Inadvertent Rain Gauge Inconsistencies and Their Effect on Hydrologic Analysis

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Introduction

Consistent rainfall data is, perhaps, the most significant ingredient in developing accurate hydrologic analyses. Without consistent rainfall data from storm to storm or even within storms, accurate streamflow simulations and forecasts are extremely difficult to achieve. Even though most hydrologists readily acknowledge this fact, rainfall records are rarely scrutinized to the degree necessary to develop an "engineered" data set that best indexes the true rainfall entering the watershed. This paper will review some of the factors that lead to inadvertent inconsistencies in rainfall data, provide some insights into the sensitivity of streamflow simulations to rainfall errors, and offer some suggestions to improve gauge and data management procedures in order to help improve data consistency.

Historical Perspective

Some of the problems associated with rainfall measurement have been known for hundreds of years. For example, a demonstration performed in 1769 showed that a rain gauge located on the top of a 30 foot tall house caught just 80% of amount measured in a ground-level rain gauge. Similarly, a gauge atop a 150 foot abbey tower caught just over 50% of the ground level catch. (See Figure 1) It took until the late 19th century to fully understand that the reduced rain gauge catch associated with height above ground was due to the turbulent airflow around exposed gauges in strong winds. (Frisinger, 1977)

Similar observations were reported a century later by Symons (1881). Symons compared rain gauge catch at various elevations with the catch at two inches above ground level. Symons' results as shown in Figure 2 represent conditions prevalent at the time of his experiments. He did not consider the gauge catch variation with varying wind conditions as later researchers would.

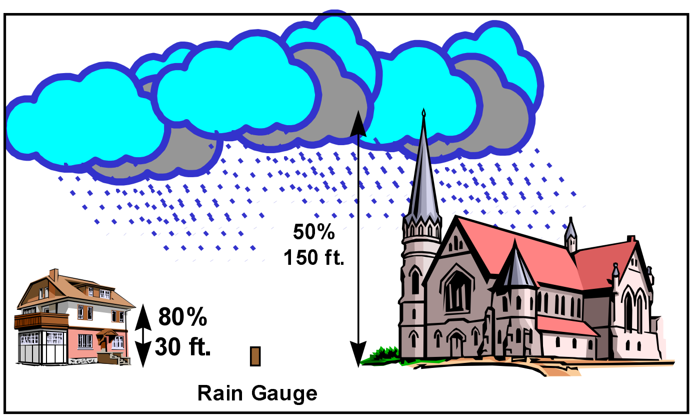

Figure 1: A demonstration in 1769 showed that a rain gauge located at the top of an 150 ft. abbey tower collected just 50% of the ground level rainfall and a gauge on the roof top of a 30 ft. house collected 80% of ground level rainfall.

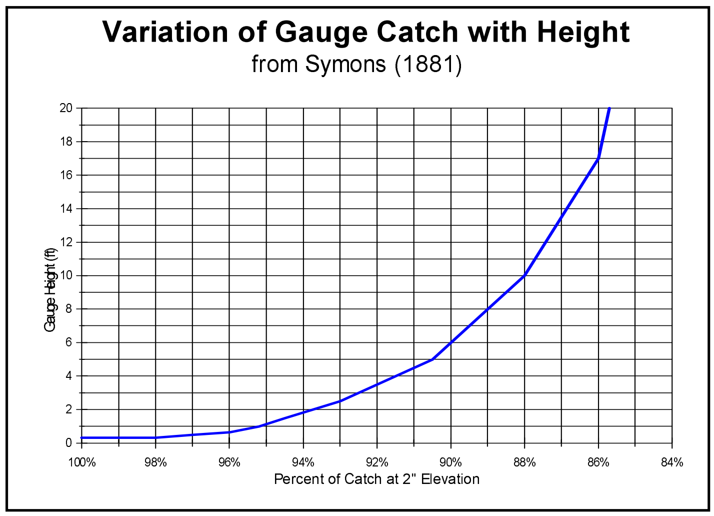

Figure 2: Variation of gauge catch with height for a given set of wind conditions as report by Symons (1881)

Inadvertent Inconsistencies

Inconsistent rainfall records had been brought about by a variety of actions, many of them well intentioned, and most of them quite inadvertent. Rain gages have been moved short distances to accommodate the wishes of a cooperative observer who wanted to raise vegetables where the gage stood. Or, the observer might want to put in a walk way, or build a chicken coop, or provide space for children to play; at other times, a rose garden might be desired so that it wouldn't be necessary to look at that eyesore called a rain gage. It would be difficult to determine how many records have lost consistency because someone wanted to beautify the area around that dented, dirty old can with an attractive planting.

The National Weather Service occasionally contributed to this confusion by moving gages as vegetation altered site characteristics - the correct procedure would have been to keep the height of the surrounding vegetation constant. Unfortunately, the cost and politics of such actions were well beyond the capability of a government agency. Another problem impairing data consistency occurred when an observer terminated their observation program. At such times, the gauging equipment would frequently be moved to another property in the general area. A location which was considered by the NWS substation specialist as being a compatible site. All too often, the term compatible was used to describe any site which had its mail delivered by the same post office. Unfortunately, many of these records were published as a continuing record with inadequate documentation of the change in location.

Even the best intentions of those who were running the rainfall data program led to a variety of inadvertent changes in record through the necessary, but frequently injurious, effort to maintain and improve the quality of data collection. This occurred when equipment wore out and was replaced with equipment which had an orifice at a different elevation and/or was designed with a shape that had different aerodynamic properties. Changes which confused the hydrologic consistency of the data might be as obscure as installing a platform so the observer didn't have to stand in the mud, or as physically obvious as installing a wind shield to "improve" the catch under windy conditions. But all of these actions had one thing in common, they altered the exposure of the gage orifice to the wind and in so doing modified the representativeness of the resulting rain catch.

Many different factors that affect rain gauge records have been identified and, to some degree, quantified. Some of these factors are reviewed in the following sections.

Natural Variation in Rainfall

Rain gauge measurements taken by identical gauges located a few feet apart have experienced differences as much as 20%.

Size of the Tipping Bucket

At the end of the storm, the expected amount of unreported rainfall is ½ the tipping bucket size. If all or part of this rainfall evaporates before the next tip, this amount of rainfall is unrecorded. In areas with 50 storms per year, a 1 mm (0.04 in.) tipping bucket might fail to report 25 mm (0.98 in.) of rainfall over an annual cycle. Under the same conditions, a 0.01 in. tipping bucket gauge might fail to report 0.25 in. of rainfall during the same annual cycle.

Tip Time

Tipping buckets miss a small amount of rainfall during each tip of the bucket due to the bucket travel and tip time. As rainfall intensities increases, the volumetric loss of rainfall due to tipping tends to increase. At rainfall intensities above six inches per hour, 1 mm tipping buckets will under report rainfall in the range of 0-5% depending on how the gauge was calibrated. Smaller tipping buckets can have higher volumetric losses due to higher tip frequencies.

Gauge Height

The height of the gauge above ground can have a dramatic affect on gauge catch. As gauge height increases from ground level, wind speed at the gauge orifice increases due to decreasing frictional effects on the air stream caused by the ground surface. Larson and Peck (1974) show results that indicate wind induced undercatch is on the order of 1% for each mile per hour of wind at the gauge orifice. Assuming a logarithmic wind profile with height (Figure 3), a 15 mile per hour wind at the standard ALERT gauge height of 10 feet could be expected to induce a 15% loss compared to a 12% loss if the same gauge were just 4 feet high.

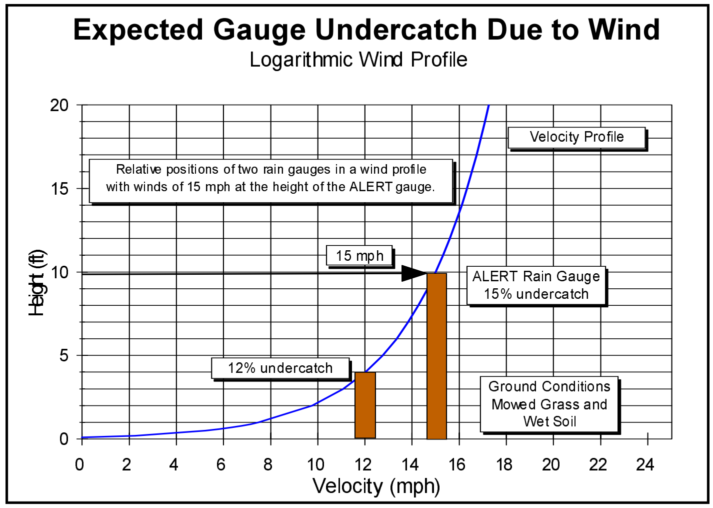

Figure 3: Expected gauge undercatch due to 15 M.P.H. wind

Discrete Exposure

Gauges located in an area with variable protection relative to different wind directions will produce different results. For example, consider Figure 4 with two gauges located in the same general area. In the wind field shown, gauge **A** is protected by nearby vegetation and experiences a 10 m.p.h. hour wind. However, gauge **B**, located a few feet away, may experience 20 m.p.h. winds due to more direct exposure to the general wind field. Under these conditions, Gauge **A** might experience a 10% reduction in catch due to wind but gauge **B** could experience a 20% reduction in rainfall catch due to higher wind speeds at its location.

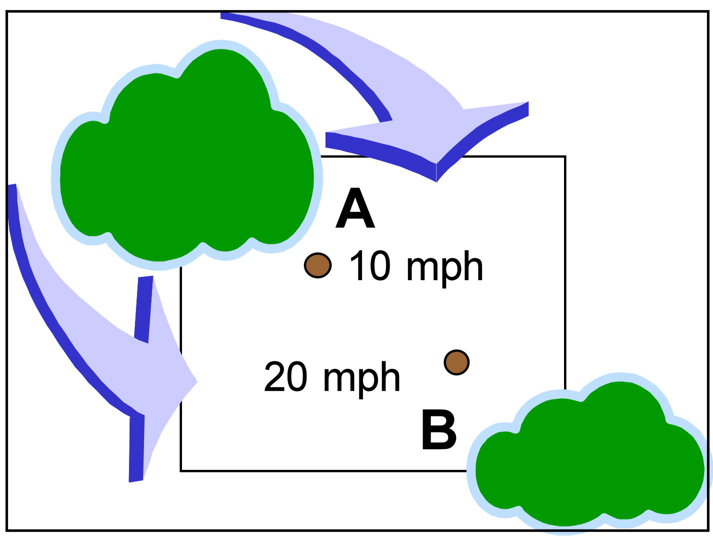

Figure 4: Location of gauge relative to local wind field affects gauge performance.

Time Variability

Site exposure conditions that change with time will also affect rain gauge performance. As vegetation grows and/or changes relative to the gauge site or as the number, size, and shape of nearby buildings change, site aerodynamics change over time and can produce significant changes to the rain gauge performance. Figure 5 shows how growth of vegetation can modify wind at the gauge and alter precipitation catch.

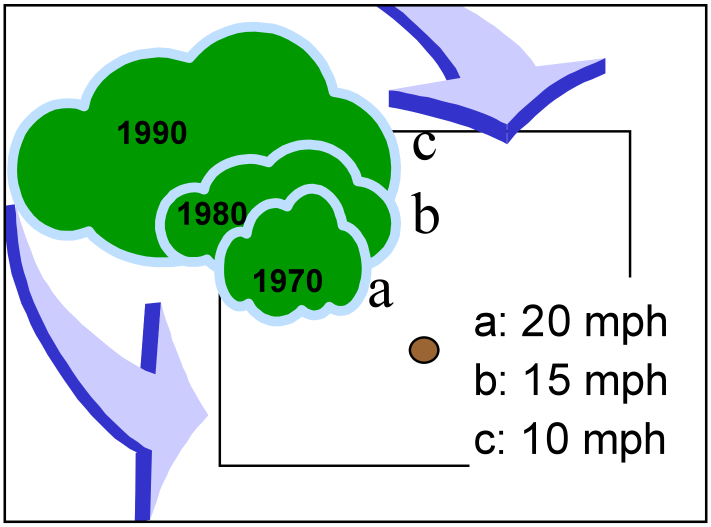

Figure 5: Growth of vegetation over time significantly changes wind velocity at gauge site and alters catch characteristics.

Gauge Change

Each gauging system has its own unique rainfall measurement characteristics. Both external and internal gauge system attributes affect gauge performance. External factors include site and locational characteristics. Internal factors include the physical, mechanical, and electrical characteristics of the gauge itself. As long as these attributes stay the same, gauge records remain consistent. Any errors or biases present in a consistent rainfall record are overcome in hydrologic model calibration.

Table 1 presents some of the important systematic errors identified in a World Meteorological Organization report that are associated with rain gauges. Each gauge has a specific set of systematic errors. If a gauge is changed either for a new model or a new gauge type, these systematic errors change, making the record inconsistent.

Gauge Calibration

Rain gauge calibration has an impact on record consistency, especially if the method of calibration changes periodically. For example, if a static calibration is used one time and a dynamic calibration is used another, rainfall measurement will be inconsistent.

Static calibration of an ALERT tipping bucket usually sets the 1 mm tipping bucket to tip after the accumulation of 72.94 grams of water. (i.e. the weight of 1 mm of water across the area of the 12.0 in. ALERT gauge orifice) Dynamic calibration, on the other hand, sets the bucket to tip the correct number of times associated with a certain rainfall rate, usually 6 in./hr. for ALERT gauges.

Unfortunately, its impossible to have an ALERT tipping bucket calibrated to tip at exactly 1 mm (72.94 grams) ***and*** be calibrated for zero error at a rate of 6 in./hr. In other words, you can't have your cake and eat it too!

The reason for this paradox is that in dynamic operation, the tipping bucket takes a finite amount of time (e.g. on the order of 0.5 sec) to tip. If the bucket is calibrated to tip at exactly 1 mm, rain will still accumulate in the bucket until the bucket moves past the midpoint of the tip and the rain begins to accumulate in the second bucket. This 'extra' rain accumulating in the first bucket during the tip is unmeasured. A bucket calibrated to tip at exactly 1 mm will tip fewer times and under report rainfall at higher rates.

Dynamic calibration takes the tip time into account implicitly. In order

Component of Error	Magnitude	Meteorological Factors	Instrumental Factors
Loss due to wind field deformation above the gauge orifice.	2-50%	Wind speed at the gauge rim during rainfall and the structure of rainfall.	The shape, orifice area, and depth of both the gauge rim and collector.
Losses from wetting on internal walls of the collector and in the container when it is emptied.	2-10%	Frequency, type, and amount of precipitation, the drying time of the gauge, frequency of gauge emptying.	The shape, orifice area, and depth of both the gauge rim and collector. In addition, the color, material, and age of collector and container.
Loss due to evaporation from container	0-4%	Type of precipitation, saturation deficit, and wind speed at the level of the gauge rim during the time interval between the end of precipitation and measurement.	The orifice area and isolation of the container, the color and, in some cases the age of the collector, or the type of the funnel.
Splash in and splash out	1-2%	Rainfall intensity and wind speed	The shape and depth of the container and the kind of gauge installation.

Table 1: Main components of systematic error in precipitation measurement and their meteorological and instrumental factors listed in order of importance. (Sevruk, 1982)

to calibrate a tipping bucket to have zero error at a rainfall rate of 6 in./hr., the bucket must be calibrated to tip at a lower volume (e.g. 69.6 grams, approximately). This lower volume plus the volume associated with the tipping time will total 1 mm and the tipping bucket will exhibit zero error at the dynamic calibration rate of 6 in./hr.

Calibrating a tipping bucket to zero error at 6 in./hr. using a smaller volume to initiate a bucket tip implies that the tipping bucket might tip more frequently at lower rainfall rates and, therefore, over report the rainfall. However, at least in some ALERT tipping buckets, the tipping time is slightly longer at lower rainfall rates which compensates for the lower calibrated volume. A properly functioning ALERT tipping bucket dynamically calibrated to zero error at 6 in./hr. shouldn't over report at lower rainfall rates by more than 1-2%.

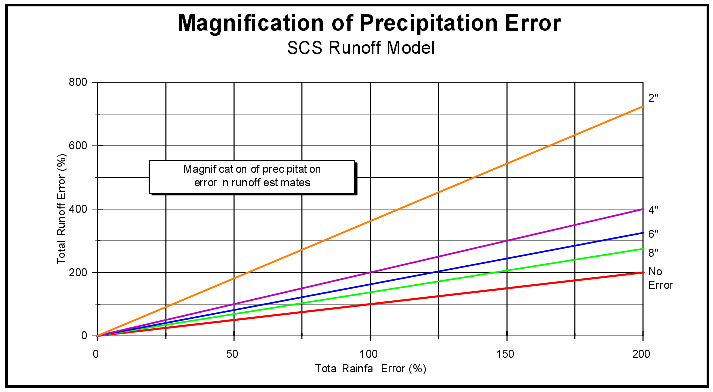

Figure 7: Errors in rainfall estimates produce relatively greater errors in runoff estimates.

Implications for Hydrologic Analysis

How systematically must the precipitation indexing capability be maintained in order to be useful in determining runoff? Figure 6 shows the effect which an inconsistent gauging network would produce in evaluating the storm's contribution to peak discharge. Assuming moderately dry initial soil moisture conditions, a variety of storms of various magnitudes were analyzed to determine the relative difference in the expected contribution to peak flow if the precipitation was overvalued by 5% compared to being undervalued by 5%. These relatively small changes in precipitation indexing capability produce errors which are inversely related to the quantity of runoff. The proportional variation in peak flow can readily exceed three hundred percent when runoff volumes are small. In a major flood event, with high runoff volumes, the runoff error converges very slowly toward the rainfall error. This convergence is however, so slow that for the storm rainfall values used to produce Figure 6, the proportional runoff variation is just dropping below 20% for very large storm rainfall volumes. Thus, for even major events, we can conclude that inconsistency in evaluating precipitation which is as little as 5%, can have substantial impacts upon runoff determination.

Figure 7 again shows how rainfall errors are magnified. When soils are nearly saturated, runoff nearly equals the rainfall and the runoff error is just slightly larger than the rainfall errors in large events. However, for smaller events and dryer soils, the effect of errors is much more pronounced. In this case, a 100% rainfall error is magnified by a factor of 3.5 to 4 for a 2 inch event.

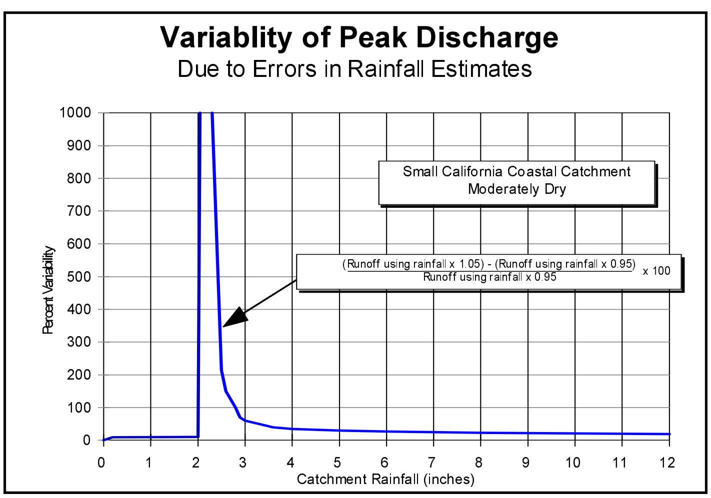

Figure 6: Errors in rainfall estimates can generate large errors in estimates of peak discharge

Summary

Unfortunately, there are so many factors which can influence the accuracy of precipitation measurements that no one has yet been able to devise a gage that will consistently measure "true rain". The measurements which have been judged most accurate are those which have been observed with pit gages. But pit gages are extremely expensive to operate and have major constraints which substantially limit their application to research projects. The best that can be hoped for is that the gauging equipment will operate close to the scale of reality and with a degree of consistency which will provide a stable index to the rainfall-runoff process. Inasmuch as it takes many years of consistent data to define the rainfall-runoff relationship, it is a mistake to continually modify an operational gage seeking a better approximation of 'true rain'.

There are two essential elements in the effective application of rainfall data to streamflow forecasting. The rain gage network must adequately index the precipitation falling on a catchment and it must do so in a consistent manner which does not alter the indexing capability with time. The first of these elements is achieved by installing an adequate network of appropriately sited and consistently measuring precipitation gages. Regardless of the density of the gauge network, a second element is necessary. A consistent representation of the runoff regime is dependent upon effective systematic maintenance of both the equipment and the gauging site. Only through these steps can the investment in real-time data produce the flood warning capability for which the ALERT system was intended.

References

Alena, Thomas; et. al., *Measurement Accuracy Enhancement of Tipping Bucket Rain Gauges at High Rainfall Rates*, Fifth International Conference on Interactive Information and Processing Systems, AMS publication, 1989

Frisinger, H. Howard, **The History of Meteorology: to 1800**, Science History Publications, AMS, 1977, pp 88-91

Larson, Lee and Eugene L. Peck, *Accuracy of Precipitation Measurements for Hydrologic Forecasting*, **Water Resources Research**, Vol 10, No. 4, 1974

Sevruk, B., *Methods of Correction for Systematic Error in Point Precipitation Measurement for Operational Use*, **Operational Hydrology Report 21**, World Meteorological Organization, Geneva, Switzerland, 1982

Symons, G. J. *On the Rainfall Observations Made Upon Yorkminster by Professor John Phillips, F.R.S*, **British Rainfall**, pp 41-45, 1881

Weiss, L. L. and W. T. Wilson, *Precipitation Gage Shields*, **International Union of Geodesy and Geophysics**, General Assembly of Toronto, 1957, Volume 1, pp 462-484