# PROBLEMS OF MEASURING MELTWATER IN THE SNOWPACK

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## Abstract

In modelling snowmelt runoff much effort has been devoted to estimating the melt rates, but until recently little attention has been paid to the role of the snowpack in controlling runoff. The reason lies partly in the difficulty of making the necessary observations and measurements, and partly in the mathematical and conceptual problems of modelling the movement of water in the snowpack.

In this paper the problems of measurement of liquid water content are discussed with reference to techniques presently in use. Recent developments are described and a classified bibliography is given.

## Introduction

In recent years snowmelt has received a considerable amount of attention in hydrologic models because it is the process by which water stored in seasonal snowpacks is released into the system. Such models, however, take little or no account of the role of the snowpack itself in routing the meltwater. This is in spite of the fact that sudden and catastrophic runoff from snow, not explicable by the rate of snowmelt, has been known for forty years or more.

For example, in a careful study of the 1936 spring floods in New England, Wilson (1941) concludes that, for the 104 sq. mile Pemigewasset basin, at least four inches of water equivalent came from the snow alone in one day. In fact in 1941 the Eastern Snow Conference Research Committee listed as a major project a study by C.F. Merriam of the Susquehanna basin whose object was to study the critical conditions by which snow"suddenly loses its water content." (Church, 1941).

In relation to this problem, measurements of liquid water content are necessary for two reasons. First, the permeability of the snow is a function of liquid water content. Since the permeability is of fundamental importance in modelling the runoff rate, whatever the model, water content data are required. Second, under certain conditions, the snowpack is capable of storing water, either as static internal ponds or by dynamic detention (Langham, 1973 a, b). The release of this stored water is obviously related to the problem of sudden runoff. The effect of saturated zones in the snowpack is not limited to the water they contain but includes changes in capillary suction and the water content in their vicinity.

The liquid water content of snow is also a critical factor in the release of wet avalanches. The mechanism is poorly understood at the moment and, moreover, the means of conducting such studies are limited because of the danger. The effect of slope and orientation on the intensity of solar radiation falling on the snow makes it difficult to accept the working hypothesis of some workers that the liquid water content of nearby safe snow is similar to that in avalanche areas. The work discussed in this paper is therefore primarily related to the hydrologic problem.

In describing liquid water in the snow the following terms are used by other authors: liquid water content, free water, water content and thermal quality. "Water content" is ambiguous because it is also used to mean water equivalent. Thermal quality is the complement, in percent, of the liquid water content. It is sometimes used when the warming of the snowpack is being studied (eg. Leaf, 1966).

Throughout this paper the liquid water content is expressed as a percentage of sample volume. It varies from 0% in dry snow to about 50% in saturated snow. In drained snow, values given by various authors vary considerably according to conditions and the reliability of the measurements. In order to appreciate the problems of measurement, however, it may be said that in general values lie between 2% and 10%.

The accuracy claimed by the authors depends on the capabilities of a given technique, the precision of measurement, the care in experimental procedure and the optimism of the author in estimating his error.

A bibliography of publications classed by method of measurement is given at the end of this paper. The principal methods are based on calorimetry, dielectric property and centrifugal separation.

## Calorimetry

The use of this method for measuring the liquid water content of snow was first described by Yosida (1940). In the following years the method was used by various other workers. In principle it is simple. Enough hot water is added to a sample of wet snow to melt it. The temperatures of the hot water and the final mixture are known together with their masses. It is then possible to calculate how much of the heat was used as latent heat to melt the snow and hence how much of the sample was solid and how much liquid.

The difficulties of the method are:

a) The method is very sensitive to heat lost from the calorimeter.
b) The precision of temperature measurement in relation to the temperature change limits the accuracy.
c) The method requires time and care to produce good results and so only a limited number of measurements separated by long intervals may be made on a given day. Unfortunately the liquid water content of the snow varies sufficiently both in time and in space that it is difficult to relate these measurements to each other. This is also a problem with many of the other methods.

Estimates of the accuracy of this method are about ± 5% in the liquid water content.

The method was improved by de Quervain (1948) by the use of an electric heater. Heat is supplied continuously at a measured rate until all the snow has melted. As soon as the temperature starts to rise above zero the heating stops. Thus the method is rather like differential thermal analysis. More accurate results are obtained than with hot water the error,being estimated at about ± 1.5% in the liquid water content.

An improvement of a different kind was used by Radok et al (1965) in which the sample was frozen instead of melted. The advantage is that the latent heat is now used to freeze the small amount of water rather than to melt a large amount of snow and as a result the measurements are more sensitive to variations of liquid water content. Radok in comparing the electric and freezing methods attributed to them errors of ± 2% and ± 1% of the liquid water content.

Yosida, who has used various methods since his early work, presently advocates a double vessel hot water calorimeter (Yosida, 1967). His error is at least ± 1% in the liquid water content.

A logical development of the freezing technique, along the lines of the electric melting calorimeter, would be to freeze the sample electrically. This could be done quite simply with the aid of a peltier effect cooling device. These are commercially available and are inexpensive.

## Dielectric properties

The Debye relaxation frequency for ice falls between $10^3$ Hz and $10^4$ Hz whereas that a liquid water falls between $3 \times 10^9$ Hz and $3 \times 10^{10}$ Hz. At these frequencies the respective dielectric constants decrease from 80 to about 3. Thus at intermediate frequencies, since the dielectric constants differ by a factor of 25, the application of the theory of dielectric mixtures should enable the proportion of liquid water present in a sample to be determined with high accuracy.

The method appears to have been suggested by Baier (1951) and Person (1951) although the dielectric properties were known much earlier. There is an extensive litterature on the theory, significance and measurement of these properties. It is not referred to in the bibliography since it does not relate directly to liquid water in snow. Yosida (1958) gives a good general account and some basic references.

This method has been used extensively by Ambach and his colleagues and most other reports of its use are developments of his work. There are difficulties of interpreting these measurements using the theory of dielectric mixtures. Empirical calibrations seem to indicate errors of the order of ± 3% in Yosida's work and ±.5% in Ambach's work.

The practical difficulties depend on the procedure. Yosida packs the snow into a special box for measurements whereas Ambach rams his capacitor plates directly into the snow. In this way Ambach avoids handling the snow and the possibility of melting the sample.

## Centrifugal separation

In principle the centrifugal separation of the liquid water from the snow is the simplest of these techniques. The biggest single problem is the melting of the snow sample in the centrifuge due to the enhanced heat transfer caused by the high speed at which the sample containers move through the air.

Kuroiwa (1957) used a hand centrifuge and surrounded his samples with snow. Descriptions of various modifications of this technique have been published by other japanese authors since then. These include the use of a fluid of intermediate density (diethylaniline) to separate the liquid water from the snow and the use of an electrically driven centrifuge which has a cylindrical vertical screen to separate the two phases.

Yosida (1967) states that the centrifuge technique was abandonned partly because it was difficult to use in the field. The evidence for the inadequate separation is according to Kuroiwa (1954) that after centrifugal extraction the difference between the imaginary parts of the dielectric constant for dry and centrifuged wet snow corresponds to about 7% liquid water remaining in the sample. The centrifuges used however commonly develop accelerations above 100 g. and under these conditions the snow cannot retain more than a few thousandths of 1% liquid water content. The difficulties experienced by the japanese probably derive from melting caused by incomplete cover of the sample by the ice jacket and handling during the filling of the dielectric measuring chamber.

Langham (1974) has overcome the melting problem by a technique of repeated centrifuging. In this way data is obtained that permit the amount of liquid water present before centrifuging started to be found with an accuracy of about ± 0.1%. In terms relative to the liquid water content this may vary between ± 3% and ± 30% or more depending on the amount of liquid water present. The mean is about ± 7% of the liquid water content.

## Other methods

At various times other methods have been proposed. Although none of these has come into common usage some of them are interesting. Bader (1950) suggested a method that could avoid the need for the hot or cold fluids in the calorimetric method. A quantity of a solution such as sodium hydroxide would be added to the sample and the dilution measured either by the depression of freezing point or by titration. Although the method appears to have generated some interest, the accuracy of measurement required for either temperature or titration, the hazards of carrying caustic soda, and complication due to associated phenomena such as heat of dilution all seem to militate against the idea.

Williams (1956) has found a simple relationship between the density of tamped snow and the water content. The most consistent results are obtained by tamping four times with a 1 Kgm weight which falls 10 cms. The density tends to stabilize after the first few blows and the method gives figures within 1-2% when the liquid water content is above 5%. Below that figure the difference in behaviour between fresh and old snow becomes rather large. Although the main recommendation of the method is its simplicity the quality of the data obtained compare favorably with other methods.

Tusima (1971) has described a dilatometer method of measuring the liquid water content. His equipment is complicated and since volume changes are the result of the melting of the sample, it doesn't seem to offer significant advantages over calorimetric methods. The error of measurement is about ± 1% in the water content.

## Possibilities of using microwaves

The fact that the dielectric relaxation frequency for water is about 10 G Hz means that, for microwaves of this frequency, there will be an absorption of energy which is a function of the amount of water present in the snow. Various workers (e.g. Hoekstra and Spanogle-1972) have experimented with this idea with the object of either measuring the water content of small samples placed in a waveguide or resonant cavity or of measuring average water contents of snow over large areas using an antenna system to emit and receive the radiation.

In principle these techniques are very elegant. The sophisticated equipment is not necessarily a problem since it can be readily obtained as military surplus. There are however problems in interpreting the data. In closed systems condensation of water on the waveguide wall or uneven distribution of the snow can lead to errors of measurement and in open systems surface irregularities and layered structures create geometrical and internal reflection problems. The idea is still potentially very promising but the successful application may well depend on some new technical development such as the use of small solid state microwave generators.

Associated with the microwave absorption technique is microwave emission. Microwaves can be emitted as thermal radiation at terrestrial temperatures provided that the substance in question is a good emitter. Water is a good absorber at 10 G Hz and so according to Kirchhoff's law it should be a good emitter at that frequency.

Research on the application of this phenomenon to the measurement of the liquid water content of snow is still going on (e.g. Linlor-1972). It seems most promising for obtaining average water contents over relatively large areas i.e. from a few hundred square metres to a few square kilometres. There are problems related to depth, and stratification that could be alleviated by further research. The technique may very well prove to be of most value as an areal indicator of the ripeness of the snowpack.

## Conclusions

Many of the methods proposed are hardly accurate enough for the required measurements. Some of the more recent methods offer the required accuracy but there is a problem of absolute calibration which presents some obstacles to their evaluation. Most methods are calibrated against one of the others, which is unsound. Some workers have added a known amount water at 0°C to a known quantity of dry snow. The difficulty is to ensure that absolutely no phase change occurs in either direction during the experiment. One possible solution is to adapt the repeated centrifuge technique. After the linear part of the graph has been established a small quantity of water previously measured and stored in the wet snow (i.e. at 0°C) would be added and the centrifugal extraction continued. It is proposed to follow this procedure during snowmelt experiments next spring.

In the bibliography given below some work has been published several times. Although modifications to the method are not always made in such circumstances all references are given since different presentations often clarify some detail of construction or procedure.

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