# 2 PRECIPITATION

## 2.1 THE OCCURRENCE OF PRECIPITATION

### Formation of Precipitation

Precipitation is the fundamental hydrologic function. It replenishes rivers, lakes, soil moisture, and aquifers. Of interest to the hydrologist is the form, spatial distribution, and temporal variability of precipitation in a given watershed or geographical region. Qualifying and quantifying these features are of fundamental importance in regime characterization and in many hydrologic applications. While meteorologists study the occurrence of atmospheric moisture and the physics of precipitation as it relates to climatic conditions, hydrologists are mainly concerned with precipitation once it approaches the surface of the earth. Nevertheless, a basic understanding of the origins and formation of precipitation helps in the interpretation and extrapolation of precipitation characteristics.

The formation of precipitation requires an accumulation of water vapor in the atmosphere. Water vapor results from the processes of natural evaporation and water vapor transport caused by the wind. The fraction of water vapor in the atmosphere is very small as compared to quantities of other gases present. A mass of air can hold only certain amount of water vapor. The maximum amount of water vapor the air can hold is called the saturation water vapor. When the amount of water vapor exceeds the saturation water vapor, condensation begins to occur and the process of precipitation may be initiated. The saturation water vapor is a function of air temperature. As the temperature increases, so does the saturation water vapor. Similarly, as the temperature decreases, so does the saturation water vapor. It follows that when a mass of air is cooled, the excess of water vapor over the decreasing amount of saturation water vapor begins to condensate.

From above, the first requisite to the formation of precipitation is the *cooling of moist air masses*. Air can be cooled in several ways. Adiabatic cooling by reduction of pressure through lifting is by far the most important natural process by which large masses of air can be cooled rapidly enough to produce appreciable amounts of precipitation. The rate of precipitation depends on the rate of cooling and on the rate of inflow of water vapor into the air mass to replace the water vapor being transformed into precipitation.

The lifting required for the cooling can be caused by horizontal convergence, frontal lifting, or *orographic lifting*. Horizontal convergence is caused by the flow and concentration of air in a low pressure area, which forces the masses of air upward. Frontal lifting takes place when a warm mass of air flows toward a colder, and denser, mass of air. The colder mass of air acts as a wedge and the warm air is forced upward. The surface of separation between the two different air masses is called a frontal surface. A frontal surface slopes upward toward the colder air mass. This slope is usually so small that the frontal surface covers large portions of the land. The intersection of the frontal surface with the ground is called a front (see Figure 2.1). Orographic lifting occurs when air flowing toward an orographic barrier (i.e., a mountain range) is forced upward in order to pass over it. The slopes of orographic barriers are steeper than those of frontal surface and therefore the air is cooled much faster.

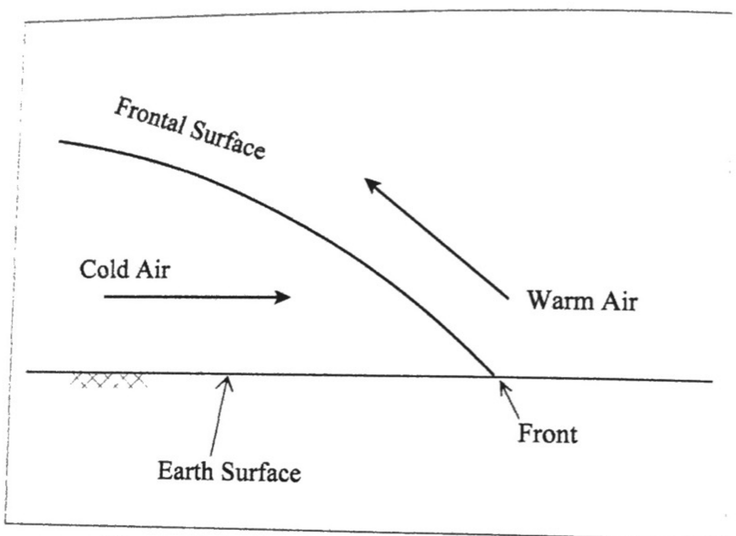


Figure 2.1: Profile of a Frontal Surface

The second requisite for the occurrence of precipitation is the *condensation of water vapor* into liquid or solid form. This is a change of phase from water vapor into liquid droplets, or at low temperatures from water vapor into crystals. This usually results in the formation of clouds, which are airborne liquid-water droplets, ice crystals, or a mixture of the two. Condensation is the result of saturation of air masses. However, condensation requires not only saturation, but also the presence of solid nuclei around which the droplet or crystal begins to grow. There are enough solid particles in the atmosphere to produce condensation when the air reaches saturation. Products of combustion and salt particles from the sea encourage the condensation process. Thus, a byproduct of air pollution is the abnormal enhancement of condensation visually observable in the form of fog near areas of contamination. As an application of this principle, the atmosphere may be seeded with artificial nuclei for the purposes of inducing precipitation over a particular area. Among the legal and environmental issues associated with artificially induced precipitation are the effects such practices have on the mean annual precipitation of an area and its time distribution. Fortunately, humans have learned that although they may affect the rate of condensation, their control over precipitation variables is not direct. This is an active area of research which may yield important results in the future.

The final requisite for the occurrence of precipitation is the growth of *water droplets* of crystals to a critical mass sufficient to overcome the upward currents of air. The rate of precipitation from a cloud depends on the velocity of upward currents producing the cooling, the rate of growth of the raindrops heavy enough to overcome the vertical currents, and the rate of water vapor inflow replacing the precipitated water.

**Types of Precipitation**

Precipitation may occur in the form of rain, snow, hail, drizzle, and sleet. The form of precipitation depends on the rate of cooling and the air temperature. More important than the form of precipitation is an understanding of the basic storm types, which depend on the cooling conditions. In this respect, the three major categories of precipitation are: *cyclonic precipitation*, *orographic precipitation*, and *convective precipitation*.

As stated before, cyclonic precipitation is the one associated with horizontal convergence and frontal lifting. It usually produces patterns of precipitation that cover large portions of the land, long storm durations, and low intensities of precipitation. Cyclonic precipitation is a regional event that may be easily tracked by surface or satellite radar sensors. Because of its large size, the generation of cyclonic precipitation systems may be detected early in its development. The system may be observed over a period of time for variables such as precipitation rate, total precipitation depth, and storm duration. Other variables concerning the velocity of movement of the storm and its mean geographical direction may be monitored. This information may be extrapolated with the aid of mathematical models and used for weather forecasting purposes.

Orographic precipitation results from the mechanical lifting of horizontal air currents over natural barriers such as mountain ranges. Factors that are important in this process include land elevation, local slopes, orientation of land slope, and distance from the water vapor source. Elevation above the sea level is an important factor affecting the magnitude of precipitation. Figure 2.2 shows a typical relationship between elevation above the sea level and mean annual precipitation. Precipitation increases with altitude over the first few hundreds of meters of elevation, beyond which there might be a decrease in the precipitation magnitude. Several rain gages in a watershed, each exhibiting good long-term data, may be used to define such a relationship. This relationship may then be used to extrapolate precipitation data to regions with scarce information in the watershed, or to fill in missing data values in existing rain gages. Relationships between monthly precipitation and elevation may not be as well defined and should be used with caution.

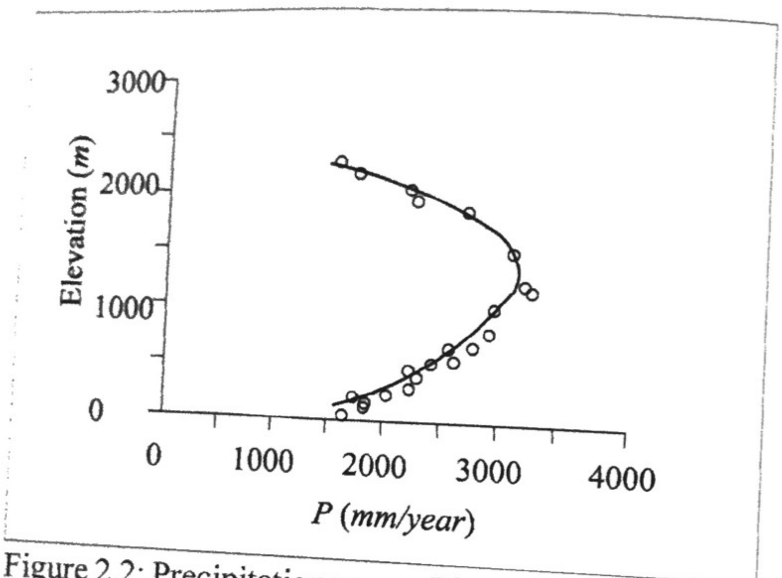


Figure 2.2: Precipitation versus Elevation Relationship

Convective precipitation is typical of tropical regions. It results from the heating of the air at the interface with the ground surface. Heated air expands and loses density, while receiving a substantial amount of water vapor via evaporation from soil moisture. The warm moisture-laden air begins to rise. At the same time, pronounced vertical currents are developed. As the warm air rises, dynamic cooling takes place, causing condensation and precipitation. Convective precipitation usually generates storms of extremely high intensity, but of relatively short duration as compared to cyclonic storms. Convective precipitation covers relatively small areas. Because of its small size and the strong winds accompanying convective precipitation development, highly mobile thunderstorms are usually generated. This results in rainfall phenomena that are difficult to forecast by conventional large-scale measurement devices, and that produces high spatial variability of precipitation amounts.

## 2.2 MEASUREMENT OF PRECIPITATION

As described in chapter 1, hydrologic variables are measured either in accumulated volume of water, or in liquid-water depth assumed uniformly distributed over a reception area. Precipitation is measured with rain gages. A rain gage is an instrument that captures precipitation and measures its accumulated volume during a certain period of time. The precipitation depth for the same period is equal to the accumulated volume divided by the collection area of the gage. Any open container with vertical sides could be used as a rain gage. However, to compare measurements of precipitation with those obtained elsewhere, it is necessary to use standard equipment with similar characteristics of size and shape.

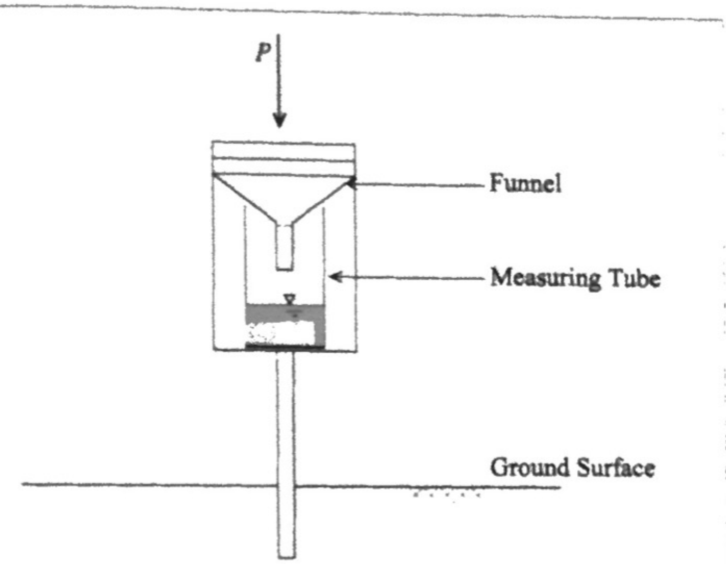


Figure 2.3: Cross Section of a Non-Recording Rain Gage

Rain gages can be of two basic types: non-recording and recording. A non-recording gage measures the total rainfall depth accumulated during a period of time. This period may be 12 hours or one day. There are many kinds of non-recording rain gages, depending on the manufacturer and the standards utilized by the monitoring agency. Figure 2.3 is an illustration of a typical non-recording rain gage. It is an aluminum cylinder of about $25cm$ in diameter located about one meter from the ground surface. Rain is caught by the top collector and funneled into a measuring tube. The cross-sectional area of the measuring tube is one-tenth of that of the collector. Consequently, rainfall depths are amplified ten times as they pass from the collector to the measuring tube, thus increasing the accuracy of the measurement. At measuring time, the observer introduces a stage meter into the measuring tube and records the water depth on a sheet. The stage meter has been properly graduated in millimeters and fractions of millimeters scaled up by a factor of ten. Finally, the measuring tube is emptied. Figure 2.4 shows a plastic rain gage.

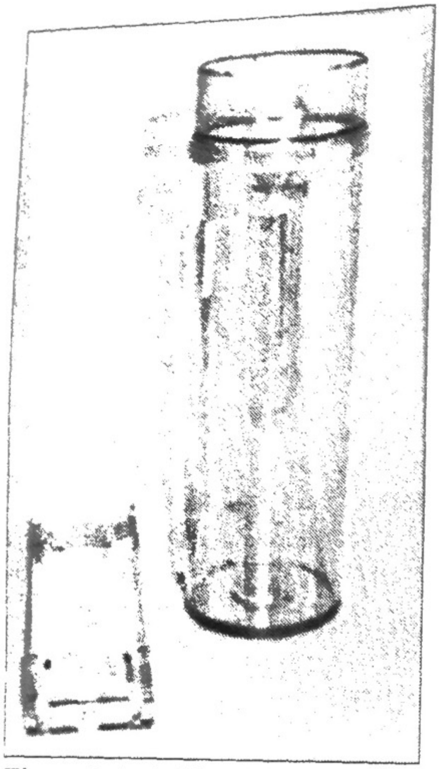

Figure 2.4: A Plastic Rain Gage (*courtesy of NovaLynx Corp.*)

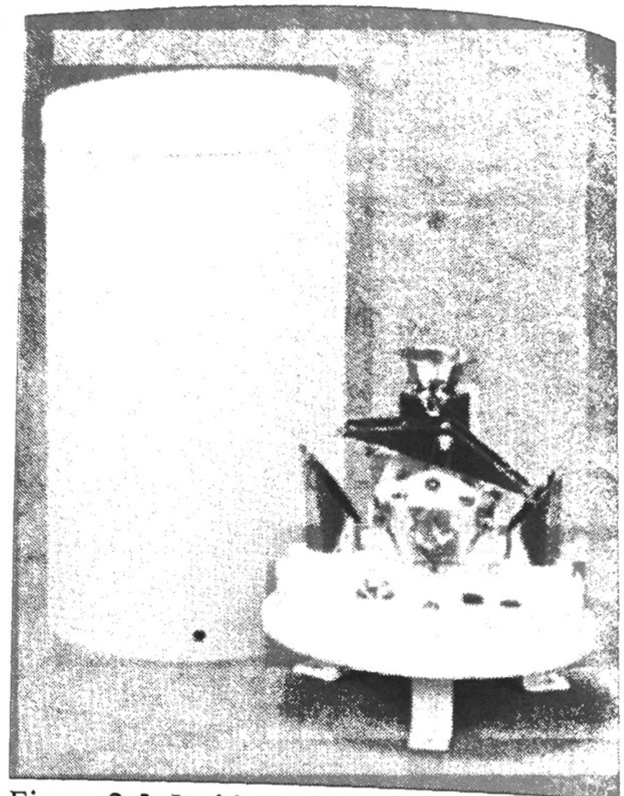

Figure 2.5: Inside of a Tipping Bucket Rain Gage (*courtesy of NovaLynx Corp.*)

The non-recording rain gages are inexpensive and simple to operate. However, they are only useful when periodic total rain depths are required. A recording rain gage continuously registers the rate of rainfall and its time of occurrence. It provides not only a measure of rainfall depth, but also of rainfall intensity. Recording rain gages can be of the tipping bucket type, the weighing mechanisms type, or the float chamber type. The tipping bucket gage (Figure 2.5) features a two-compartment receptacle, or bucket, pivoted on a knife edge. The gage is calibrated so that when one of the compartments is full of water and the other is empty, the bucket overbalances and tips. First the rain is funneled into one of the compartments, while the second remains empty. When the first compartment is full, the bucket tips, emptying its contents into a container and at the same time placing the second compartment into filling position. The tipping closes an electric circuit, which drives a pen that records on a strip chart attached to a clock-driven revolving drum. Each electrical contact representing a specific amount of rain is recorded. The alternate filling and emptying of the two compartments continue until the rain ceases. Although the tipping bucket gage is durable, simple to operate, and reliable, it does not record properly during periods of intense rainfall.

The weighing gage has a device that weighs the rain or snow collected in a bucket. As it fills with precipitation, the bucket moves downward and its movement is transmitted to a pen on a strip-chart recorder. These gages are useful in cold climates that require measurements of rain as well as snow. However, they are sensitive to wind instability, which produces erratic traces on the chart.

Float gages are water level recording instruments. A float located inside a chamber is connected to a pen on a strip-chart recorder. The float rises as the collected rainwater enters the chamber, and the rise of the float is plotted on the chart. As the level of the water reaches a maximum level, a siphoning mechanism empties the chamber and returns the pen to a zero position on the strip chart. This type of rain gage operates normally in warm climates. In cold climates and during severe storms, water freezing and the siphoning mechanism may produce inaccurate measurements.

Traditional rain gages can be implemented with a telemetric system to automatically transmit rainfall information. This produces a self-reporting gaging station whereby the tipping bucket mechanism generates a digital input signal whenever one millimeter of rainfall drains through the funnel assembly. The signal from the gage is automatically transmitted to a receiving station, where it records the station number and an accumulated amount of rainfall. The receiving station records the time at which the message was received and rainfall rates for desired periods can be calculated accordingly. Self-reporting gages can easily be incorporated into real-time monitoring systems that can be used in a variety of forecasting and simulation modes (Strangeways, 1985).

Weather-radar systems are useful tools for measuring spatial distribution and temporal variability of rain storms. Radar is a device that emits a regular succession of pulses of electro-magnetic radiation from an antenna. In between the emissions, the antenna becomes a receiver of the energy of the emitted pulses scattered by various targets. The returned signals are displayed on the radar scope. The wavelength of the emitted signal may be adjusted to detect raindrops of various sizes (Battan, 1974), and in particular high intense storms, which are likely to produce extreme floods. The importance of the radar lies in its ability to detect at distance and map the distribution of a storm. Subsequent observations of the radar scope produce a reconstructed picture of the storm movement, from which variables such as storm velocity and rainfall intensity are estimated to feed computer simulations of weather forecast. The difficulty with radar measurements is the possibility of missing the target by improperly orienting the radar beam, especially at long ranges. Radar reflectivity could be used to estimate precipitation intensity. However, these estimates have to be calibrated with ground rain gages.

Satellite measurements of precipitation have many of the advantages exhibited by ground-based radar measurements. In addition, satellite-mounted probes can detect a variety of electromagnetic signals from various bands of the spectrum, which form a more detailed picture of the clouds' physics as it relates to the generation of precipitation (Collier, 1985). In addition, the privileged position of the satellite system may detect the origin and evolution of large storm systems, which provide valuable information in weather forecasting. However, estimates of precipitation intensity, like ground-based radar estimates, must be calibrated with conventional rain gages. Remote sensing is a rapidly developing field, and an active area of research. It is expected that some of these limitations will be overcome in the near future.

## 2.3 ANALYSIS OF POINT PRECIPITATION

As the name implies, the analysis of point precipitation is the study of precipitation information at a fixed location (i.e., an individual rain gage). Two general kinds of analyses are performed: analysis of the quality of precipitation data, and analysis of the time distribution of precipitation.

### Quality of Precipitation Data

Precipitation data is available from a multitude of private and governmental organizations. Most countries have a national official institution in charge of the collection of precipitation and other meteorological information. However, depending on the country and the location within a country, institutions with various degrees of interest in meteorological, agricultural, hydrological, and environmental projects are involved in the collection and distribution of precipitation information. Although progress has been made by the World Meteorological Organization towards an adoption of international standard precipitation information practices, there is a wide range of variability in the procedures, accuracy, and instrumentation. Thus, comparison of precipitation information is often a difficult task.

There are many uncertainties associated with precipitation data. Some refer to the type of instrumentation used. For example, precipitation information is related to the size and the orientation of the gage receptacle. Some rain gages are provided with small structures that protect the receptacle from wind instability. The height of the receptacle is another important variable. The location of the rain gage with respect to obstructions such as trees and other structures affect the measurement. During high intensity rainfall events, the splash may affect the readings. Depending on the frequency of gage readings, accuracy may be affected by evaporation of some of the water between subsequent observations. Systematic measurement errors are another source of uncertainty, because of the mechanics of operation of certain instruments. The observer also plays an important role in the generation of random errors of observation, or in systematic errors of reading and transcription. Finally, errors caused by low intensity rain, below the resolution of the instrument are common.

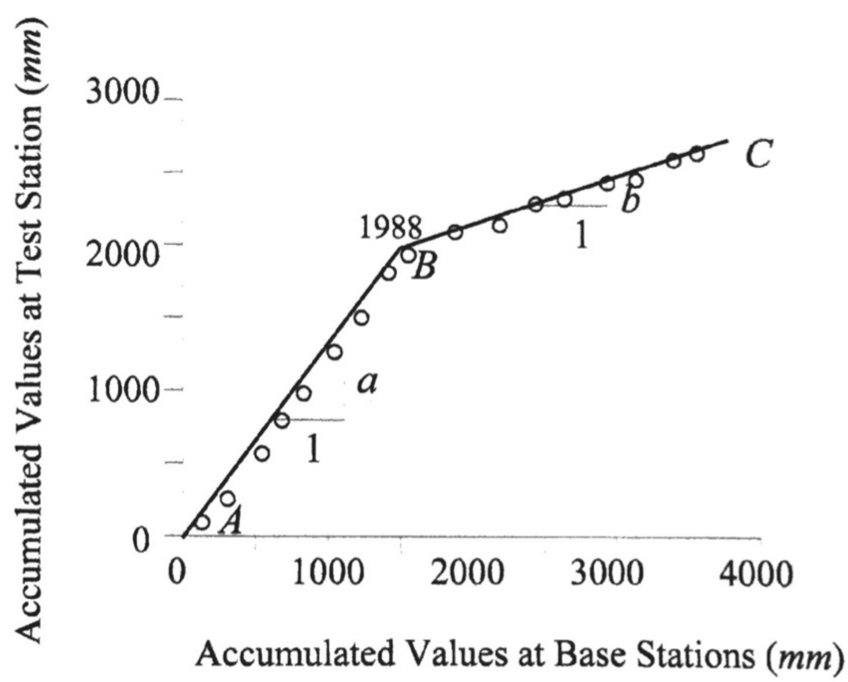


Figure 2.6: Double-Mass Analysis for a Given Rain Gage

Given the importance of precipitation data in any hydrologic calculation, it is crucial to investigate the quality of data reported by each rain gage before it is used. If the information is to be used in the design of a large-scale water resources structure, it is important to employ good quality of precipitation information. Regardless of the degree of sophistication of subsequent hydrologic analysis, the results of any calculation based on poor-quality data are bound to be inaccurate.

It is recommended that the hydrologist begins the analysis of precipitation data by studying the precipitation station itself. In other words, investigate the history of information provided by the rain gage; determine how long it has been in operation; the type of instrumentation used; and the consistency of maintenance and operation. Rain gages operated for short periods of time, are poorly maintained, or are often moved yield unreliable information. Information from these rain gages should be eliminated from the study, or at best used with caution.

The double-mass analysis is a test to detect whether the precipitation data of a station is consistent. The test uncovers significant changes in observation practices. In this analysis, a plot is made of accumulated annual or seasonal precipitation values at a site being studied for consistency (the test station) against the current accumulated values of several surrounding stations (base stations), which exhibit good quality data. Specifically, the mean precipitation is used in the accumulative values for the plot (Figure 2.6). If the data is consistent, a straight line will fit the points. Inconsistent data, on the other hand, will exhibit a change in the slope or a break at a point where changes in observational procedures, instrument moving, or instrument damage occurred. Changes in meteorological conditions will equally affect all stations involved in the test and will not appear in the double-mass graph.

Table 2.1: Annual Precipitation Data for Example 2.1 (*mm*)

| Year | $P_1$ | $P_2$ | $P_3$ | $P_4$ | $P_5$ | $\bar{P}_{base}$ | $\sum P_1$ | $\sum \bar{P}_{base}$ |
|---|---|---|---|---|---|---|---|---|
| 1979 | 668 | 759 | 624 | 929 | 808 | 780 | 668 | 780 |
| 1980 | 570 | 627 | 833 | 783 | 804 | 762 | 1238 | 1542 |
| 1981 | 681 | 853 | 822 | 981 | 854 | 878 | 1919 | 2420 |
| 1982 | 601 | 811 | 660 | 704 | 841 | 754 | 2520 | 3174 |
| 1983 | 483 | 738 | 746 | 917 | 641 | 761 | 3003 | 3935 |
| 1984 | 1186 | 744 | 1267 | 1083 | 1129 | 1056 | 4189 | 4991 |
| 1985 | 940 | 785 | 972 | 814 | 978 | 887 | 5129 | 5878 |
| 1986 | 616 | 546 | 665 | 601 | 810 | 656 | 5745 | 6534 |
| 1987 | 950 | 659 | 734 | 847 | 923 | 791 | 6695 | 7325 |
| 1988 | 773 | 845 | 624 | 978 | 912 | 840 | 7468 | 8165 |
| 1989 | 870 | 637 | 721 | 802 | 663 | 706 | 8338 | 8871 |
| 1990 | 771 | 897 | 796 | 896 | 932 | 880 | 9109 | 9751 |
| 1991 | 1029 | 1029 | 879 | 791 | 936 | 909 | 10138 | 10660 |
| 1992 | 876 | 835 | 1013 | 845 | 1011 | 926 | 11014 | 11586 |
| 1993 | 1027 | 793 | 973 | 1009 | 960 | 934 | 12041 | 12520 |
| 1994 | 699 | 700 | 653 | 649 | 753 | 689 | 12740 | 13209 |

The double mass analysis also provides a means of adjusting the inconsistent data. In the example in Figure 2.6, a break point $B$ occurred in 1988. If the slope of the line $AB$ is $a$ and the slope of the line $BC$ is $b$, the adjustment of the inconsistent data is made by the ratio of the slopes of the two lines. Thus, it is possible to adjust the data to reflect the conditions that existed prior to the point $B$. This is done by multiplying each precipitation value at the test station occurring after the break point by the ratio $a/b$. Alternatively, the data may be adjusted to reflect recent conditions following the break. This is done by multiplying each precipitation value at the test station occurring before the break point by the ratio $b/a$. An important point to remember is that the double mass analysis should not be used in mountain areas, or to adjust storms of short duration (e.g., daily totals).

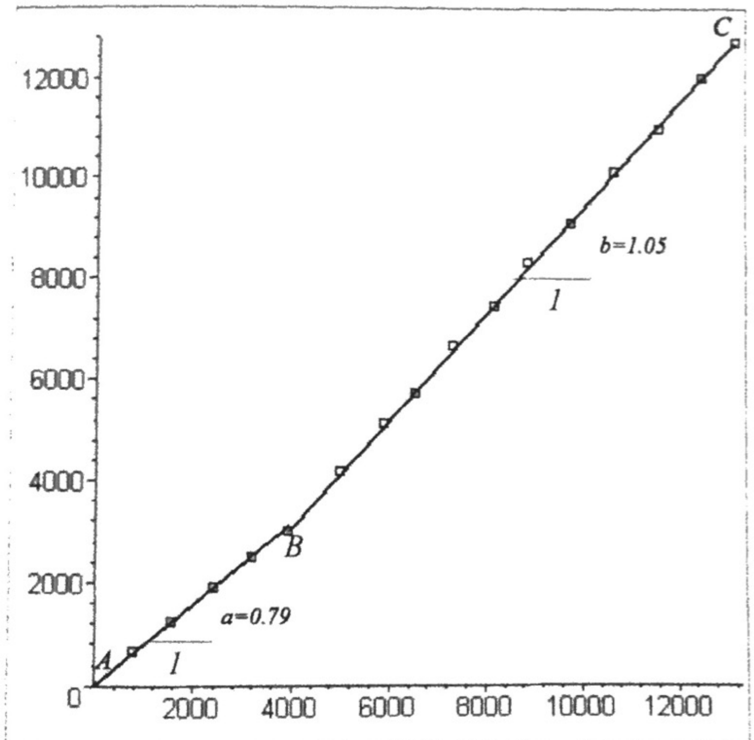

Figure 2.7: Double Mass Analysis of Example 2.1

**Example 2.1**

Given the annual precipitation values at stations 1, 2, 3, 4, and 5 in Table 2.1, analyze the records of station 1 for consistency and correct its values if necessary.

**Solution**

Table 2.1 summarizes the calculations. Columns $P_1$, $P_2$, $P_3$, $P_4$, and $P_5$ contain the annual precipitation at stations 1, 2, 3, 4, and 5, respectively.

### Time Distribution of Precipitation

Recording rain gages provide a continuous graph of precipitation depth with respect to time. A typical portion of a chart from a recording gage is illustrated in Figure 2.9. The solid line shows the level of precipitation, $P$, in millimeters accumulated at a given time, $t$. When the precipitated water reaches the maximum level, a siphon mechanism empties the water in the chamber. This is shown by a vertical line in the chart. The cumulative water level with time may be transformed into precipitation intensity, $p$, or precipitation rate at a given time. At a given time, the slope of the line $P$ versus $t$ is approximated as $\Delta P/\Delta t$, where $\Delta P$ is the difference in precipitation depth during a short time interval $\Delta t$. If the time interval is $\Delta t = 1\,hour$, then the precipitation intensity is simply the difference in precipitation depth during one hour.

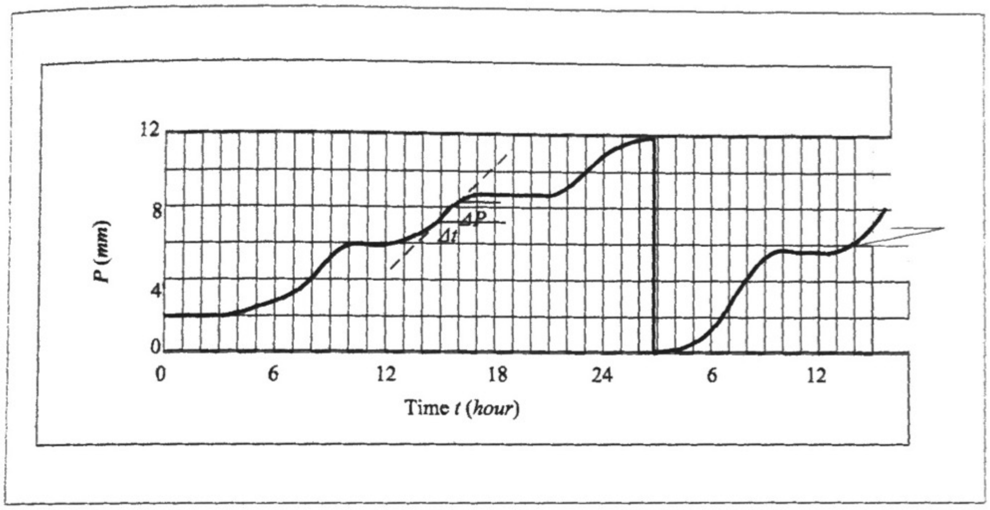


Figure 2.9: A Chart of a Recording Rain Gage

From above, information from recording rain gages is usually digitally processed and archived in the form of precipitation intensity, $p$ (*mm/hour*), versus time, $t$ (*hour*). A graph of precipitation intensity versus time is called the rainfall hyetograph. The hyetograph of a storm (Figure 2.10) shows the time distribution of precipitation intensity, and as such it may be used to observe the periods of low intensity, the periods of high intensity, the magnitude of maximum precipitation intensity, $p_{max}$, and its time of occurrence, the total duration of the storm, $t_d$, and the total precipitation depth, $P$ (*mm*).

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**Example 2.4**

Figure 2.10 shows the rainfall hyetograph of a particular storm, as deduced from a continuous recording gage. Estimate the maximum precipitation intensity and its time of occurrence, the total duration of the storm, and the total precipitation depth.

**Solution**

From Figure 2.10, the storm started at 8:00 AM and ended at 4:00 PM (16 *hours*). There are two periods of rainfall: from 8 to 12 PM, and from 1 to 4 PM, separated by a rainless period from 12 to 1 PM. Precipitation storms are sometimes clustered in several rainfall periods separated by calm intervals in between. Thus, the duration of the storm is $t_d$=8*hour*. The maximum precipitation intensity is $p_{max}$=6*mm*/*hr*, and occurred between 10 and 11 AM. The total precipitation depth of the storm, or cumulative precipitation, is the area under the rainfall hyetograph:

$$P = \sum_{t=8}^{t=16} p_t \, \Delta t = (1+3+6+2+1+5+4) \, \frac{mm}{hour} \times 1 \ hour = 22 \ mm$$

where $p_t$ is the precipitation intensity at time $t$.

The time evolution of precipitation intensity at a fixed point (i.e., at a rain gage) is of interest in many hydrologic applications. The characteristics of the rainfall hyetograph, particularly during extremely intense events, offer valuable information to the water resources engineer. The design of water resources and hydraulic systems consists in the dimensional definition of structural components such that when fully operational at capacity level the system will be able to function under an extreme precipitation event called the design storm. Urban storm sewers, airport drainage systems, mining and underground excavations are examples of engineering applications of hydrologic analysis of the time distribution of point precipitation.

The time distribution of point precipitation at time scales larger than that of an individual storm supplies information on the seasonal, annual or multi-annual variability of precipitation, and as such it is of interest in a variety of studies in surface hydrology, groundwater analysis, and climate variability. Figure 2.11 shows a monthly time distribution of precipitation at a point. If the graph is built for a particular year, the intensity of precipitation throughout the year indicates the seasonal variability of precipitation, and the severity of the wet and dry months during the year in question. On the other hand, if the graph is built to depict the mean monthly precipitation at a point (i.e., the value for a month is calculated as the average of that month over at least 20 years), then the intensity of precipitation throughout the year indicates the seasonal precipitation regime for the location studied. For example, if Figure 2.11 is actually the mean monthly precipitation at a point, then there is one wet "season" from April to May, and a second less important one from October to November. The dry "seasons" at this location are from June to September and from December to March of the following year. The precipitation intensities indicated are the mean, or the expected, precipitation in an average year.

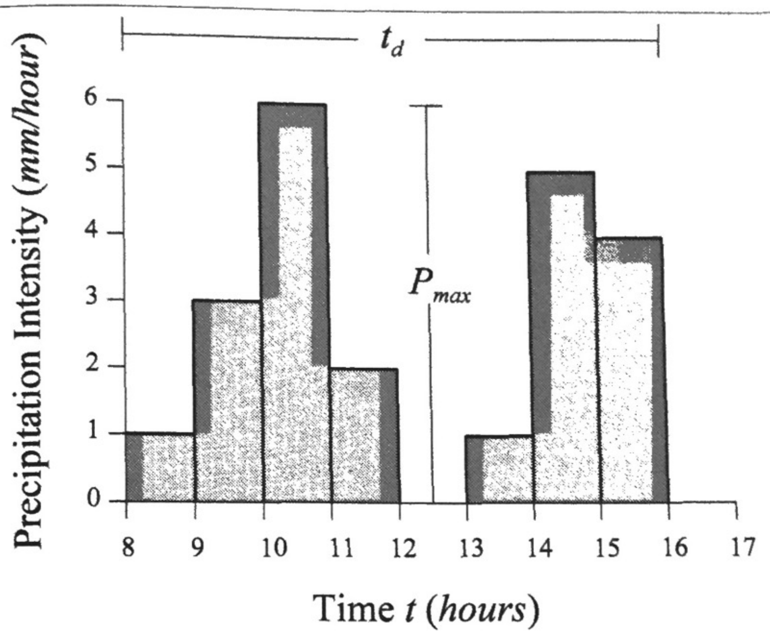


Figure 2.10: Rainfall Hyetograph of a Storm

A similar graph may be built for a typical wet year, or a typical dry year. The visual information offers a simple, yet effective, way to understand the hydrologic regime at a location, and provides valuable information for water resources planning.

Total annual precipitation distribution graphs are plotted for the purpose of observing the long-term variability of precipitation at a location. When this analysis covers several decades, the pattern of natural fluctuation in precipitation responding to climatic conditions may be deduced. The hydrologist takes note of the average duration of dry years and that of wet years, trends in precipitation, and amplitudes in fluctuation of precipitation from wet to dry years. This information is used in connection with water resources planning and management. Figure 2.12 shows an annual distribution of precipitation obtained from one station.

For the late series (1937 to 1999), calculate the mean precipitation for January.
Store in array PL[ ]. Repeat for each month and prepare for plotting.

```
> for j from 1 to 12 do
  PL[j]:=sum(P[m][j],m=1999-Mid..1999)/Mid:
  end do:
  PLate:=[seq([m,PL[m]],m=1..12)]:        #for plotting
  G2:=plot(PLate,color=black,thickness=2,legend=`1937 to 1999`):
```

Display plots in one graph

```
> plots[display](G1,G2,labels=[`Month`,
     `Mean Monthly Precipitation (mm/month)`],
    labeldirections=[`horizontal`,`vertical`],
    font=[TIMES,ROMAN,16],labelfont=[TIMES,ROMAN,16]);
```

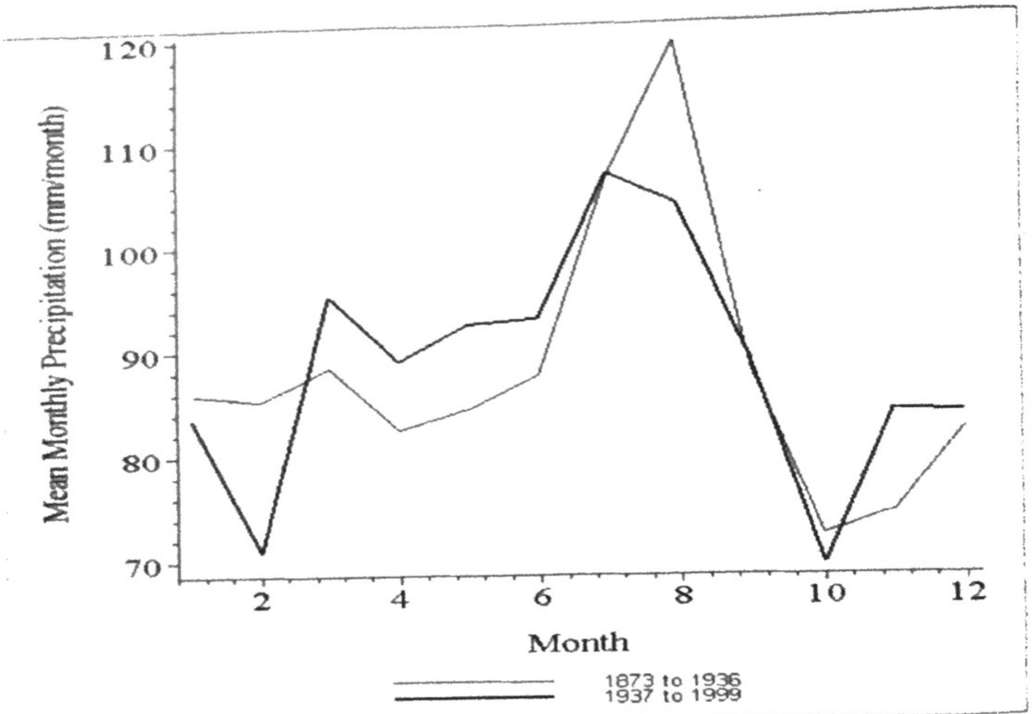


Figure 2.14: Long-Term Seasonal Precipitation in Philadelphia

## 2.4 SPATIAL DISTRIBUTION OF PRECIPITATION

If the analysis of time distribution of precipitation studies its temporal variability at a fixed point, the spatial distribution analysis studies its regional variability. Given different precipitation depths recorded at several rain gages across a watershed after a storm, a month, a year, or several years, it is often required to estimate an equivalent precipitation depth for the entire watershed during the same duration. For a uniformly spaced, dense, rain-gage network in a flat area, the simplest approach is to use the *arithmetic average*:

$$\bar{P} = \frac{1}{N}\sum_{i=1}^{N} P_i \tag{2.3}$$

where

$\bar{P}$ = average precipitation over a region, during a given time ($mm$)

$P_i$ = precipitation on gage $i$ during the same time ($mm$)

$N$ = number of rain gages

The arithmetic average method, although simple, does not take into consideration the rain gage density. The *Thiessen polygons* method is another method of calculating precipitation averages. In this method, an afferent area is assigned to each rain gage, depending on the gage location relative to neighboring ones. Thus, widely spaced gages receive a larger area of influence than closely spaced ones. Within each area, it is assumed that the precipitation magnitude is the one recorded at its gage. A geometrical construction is needed to trace the polygons that delimit each afferent area.

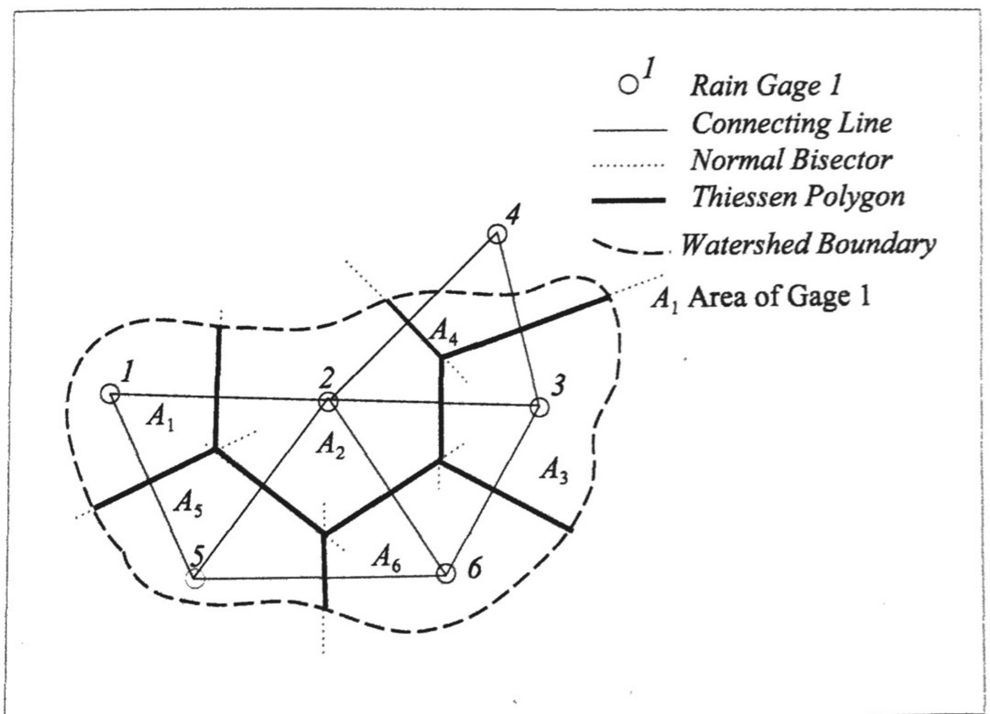


Figure 2.15: Construction of the Thiessen Polygons of a Watershed

Referring to Figure 2.15 as an example, the construction of the Thiessen polygons is as follows:

(1) Connect the stations with straight lines (continuous thin lines in Figure 2.15). Due to lack of precipitation information in certain watersheds, sometimes it is useful to include rain gages outside the

Other methods for estimating areal precipitation from point values have been developed. These include eyeball isohyetal method, least-squares surface method, Lagrange-polynomial surface method, spline-surface method, inverse-distance interpolation, multi-quadratic interpolation, optimal interpolation/krigging, empirical orthogonal functions, and hypsometric method (Bonnor, 1975; Creutin and Obled, 1972; Omernik and Kinney, 1983; Shaw, 1988; Shaw and Lynn, 1972; Tabios and Salas, 1985; Wallis and Bowden, 1962).

## 2.5 FREQUENCY ANALYSIS OF PRECIPITATION

### Precipitation Variability, Frequency, Return Period, and Design Rainfall

Precipitation is a climatic variable subject to environmental fluctuations. These fluctuations tend to decrease in magnitude as the hydrologist increases the temporal scale of observation. For example, with the advent of sophisticated electronic instrumentation, it is now possible to measure precipitation intensity by the minute. With these instruments the observer often finds that a typical thunderstorm may register periods of rainfall intensity of over 100*mm/hour* that lasts for a duration of a minute or two, followed by short periods of significantly lower rainfall intensity (i.e., less than 10*mm/hour*). If the same storm is measured in a standard hourly recording rain gage, the hydrologist may conclude that the hourly precipitation intensity is of the order of 20 or 30*mm/hour*. That is, the hourly precipitation intensity (i.e., the slope on the continuous recording chart; see Figure 2.9) is averaged over a longer period of time and thus the resulting intensity fluctuates less than a hyetograph built with higher temporal resolution. Consequently, a monthly precipitation distribution at the same gage may show less fluctuation in the magnitude of precipitation from month to month. The monthly precipitation is expected to fluctuate around seasonal averages. Similarly, annual point precipitation is expected to show even less fluctuation from year to year. The annual precipitation fluctuates around long term trends governed by global climatic changes.

From the above discussion, the hydrologist should expect less variability, and less resolution, in precipitation as the temporal scale of observation increases. Conversely, one should expect more variability, and more resolution, as the temporal scale of observation decreases. This is especially important since the hydrologist is often not concerned with the prediction of seasonal or annual precipitation regimes, but rather with the objective estimation of a typically adverse rainfall event. The adverse event is then used to design a water resources structure to withstand the occurrence of such a rainfall event. The rainfall event is called the *design rainfall*. Urban storm sewers, mining drainage systems, airport drainage systems, highway box culverts, bridge foundations, and dams are but a few examples of water resources and hydraulic structures which must be designed to withstand an objectively estimated design rainfall. The design rainfall must be quantified based on a conscientious prediction of possible future rainfall events during the service life of the structure. The design event is not the worst possible event one can imagine, for such an approach would produce an expensive design even if the event actually occurs, unless the project in question is a large scale water resources project. Most water resources projects are designed to withstand an event whose magnitude is proportional to the size of the structure. For instance, the failure of a small highway bridge during a particular event may cause some temporary transportation inconvenience, but it is not expected to be a catastrophic accident as that of the failure of a large dam during a flood. The latter would cause enormous human and property losses downstream. Therefore, the magnitude of the design rainfall for a dam should be significantly greater than that of the small bridge. How does the hydrologist predict precipitation in an objective manner?

The occurrence of precipitation depends on many meteorological and geographical variables. The physical interaction between these variables is complex and often difficult to quantify. For these reasons, the prediction of precipitation intensity and its geographical distribution faces practical obstacles. A fundamental problem the hydrologist faces relates to the estimation of the design rainfall under uncertainty. An approach to precipitation prediction is based on a careful evaluation of precipitation data recorded over many years. Although a historical record of precipitation is unlikely to occur again in the future, having good quality rainfall data collected over several decades is by far the best way to study the behavior of an uncertain variable. By studying the historical records of precipitation, it is possible to observe the characteristics of time distribution of precipitation on an hourly, monthly (or seasonal), and annual basis. Relationships between precipitation intensity and duration may be developed. Also monthly (or seasonal) average precipitation values (see Figures 2.11, 2.12, and 2.14) calculated over many years, and mean annual precipitation values (see Figure 2.13) may be estimated. In addition, average deviations (i.e., variances) from the calculated means may be evaluated (see Figure 2.13). In other words, by studying long term records of point precipitation the hydrologist may quantify the statistical properties of precipitation. Since a precipitation amount may not be accurately predicted due to the many uncertainties, at least one may predict it in a broad statistical sense. Furthermore, knowing the statistics of precipitation facilitates the fitting of theoretical probabilistic models (i.e., probability distributions, stochastic processes, random fields, etc.). Probabilistic models are useful in the study of the properties of precipitation, and in extending historical records for the purpose of testing water resources structures with respect to various possible occurrences of precipitation events.

From the above discussion, one must realize that while we are unable to predict the occurrence of a particular rainfall event, at least we can predict the frequency of its occurrence. In other words, a statistical analysis of historical records allows the hydrologist to predict, in all likelihood, *how often* a particular rainfall event may occur during a given period of several years. For instance, the occurrence of a storm with a maximum hourly intensity of 120*mm/hour* may not be determined for a particular year in the life of a structure. However, after collecting long-term precipitation information in the nearest rain gage one can ascertain that this rainfall intensity occurs an average of once every 200 *years*. This average interval of time is called the *return period*, *T*. We remark that this is an average interval between successive occurrences of the event. It does not mean that if the event occurs in a given year, one has to wait 200 years for the next occurrence. A return period of T=200 *years* means that if one had a very long precipitation record (i.e., 1,000 *years* of record, called a *population* in statistics), the event would occur *on an average* of once every 200 *years*.

High intensity rainfall events tend to be less frequent, and correspondingly exhibit long return periods. Similarly, low intensity events are more frequent, and correspondingly exhibit short return periods. This implies that, for a given duration, $t_s$ (*hours*, *min*), there is an inverse relationship between precipitation intensity, $p$, and $T$. The duration is important. Again, as the duration (i.e., the temporal scale of observation) increases the variability of precipitation decreases.

Since there is an intrinsic relationship between precipitation intensity, duration, and frequency (IDF relationship), it follows that an objective criterion to select a design storm under uncertainty is to assign a return period according to the size of the structure. Government organizations, regulatory agencies, and professional experience recommend a given return period for the design of a water resource project. The larger the size of the structure, the higher the magnitude of the design $T$. The hydrologist must establish the IDF relationship for the locality in question to convert the given $T$ into the design rainfall $p$. The design rainfall is