THE STORAGE AND TRANSMISSION OF WATER IN SNOW

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by R. W. GERDEL*

• This paper on the storage and transmission of water in snow presents the more important phases of the subject covered by the author in a number of papers presented previously at regional meetings of the American Geophysical Union and the Western Snow Conferences, and in part, as a discussion of the paper, "Snow Hydrology for Multiple Purpose Reservoirs", by H. S. Riesbol, published as Separate No. 189, Volume 79 Proceedings, American Society of Civil Engineers.

INTRODUCTION

The amount of melt water or rain which can be stored on a snow covered watershed and the rate at which the liquid water will be transmitted through snow and affect stream flow has been a controversial subject for many years.

The question is not whether percolating water freezes at depths in the pack where temperatures may be below 0°C, but whether appreciable amounts of liquid phase can be held by surface or capillary tension, or otherwise retained in a snow pack which is isothermal at 0°C, and whether the snow pack exerts sufficient influence on the rate of discharge of excess water to warrant adjustments in the forecast scheme.

Some hydrologists assume that no runoff from a snow covered area occurs until a homogeneous structure and a critical density is reached and the detention capacity satisfied. Frequently a density of 40 percent has been cited as the threshold condition while water holding capacities up to 50 percent by weight of wet snow have been ascribed to the snow cover.

In 1948 the writer reviewed the literature in a search for information on the physical properties of a ripe, discharging snow pack, for a report to the International Commission on Snow and Glaciers (1), (see bibliography). It was found that densities between 25 and 56.5 percent for a ripe, melting actively discharging snow pack were reported by several investigators. A pack usually consists of a number of readily identifiable layers which are the product of definite storms. The variation in density between these layers may be large at the time of deposition and this variation is maintained throughout their life, even in a ripe pack. Work (2) found that homogeneous density was never obtained in a ripe pack and that the density of different layers in a late April ripe snow pack varied between 45 and 58 percent. At the Central Sierra Snow Laboratory, in California, variations of more than 10 percent in the density of ripe, discharging spring snow packs were found between different sample points in the 4-square mile basin.

The results of investigations on the discharge of water from a melting spring snow pack made by the U. S. Weather Bureau at the Soda Springs Cooperative Research Project (3), showed that a pack of 52.8 percent density lost 1 inch of water equivalent snow in about 12 hours and retained about 1 inch of liquid water in a 5-foot deep pack, after melting ceased for the day. The 1944-45 report from this project (4) presents the results of some investigations of a heavy rain on new and old snow. A new snow of 10 percent density had been deposited on top of an old pack of 38 percent density. In places, the new snow was deposited on clean black-top and concrete roadways. During one day 1.44 inches of rain fell upon the new snow which was 5 inches deep at the time the rain started to fall. During the height of the storm, the new snow, overlying old snow, contained only 13 percent liquid water. On the paved roadway where water was impounded in depressions, the slush which developed had a free water content of 30 percent. Under no circumstances could such high free water content be attributed to the water holding capacity of the snow. It was definitely the result of snow floating on or being submerged in water impounded in a depression with an impervious bottom. It is interesting to note that when efforts were made to measure the density of the slush, the water drained out of the sample so rapidly that the maximum measured density was only 16.5 percent.

During the period between 1943 and 1950, when the writer was actively engaged in snow hydrology research in the Western States a number of experiments were undertaken to determine the effect of large amounts of water on the shrinkage, and increase in density of monolithic cylindrical samples of snow. Water at 32° was applied to the top of 24 inch long snow cores held in a core sampler with a screen bottom. When 2 to 3 inches of water was applied to a sample of 18 percent density almost all the water passed through the snow in a few minutes. The density at the end of the drainage period was 26 percent and the increase was almost entirely the result of volume shrinkage.

Repeated addition of liquid water, equal to 3 times the water equivalent of the original solids in one sample, changed the density from 22 percent to 34 percent by reduction in volume while allowing more than 15 inches of liquid water to pass through the initial 24-inch long core of snow.

Some experiments reported from the Central Sierra Snow Laboratories (5), where artificial rain was applied to a 6-foot deep snow pack, of 0.35 gm/cm^2 density indicated that about 0.3 inches of liquid water could be temporarily detained in the pack and almost all of that drained out within two hours after application of the rain was discontinued.

During the course of many experiments on the water holding and transmission capacity of snow, the author has been unable to add water to the snow surface faster than it could be absorbed.

It has been observed that buried crusts may be impermeable planes for a period and then become the chief horizontal flow zone as the ice bonds between the coarse grained crystals break down. These coarse-grained flow zones are similar to the "rock drains" sometimes used in highway and agricultural practices.

The presence of flow zones or drains within a snow pack is frequently indicated by a dendritic or pock-marked pattern on the snow surface which is produced by the subsidence of the surface above internal flow channels, usually directed toward a stream.

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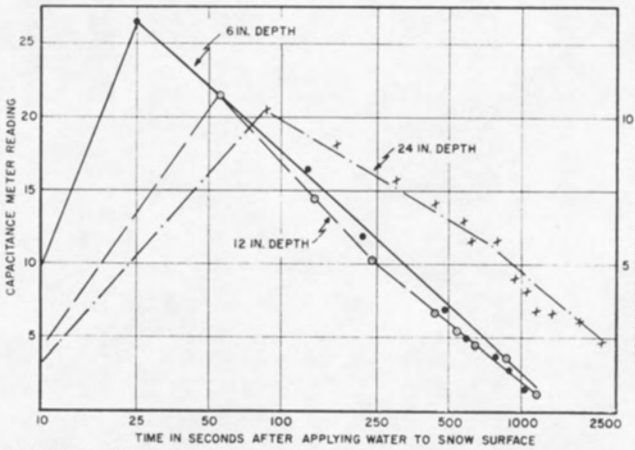


FIGURE 4 — Water movement through snow of 0.46 density as measured by the change in capacitance.

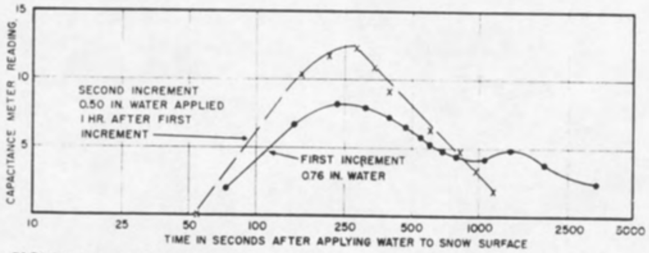


FIGURE 5 — Effect of successive additions of water on the transmission capacity of the snow pack. Capacitance probe at 18 in. below snow surface.

INSTRUMENT DEVELOPMENT

Studies on the movement of liquid water in snow are complicated by the lack of satisfactory methods for measuring the non-frozen water content and difficulties associated with sampling techniques which distort the physical properties of the sample and destroy the sample site. In an effort to devise a technique suitable to the in situ measurements of liquid water in snow an instrument was developed which makes use of the difference in the dielectric constants between the solid and liquid phases of water.

At 0°C the dielectric constant for water is 88.3, and for ice it is very close to 3.0 at frequencies above 1 megacycle. Since the dielectric constant for air is 1.0 a very small change in the amount of free water should produce a measurable difference in the capacitance of a mixture of snow, air and water. On a purely empirical volumetric basis the dielectric constant of a unit mass of snow would be equivalent to the sum of the ratios of the dielectric constants of the ice, water and air in the sample.

After the most suitable working range was determined a resonance type of capacitance meter which proved to be very sensitive to small changes in the free moisture content of the snow was constructed. A block diagram for this instrument is shown in Figure 1. It is essentially a beat frequency oscillator operating at about 1.5 megacycles. The frequency of one oscillator is varied by changes in the capacitance of a parallel plate probe inserted in the snow and the second oscillator is brought into resonance by means of a manually operated precision condenser equipped with a vernier dial. Resonance is indicated by a null meter. The field instrument is provided with five stainless steel probes connected through a low capacitance switch unit to the meter. One of the probes is shown in Figure 2 and the meter with probes installed in the snow is shown in Figure 3.

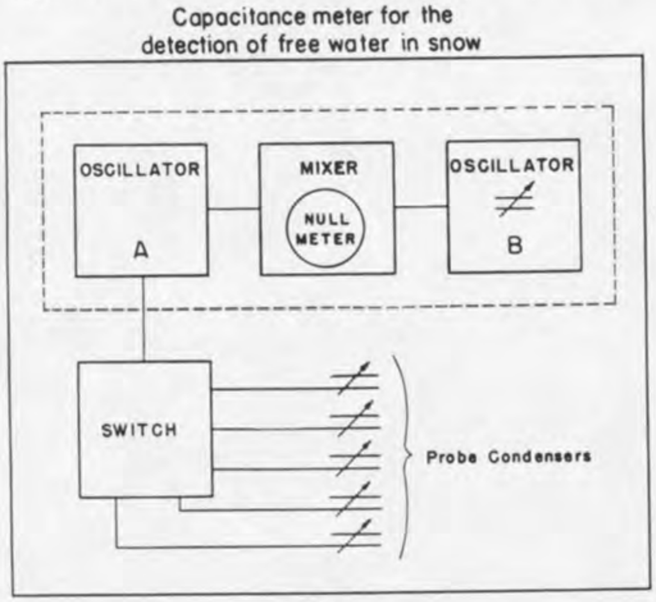


FIG. I

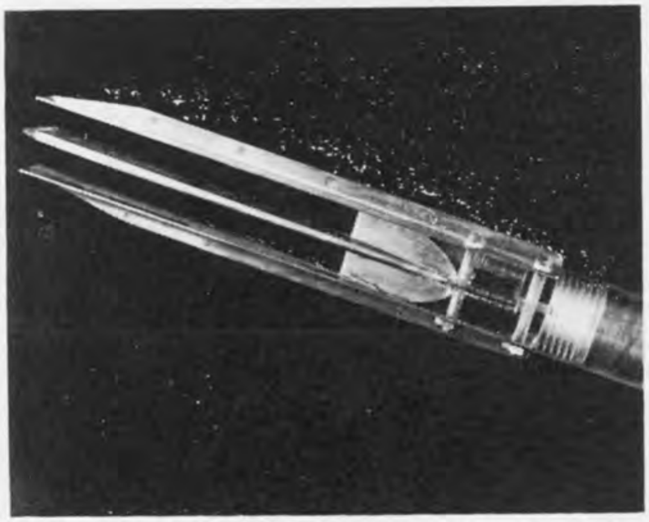
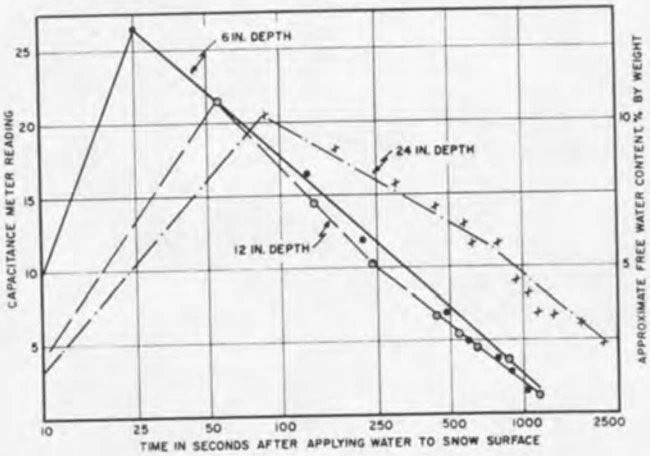
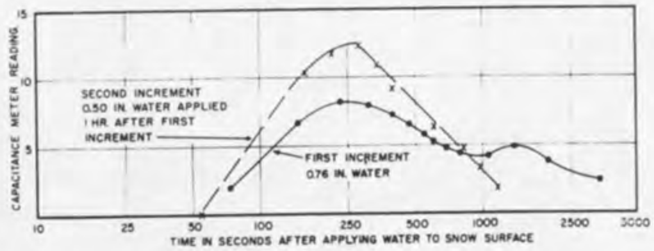


FIGURE 2 — The Snow probe capacitor used with the Snow Moisture Capacitance Meter.

FIGURE 3 — The Snow Moisture Meter with probes inserted in a snow profile at flow zone points previously identified with fuchsine dye.





Neither dry snow nor a mixture of snow, air and water are perfect dielectrics. The size, shape and axial orientation of the crystals which make up the matrix of a snow pack contribute to a phase defect which is difficult to measure. Since the capacitance values indicated by the meter are the product not only of the liquid and solid phase but also of the snow density and the size of the crystals, the instrument must be directly calibrated in terms of the volume of free water present for each type of snow studied.

EXPERIMENTAL PROCEDURE

The capacitance meter was used in a series of experiments to measure the rate of transmission of water through a snow cover at the Central Sierra Snow Laboratory.

These studies were conducted on a 4- to 8-foot deep snow pack covering gently sloping ground which had good internal and surface drainage to a nearby stream. During a period in May 1948 when the snow pack had become isothermal at 0°C and active melting was taking place, a small amount of fuchsine dye was scattered over about 2 square feet of the snow surface. Twenty-four to forty-eight hours after the application of the dye the path of the melt water through the snow was determined by excavation and careful exposure of a profile. The probe condensers were then inserted at suitable intervals in the identified flow zone.

A measured amount of water at 0°C was rapidly and uniformly applied to the snow surface where the dye had originally been placed and the probe values read at stop-watch intervals as rapidly as the capacitance meter could be balanced and the selector switch operated. Except for one experiment which will be discussed later, water was not applied nor were dielectric measurements made twice on the same profile.

The sensitivity and response of the instrument to rapid changes in the liquid water in snow and the well defined interval between peak flow past each probe site in the pack is illustrated in Figure 4 in which the data from one experiment have been plotted.

During the course of each experiment several samples were removed from the dyed zone adjacent to one of the probes for determination of the free water content by the usual calorimetric method. From the data obtained in these experiments the transmission capacity of the snow was computed from the time interval between peak flow past each probe and the thickness of the horizon between the probes.

The water transmission rate for a snow pack as derived by these studies may be considered as analogous to the travel time for a flood crest through a specific reach of a stream. When the water in transit through the snow pack is the product of surface melt, a deep snow cover of 6 to 20 feet, such as is common in the western mountains, will have within it a diurnal wave of moving water which is an extension of the diurnal wave characteristic of the hydrograph of snow fed streams. The same analogy, with adjustment for the time element, applies to storm rainfall moving through a deep snow pack.

In most of the Eastern United States the passage of melt or rainwater through the comparatively shallow snow cover would appear to be so rapid that the effects of delay or storage can be ignored.

DISCUSSION OF RESULTS

The transmission rate for snow as measured by the change in capacitance produced by a moving front of water varied between 0.9 and 24.0 inches of snow per minute for eleven measurements as shown in Table 1. From these experiments, conducted on snow packs of 0.35 to 0.46 density, it appears that high transmission rates are associated with high density.

The high rate of water transmission through high density snow is compatible with the accepted idea that the maximum rate of discharge from a melting snow pack does not occure until it becomes "ripe". Although "ripeness" is difficult to define, it is a physical property associated with the natural processes which produce large crystals, increased density and well developed flow zones in the residual snow pack. The results of these studies indicated that the retention capacity of a "ripe" snow, analogous to the field moisture capacity of a soil, is equivalent to about 0.1 inch of rain or melt water per foot of snow, or the same amount that is held by a sandy soil.

It is apparent from this study that the snow pack is much like a coarse sand in its capacity to transmit or hold water, except that the transmission constant and field capacity for a sand profile will vary little from time to time whereas the transmission capacity for snow may improve with each successive rain or unit of melt water moving through the pack. This improvement in the porosity of the snow is shown in Figure 5.

The data plotted in this figure were derived from a snow profile about 18 inches thick which was initially laminated with several wind or sun crusts buried beneath snow layers from subsequent storms. A single probe was placed at the bottom of the stratified horizon which had an average density of 0.40. Approximately 0.8 inches of water at 0°C was applied to the snow surface and the change in capacitance measured at stop-watch intervals.

Table 1
TRANSMISSION OF WATER THROUGH SNOW

Snow Density	Probe Spacing	Water Applied	Transmission Rate*	Free Water Content of Snow			Duration of Observation
				Initial	Peak	End	
gm/cm^3	in	in	in snow/min	pct	pct**	pct	min
0.35	25	2.0	1.1	4.0	16.2	5.5	19
0.35	41	2.0	1.1	1.4	9.3	1.1	19
0.40	7	0.8	0.9	3.8	6.2	1.1	18
0.40	17	0.5	3.7	4.1	6.2	1.7	18
0.46	6	2.0	12.0	6.0	10.7	5.1	48
0.46	12	2.0	16.0	4.0	9.8	0.9	48
0.46	18	2.0	18.0	4.0	10.3	0.9	48
0.46	6	2.0	24.0	5.0	10.3	2.6	35
0.46	12	2.0	24.0	2.9	10.3	0.7	35
0.46	6	2.0	24.0	3.0	10.3	2.0	35

*Computed from time interval between peak flow and spacing of Capacitor Probes.

**Interpolated from calibration curve derived from capacitance readings and calorimeter measurements.

About one hour later a second increment of water, amounting to 0.5 inches, was applied to the snow and the change in capacitance again measured.

The wave-like curve for the transmission of the first increment of water through the snow shows the effect of temporary impounding of water and the subsequent disintegration of the less permeable crusts. The curve for the second increment of water indicates that a greater porosity has developed as a product of the movement of the first unit of water through the pack.

The free water retained in this pack was about 1 percent or less than 0.05 inches of liquid per foot of snow. Whether subsequent additions of water would have produced a further increase in porosity was not determined. At the termination of this experiment the 18-inch layer of stratified snow did not have the structural appearance of a coarse grained, "ripe" snow pack and further metamorphism and a greater increase in transmission capacity might have been produced if additional increments of water had been applied to the snow surface at this site.

Efforts to apply water at high rates over a sufficient area of snow to provide reliable values for head differentials resulted in the rapid disintegration of the surface and internal structure of the snow pack. Inability to obtain suitable data for the derivation of a permeability constant further substantiates the high transmission rates actually measured.

DISCUSSION

In a recent paper (6) it was pointed out that the movement of water through the snow pack follows definite channels which develop perpendicularly and horizontally within the pack. These channels of coarse grained snow have long been recognized by glaciologists who refer to them as "firn pipes" or "glands". When the ground is exposed as a melting snow pack recedes in the mountains, the flow channels which have developed at the contact between the snow pack and the ground are very evident, on some soils, as a dendritic pattern of erosion marks. Over rock and less erodible soils these channels develop as arched piping in the bottom snow layer.

There is little experimental evidence to indicate that a deep and dry snow cover will retain appreciable amounts of rainfall or melt water. The presence of free water induces a rapid metamorphic process which reduces the surface area of the individual snow crystals to the minimum compatible with the mass and stable form of the crystal. That is, the feather-like or dendritic snow flakes are converted to small crystals or hexagonal form which resemble table salt or rock salt. The surface detention capacity of the snow flake is rapidly reduced by the metamorphic process and the water which may have been retained on the larger surface area is discharged. This metamorphic process is not uniform throughout the pack. It appears to proceed faster at one place than another, which accounts for the development of the flow zones within the pack and at the ground surface.

The size of the metamorphosed grains in a spring snow pack is of the same order as a mixture of fine and coarse sands, about .02 to 2.0 mm diameter. A soil with such a particle size distribution will hold, at field capacity, from 1 to 3 percent liquid water, the same quantity as has been measured and reported frequently for a spring snow pack.

The temporary detention of liquid water in snow is a function of the time required for the development of internal flow channels and hydrologically these channels are effectively temporary supplemental tributaries to the normal drainage pattern of the basin. There is no evidence to support an assumption that snow must achieve some threshold density before this supplemental tributary system becomes operative.

SUMMARY

1. Studies on the rate of movement of water applied to the snow surface indicate that the transmission rate for snow of 0.35 to 0.46 density may vary from 0.9 to 24 inches of snow per minute. The higher transmission rates appear to be associated with high density and a "ripe" pack structure.

2. The transmission rate may increase with successive additions of water to the surface of the snow.

3. It is possible that a snow pack may have a high temporary storage capacity for free water pending the development of internal flow zones and channels at the contact with the ground surface. These flow zones may reach full development within a few hours when a large amount of free water is available.

4. The ultimate field moisture capacity of a "ripe" snow pack appears to be about 0.1" of water per foot of snow.

5. When the drainage network is established within the pack and its field moisture capacity is satisfied, the discharge of melt or rain water will be approximately equal to the rate that the liquid phase is available at the surface of the snow.

6. Hydrologically it appears that a deep snow pack is effectively a pattern of small, temporary tributaries supplemental to the normal drainage network of a basin. If the pack is sufficiently dense and deep, a routing coefficient may be applicable to basins well covered by snow.

ACKNOWLEDGMENT

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