Snow Measurement Predicament

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Abstract. Increased interest in snow and snowmelt runoff has resulted in the need for a better knowledge of snowfall and the water equivalent of snow cover. Present measuring methods have proven valuable for seasonal runoff prediction and other water management requirements in major snow areas. However, more accurate estimates of the actual snowfall and the average areal snow cover are required for detailed water budget and water use studies and for input for the conceptual forecasting models now being developed. The limitations of present measuring systems are analyzed, and guidelines for their usefulness as indices are presented. The basic problems involved in determining more representative values are discussed, and suggestions are given for methods to improve measurements.

This paper should provide a basis for examining the difficulties encountered in precipitation measurement. My comments will be limited to those problems associated with measurements of snowfall (precipitation) and the water equivalent of the snowpack.

As early as the thirteenth century, in each provincial and district capital the Chinese had rain gages similar to the nonrecording gages of today [*Needham and Ting*, 1959]. A book published in 1247 A.D. described the problems of improving the shape of the rain gage and the methods of computing the average precipitation for an area from the recorded catch. The book also described the first known snow gage (actually a snow bin), which was a large bamboo cage used in areas of high elevation to collect snow and to provide information similar to that obtained from our present day snow courses.

The recent work of *Israelsen* [1967] extended the excellent review of the literature on precipitation gage measurements compiled by *Kurtyka* [1953]. There are numerous references in these two publications to studies conducted during the past 100 years to solve the problems that confronted the early Chinese. However, the knowledge gained during the past century has not been sufficient to provide the information needed to measure adequately either snowfall or areal snow cover. For example, the published information on average snowfall in the northern Central Plains of the United States is probably significantly less than the 'true' average.

With the recent developments in conceptual watershed models for snowmelt and river forecasting, it is evident that our inability to evaluate adequately the areal average water equivalent of the snow cover is the greatest limitation on future improvement in the reliability of snowmelt forecasting. This limitation applies to many water resources and related studies for which an accurate accounting of the water in the snow is essential.

SNOWFALL MEASUREMENT ERRORS

Snowfall is the form of precipitation that is most difficult to measure. The World Meteorological Organization (WMO) defines precipitation as 'the quantity of meteoric water, liquid or solid, which passes through a given horizontal surface.' Most gages have an orifice that is exposed in a horizontal plane for intercepting the falling precipitation. Errors in precipitation measurements have been studied in considerable detail, and the purpose of this report is not to review these problems.

The effect of wind action on a gage is recognized to be the largest and most varied source of measurement error, especially when the precipitation is snow. Many attempts have been made to design a gage that would overcome this adverse effect or to protect gages by means of a windshield or other structure. For rainfall, pit or ground surface gages adequately protected from such phenomena as splash provide a fairly reliable measurement of the ground true precipitation. However, this type of gage is unsuitable for measuring snowfall.

There have been many studies to develop methods for predicting the ground true snowfall from the catch in various precipitation gages. The results of these studies are not consistent, and it is evident that the experiments were not conducted under similar conditions. The basic assumption underlying many of these studies is that the error in the catch is related to the horizontal wind movement during the time of precipitation. Although this assumption has merit and has provided techniques for determining a better estimate of the true snowfall at specific locations under specified conditions, the results have not been found to have universal application.

Figure 1*a* shows the classic diagram used to illustrate the effect of introducing a gage into a horizontal wind field with the resultant increase in wind speed over the orifice of the gage. Smaller raindrops and snow particles are assumed to be deflected, and the amount of precipitation entering the gage is less than the amount that would have passed through the same horizontal area if the gage had not been placed in the wind field. Figures 1*b* and 1*c* show that turbulence induced by roughness in the area of the gage can result in increased upflow or actual downflow over the orifice in comparison to the flow shown in Figure 1*a*. The variation in the flow depends on many factors, such as the location and direction of the roughness elements in relation to the gage, the wind direction, the wind speed, the stability of the air, and the vertical wind movement associated with the falling precipitation.

In addition to aerodynamic effects, there are many other possible causes of the variation in relative catch reported by investigators. The work in the United Kingdom by Rodda and others [*Rodda*, 1967; *Robinson and Rodda*, 1969] has shown that the relative catch for the same type of gage varies with location and season. Figure 2 from the 1968 report of the Institute of Hydrology shows the difference in the relative catches of a standard rain gage and a ground level gage during the year at the Wallingford location, where almost all precipitation is in the form of rain.

The Working Group on Measurement of Precipitation, Commission for Instruments and Methods of Observations, WMO, recently completed a study comparing the catches of different types of gages to the catch of an accepted interim reference precipitation gage [*World Meteorological Organization*, 1969]. The comparisons were made in many countries under different climatic conditions. The objective was to determine a reduction factor for each type of gage that would reduce all measurements to a single international scale. The committee reported that it was impossible to obtain a single system of reduction coefficients and that for a long period of time (not less than 4–5 years) the reduction coefficients were found to be close to unity.

Unlike rainfall, snow is subject to redistribution after it has fallen past the plane of the orifice of the gage. Anyone who has been in a midwestern blizzard realizes the impossibility of distinguishing blowing snow from falling snow. In mountainous areas snow occurring as precipitation on rocky cliffs or on windward slopes is often blown into protected areas during or following precipitation and may be measured more than once.

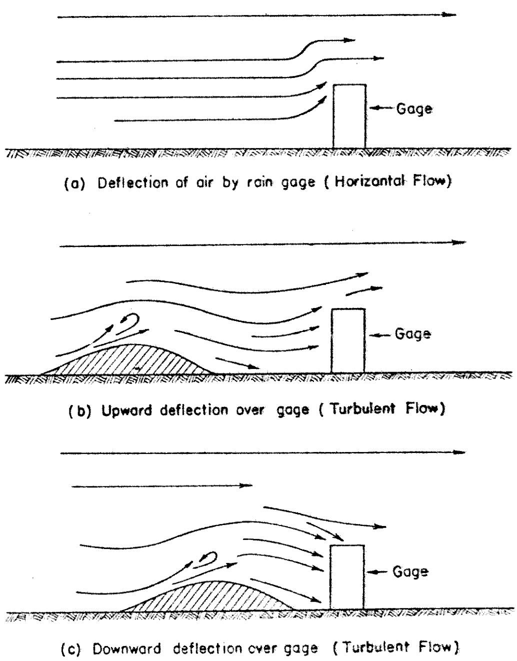

Fig. 1. Variation in airflow over precipitation gage.

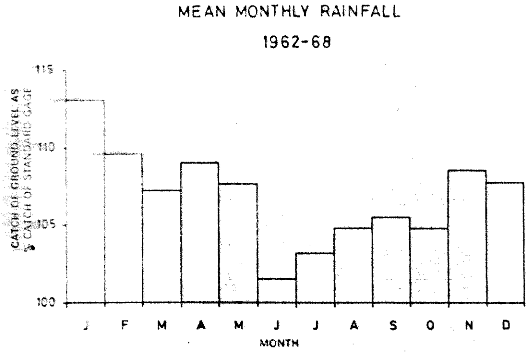

Fig. 2. Seasonal differences between ground level and standard rain gages at Wallingford, United Kingdom.

After reviewing the many efforts to reduce snowfall measurements in precipitation gages to a standard or ground true value, one finds that unless additional studies are based on new principles the techniques will continue to have only provincial application. The use of dual gages as suggested by Hamon and Smith (unpublished report, 1968) has shown some promise but is subject to some of the sources of error and variation affecting other methods of measurement.

WATER EQUIVALENT MEASUREMENTS

Point measurement of the water equivalent on the ground can be made within known limits of error. New techniques such as the twin probe snow density gage (Howe and Houghton, unpublished manuscript, 1968) have shown promise of providing continuous reporting of the point measurement of the water equivalent. However, the redistribution of snow may cause variations in the snow cover at the site that make the measurement unrepresentative of the average areal value. In mountainous areas the roughness of the terrain or the presence of snow fences may result in the deposit of more or less than the average amount of snow at the measurement site. This increase or decrease relative to the areal average is related to the type of snow and the magnitude, direction, and time of wind occurrences. In the northern Central Plains of the United States the amount of snow that remains on the ground in any location depends on the type of ground cover. Snow in stubble fields may be several times as deep as snow in adjacent grass range areas. The U.S. Forest Service reported in a recent International Hydrological Decade Snow and Ice Conference that, even in mountainous areas under nearly ideal site conditions, measurements made in small forest openings were larger than the average for the research watershed based on hundreds of individual measurements.

VALUE OF PRESENT MEASUREMENTS

The value of snowfall and snow survey data is questionable if the errors of measurement are considered. However, snowfall and snow survey data measured at sites that are well protected from wind movement may be close to the actual point snowfall [*Wilson*, 1954; *Brown and Peck*, 1962; *Corbett*, 1965]. Natural protection reduces the turbulence and eddy current near a gage, and if the shelter is sufficient, the snow fence effect at the snow survey site is also greatly reduced. The value of records from well-protected sites may be seen in Table 1.

Correlation coefficients are shown for the October–June precipitation records at Silver Lake Brighton and Snake Creek, Utah, and April–September streamflow records from streams in northern Utah. Snow survey course data from such protected sites also correlate well with streamflow measurements. However, the coefficients are much higher for the intermountain area than for most stations. Records

TABLE 1. Correlation between October–June Precipitation and April–September Streamflow, Northern Utah

	Precipitation Stations	
Streams	Silver Lake Brighton	Snake Creek
Weber River near Oakley	0.89	0.86
Chalk Creek at Coalville	0.79	0.82
East Canyon Reservoir inflow	0.80	0.86
American Fork near American Fork	0.87	0.94
Parley Creek near Salt Lake City	0.77	0.84
Moon Lake Reservoir inflow	0.84	0.83
Rock Creek near Mountain Home	0.89	0.87
Duchesne River near Tabiona	0.86	0.93
Strawberry Reservoir inflow	0.88	0.93

from less protected sites do not correlate nearly so well with streamflow records as records from well-protected sites do, and the records from less protected sites have little or in many cases no value for prediction purposes.

Before the 1969 spring snowmelt floods in the Midwest, an intense survey was made of the water equivalent of the snow in the Rock River basin in Iowa and Minnesota. Although the point measurements of the snow on the ground varied considerably, the average values determined for subbasins correlated well with the total precipitation from the date of first continuous snow cover for stations located in small towns with good protection from the wind.

Until methods are devised for determining true snowfall values and basin average water equivalent, records from a few selected sites may offer much more reliable estimates for forecasting snowmelt runoff than measurements from a large number of stations with variable wind exposure conditions.

Detailed information on the exposure and roughness in the immediate area of precipitation gages and snow survey courses may prove useful in evaluating the usefulness of existing records. The installation of all stations for the index measurement of snowfall should be at protected sites whenever possible to obtain the most consistent and reliable measurements.

NEW APPROACHES TO MEASUREMENT

Attempts during the past 100 years to use precipitation gages to obtain a reliable and consistent measurement of snowfall have been unsuccessful. Using point or snow course measurements to obtain an accurate areal average of the water equivalent of the snow cover has likewise been unsatisfactory. A representative measurement of the snowfall may be obtained only at a level above the ground where blowing snow or redistributed snow does not occur in appreciable amounts. The height at which such measurements should be made varies depending on the climate. A technique for obtaining an areal measurement of the water equivalent of the snow cover directly is also necessary to avoid the redistribution problem.

The possible use of radar to measure snowfall was promising for several years, but the latest developments and reports have been disappointing. A new method for obtaining a measurement above the level at which redistribution of snow occurs is now being investigated by the Wave Propagation Laboratory of the National Oceanic and Atmospheric Administration at Boulder, Colorado. This method measures the microwave attenuation between two points across a valley floor with Doppler radar, which obtains measurements of the terminal velocity of the precipitation particles. This method should provide an integrated measurement over the path and be a step toward obtaining an areal measurement.

The Hydrologic Research and Development Laboratory of the National Weather Service has contracted with EG&G Incorporated to use planes equipped by the Atomic Energy Commission for research on the use of the areal survey of natural gamma radiation as a tool for measuring the average water equivalent of a snow cover. The attenuation of the natural gamma radiation provides a measure of the water equivalent of the snowpack. The Soviet Union has tested this approach for several years and has reported success in measuring water equivalents up to 300 mm. A second method, which does not require calibration flights when there is no snow cover, is also being investigated. This approach would use differences in photo peaks of energy levels for direct correlation with the water equivalent of the snow cover. These approaches would provide rapid collection of data for large areas without the problems involved in the extrapolation from point measurements. (See *Water Resources Research* 7(5) for more information.)

CONCLUSION

The growing need for reliable and consistent measurement of snowfall calls for a change from the continuation of the limited research efforts to improve the usefulness of present day precipitation gages. There is also a critical need to measure the areal snow cover water equivalent directly without using questionable point measurements as a starting point. The development of adequate techniques will require investigations of entirely new approaches free of the deficiency caused by poor exposure and the redistribution problem associated with present day measurement methods. This research and development will require more research funds than are now being expended on snow research in the United States. Significant improvement in snowmelt flood forecasting and further advances in many hydrologic and water resources study areas will have to await the development of more reliable measurement methods. Until that time hydrologists will continue to be plagued with the snow measurement predicament.

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