SNOW WETNESS MEASUREMENTS AND RUNOFF FORECASTING

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INTRODUCTION

Various instruments and techniques have been employed in the past to measure the liquid-phase water present in snow (termed "snow wetness"). These include calorimeters (Radok et al, 1960; Yoshida, 1960; Leaf, 1966; Bergman, 1978; Jones, 1979; and Jones et al, 1980); centrifuges (LaChapelle, 1956; Langham, 1974; Carroll, 1976); tensiometers (Klute and Gardner, 1962; Colbeck, 1976; Wankiewicz and de Vries, 1978); dielectric constant measurements (Gerdel, 1954; Kuroiwa, 1954; Yoshida, 1955; Watt and Maxwell, 1960; Yoshino, 1961; Ambach and Howorka, 1966; Ambach and Denoth, 1972; Linlor and Smith, 1974; Denoth and Schittelkopf, 1978); and microwaves (Cumming, 1952; Linlor, 1973: Sweeny and Colbeck, 1974; Linlor et al, 1974; Linlor et al, 1975; Linlor et al 1975a; Tobarias et al, 1978; Linlor, 1980; Linlor et al, 1980).

Although proponents can be found for any of the above methods for measuring snow wetness, practically all are unsuitable for the present application, which involves the following requirements:

a. Automatic data acquisition
b. Repetitive operation on the same snowpack
c. Data for two or more levels within the snowpack

The method to be described in this paper is based on the dependence of snow electromagnetic properties on wetness, the calibration relation being (Linlor, 1980, page 2813):

$$dB/cm = W_v\{0.045(\nu - 4) + 0.066\}$$

where ν is the frequency in GHz, W_v is the wetness in volume percent (i. e., grams of water per cubic centimeter multiplied by 100), and dB is the attenuation in decibels.

The topics in this paper include the site description, meteorological data, microwave system and data, results, and conclusions.

SITE DESCRIPTION

The Central Sierra Snow Laboratory (CSSL) is a field station of the Pacific Southwest Forest and Range Experiment Station of the Forest Service, U. S. Department of Agriculture. It is located near Donner Pass, between Soda Springs and Norden, California, on a 10-square-kilometer area ranging in elevation from 2,100 meters to 2,770 meters, the mean elevation being 2,286 meters. It is inclined toward the south-southwest. The winter temperatures average a few degrees below freezing. Most winter precipitation falls as snow, occasionally interspersed with rain. The snowpack begins to accumulate in November and increases by the end of March to an average basin water equivalent of approximately one meter.

METEOROLOGICAL DATA

Environmental data are obtained every work day by measurements of precipitation (rain and/or snow), incident and reflected solar radiation, air temperature, relative humidity, wind speed and direction, vertical profiles of snow temperatures and soil temperature. Snow depths and snowpack density profiles are measured at "open" and "forest" locations, yielding snow mass (i. e., snow water equivalent). The "open" site is about 7 meters away from the microwave measurement location.

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Of the available meteorological data, only a portion is used in this report, namely air temperature and snow water equivalent. The microwave data is considered to be in preliminary status, subject to confirmation in future winter seasons, so a comprehensive analysis is not appropriate.

Examples of the snow density profiles (taken every day as a part of the CSSL program) are shown in Fig. 1 for 4/10/80 and in Fig. 2 for 4/30/80. The snow water equivalents for these days are 119 cm and 72 cm respectively.

Air temperature readings are shown in Fig. 3 for March, April, and May 1980. These are the average of the maximum and minimum values for a given day. Inspection of continuous time-temperature plots (not included here) shows that integrated degree-hours above and below the average temperature are about equal. The significance of the average temperature is that the snowpack does not lose meltwater by drainage until the average temperature remains appreciably above zero degrees C. The data of Fig. 3 indicate that very little snowpack mass should be lost until approximately April 10, 1980 via melting.

A special temperature event occurred on May 9. A cold front brought new snow, and maintained the air temperature below freezing for that entire day. Also, the measured net radiation was insufficient to produce more than superficial snow surface melting. Thus for May 9 no meltwater was added to the snowpack. These unusual conditions are clearly evident in the microwave data, as will be discussed below.

Snowpack water equivalent measurements are shown in Fig. 4 for March, April, and May 1980. These are obtained from the density profile data taken daily (illustrated in Figs. 1 and 2). The data represent the net mass of snow; precipitation in the form of rain or snow can be distinguished by the snowpack height, but losses by evaporation or by water drainage cannot be separated into such categories. Extensive studies of evaporation have been made in previous years at CSSL, with the conclusion that in open sites water losses as high as 15 cm can occur during winter and spring.

Examination of Fig. 4 shows that the water equivalent starts to decrease in regular fashion after April 10. However, as noted in the preceding paragraph, the allocation of losses into evaporation and drainage is not feasible from Fig. 4 alone. If the somewhat arbitrary assumption is made, as a limiting case, that 15 cm of water equivalent are lost after April 10 via evaporation, then the snowpack should begin to acquire wetness when the water equivalent decreases from 119 cm (April 10) to the value of 104 cm (April 17). Of course additional days would be required for meltwater to move through the snowpack. If no water was lost from the snowpack by evaporation, then the microwave horns at the highest level (6-ft) should measure wetness a few days after April 10, perhaps on April 14 or April 15.

During December 1979 when the snowpack was approximately 125 cm deep, about 3 cm of rain occurred. This was subsequently covered with snow. As will be discussed below, this affected the wetness measurements for the microwave horns at the "4-ft level".

MICROWAVE SYSTEM AND DATA

The microwave system had a swept-frequency source coupled to a six-position rotary switch. Terminal 1 of the switch was connected to a coaxial cable having an attenuator. The remaining five terminals of the switch were connected to microwave horns positioned on a wooden framework at various heights above ground. At a lateral distance of 50 cm was another set of microwave horns, each connected to one of the five terminals of a second rotary switch, whose terminal 1 was connected to the coaxial cable. The output of the second rotary switch was connected to a broad-band amplifier, having a crystal detector on its output. The crystal detector was connected to a logarithmic conversion unit, so that the signal was received by an XY plotter, which produced the curve of decibels versus frequency.

The system was calibrated by introducing known attenuation in each line, and recording the corresponding signal on the XY plotter. The response of the system when the coaxial cable (and its attenuator) connected the two rotary switches verified that all units were operating properly.

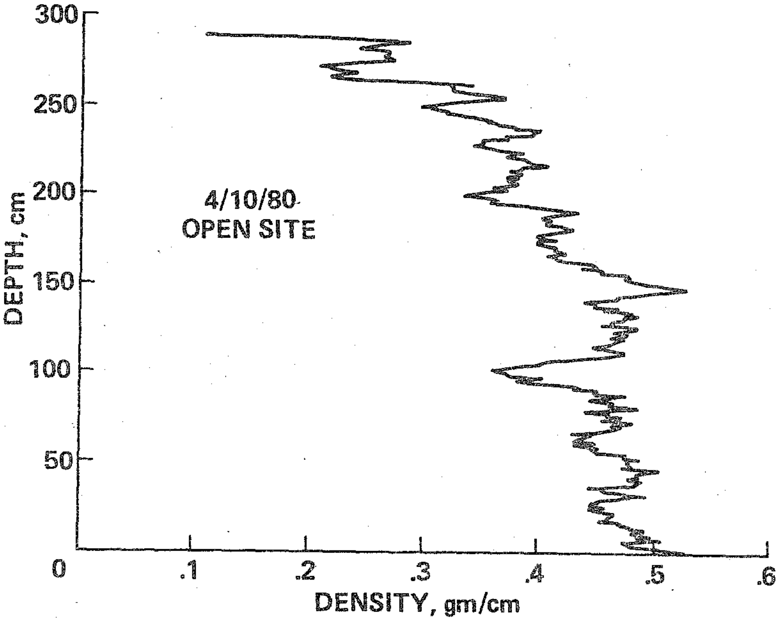

300
250
200
150
100
50
0
DEPTH, cm
4/10/80
OPEN SITE
.1
.2
.3
.4
.5
.6
DENSITY, gm/cm

FIG. 1

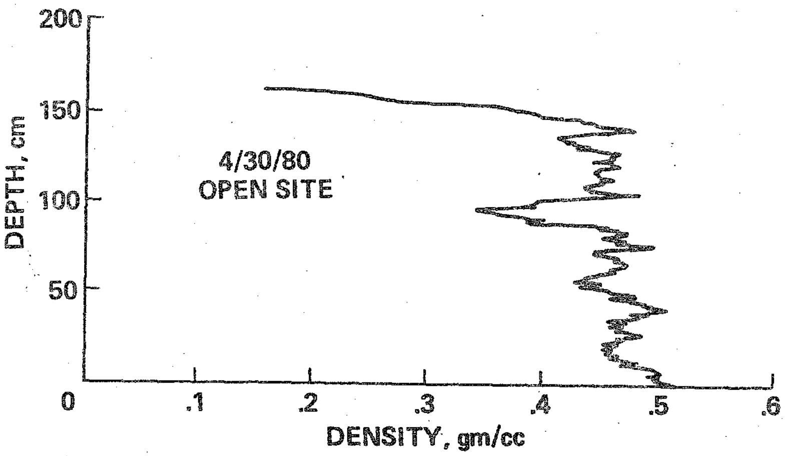

200
150
100
50
0
DEPTH, cm
4/30/80
OPEN SITE
.1
.2
.3
.4
.5
.6
DENSITY, gm/cc

FIG. 2

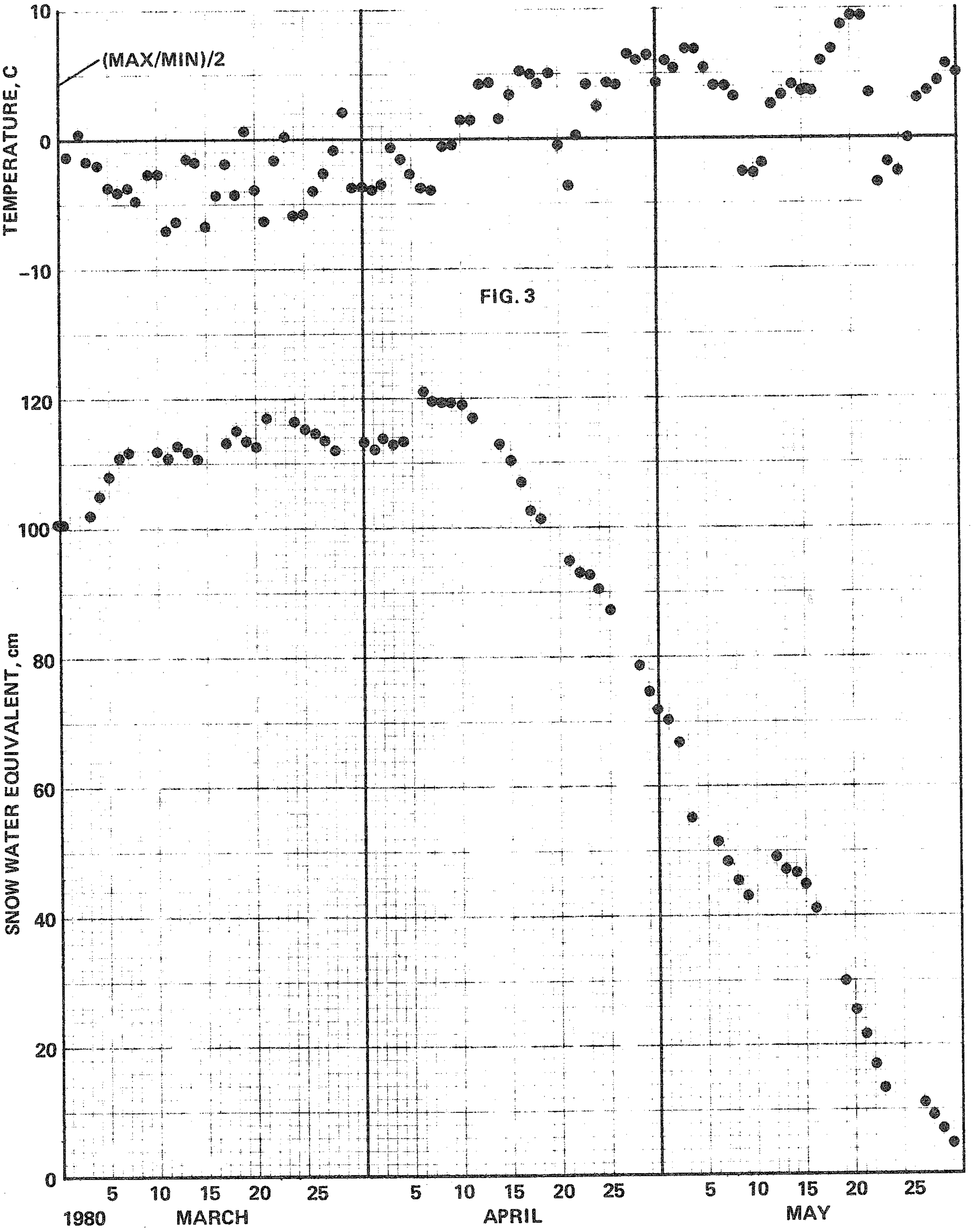

10
0
-10
TEMPERATURE, C
(MAX/MIN)/2
120
100
80
60
40
20
0
SNOW WATER EQUIVALENT, cm
5
10
15
20
25
5
10
15
20
25
5
10
15
20
25
1980
MARCH
APRIL
MAY

FIG. 3

FIG. 4

Five pairs of microwave horns were employed. Because this was the initial test of the system, and the amount of attenuation during active snowpack melting was not known, the frequencies were selected so that adequate signals would be obtained at all times. Because the attenuation is essentially proportional to frequency in the ranges of interest, the highest frequency horns were located at the highest level, so that the onset of wetness would be measured with the most sensitive horns. Two sets of broad-band horns were employed, although this required trading off gain for the broad frequency range; it turned out that the signals from these two sets of horns were too weak to be useful for most of the melt season.

The selection of microwave horns that produced useful data was:

Frequency range: 4 to 6 GHz Height: 61 cm ("2-ft level")
Frequency range: 6 to 8 GHz Height: 122 cm ("4-ft level")
Frequency range: 8 to 12 GHz Height: 183 cm ("6-ft level")

The procedure for data acquisition consisted of the following steps. First the response of the system was obtained with the coaxial cable and its fixed attenuation. This was verified to be constant. Then each pair of horns was connected in sequence to the source and detection units with the two rotary switches, and the output versus frequency was recorded on the XY plotter. Such data were acquired twice daily, at approximately 8 a.m. and 4 p.m. No data were obtained with this system on week-ends.

RESULTS

The snow wetness is calculated from the data with the relation given previously in the introduction. The measured attenuation, in dB, is divided by the known distance between the horns, 50 cm, yielding a value for dB/cm, for a selected frequency. From the equation one calculates the snow wetness in volume percent. For any pair of horns, this calculation was made for at least three frequencies, and the three resulting values for snow wetness was averaged.

The development of wetness in the snowpack is shown in Figs. 5, 6, and 7. These give the volume percent wetness at the respective levels of 2-ft, 4-ft, and 6-ft. All three figures show the beginning of wetness between April 15 and April 20.

Figure 5 shows that the snowpack wetness is less than one percent by volume until April 18. On this date the morning value is 1.2 percent, and the afternoon value is 2.0 percent. The successive days show the wetness increasing, with the afternoon wetness being about one percent greater than the morning value. However, for the last date of May 15, the wetness was 3.4 percent in the morning, and 6.9 percent in the afternoon (volume percent).

On the date of May 9, 1980 Fig. 5 shows that the afternoon wetness is 2.5 percent, compared to the morning wetness of 3.0 percent. The reason for this effect was discussed previously: a storm occurred that kept the temperature below freezing for the entire day, together with extensive cloud cover. Consequently no snowpack meltin occurred on May 9, and so the wetness continued to decrease during the day. The dates of May 10 and May 11 were week-end days, so no data were obtained. The morning reading of May 12 showed a wetness of 2.3 percent by volume, which is lower than the May 9 values

Figure 6 shows the snowpack wetness for the 4-ft level. As mentioned previously, a rain in December 1979 occurred; this probably is the reason why the wetness values lie in the 1.5 percent region prior to the start of active snowpack melting. There is a question whether the December rain produced crystal growth, thereby lowering the water retention capability of the snow. The snow level dropped below the horn level at April 30. The development of snowpack wetness is clearly evident, althoug not as pronounced as in the case of Fig. 5.

The snowpack wetness for the 6-ft level is shown in Fig. 7. Prior to the start of melting, the snowpack wetness was less than 1 percent. Significant increases in wetness occurred about April 17, and continued until the snow level dropped below the horn level. The snow at the 6-ft level was not subjected to rain events, so this figure serves as the best example of the process of snowpack wetness development. The beginning of active melting is clearly April 17; the maximum afternoon wetness occurred on April 28, the value being 4.0 volume percent.

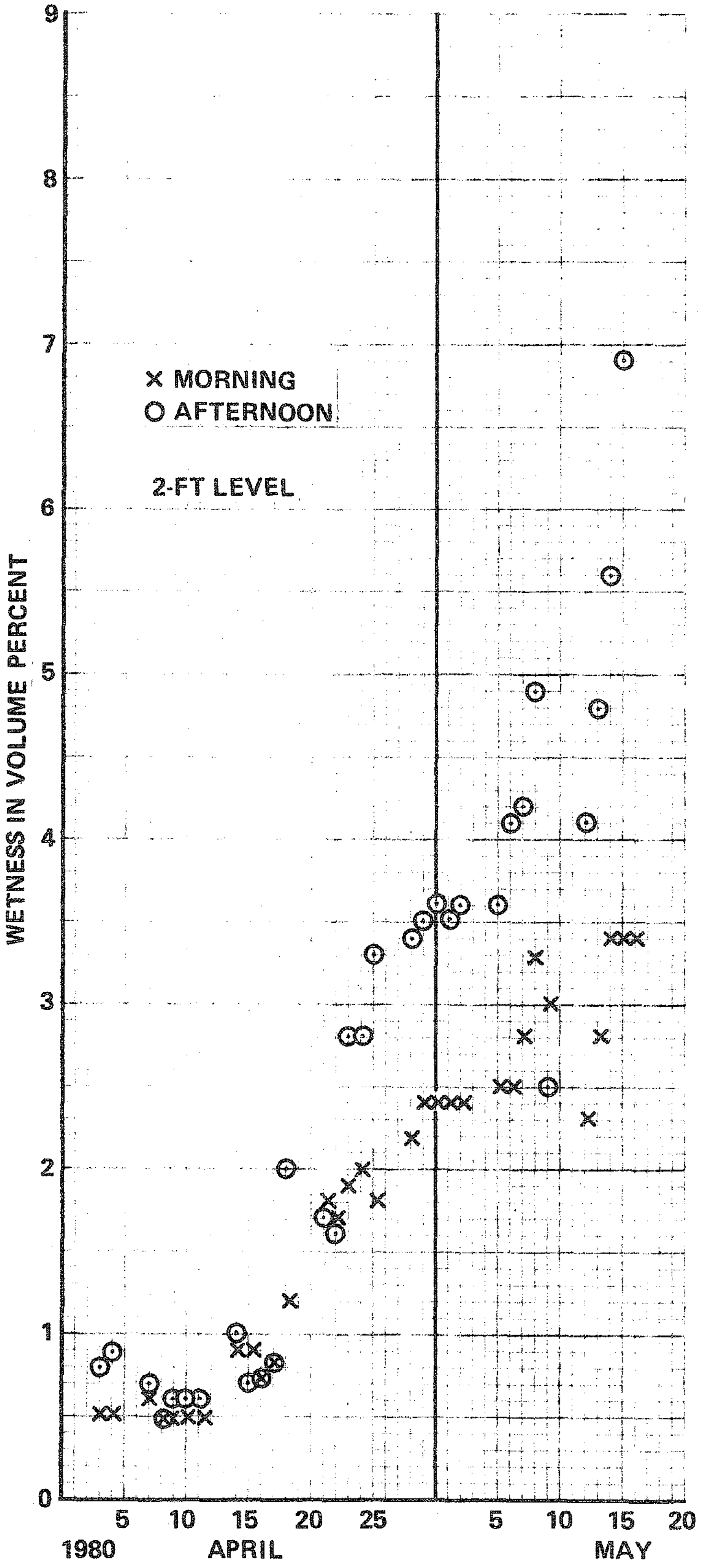


FIG. 5

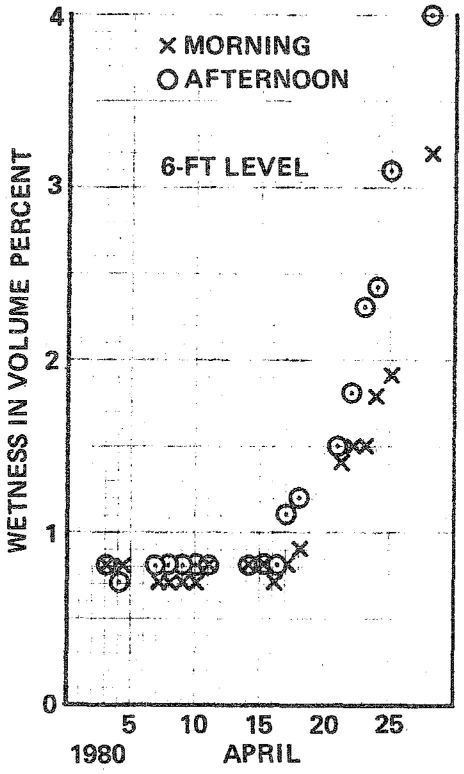


FIG. 7

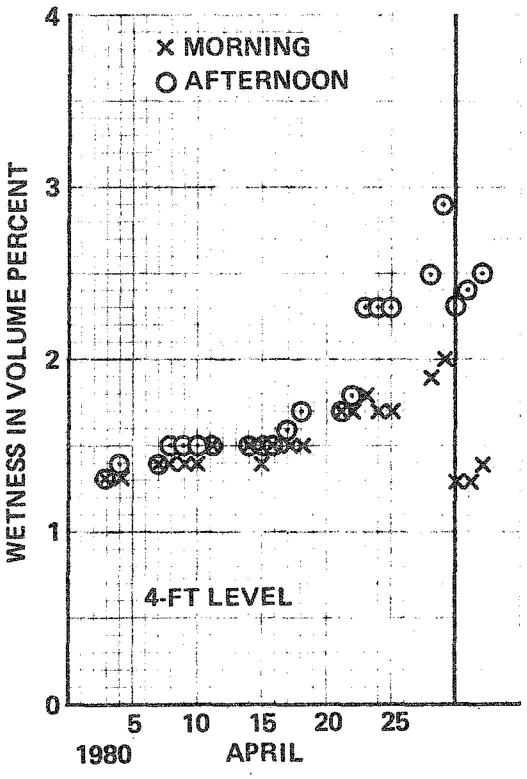


FIG. 6

The results are now presented in weight percent. This represents the weight of the liquid-phase water per gram of dry snow, multiplied by 100. Such information is useful in that it provides a separation of the snowpack mass into water- and snow-components. To convert the wetness from volume percent to weight percent, the density must be known. This is obtained from the snow density profiles (as illustrated in Figs. 1 and 2). The snow density at the 2-ft, 4-ft, and 6-ft heights is taken from the curve for the day under consideration.

With the procedure just described, the volume percent wetness was converted into weight percent wetness; the results are plotted in Figs. 8, 9, and 10, for the 2-ft 4-ft, and 6-ft levels.

In Fig. 8 the initial wetness is about 2 percent, and the maximum wetness in the afternoon of May 15 is 16 percent by weight.

In Fig. 9 the initial wetness is about 3 percent, and the maximum wetness is about 6 percent on April 29.

Figure 10 shows the development of snowpack wetness very clearly. The initial value is about 2 percent by weight. On April 17 active melting is evident, and the snowpack continues to acquire wetness until April 28, the maximum being 13 percent in the afternoon, this being wetness by weight percent.

CONCLUSIONS

Although these results should be considered to be preliminary, subject to confirmation in future winter seasons, some conclusions seem to be justified:

1. The microwave system clearly provides information to determine active snowpack melting.

2. The microwave system can assess the wetness state of the snowpack.

3. The wetness of the snowpack decreases overnight in amounts ranging from 2 to 6 percent by weight, depending on the value in the afternoon. No single number is appropriate to characterize the snowpack wetness.

APPLICATION OF WETNESS DATA TO RUNOFF FORECASTING

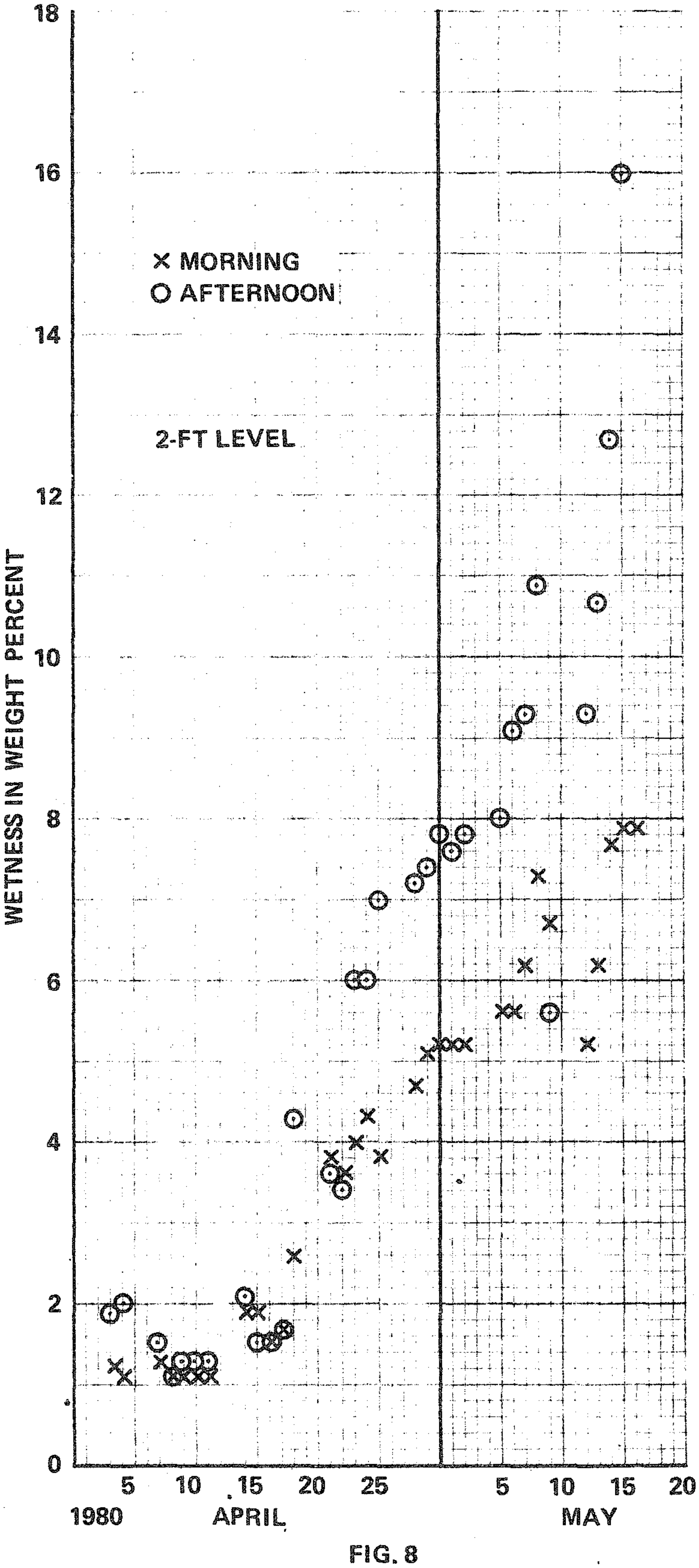
The following remarks are intended to suggest a few of the applications of wetness data to runoff forecasting. As more experience is accumulated, alternative and more sophisticated applications undoubtedly will emerge.

From the wetness state of the snowpack at two or more levels the determination can be made regarding the beginning of active melting. (A pressure-pillow or profiling gage may indicate a loss of snow water equivalent, but this can be produced by evaporation.)

From the diurnal variation in wetness (afternoon and morning), together with the percent wetness, the daily drainage of the snowpack can be obtained; this represents the key information.

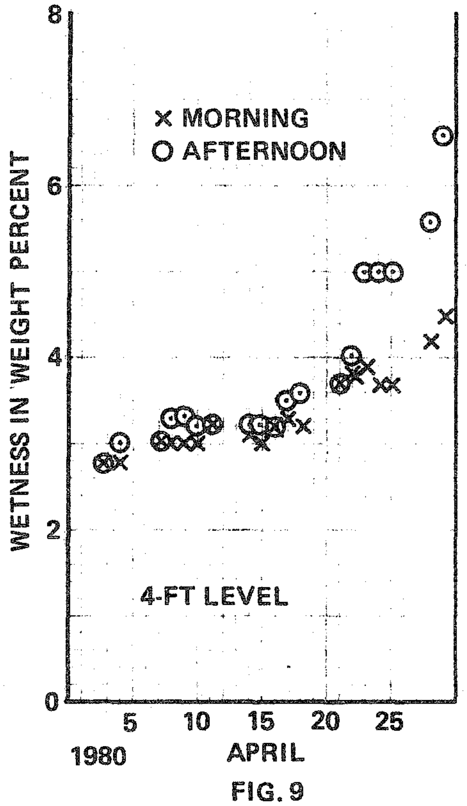
For the (probably rare) situation of a heavy rain in January or February, the loading of the snowpack with liquid water can be determined. Subsequent snow crystal metamorphism into large grains may be estimated. Such snow apparently is limited in its water-holding capability to about 6 percent by weight, compared to about 16 percent by weight for snow having small grains. This implies that the water during subsequent melting would flow rapidly through the snowpack, and drain to about 4 percent by weight overnight.

These comments refer to the snowpack characteristics, from which calculations can be made for the basin runoff. The implicit assumption is made that a sufficient number of microwave installations are available to determine the snowpack state in the basin.



18
16
14
12
10
8
6
4
2
0
WETNESS IN WEIGHT PERCENT
× MORNING
O AFTERNOON
2-FT LEVEL
5
10
15
20
25
5
10
15
20
1980
APRIL
MAY

FIG. 8



8
6
4
2
0
WETNESS IN WEIGHT PERCENT
× MORNING
O AFTERNOON
4-FT LEVEL
5
10
15
20
25
1980
APRIL

FIG. 9

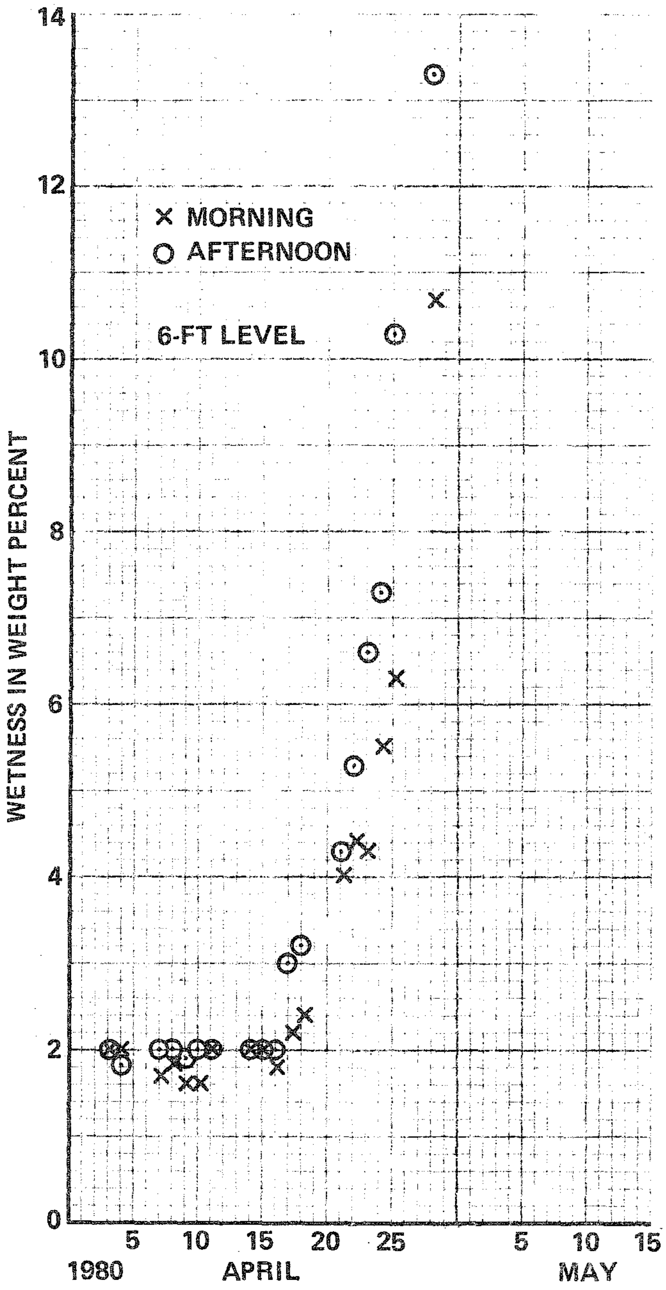

14
12
10
8
6
4
2
0
WETNESS IN WEIGHT PERCENT
× MORNING
○ AFTERNOON
6-FT LEVEL
5
10
15
20
25
5
10
15
1980
APRIL
MAY

FIG. 10

APPENDIX

Instrumentation for 1980-81 Season

A second microwave system was installed at CSSL for the 1980-81 winter season. This consisted of five sets of microwave horns, all of which operate in the frequency range of 4 to 8 GHz. They are installed at the 2-ft, 4-ft, 6-ft, and 8-ft levels, with two sets being at the 4-ft level. The support structure consists of aluminum channels, the horns being at the ends of cantilever supports. The electrical components are similar to the items described in the present paper, except for the horns.

Up to March 27, 1981, the snowpack has barely covered the horns at the 4-ft level, as the maximum height. For most of the season data were obtained only with the horns at the 2-ft level.

Analysis of Microwave System Cost

The instrumentation employed in the tests to date involve general-purpose equipment, powered by 110-volt circuits. A preliminary design has been made for a system that can make the measurements automatically, whose components and cost are listed as follows:

	Item	No.	Each	Cost
A.	Rotary switches	2	800	1600
B.	Power supply	1		100
C.	VC Oscillator	1		900
D.	Microwave horns	6	255	1530
E.	Detector	1		150
F.	Clock & Sweep-generator	1		200
G.	Log output amplifier	1		400
H.	Miscellaneous (cables, horn mounts, cabinets, etc.)			1500
			Total:	6380

Notes: Items F and G are "custom" products, and require an initial design and testing cost of approximately $2,000 each.
The horn frequency range is 4 to 6 GHz.
The data output is assumed to be transmitted by equipment not included here, to suitable storage or to a receiving station.
Further development probably would permit reduction of the costs.
Mass production (greater than 50 systems) would greatly reduce the costs.

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