.nationalatlas.gov/printable/images/pdf/pageprecip_us3.pdf. Accessed: June 2011.

Serrano, S. E. 1997. *Hydrology for Engineers, Geologists and Environmental Professionals*. HydroScience, Inc., Lexington, Kentucky. 452 pp.

Soil Conservation Service (SCS). 1986. *Urban Hydrology for Small Watersheds*. Technical Release No.55. Soil Conservation Service, U.S. Dept. Agriculture, Washington, D.C.

Thompson, L. M. 1973. Cyclical weather patterns in the middle latitudes. *J. Soil Water Cons*. 29: 87-89.

U.S. Department of Commerce/ National Oceanic and Atmospheric Administration (NOAA). 1994. Federal Standard for Siting Meteorological Sensors at Airports. FCM-S4-1994. Washington, D.C.

Weibull, W. 1951. A statistical distribution function of wide applicability. *J. Applied Mechanics* 73: 293-297.

Weis, L. L. 1962. A general relation between frequency and duration of precipitation. *Mon. Weather Rev*. 90: 87-88.

Problems

3.1 Determine the total rainfall to be expected once in 5, 25, and 100 years for a 60-min storm at your present location.

3.2 Determine the maximum rainfall intensity to be expected once in 10 years for storms having durations of 20, 30, 120, and 360 min at your present location.

3.3 Determine the parameters for Equation 3.3 for your present location.

3.4 Compute the average rainfall for a given watershed by the Thiessen polygon method from the following data. How do the weighted average and the gauge average compare?

Rain Gauge	Area (ha)	Rainfall (mm)
A	14.0	58
B	4.5	41
C	5.3	51
D	4.9	43

3.5 During a 60-min storm the following amounts of rain fell during successive 15-min intervals: 33 mm, 23 mm, 15 mm, and 5 mm. What is the maximum intensity for 15 min? What is the average intensity? If the storm had occurred in Lexington Kentucky, how often would you expect such a 60-min storm to occur? What type of storm pattern was it?

3.6 For your present location, compute a synthetic storm with a duration of 5 hours and a 50-yr return period using a time increment of 30 minutes.