SNOW WETNESS MEASUREMENTS FOR MELT FORECASTING

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ABSTRACT

A microwave technique for directly measuring snow pack wetness in remote installations is described. The technique, which uses satellite telemetry for data gathering, is based on the attenuation of a microwave beam in transmission through snow.

INTRODUCTION

The water-equivalent of snowpacks represents an important resource. In California, for example, the Sierra Nevada snowpack provides more than half of the total water supply and about one-third of the electric energy. For the western United States in 1972, Federal Power Commission records show that a total of 1.7×10^{11} kWhr of electricity were generated by hydroelectric stations. A barrel of oil burned in the best central station produces 650 kWhr, so the hydroelectric energy is equivalent to 2.62×10^8 barrels of oil. At a cost of $10 per barrel, this represents $2.62 billion. Efficient operation of hydroelectric installations requires maximum head consistent with avoidance of spilling water if sudden inflows should occur. Effective management of water resources for power generation, irrigation, domestic use, and many other applications including flood control, is evidently dependent on adequate knowledge on a timely basis of the snowpack characteristics.

The _amount_ of stored water is obtained from snow course sample measurements of depth and weight, with additional information from automatic instrumentation such as pressure pillows and gamma-ray density profilers. However, the _time_ of snowpack melting and related water discharge rates involves ripening and wetness of snow; at present, this information is obtained indirectly from such quantities as heat input factors and temperature index measurements.

The purpose of this paper is to summarize water runoff forecasting under snowmelt conditions, and to discuss the importance of including measurement information of snow wetness. For background and convenient reference, brief reviews are given regarding the water-holding capacity of snow, present-day methods for measuring snow wetness, and the electromagnetic systems under development. The discussion of snowmelt runoff forecasting techniques

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is necessarily quite simplified and contains no new information for the snow hydrologist; however, the review may be helpful to remote-sensing specialists who do not ordinarily come in contact with the problems of the operational water management specialists. An authoritative source of information regarding detailed aspects of water forecasting under snowmelt conditions is the monumental work, "Snow Hydrology," prepared by the U.S. Army Corps of Engineers (1956).

Although a standard nomenclature is emerging in snow hydrology literature, terms such as "water content" have varying meanings in current papers. To avoid possible ambiguity, definitions of terms for this paper are given in Appendix A. Two terms should be particularly identified: "water-equivalent" means the amount of water that would be obtained from the complete melting of a given volume of snow, regardless of whether the snow is initially dry or wet; "water-content" means the amount of liquid-phase water present in the snow, also known as "wetness."

WATER-HOLDING CAPACITY OF SNOW

Dry snow consists of ice crystals and air. The density of newly-fallen snow may be 0.1 gram/cm^3 or less; during the winter and spring months a variety of processes occur, producing snow density up to about 0.4 to 0.6 grams/cm^3. It has generally been assumed that snow density must reach about 0.4 grams/cm^3 before melt water can begin to drain from the snowpack (Kittredge, 1948, and Bertle, 1965). However, as pointed out by Smith (1974) this is not always true. At the Central Sierra Snow Laboratory (CSSL) melt water has been observed to flow through the pack all winter long in most years, with density in various layers ranging from 0.2 to 0.7 grams/cm^3.

Various values have been reported regarding the water-holding capacity of snow. Because of the importance of determining this quantity, and the divergence of views expressed in the literature, direct quotations from recognized authorities are given in Appendix B for convenient reference.

Snow Hydrology (1956) expresses the opinion that ripe snow has a liquid-water-holding capacity between 2 to 5 percent by weight, with the qualification that the lack of information on the capacity of snow to retain liquid water against gravity, as a function of some index of the stage of metamorphism, constitutes a major gap in knowledge of the storage effect of snow on runoff. The point is stressed that at times the snowpack may be similar to a vast "sponge," but that at other times the storage potential may become very small. At any given time the actual condition of the snow must be determined in order to evaluate the storage capacity.

A laboratory experiment by Garstka and co-workers has been reported by Bertle (1965) in which runoff from an artificially-wetted snow sample did not occur until the added-water reached 83 percent by weight, relative to the original dry snow.

According to Smith (1974), water-holding capacities for snow-packs from natural and simulated rain have been studied with the

profiling snow gage at CSSL. Density increases from water uptake and retention against the pull of gravity ranged from 0.03 gram/cm^3 for matured snow, to over 0.20 gram/cm^3; increase was directly related to the original density and wetness of the snow. Other studies by Smith et al. (1969) show that the amount of retained water in the normally isothermal (0° C) snowpacks of the Sierra Nevada appears to be related to a pore space function: the greater the density, the less the pore space size, and the greater the amount of water that can be held. Such results obtained at CSSL indicate that naturally occurring snowpacks can at times have a stored liquid-phase water as high as 30 to 40 percent by weight.

In recent review paper de Quervain (1972) reports that some authors have the opinion that liquid-phase water ranging from 1 to 6 percent is usually found in equilibrium with snow. However, de Quervain (1948) believes that a more realistic range is 5 to 25 percent, and Moskalev (1966) finds the upper limit to be as high as 55 percent. Wakahama (1968) reports snow layers with 20 to 30 percent liquid-phase water.

The importance of direct measurements of stored liquid-phase water, (water content) of the snowpack becomes evident from the foregoing information. Snowmelt water or rain on snow may be produced by sunny or stormy weather; in either event, when such water is present within the snowpack, accurate forecasts of the runoff rate are not possible unless the state of the snow wetness is known. If as much as 10 to 40 percent by weight is involved, it represents a major factor in the runoff rate, and may in such an event predominate over all other factors.

Those portions of the snowpack having essentially horizontal ice lenses may temporarily hold liquid water by ponding. Such a situation is unstable in the sense that an additional load can cause failure of the ice lenses or detention layers, resulting in rapid discharge of the ponded water. The additional load may be produced by rapid increase in melt water, or by a brief but intense rainfall.

An apparent example of the "triggering" action implied by the preceding paragraph was experienced at Bull Run, Oregon in December 1964. With a snowpack about 60 in. deep, a rainfall of about 2 in. was recorded, and hydrograph records from similar storms showed that the runoff should have occurred within 8 hr. Instead, it appeared to be delayed 24 hr. Subsequent rainfall apparently required only a few hours for its runoff to occur, based on the observed flow records. The peak streamflow was about twice the value expected from the rainfall intensity pattern. This episode is reported by Hydrocomp, Inc. (1974) with the statement: "It appears that Bull Run experienced a phenomenon of liquid water storage in the snowpack followed by a sudden release. The snowpack apparently collapsed much more rapidly than rates of snowmelt from heat balance would predict. Many other reports of this phenomenon are found in the literature."

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The purpose of this paper as previously mentioned is a dis-
cussion of water runoff forecasting under snowmelt conditions,
aided by direct measurement information of snow wetness. We shall
review and summarize four basic procedures, although in any opera-
tional situation these may be combined in various ways depending
on the requirements for the forecast:

    1. Historical normal
    2. Index method .
    3. Water-balance method
    4. Hydrologic models

An important distinction must be made between seasonal or
annual runoff forecasts versus short-term runoff forecasts. The
former is important in agricultural planning, irrigation schedules,
filling and lowering of large reservoirs, and similar activities
for which the time scale is months or longer. The short-term run-
off forecasts are important in flood forecasting, reservoir opera-
tion for power production, and other applications for which the
time scale is a few days. The latter situation is of primary
interest in this paper.

Historical Normal

Historical records provide the simplest (and least dependable)
basis for water runoff forecasting. For example, the forecast for
a selected time interval in the future is likely to be similar to
the average runoff for the same time interval during the past
10 years (or more). Some idea of the expected range within which
the actual runoff value will occur can also be obtained from the
distribution of historical values. These approximate statements
can of course be refined by statistical treatment for more precise
expressions involving probability values.

Index Method

The index method is based on correlations of historical
records of runoff with indexes of important determinants of runoff
for the area under consideration. An adequate number of years for
the measurements is essential to establish the relationships,
known as regression functions. The forecasting procedures may be
based on combinations of statistical and graphical correlations,
relating the means and deviations of the measured index values
with the actual subsequent runoff.

The index method of forecasting has been used for many years
by the California Cooperative Snow Survey Program. Brown (1974)
states: "Each major river basin whose runoff is to be forecasted
has several discrete 'points' in the form of snow courses, where
several months each winter the water equivalent of the snowpack at
that location is measured. After several years a statistical
relationship is built up which relates the water equivalent at
that point and the other points in the basin at any given time of

measurement to the runoff to be expected from that basin. Thus,
the collective measurements of water equivalent at several snow
courses within and adjacent to a basin provide an 'index' to the
anticipated April–July runoff. The actual forecasting procedures
take into account other factors, in addition to the water equiva-
lent of the snow, such as antecedent precipitation and cumulative
runoff from the beginning of the Water Year up to the date of the
forecast. Precipitation in future of the forecast is assumed to
be equal to the historical normal for those months in the forecast
period beyond the date of the forecast."

    For the index method of forecasting, determinants in addition
to the water equivalent provide useful information. These include,
for example: (1) area of snow cover; (2) accumulated heat supply,
such as degree-days, to be discussed later; and (3) low-elevation
winter streamflow. A graphical method of determining the effect
of several variables on runoff is the "coaxial method" described
by Linsley et al. (1949). Multi-variable statistical procedures
can also be employed.

    We suggest that measurement of snow wetness at selected sites
should receive consideration as one of the determinants, particu-
larly in areas where melt or rain-on-snow events may occur
throughout the snow season. Because of expected rapid changes in
wetness levels, automatically operated instrumentation in remote
stations appears to be desirable.

Water-Balance Method

    Runoff forecasting with the water-balance method consists of
evaluating each of the major components of an input-output equa-
tion and summing them algebraically. If all factors are evaluated
correctly, the total input to a basin must equal the total output.
Water input to a selected basin is represented by total snow
accumulation plus total rainfall during the time interval of
interest. For that same time interval the water output includes
losses, storage, and runoff for the basin. The losses may occur
by evaporation, sublimation, transpiration, and similar effects;
the storage includes the change in snowpack water equivalent,
which can be either positive or negative, and ground-water storage
including soil moisture. Basin runoff includes mainly streamflow.
If water flow in underground channels is appreciable, it must also
be included (by measurement or estimate), as a part of the basin
runoff.

    The distinguishing feature of this procedure is that index
values are not used, but rather the effect of each major factor on
runoff is evaluated separately, in accordance with its actual
value. Because of the large amount of data input that is required,
the water-balance method is useful mainly for highly instrumented,
relatively small basins. The value of the water-balance method is
the assurance that all major factors have been properly assessed —
otherwise the input-output equation would not add algebraically to
zero. Although historical data are used in the development of the
method, the forecast of runoff is based upon an appraisal of each

component for the time interval desired, rather than upon the effect produced by a given set of conditions in past years.

As suggested for the index method, measurement of snow wetness should receive consideration in the water-balance method as one of the contributing factors. For example, an increase in snow wetness may account for storing rainfall input; a decrease in snow wetness may produce a (runoff) output. Changes in snow wetness, alternatively, may have no effect on input or output, but instead may represent the integrated effect of heat exchange with the surroundings. Field measurement data are necessary to evaluate the relationship between snow wetness and basin water balance. Such measurements should be made automatically, repetitively in time, without impairing the snowpack, over representative areas of the basin.

Hydrologic Models

Simply stated, a hydrologic model represents a technique for mathematical simulation of physical processes or relationships. Modern computer technology makes practical the accompanying extensive numerical calculations. The mathematical model can include all of the techniques so far discussed: historical relationships, index data, or actual input-output information can be utilized, together with meteorological predictions. If some of the information has elements of uncertainty, the numerical values supplied to the mathematical model can be altered in successive runs to demonstrate the net effect.

The hydrological model can simulate daily, weekly, or seasonal flow from a basin or watershed, utilizing a host of hydrologic and meteorologic parameters. Reservoir storage and maximum-efficiency hydroelectric power generation can be scheduled on the basis of predicted stream flows, with the constraint that flood-risk situations must be avoided.

Snow wetness data can readily be included in a hydrologic model. The snowpack water equivalent represents a special type of reservoir storage, a component of which is the wetness that can act either in a positive (storage) or negative (release) fashion.

SNOWMELT RUNOFF RATE

The snowpack water equivalent represents the major portion of the annual water supply in many western U.S. watersheds. A review of the snowmelt process is useful in regard to understanding snow wetness and its measurement.

The rate of snowmelt runoff is dependent on the rate of heat supply. For snow at $0°$ C, 80 cal/cm^2 must be absorbed for each centimeter of liquid water produced, which can be recognized as being the latent heat of fusion of ice. The sources for such heat include net radiation absorbed, conduction and convection of heat from the ambient air, condensation of water vapor, heat supplied by rainfall, and conduction from the underlying earth.

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A convenient resume of the theoretical aspects of heat input to a snowpack is given by Gray (1970, pp. 9.2-9.12). An extensive treatment is given in Snow Hydrology (1956, Chap. 5). To indicate the type of analysis that is necessary, an illustrative example is given in this paper of radiant energy interchange between the snowpack and its surroundings.

The amount of solar radiation effective in producing energy input to the snow is dependent on the reflectivity, or albedo, of the snow. For new snow almost 90 percent of the incident radiation is reflected; however, as the snow matures, its albedo can drop to 50 percent or less. The intensity of solar radiation above the earth's atmosphere perpendicular to a square centimeter is 0.14 W. For a "reasonably clear day" in March at 40° north latitude, the energy incident on a horizontal square meter during a 24-hr day is about 3.3 kWhr (Hildebrandt et al., 1972). Converting this into snowmelt equivalent, assuming an albedo of 50 percent, the liquid water produced is about 2 cm. Snow radiates in "black-body" fashion; the outgoing long-wave radiation at 0° C during 24 hr is equivalent to about 8.4 cm of (negative) melt. The atmosphere intercepts and re-radiates a portion back to the snow, the amount depending on the air temperature, atmospheric vapor pressure, and extent and type of cloud cover. With clear sky, and 0° C temperature for dewpoint, air, and snow, the net loss of heat by the snow during a 24-hr day caused by long-wave radiation is equivalent to about 2 cm of water (Linsley et al., 1958). Local conditions such as snow albedo and prevailing cloud cover represent significant factors in determining the radiative heat exchange of the snowpack. Other considerations exist in addition, such as variations in elevation, slope, aspect, forest cover, snow density and wetness, etc.

For rain-on-snow conditions, the heat interchange relations are complicated. Snow Hydrology (1956, page 326) states: "The computation of snowmelt during periods of significant rainfall is a problem quite different from the computation of melt during non-rain periods. Because of the generally overcast conditions, solar radiation has but a minor role in the melt scheme; longwave radiation losses are small, and at times there is even a net heat gain from this source. Because of the turbulent conditions which usually accompany rainstorms, convection and condensation melts are relatively large. In addition, fairly high vapor pressures result from the high relative humidities encountered in this situation, tending further to increase condensation melt."

It is evident that a heat-balance equation for predicting snowmelt is quite complicated; it would be of little point in this paper to consider the various heat-interchange processes in detail. Ideally, extensive instrumentation would be desired to provide field data for an operational heat balance analysis. This is not always necessary, because often the major heat balance terms can be estimated or found from correlations; that is, long-wave radiation exchange can be correlated with forest cover and cloudiness. The results do not replace instrumentation, but can be superior to degree-day calculations, which are discussed next.

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Index factors for snowmelt rate are often useful. An index based on temperature has been given the name "degree-day" method. A degree-day is defined as a departure of one degree in mean daily temperature above freezing. A day whose mean temperature is 42° F thus has 10 degree-days. (Engineering units are employed, to avoid conversion from values given in the literature.) The term degree-day-factor (DDF) is defined to be equal to the inches of water melted from the snow per degree-day. The DDF varies with local conditions of weather, time of day, month, snow condition, altitude, etc. Index temperatures can be chosen to be maximum rather than mean values for a day, and base values can be chosen other than 32° F. As illustrative values, the DDF at the Central Sierra Snow Laboratory has been found to vary from 0.07 at the minimum melt station to 0.13 at the maximum melt station. These are averages for several years. Individual values for within-year periods exhibit a wide range of values.

It should be noted that these DDF values are obtained by correlating degree-days with measured changes in snowpack water equivalent. However, water content of the snowpack affects the results. For example, if the snowpack is initially dry, absorbed heat causes a certain amount of melting which we assume is retained by the snowpack. The water content is increased, but no change in water equivalent can be measured. For these conditions the incorrect conclusion could be made based on gravimetric data that the snowpack did not absorb heat. Thus it is evident that measurement of water equivalent or local runoff with lysimeters does not necessarily correspond to heat absorption or loss by the snowpack. Only under the condition that no changes in snow wetness occur does the measurement of water equivalent yield information regarding heat absorption.

Clearly a system to measure snow wetness directly, preferably a depth profile, would provide important information for snowpack water runoff predictions, because the wetness is the integrated result of the effects of temperature, radiation, local wind, etc., which produce heat transfer to the snowpack.

PRESENT-DAY INSTRUMENTATION FOR SNOW WETNESS MEASUREMENT

This section presents a summary of current instrumentation for measurement of snow wetness, and field tests of performance. The subsequent section describes systems under development.

Existing methods for obtaining snow wetness are based on three effects: calorimetric, centrifugal, and capacitive. The calorimetric method (Radok et al., 1956, and Yosida, 1966) is based on the temperature change of a heat reservoir necessary to melt (or freeze) a known quantity of wet snow. Hot water can be used for the melting process, or chilled gasoline for the freezing process. The centrifugal method (Langham, 1973) involves rotating a sample of wet snow to extract the water. The capacitive method (Ambach, 1966) yields the net dielectric constant of snow mixed with water, the latter contributing a relatively large dipole moment.

A comparative study of these three techniques was performed by Edgerton and Sakamoto (1970). They used a freezing calorimeter and two hot-water calorimeters; two centrifuges having 35 cm^3 and 500 cm^3 containers; and a capacitance meter designed by Ambach and Howorka (1966). A site on South Cascade Glacier, Washington, was selected because typically the snow cover on glaciers is relatively homogeneous, and thus allow a reasonably critical evaluation of the techniques.

The tests were performed on 7 and 8 August 1969 with snow grain sizes ranging from 0.5 mm to 1.5 mm; snow density was 0.52 gm/cm^3 on 7 August and 0.57 on 8 August. Results are given in Table 1 and plotted in Fig. 1; snow wetness is given in percent by weight versus time.

TABLE 1.- SNOW WETNESS MEASUREMENTS IN PERCENT BY WEIGHT*

| Date | Calorimeters | | | | | |
| | Freezing | | Sakamoto | | Combination (Yosida) | |
	Avg.	Range	Avg.	Range	Avg.	Range
7 Aug. 1969	11.2	8.0-14.7	15.4	12.1-28.2	28.7	23.3-37.8
8 Aug. 1969	5.8	4.1- 7.9	9.3	3.7-28.0	15.7	7.3-22.7

| Date | Centrifuge | | | | Capacitive | |
| | 500 cc | | 35 cc | | Ambach | |
	Avg.	Range	Avg.	Range	Avg.	Range
7 Aug. 1969	9.3	7.9-10.9	7.5	6.4-8.7	9.2	7.1-14.0
8 Aug. 1969	2.3	1.4- 4.7	---	---	0.6	0.0- 1.5

*Data from Edgerton and Sakamoto, 1970.

Edgerton and Sakamoto state: "Large variations in snow wetness were indicated by all techniques on consecutive measurements, and a comparison of results obtained with different instruments shows even larger differences between them. . . . This suggests that instrument accuracies are not sufficiently high and/or large natural variations of snow wetness within the snowpack exist."

The development of the density-profiling gage (Smith and Halverson, 1969, and Smith et al., 1972) has made possible accurate measurements of snowpack density profiles, and determination of changes that occur. Since the snow properties can be measured at the time of deposition, and regularly thereafter, the retention of any rain that may occur can be measured by changes in the density profile. Smith (1974) states: "Utilizing the water holding data so generated, and working with snow density profiles taken prior to rainstorms Smith et al., 1969, were able to successfully predict the amount of water snowpacks at CSSL could retain from rain-on-snow storms before water began draining from the snowpacks."
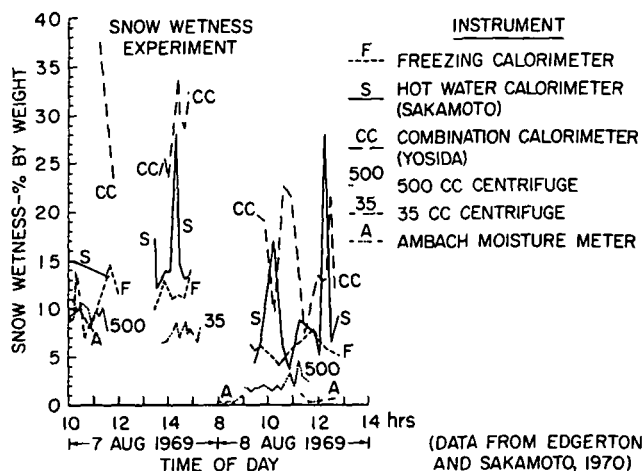
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Fig. 1-Comparison of snow wetness instruments

SYSTEMS UNDER DEVELOPMENT FOR SNOW WETNESS MEASUREMENT

Three electrical methods for measuring snow wetness are being developed, for which descriptions have been given by Linlor and Smith (1974), Linlor et al. (1974) and Linlor et al. (1975):
1. Change in capacitance of a sample before and after freezing
2. "Quality factor" of a sample in a high-frequency field
3. Attenuation of a microwave beam in transmission through snow

These methods have been tested with natural snow at the Central Sierra Snow Laboratory, yielding results in accordance with theoretical predictions. Calibration of the systems requires elaborate procedures that are presently being developed. Our investigations have been expedited by the use of a host medium, foam polyurethane, whose properties can be readily controlled and are reproducible. Weight of a sample before and after adding water yields the volume percent wetness. Results can be expected to serve as a guide to the behavior of wet snow, because the basic interaction involves the liquid phase water rather than the host substance.

The capacitance of a given test unit is proportional to the net dielectric constant of the medium between the electrodes. For

dry snow — a mixture of air and ice — the factors that affect the net dielectric constant include (1) the individual dielectric constants of the air and the ice, (2) the relative proportions of each, (3) the temperature, (4) the oscillation frequency at which the measurements are made, and (5) the "form factor" (also called the "formzahl"), which depends on the shapes and orientations of the individual crystals of snow.

For wet snow, the situation is more complicated, even though the temperature is not a variable, being essentially $0°$ C. The dielectric constant of pure water at $0°$ C is 87.7, but when the water is in contact with snow crystals, intramolecular forces can affect the dipole moment of the water molecules. Nevertheless, the dielectric constant of snow is greatly increased by the presence of liquid-phase water, and this fact has been the basis for previous methods of determining snow wetness by Gerdel (1954) and Ambach and Denoth (1972).

The relative dielectric constant $k*$ has real and imaginary components k' and k'', the latter also being known as the "loss factor." The ratio k'/k'' is known as the "quality factor" or Q.

$$k* = k' + k'' \qquad (1)$$

$$Q = k'/k'' \qquad (2)$$

Change in Capacitance upon Freezing

The change in capacitance of a sample before and after freezing is directly related to the amount of moisture initially present. Since the effects of form factor and density are unchanged in both measurements, the net contribution vanishes in the subtraction process. Let C_0 represent the capacitance of the empty unit (only air being present), C_1 the capacitance of the unit having wet snow, and C_2 the capacitance of the unit after freezing:

$$C_1/C_0 - C_2/C_0 = A \, W \qquad (3)$$

where A is a proportionality factor, and W is the volume percent wetness (defined to be equal to 100 times the grams of water per cm^3 of wet snow). The value of A must be determined by calibration tests.

Specimens of foam polyurethane having known wetness were placed between the plates of a capacitor for measurement of the change in dielectric constant with wetness, at a range of frequencies. Results are shown in Fig. 2, where the increase in the real part of the dielectric constant (k') is plotted versus wetness at selected frequencies.

Quality-Factor Dependence on Wetness

The dependence of the intrinsic quality-factor Q_s of a snow sample on wetness is shown in Fig. 3. Water was added to
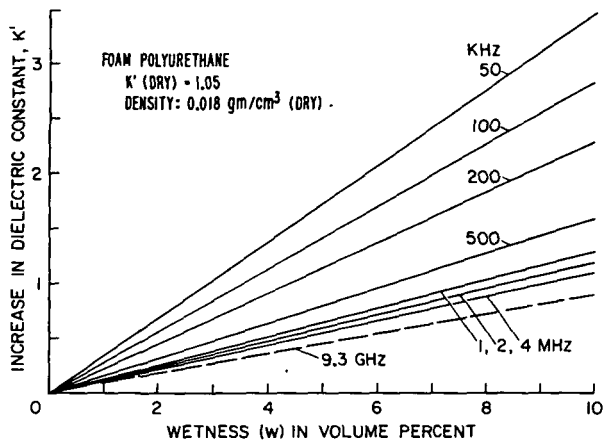
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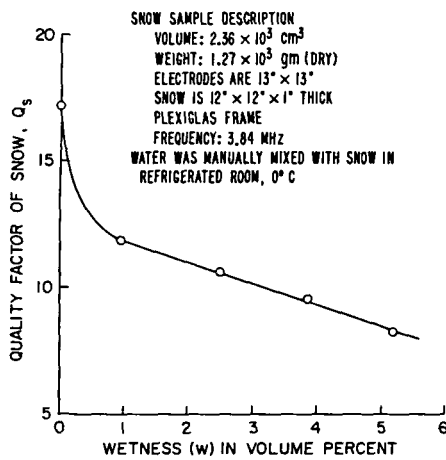
Fig. 2-Dependence of dielectric constant on wetness

Fig. 3-Quality factor of snow capacitor versus wetness

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initially-dry snow and manually mixed with it in a refrigerated room. The intrinsic quality factor is given by:

$$Q_s = \frac{Q_1 Q_2 (C_1 - C_2)}{C_1 (Q_1 - Q_2)} \qquad (4)$$

For the Q-meter and associated coaxial leads, let the initial readings be designated C_1 and Q_1, where C_1 includes the lead capacitance plus the dial-indicated capacitance. Next with the snow capacitor connected to the Q-meter, let the readings be designated as C_2 and Q_2; C_1 minus C_2 represents the capacitance of the snow capacitor, and Q_s represents the quality factor associated with the snow.

Microwave Beam Attenuation

Measurement of snow wetness by the attenuation of a microwave beam can be accomplished in a variety of alternative configurations. The basic interaction is the absorption of microwaves by liquid-phase water, in the frequency range of 10^9 to 10^{10} Hz. The wetness of a sample can be obtained by placing it in a beam of known intensity, and measuring the transmission. The average wetness of a snowpack can be obtained by placing a transmitter on a tower and a properly-packaged receiver on the earth beneath the snow, and measuring the transmission. A profile of the wetness of a snowpack can be obtained by placing the transmitter in a vertical tube, with a receiver in another vertical tube spaced about a meter away; with these units moving in synchronism vertically, a transmitted horizontal beam traverses the snowpack, and its attenuation at successive levels yields the wetness profile.

Transmitters were constructed to operate at the frequencies of 1.83, 2.73, 5.00, and 8.00 GHz. Tests in an anechoic chamber yielded the results shown in Table 2. The received power levels are relative to an arbitrary level; at -60 dB the receivers reached the noise level. Thus at the distance of 100 cm between source and receiver the dynamic range was about 30 dB or greater for all frequencies.

TABLE 2.- RELATIVE POWER AT RECEIVERS

Frequency, GHz	Relative power at receivers, dB	
	Distance, 50 cm	Distance, 100 cm
1.83	-17.1	-23.4
2.73	-21.4	-26.3
5.00	-23.5	-30.7
8.00	-24.8	-30.5

To measure the effect of wetness, transmission tests were performed on samples of foam polyurethane. At a selected

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frequency, transmission levels were measured through interposed layers of foam polyurethane, each having approximately the same wetness. The transmission test results for foam polyurethane with an average wetness of 8.5 volume percent are given in Fig. 4. At 5.00 and 8.00 GHz the data points fall reasonably well on the straight lines that are expected for exponential attenuation. At 1.83 and 2.73 GHz the data points exhibit oscillations with regard to the exponential attenuation lines. Such oscillations are expected on the basis of theory, produced by interference effects at the front and back surfaces of the foam polyurethane stack. Refinement of the experimental technique to remove the interference effects is possible, but adequate information can be obtained from the straight lines that are fitted to the data points.
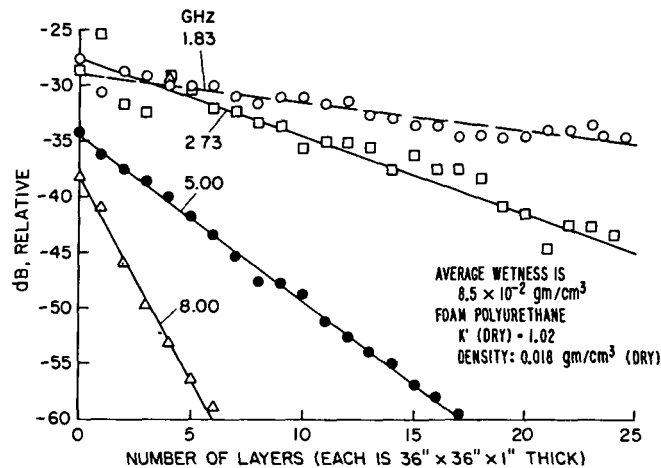

Fig. 4-Microwave beam intensity versus thickness of wet foam polyurethane

Tests were run at 8.00 GHz for other values of wetness, with the results given in Table 3. If the absorption coefficient is proportional to the wetness, then the absorption per unit of electrical length (equal to the physical length multiplied by the square root of the dielectric constant) divided by the volume percent wetness should be a constant for a selected frequency. Our measured values for the absorption in decibels divided by the electrical length in centimeters and volume percent wetness are:

TABLE 3.- ABSORPTIVITY DEPENDENCE ON FREQUENCY

Frequency, GHz	Wetness, vol. %	Dielectric constant k'	dB/cm	dB/cm % $\sqrt{k'}$
1.83	8.5	1.78	0.101	0.0089
2.73	8.5	1.78	0.276	0.0243
5.00	8.5	1.78	0.587	0.0517
8.00	8.5	1.78	1.444	0.1272
8.00	4.8	1.45	0.722	0.1248
8.00	10.5	2.01	1.693	0.1139
8.00	12.0	2.32	2.150	0.1176

0.125, 0.127, 0.114, and 0.118 for the respective volume percent wetness values of 4.8, 8.5, 10.5, and 12.0. These four absorptivities have an average value of 0.121 and a standard deviation of ±0.006.

To obtain the electrical length, a measurement of the dielectric constant k' is necessary. This was done by measuring the phase shift produced by the wet foam polyurethane. The signal from a microwave source operating at 9.3 GHz was divided into two legs, one of which had transmitting and receiving apertures; the other (comparison) leg had a calibrated phase shifting unit and a variable attenuator. The signal in the comparison leg was adjusted in phase and amplitude so as to essentially cancel the signal from the other leg; that is, a phase difference of 180° was obtained. As each layer of the wet foam polyurethane was inserted into the transmitter-receiver leg, the change in phase and attenuation in the comparison leg, necessary to preserve the 180° relationship, was measured. The phase shift is a measure of the electrical length of the inserted foam polyurethane layers, and because the physical length is known, the dielectric constant k' can be calculated.

Results are shown in Fig. 5 for the dielectric constant, as a function of wetness in volume percent, for a frequency of 9.3 GHz. Six samples were tested at a variety of wetness values; the straight lines were fitted to the data points.

The data given in Table 3 have been plotted in Fig. 6, showing the attenuation per unit electrical length and per unit volume percent wetness, for the four frequencies. A theoretical curve for pure water, based on data published by Peter Ray (1972), is also shown, for which the abscissa is given at the top of the page.

Preliminary tests using microwave equipment were made at the Central Sierra Snow Laboratory. On 29 January 1975 the snow was about 65 cm deep and was below freezing, so it could be characterized as being dry. Two receiver distances were employed with each of the four transmitters: 223 cm and 798 cm. No measurable absorption was observed at any of the four frequencies. Some "ducting" effects on the transmitted signal were noted, as well as the expected multi-path interference effects.

Another set of measurements was taken at CSSL during the week of 17 March 1975; the snow was about 250 cm deep. Multi-path interference effects were noted; however, between the snow depth
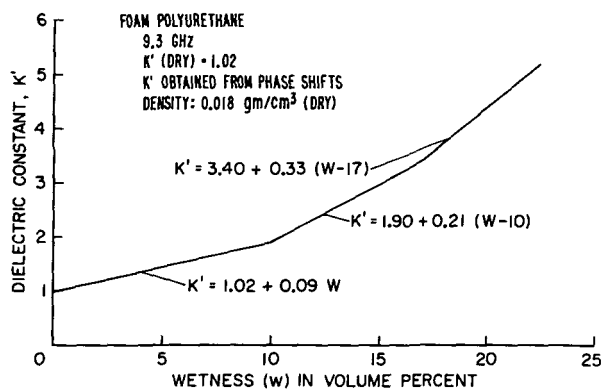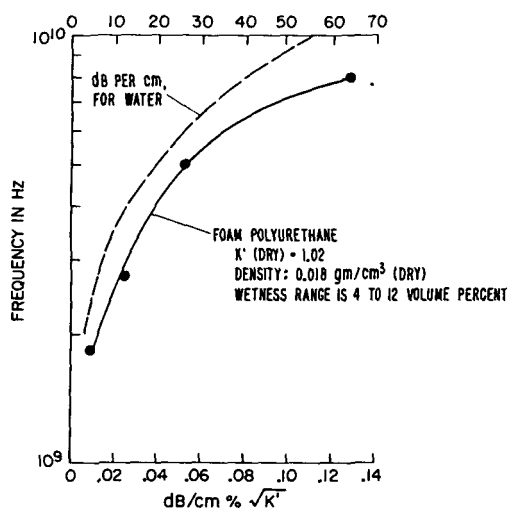
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Fig. 5-Phase shift produced by wetness

Fig. 6-Absorptivity versus frequency for wet foam polyurethane

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levels of 125 cm to 175 cm a wet layer was evident. If the assumption is made that the wet snow is similar to wet foam polyurethane in absorption characteristics, this snow layer had an average wetness of about 1 percent by volume. For the average snow density of about 0.35 gm/cm^3, this is equivalent to about 3 percent wetness by weight.

A third set of measurements was made in late May 1975 at CSSL, when the snow was actively melting, having a depth of about 170 cm. These data are being analyzed; results to date are in agreement with theoretical predictions. Phase shifts are evident, caused by density gradients in the snowpack producing "fading" that is similar to attenuation, but this effect is being removed on the basis of pattern structure (variation with depth).

Although our experience with in situ measurements of snowpack wetness with microwave systems is in the initial stages, the results are very encouraging. The planned program for the immediate future includes (1) tests of snowpacks, under natural conditions, with circularly-polarized antennas (to discriminate against reflections) and automatic profiling; (2) comparison of attenuation of microwave beams with dielectric constant measurements and with quality-factor of snow samples; and (3) comparison of electrical measurements with density-profiling gage data. Calibration of the systems on an absolute basis will be investigated. As soon as possible the systems will be coordinated with measurements involving passive microwave systems.

Theoretical studies are being made to determine the suitability of an active electromagnetic remote-sensing system to measure snowpack wetness from an airplane or helicopter. Descriptions have been published (Linlor, 1974; Linlor and Jiracek, 1975; and Linlor, 1975), based on snowpack layers whose electrical properties were determined by field measurements. The proposed airborne system is a multi-frequency sounder; that is, a transmitter sends a sequence of pulses of stepped frequencies, and the reflections are measured by a sensitive receiver. The combination of snowpack and earth interact with the electromagnetic wave so as to modify the characteristics of the reflected signals. The variation of the reflected intensity with frequency provides the desired information.

The presence of wetness in the snow greatly affects the reflected signal characteristics. A frequency can be selected so that the skin depth is approximately one-half of the snowpack thickness, so that earth roughness is immaterial. Analyses are being made to determine the applicability of this approach in a practical system.

Passive microwave systems in airplanes or satellites can provide important information regarding snowpack areal coverage and water equivalent (Meier, 1972). Such methods make use of the natural radiation from observed objects. The characteristics of this radiation are determined by the emittance, transmittance, reflectance, and temperature of the object (that is, snowpack). Meier (1972) points out that passive microwave systems can determine the areal coverage of snow in mountainous regions despite the presence of cloud cover. Mapping of the snow-covered area may be

unnecessary because the radiometric data provide integrated measurements, yielding the fraction of the land that is snow covered. The total mass of the snow and its wetness may perhaps be obtained by the use of several carefully selected frequencies, viewing angles, and polarizations. Because wetness affects the measurements strongly, ground truth instrumentation is necessary for proper interpretation of the passive microwave data. The methods described in this paper can provide such needed information.

DISCUSSION AND CONCLUSIONS

Water runoff forecasting under snowmelt conditions is difficult because the amount of liquid water that is already present or that may still be stored in the snowpack is not known in general. A review of the literature regarding water-holding capacity of snow shows wide divergence of estimates.

Present-day instrumentation apparently is not adequately accurate, or else considerable differences in snow wetness occur on successive days at the same site under conditions where uniformity would be expected. Also, available techniques are difficult to automate.

Three new approaches to the problem of measuring snow wetness have been discussed, of which the microwave absorption method can be operated entirely automatically in remote installations, thus permitting repetitive measurements of a snowpack to determine how its wetness changes with time.

Density and wetness profiles of the snowpack can be obtained simultaneously over essentially the same path by combining a microwave and radioactive source in a vertical tube, with another vertical tube about a meter away containing microwave and gamma-ray detectors. When both density and liquid-water profiles are available, the condition of the snowpack can be accurately determined and, combined with meteorological information, useful predictions can be made regarding the melting and water discharge rates from snowpacks. Satellite telemetry can be used for data gathering.

The elements of water runoff forecasting were briefly reviewed. It was pointed out that in-situ measurement of snow wetness can be included in all of the forecasting methods: historical, index, water-balance, and hydrologic model. For each percent increase in utilization of water runoff, the annual hydroelectric energy value is about $30 million, in the western United States.

Passive microwave systems hold great promise for satellite-based synoptic measurements of snow areal coverage and depth; however, the measurements are affected by the presence of liquid-phase water in the snow. The snow wetness techniques described in this paper can provide ground truth for the development of such passive systems.

ACKNOWLEDGEMENTS

APPENDIX A — DEFINITION OF TERMS

Water exists in the solid, liquid, or vapor forms; in this
paper the liquid phase is meant whenever the term "water" is used
alone.

"Water-equivalent" means the amount of water that would be
obtained from the complete melting of a given volume of snow. It
can be expressed as centimeters (or inches) of water, assuming that
the cross-sectional area is constant. It is also measured by the
weight of a given volume of snow, such as a Mount Rose sampling
tube.

"Water-content" means the amount of water (liquid-phase)
present in the snow (also referred to as the "wetness"). "Liquid-
water" is used interchangeably with water-content. Two sets of
units are used alternatively:

       (a)   grams of water per gram of dry snow,
       (b)   grams of water per cubic centimeter.

Multiplication of each of these quantities by 100 gives, respec-
tively, the percent wetness based on weight, and the percent wet-
ness based on volume. Quantity (b) is evidently equal to quantity
(a) multiplied by the dry-snow density in g/cm^3. As a numerical
illustration, consider a cubic centimeter having 0.4 g of dry snow
to which is added 0.1 g of liquid water. With the assumption for
convenience, though not valid in actuality, that the total volume
of wet snow remains constant at 1 cm^3, the percent wetness by
weight is (a) = 25; the percent wetness by volume (b) = 10.

"Localized-water" refers to water molecules that have an
energetically significant binding to the snow (that is, ice) crys-
tals, and remain attached until final melting of the crystal,
assuming that no freezing intervenes. Such molecules contribute
to the complex dielectric constant of the snow, but not as much as
would an equal number of molecules of pure water in the absence of
a host medium. Localized-water is also known as "hygroscopic-
water," or water held by adsorption.

"Capillary-water" is held by surface tension forces in the
capillary spaces of the snow. The pull of gravity is insufficient
to overcome the attraction of the snow and water molecules. If
the density of the snow changes, or if metamorphic processes occur,
such that the capillary spaces become modified, the water-
retention capability of the snow is correspondingly modified. For
dry snow, the water-retention capability is dependent on density
and crystal shapes.

"Free-water" is defined in Snow Hydrology (1956, p. 144):
"Free-water includes only that water permanently held within the

snowpack; that is, water held by adsorption and capillarity. It does not include water in the process of percolating through the pack or water impounded in the pack as the result of poor drainage conditions." We suggest that the hydrology term "retention storage" is applicable for free-water storage. Our definition of water-content (or liquid-water or wetness) includes free-water (retention storage) and water in transit (detention storage).

APPENDIX B — REFERENCE QUOTATIONS REGARDING SNOW WETNESS

The following direct quotations give the opinions of recognized authorities regarding water-holding capacity of snow.

Snow Hydrology (1956, p. 303)
        "Experiments on liquid-water-holding capacity of snow are limited . . . between 2 to 5 percent by weight is recommended for the liquid-water-holding capacity of snow. Additional observations are required to establish the relationship between snow density and liquid-water-holding capacity. The lack of information on the capacity of the snow to retain liquid water against gravity, as a function of some index of the stage of metamorphism, constitutes a major gap in knowledge of the storage effect of the snow on runoff. . . . It is pointed out that the liquid-water-holding capacity of snow, as discussed in the preceding paragraphs, represents conditions where free drainage of the snowpack is assured. In flat areas, horizontal drainage through channels is impeded by the lack of sufficient slope. Thus, portions of the snowpack in foothils and flat lands may hold liquid water far in excess of that for mountainous areas where free drainage is rapid."
Snow Hydrology (1956, p. 313)
        "The effect of varying snowpack conditions on runoff from either rainfall or snowmelt is one of the basic considerations of snow hydrology. Divergent opinions exist as to the storage effect of the snowpack. They range from considering the snowpack to be a vast "sponge" capable of retaining large quantities of liquid water, to the assumption that storage in the snowpack is negligible in any basin study. Actually, there are times when either viewpoint may be correct, and there is no generalization which is universally applicable. The important consideration is that the actual snowpack condition be evaluated in order to properly assess its immediate storage potential."
de Quervain (1972, p. 209)
        "Wet snow crystals are coated with a thin layer of water, and in re-entrant angles at contacting grains, water pockets are found. To what extent this water will remain as equilibrium water content and represent a free water-holding capacity has not been unanimously agreed on. Some authors accept only free water in the order of 1 to 6 percent as being in equilibrium (Gerdel, 1954 and Snow Hydrology, 1956), whereas

others assume a wider range from 5 to 25 percent (de Quervain, 1948) or even up to 55 percent (Moskalev, 1966). Wakahama (1968) reports snow layers with 20 to 30 percent water without referring to a state of equilibrium.

"Equilibrium water content, whatever its range, depends on snow density, grain size, and grain shape in a complex manner. The specific inner surface of snow, specific number of grain contacts, and pore width are important. Snow with fine grains holds more water than that with coarse grains; therefore, high equilibrium water content is related to new snow, snow of felt-like structure, and fine granular material, whereas low values are found in metamorphic coarse old snow. An optimum dry density for maximum storage obviously exists.

"In addition to equilibrium water, a considerable amount of free water may exist in a transient state during and following a melting period or a rainstorm."

Hydrologic reaction of snowpacks to rainfall is discussed in Snow Hydrology (1956, p. 323)

"In rain-on-snow situations, the effects of the snowpack are twofold: (1) to add an increment of melt water to the rainfall and (2) to store and detain, in varying degrees, the melt and rain water generated. It is the latter effect that makes the reconstitution of rain-on-snow floods most complex. Rain falling on a snowpack may be stored by the pack or pass through without depletion, depending on the condition of the pack. A considerable quantity of rain water may be stored by a dry, sub-freezing, snowpack, Moreover, a deep snowpack that has previously experienced little or no melt or rainfall of consequence may add an additional increment of storage by virtue of its delaying effect upon runoff. Impenetrable ice planes within the snowpack may give a large horizontal component to the flow of water through the pack itself (along the ice planes seeking a pervious area). Then too, water may be perched above such impenetrable layers. . . . From the foregoing discussion, one important fact stands out: the condition of the snowpack has a dominant effect upon the initial basin discharge of rain-on-snow event. Because of this, rain-on-snow floods are difficult to synthesize; some knowledge of the initial condition of the snowpack is mandatory."

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