Rainfall Measurements at a Point using Rain Gauges

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A rain gauge is simply an instrument that is designed to measure the amount of rain that reaches the ground surface during a storm. Rain gauges are considered the most traditional method for measuring rainfall. They have been used historically to provide rainfall quantities and rates at a single point in space. The basic idea of most rain gauges is to collect rainwater into a cylindrical vessel of a fixed diameter. Rainfall measurements are usually provided in units of water depth (inches or millimeters). The volume of collected water is divided by the area of the cylinder opening and converted into a depth or rain. There are different types of rain gauges that can be classified into two main categories: non-recording gauges, and recording gauges (AMS Glossary, 2000).

Types of rain gauges

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Non-recording gauges

These are basic storage devices that measure the cumulative amount of rain. A common type of these gauges is called the 8-inch Standard Rain Gauge (SRG) which has been used by the weather offices of US National Weather Service (NWS) for over 100 years. The standard gauge is simply a large cylinder with a funnel and a plastic measuring tube inside the cylinder.

Figure 1.1: The National Weather Service Standard Rain Gauge, SRG (source: http://www.srh.noaa.gov/tlh/cpm/srg_page.html

Recording gauges

Unlike non-recording gauges, a recording gauge is designed to automatically record the amount of rainfall reaching the surface as a function of time during the lifespan of a storm. The most common types of recording gauges are:

- **Tipping-bucket rain gauge**

The tipping bucket rain gauge consists of a cylinder (typically 8 or 12-inch diameter) with a funnel that drains into a pair of buckets that are balanced on a horizontal axis. When a predetermined amount of rainwater (commonly 0.01 inches) has been collected into one of the buckets, the bucket tips causing the other bucket to move quickly into position and catch the incoming rain. With each tip, an electronic signal is sent to a data logger that records the time of tip occurrence. The known amount of each tip and its occurrence time makes it possible to calculate the incremental amounts of rain over variable or fixed intervals of time. These measurements can also be used to estimate the rainfall rates during the life of the storm.

An example of a tipping-bucket rain gauge (source: NovaLynx Corporation)

- **Weighing rain gauge**

A weighing gauge collects the amount of falling rain into a vessel that sits on a scale and measures the weight of accumulated water. The measurements are traced out on a chart which can be used to determine rainfall depth and intensity.

- **Optical rain gauge**

This is a relatively new technology (Nystuen et al., 1996) that is based on measuring rain rate as proportional to the disturbance by raindrops to an optical beam between a light source and an optical receiver. This type of rain gauges is relatively expensive and has been mainly used for research purposes.

Optical rain gauge (source: The Atmospheric Radiation Measurement (ARM) Program)

- **Disdrometer**

This is another research-oriented instrument that is used to measure the drop size distribution and falling velocity of rain drops and other types of hydrometeors. Drop size distribution measurements can be then used to calculate rain rates and other relevant information. There are different types of disdrometers that are based on either optical or acoustic technologies.

Sources of errors in rain gauge measurements

Although rain gauges present the most simple and direct way for measuring rainfall amounts and rates, they are subject to several sources of uncertainties and errors. The largest source of error is due to wind effect which is discussed along with other minor sources of errors in the following sections.

Wind-induced errors

Since most rain gauges are elevated above the ground, wind eddies form around their orifices which reduces the catch of small rain drops. This problem is known as wind-induced gauge under-catch and is considered the most common and serious source of rainfall-measurement errors. Wind effect can be minimized by placing wind-shields around the gauges.

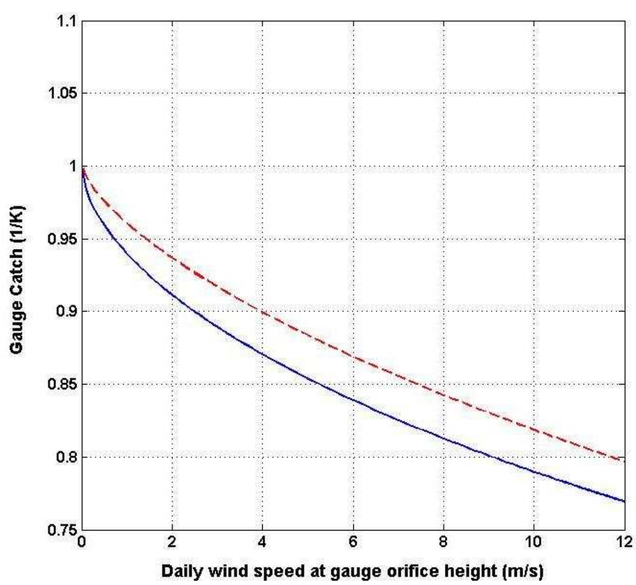
An example of wind-shield installed to reduce wind effect on rain gauge measurements (source: NovaLynx Corporation)

Several studies (e.g., Legates and DeLiberty, 1993) have developed and assessed different formulae to correct rainfall amounts due to wind effects for unshielded and shielded gauges:

Unshielded gauges: $$K = 100\ e^{(-4.605+0.062.u^{0.58})} \tag{2.1}$$

Shielded gauges: $$K = 100\, e^{(-4.605+0.062.u^{0.69})} \tag{2.2}$$

In the above formulae (Dingman, 2002) u is the daily average wind speed at the elevation in m/s and K is the wind correction factor. To adjust for wind under-catch, the calculated correction factors are multiplied by the measured daily rainfall values. The following figure shows a graphical representation of such formulae.



Gauge catch due to wind effect for gauges without wind-shield (solid line) and with wind-shield (dotted line).

Research has shown that for the US 8-inch standard rain gauge (SRG), wind under-catch can be in the order of 5 to 10% on an annual basis but can be relatively larger on individual storm scales. Therefore, it is recommended to perform wind corrections on a monthly or daily basis.

Evaporation and Wetting Losses

These losses are encountered in storage-type non-recording gauges, gauges with small orifices, and gauges recording at long intervals (several days). The magnitude of these losses depends on temperature, humidity, and time between rain and collection of the measurement. However, such errors are usually small and can be often neglected except for low-intensity rainfall events.

Calibration Errors

This error is encountered in tipping-bucket rain gauges. These gauges require calibration and adjustment of the tipping mechanism which is mostly done at a fixed small or intermediate rain rate (usually referred to as static calibration). However, at high rain rates a tipping-bucket gauge may suffer from underestimation problems due to the fact that the tipping buckets cannot keep up with heavy rain during a severe thunderstorm. To correct for such problems, rain rate-dependent calibration procedure (Humphery, 1997) should be developed; however, this can be time consuming and only static calibration is developed and provided by the gauge manufacturer. The user of such gauges should be aware of possible underestimation at high rainfall intensities (>50 mm/h).

Other sources of errors in gauge measurements

Other sources of errors include rainfall splashing, possible electronic and mechanical breakdown of gauges, clogging of gauge orifices and funnels, and observer mistakes in recording, processing and publishing rainfall measurements. Also, improper sitting configuration of rain gauges near trees or building can cause significant losses of rainfall amounts. As a general rule, an obstruction object should not be closer to the gauge than twice its height above the ground (Dingman, 2002).

How to deal with missing rainfall measurements

Missing records in rainfall measurements is not an uncommon problem. This is due to the high probability of gauge mechanical and electrical failures and is also caused by erroneous recording and publishing of rainfall measurements. Engineers often have to work with rainfall data from stations where rainfall records might be missing for a day or several days. This will limit most types of rainfall analyses such as calculation of water budgets, determining maximum rainfall intensities, and estimation of area-average rainfall intensities. Several methods have been developed to estimate missing records at a certain station from concurrent measurements at nearby stations based on a certain weighting scheme (Dingman, 2002):

Uniform weighting

This is the simplest weighting scheme where the same weight is assigned to each of the available *n* nearby station:

$$R_g = \frac{1}{n}\sum_{i=1}^{i=n} R_i \qquad (2.3)$$

In this equation, R_g is the estimate of missing rainfall record at a station g and $R_{i, i=1:n}$ are the corresponding measurements available at the *n* nearby stations.

This method is recommended if rainfall at each of the *n* nearby stations has similar trends and annual totals.

Normal-Ratio weighting

When annual rainfall in the area of study shows considerable variations (>10%) weighting factors can be assigned as follows:

$$R_g = \frac{1}{n}\sum_{i=1}^{i=n} \frac{AR_g}{AR_i} R_i \qquad (2.4)$$

In this equation *AR* represent annual-average rainfall at the missing station *g* and at the *n* nearby stations.

Inverse-Distance weighting

This method is based on the concept that gauges that are far from the gauge with missing records should be assigned smaller weights than those that are closer in distance. As such, the weight factor should be inversely proportional to the distance from the gauge with missing data. The proportionality can be either to the distance or the distance squared (most common):

$$R_g = \frac{1}{\sum_{i=1}^{i=n} \frac{1}{d_i^2}} \sum_{i=1}^{i=n} \left(\frac{1}{d_i^2} R_i\right) \qquad (2.5)$$

The user of these methods is cautioned against over weighting that may be caused by station clustering. When several of the nearby gauges are clustered together, they may bias the estimate of missing data. In such situation, only one out of the clustered stations (the closest to the missing station) should be included in the analysis.

Example:

Monthly rainfall measurements were recorded at six rain gauge stations as shown in Table 1.1. The coordinates of each gauge are given in terms of Easting (x) and Northing (y) values (Table 1.2). If the June reading of gauge 5 (G5) is missing, calculate an estimate for this value using two different methods: uniform weighting, and inverse-distance weighting.

Table 1.1: Monthly rainfall measurements (inch) at six stations

YEAR	MONTH	G1	G2	G3	G4	G5	G6
1994	1	4.4	3.4	4.7	7.6	4.0	3.8
1994	2	1.5	0.6	2.8	4.5	1.3	1.0
1994	3	2.1	4.3	5.1	4.7	2.4	2.9
1994	4	7.0	1.1	5.5	7.0	5.2	6.1
1994	5	3.4	7.8	4.6	8.0	3.8	5.0
1994	6	10.0	8.8	6.1	5.9	?	8.8
1994	7	9.2	7.7	10.8	6.0	10.7	12.0
1994	8	3.3	3.0	2.8	3.3	1.7	7.2
1994	9	3.6	10.3	3.6	4.6	6.2	9.8
1994	10	9.5	3.3	4.4	3.8	2.7	6.5
1994	11	1.3	4.1	2.3	1.2	1.9	0.8
1994	12	5.8	2.6	3.5	3.2	3.1	4.5

Table 1.2: Coordinates of the six stations

Gage#	Easting (m)	Northing(m)
G1	761257	3262310
G2	719842	3275040
G3	807849	3276620
G4	748650	3298200
G5	714621	3296010
G6	765282	3321970

Solution:

According to the uniform weighting average method, the estimated missing rainfall value is calculated as the simple arithmetic average of available measurements at the five other stations:

G5= (10.0+8.8+6.1+5.9+8.8)/5 = 7.9 inches

In the inverse-distance weighting method we have to use weights that are based on distance between the missing gauge and each of the other five gauges. Therefore, we first need to calculate such distances as follows:

$$d_{1\text{-}5} = \sqrt{(761257 - 714621)^2 + (3262310 - 3296010)^2} = 57538\,m$$

Similarly, $d_{2\text{-}5}$ = 21610 m; $d_{3\text{-}5}$ = 95223 m; $d_{4\text{-}5}$ = 34099 m; $d_{6\text{-}5}$ = 56925 m.

According to the formula of the inverse-distance weighting method, the missing rainfall value at station G5 is:

$$G5 = \frac{1}{\left(\frac{1}{57538^2} + \frac{1}{21610^2} + \frac{1}{95223^2} + \frac{1}{34099^2} + \frac{1}{56925^2}\right)} \cdot$$
$$\left(\frac{1}{57538^2}10 + \frac{1}{21610^2}8.8 + \frac{1}{95223^2}6.1 + \frac{1}{34099^2}5.9 + \frac{1}{56925^2}8.8\right) = 8.1 \text{ inches}$$

Estimation of Area-average rainfall from point measurements

While rain gauges provide rainfall measurements at individual points, it is more of interest for hydrologic engineers to know rainfall amounts over an area. Such an area can be a small drainage basin, a watershed, or a large river basin. Therefore techniques have been proposed to estimate area-average rainfall over an area or a region from point measurements. The most commonly used approaches are based on weighted averaging of rainfall measurements from individual gauges that are located within or close to the area of interest:

$$R_A = \sum_{i=1}^{i=n} w_i R_i \qquad (2.6)$$

In this equation, R_A is the estimate of area-average rainfall over an area A of interest, $R_{i,i=1:n}$ are the corresponding measurements available at the n stations within or close to the area boundaries, and w_i is the weight assigned to each station.

Two common schemes for assigning the weights are simple arithmetic averaging and weighting based on areas assigned to each gauge (Thiessen polygons):

Arithmetic Mean method

This is the simplest method for estimating area-average rainfall from individual stations. Each station is assigned the same weight $(w_i = \frac{1}{n})$:

$$R_A = \frac{1}{n} \sum_{i=1}^{i=n} R_i \qquad (2.7)$$

Thiessen Polygons method

This is the most commonly-used method for estimating area-average from point measurements. The weight of a certain station is estimated based on its relative sub-area within the total area of interest. A graphical procedure is followed to delineate the sub-areas. First, each adjacent pair of gauges is connected with a straight line to form a set of triangles that cover the whole area. Then, perpendicular bi-sectors are drawn through the sides of each triangle. The bisectors are extended until they interest with each other and with the boundaries of the area to form irregular polygons. The area of each polygon, a_i $(\sum_{i=1}^{n} a_i = 1)$, is used to calculate the weight associated with each gauge:

$$R_A = \frac{1}{A}\sum_{i=1}^{i=n} a_i R_i \qquad (2.8)$$

Where can engineers get rain gauge data from?

Rain gauges are usually operated within spatially-arranged networks that cover local, state, regional or national scales. The spatial density of rain gauges in the contiguous US is about 1.3 rain gauges per 1000 km^2 (Linsley et al., 1992) but varies considerably from a state to another. The temporal resolution of gauge recordings is usually hourly or daily with few stations reporting at 5 or 15-minute scale. The following is a list of the main available networks operated in the contiguous United States:

- Federal and State Wild-land Fire Programs operate more than 2,400 rain gages over the contiguous United States.
- The United States Geological Survey (USGS) operate about 1,734 rain gauges.
- The United States Army Corps of Engineers (USACE) operate more about 1,637 rain gages
- The National Weather Service (NWS) operate about 222 recording gauges (known as first-order stations) that provide rainfall measurements at an hourly scale.
- The National Weather Service (NWS) operate more than 8,000 nationwide stations that record rainfall measurements (also known as cooperative stations or cooperative network COOP; http://www.weather.gov/om/coop/). Unlike the first-order stations which are served by NWS staff and technicians, the COOP gauges are operated mostly by volunteers. Most COOP stations are of the non-recording gauge type which requires that the volunteer observer take daily visual readings of accumulated rainfall and record them in standard charts and tables. Some COOP stations are of the recording (weighing) gauges.
- The National Weather Service (NWS) supports other regional networks such as the Automated Local Evaluation in Real Time (ALERT;

http://www.alertsystems.org/) and the Integrated Flood Observing and Warning System (IFLOWS; http://www.afws.net/)

- Other networks are also operated by agencies such as the United States Bureau of Reclamation (USBR) and Tennessee Valley Authority (TVA).

- Several Meso-scale networks (known as Mesonets) sponsored by state and local government funded agencies (e.g., Oklahoma Mesonet, http://www.mesonet.org/)

- The Automated Surface Observing Systems (ASOS) network which is sponsored by the National Weather Service (NWS), the Federal Aviation Administration (FAA), and the Department of Defense (DOD). There are about 1000 ASOS stations distributed in regional airports around the country providing 24-hour coverage at an hourly or finer scale (http://www.faa.gov/airports_airtraffic/weather/asos/). ASOS gauges are of the tipping-bucket gauge type.

Sources of rain gauge data:

Rainfall data from the various networks and platforms discussed above are archived by the National Climatic Data Center (NCDC) in Ashville, NC. The archive can be accessed from NCDC and other regional climate centers. The website of NCDC (http://www.ncdc.noaa.gov) is probably the world-largest archive of weather data and contains extensive records of historical as well as recent rainfall data. This dataset is available in the forms of monthly publications, reports, CD Rom's and through online downloads. All online access is free of charge for government users and educational institutions, with several datasets freely available for all users.

A detailed list of "most popular" NCDC products is available at http://www.ncdc.noaa.gov/oa/mpp/; the most relevant of these products for hydrologic engineering applications are:

Hourly Precipitation Data (HPD-DS3240)
This product is based on compiling rainfall data from about 240 first order stations and 2600 cooperative stations. Data is provided in hourly values and is available since 1948 and generally have a 4-6 month time lag.

Surface Summary of the Day (DS3200/DS3210)
This product is based on measurements from about 8000 Coop stations and provides total daily rainfall values.