The Profiling Radioactive Snow Gage

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Determination of snowfall amount or whether snow is actually falling is a major problem for agencies involved in snow removal or control on remote mountain roads or on remote, unattended airfields. A system has been developed by which snow density and depth may be measured in ½-in. increments by vertical profiling of a snowpack. The system is highly accurate and may be adapted for remote operation. With it one may determine whether snow is falling, the intensity of snowfall, the depth of the snowpack, and its density at all points in the pack. One may also determine whether rain is falling onto a pack, when the rain ceases, and when snow begins to fall again. Pack settlement, melt, or ice-crust formation may also be monitored. The gage consists of a small radioactive source and a detector that are drawn at a rate of one foot per minute through two access tubes extending from ground line to a point above the highest snow deposition. The signal can be sent by telephone line or radio to a base station where the signal is converted to depth and density and is recorded.

One-third of the earth's land surface is covered by snow and ice (1). Most of the great river systems of the world depend on snowmelt water for their flows. Water for the arid regions comes largely from melted snow; in California, 51 percent of all streamflow is derived from melted snow. Some of the most disastrous floods in the United States come from snowpacks melting too rapidly or from rain falling on and melting snowpacks.

Large snowfalls are the most frequent cause of paralysis of transportation systems. These result in highway closures because of poor visibility, avalanches, or snow that accumulates faster than available equipment can remove it from the roadway.

Few resources are so extensive in area, so disruptive to transportation, so useful and yet so threatening to man as snow.

With so extensive and important a resource one would expect that man would have devised reliable systems for monitoring rates of snowfall, snow depth, and snow condition. Likewise one would expect to find a large array of formulas with which to predict the reaction of snow on the ground to environmental stimulii that cause snow to melt. Such is not the case.

Three basic forms of snow measurement have been used to date. The first, and most extensively used method, consists of one or more of the extraction or gravimetric techniques. The second, and currently popular, method makes use of a weighing system. The third, a recent innovation, uses isotope snow gages.

Most snow surveys are taken by men traveling to the snow course in the mountains and taking gravimetric samples. Hand sampling consists of driving a hollow tube into the snowpack, extracting the tube and the included snowcore, and determining the weight of the column of snow. Knowing the length of the sample and its weight, a snow surveyor can compute water content and density with an error of ±7 to ±12 percent (2, 3). Such a system is costly, destroys the sampling site, and is not usable for studying in situ changes of the pack structure.

Beaumont (4) suggested the practicality of determining the snow water equivalent with a weighing system. He proposed using a 12-ft (3.66 m) diameter butyl rubber pillow filled with methyl alcohol and installed on the ground prior to snowfall. As the snow falls on the pillow, the internal pressure is increased. The pressure is related to the mass, or weight, of the snow above it. A manometer or a pressure transducer is used to measure this pressure.

A large number of pressure pillows have been installed in the mountains of the western part of the United States. Results from their use have varied widely. We suspect that success or failure is dependent on the location of the pillow and the reaction of the snow to the environment. Snow bridging, resulting from ice lens formation, appears to disrupt the downward displacement of weight onto the pillow from the overlying snow. Measurements taken during such periods are inaccurate. Where there is no ice lensing the pillows appear to react correctly to weight changes in the snowpack.

Development of the first nuclear snow gage was reported by Gerdel et al. in 1950 (5). This gage used a cobalt-60 radioactive source at ground level with a detector positioned above the snow. The readout of this gage was a single number translatable to the water equivalent of the snowpack between the detector and the source. Since this first study there has been a constant effort to develop a better nuclear gage (6, 7).

The neutron single probe system utilizing the scatter principle from a radium-beryllium source encapsulated with a boron trifluoride gas detector tube was the first radioactive system used to profile snowpacks (8, 9). Density may be determined in approximately 6-in. (15.24 cm) vertical increments with an accuracy of ±2 percent (10). The density of thin ice lenses common to the snowpacks of the Sierra Nevada of California could not be measured. Multiple calibration lines were also necessary in order to accurately measure density near the snow-air and snow-soil interfaces.

DEVELOPMENT OF THE PROFILING SNOW GAGE

As populations expand, water needs expand, while the total supply of water remains the same. Thus it becomes necessary to increase downstream water recovery of as much of the melting snow as possible. This necessitates better control of snowpacks in lands lying above reservoirs so that melt rate may be accelerated or decelerated to secure better utilization of reservoir space. As man intensifies his activities on the flood plains of rivers, flood control agencies need improved systems of warning that will permit more time to evacuate people from the flood zones.

Present systems of snowmelt forecasting are based on lysimeter studies of net water draining from the pack. Surface melt is held in the pack until sufficient water has been generated to flow through the pack. With present prediction equations, one is unable to accurately forecast future reaction of the snowpack to rain-on-snow or other melt-producing factors. More precise study and monitoring of snowpacks require a system for measuring in situ change in the internal snowpack structure with changes in time.

The profiling snow gage was developed to accomplish this goal. The first profiling radioactive gamma transmission snow gage was tested with both Geiger-Mueller and scintillation detectors in 1964. The successful use of the gage during the winter of 1964-1965 was reported by Smith et al. in 1965 and 1967 (11, 12). Since development of this first profiling gage, slight variations of this system were installed by the Agricultural Research Service, U. S. Department of Agriculture, in Vermont, by Amarocho and Espildora in Chile (13), and by Guillot et al. in France (14).

The CSSL gage consists of 3 units: density sensor, lift unit, and signal conditioning and recording system (Fig. 1).

The density sensor includes a 10 mc ^{137}Cs source and a scintillation detector horizontally suspended in 2 parallel access tubes that extend vertically from below ground to a height greater than the maximum anticipated snow accumulation. The access tubes are set 26.25 in. (66.67 cm) apart. The inside diameter of the source and detector access tubes are 0.75 in. (1.90 cm) and 2.00 in. (5.08 cm) respectively. The scintillation detector is a sodium iodide (thallium-activated) crystal 1.50 in. (3.81 cm) in diameter and 0.5 in. (1.27 cm) thick. The crystal is attached to a photomultiplier tube. Both are sealed in a cylindrical aluminum case. The photomultiplier signal is transmitted by a coiled cable to a preamplifier housed in the lift unit.

The lift unit consists of 2 reels connected by a drive shaft (Fig. 2). One spool is positioned at the top of each of the parallel access tubes. Power is provided by a 1.25-hp dc electric motor. Steel cables from the reels are connected to both the source and

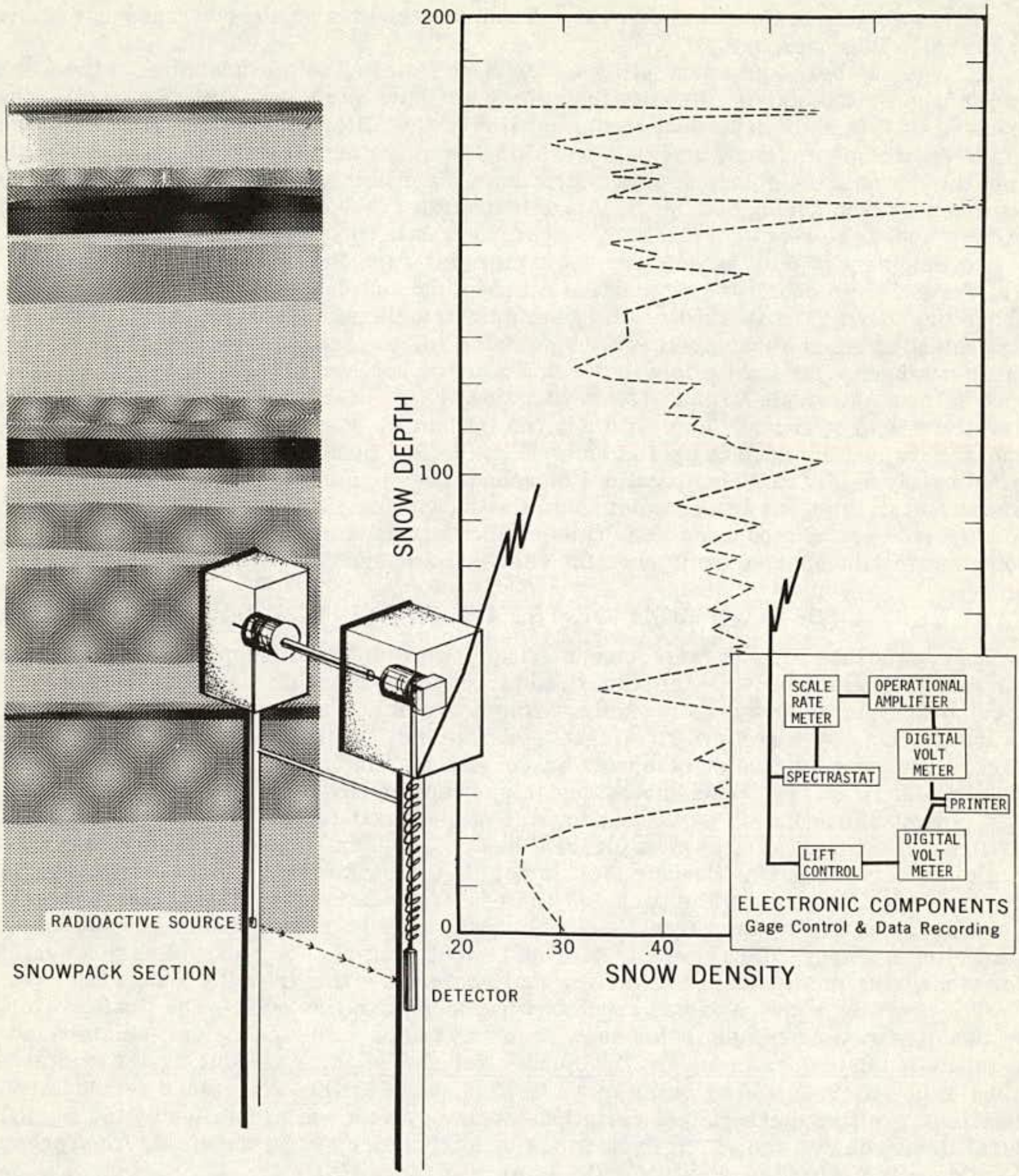
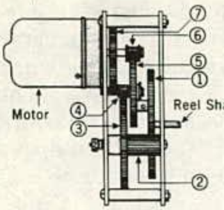


Figure 1. Profiling nuclear snow gage consists of source-detector, lift unit, and signal conditioning and recording system.

detector. The lift unit moves the source and detector at a rate of 12 in. (30.48 cm) per minute.

A secondary circuit within the lift unit indicates the position of the source-detector above or below ground level. A voltage divider is geared to the drive train and counts the revolutions of the reel spools. When a potential is applied, the source-detector position can be read from the transducer.

The signal conditioning and recording unit receives the signal from the preamplifier tube via a 250-ft (76.20 m) coaxial cable. The incoming signal is transferred to a peak-stabilized pulse-height analyzer. Gamma photons from the cesium-137 source constantly emit at their photo-peak energy into the snowpack in all directions from the



Gear Specifications		
Gear	Diam. mm.	No. Teeth
1	≃ 52.0	96
2	≃ 9.3	16
3	≃ 52.5	130
4	≃ 5.0	13
5	≃ 34.0	84
6	≃ 6.0	14
7	≃ 33.5	82
8	≃ 4.0	8

Gears are numbered in series from reel shaft to motor.

Gear Box	Cover is 95 mm. x 95 mm. x 85 mm. deep.
Motor	Barber-Colman, Rockford, Ill. BYQM 2185 12 volts D.C.
Reels	Penn 'Peer' #309 Reel modified with 50.8 mm. (2") diam. spool
Shaft	4-5 mm. x 120 cm., square telescoping shaft between reels adjustable from 67 cm. to 120 cm.

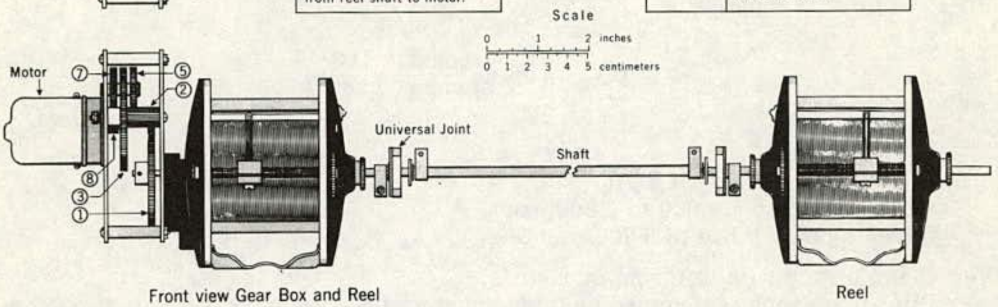


Figure 2. Lift unit consists of 2 modified fishing reels, connecting shaft, reduction gears, and motor.

source. When they collide with the electron field of the surrounding snow, some are backscattered. Some travel through the snowpack to the detector without collision and thus without loss of energy. All gamma photons striking the crystal, both backscattered and full-energy photons, create output pulse amplitudes from the photomultiplier proportional to their impact energy. A pulse-height analyzer whose window is set at the photo peak of cesium-137 receives all impulses, but passes only those in the photo-peak energy level. These are proportional to the density of the material being studied. The vertical width of the band "seen" is a function of the thickness of the NaI crystal, the rate of profiling, and the time constant of the rate-meter circuit. The pulse-height analyzer by constant searching and recentering on the photo-peak eliminates electronic drift of the photomultiplier that is caused by temperature changes in the detector tube.

From the pulse-height analyzer the signal goes to a rate-meter circuit with a $2\frac{1}{2}$-second time constant. This is sufficient to "smooth out" the random nature of the cesium disintegration. An analog signal from the rate meter is cabled to an operational amplifier circuit, which converts the signal to density (g/cm^3). The signal is digitized and transferred to one channel of a 2-channel printer. It may be placed onto magnetic tape if desired.

The depth indicating circuit in the lift unit provides a simultaneous reading with each density reading. An analog-to-digital converter is placed in parallel with the one digitizing density readings. Digital depth information is transferred to the second channel on the printer. Depth and density are printed simultaneously at a selected interval. The interval between density readings can be set by adjusting the sampling rate of the voltmeter-printer combination. The interval now used is 0.03 to 0.05 ft (0.9 to 1.52 cm). A computer program has been written to take this information and transform it into a $\frac{1}{2}$-in. (1.27 cm) thick incremental profile of depth, density, and water content, with calculations of total depth, average density, and total water content of the snowpack.

The signal conditioning unit provides power to the lift unit with a provision to reverse the direction of travel of the source-detector. Voltage for the depth indicator is also provided. These signals are connected to the lift unit with a separate cable.

CALIBRATION OF THE SYSTEM

The source and detector are stored underground in the access tubes when the gage is not being operated. When in the storage position, source and detector are separated by a hollow box containing a sheet lead standard. The transmission of gamma energy through this standard is equated to the equivalent of 26.25 in. (66.67 cm) of homogeneous material. During profiling, transmitted energy coming through the snow is taken as a percentage of energy that passed through the standard, and, through use of the operational amplifier, the actual density of the snow in g/cm^3 is printed on paper tape.

The calibration equation is

$$\rho = C - b\left(\log \frac{\text{count} \times 100}{\text{standard count}}\right)$$

where

ρ = snow density in g/cm^3,
C = constant $\approx$ 1.300 to 1.700, and
b = slope $\approx$ 0.500 to 0.700.

Note: C and b vary with different standards.

A calibration graph is obtained by taking gamma transmission readings through a series of uniform-density 2¼-in. (5.72 cm) thick polyethylene blocks. The more blocks used, the higher will be the known equivalent snow density being measured. Relation between the polyethylene blocks and snow density was determined theoretically and by gravimetric sampling of known quantities of water, ice, and snow. Plotting output count over equivalent snow density produces a straight-line graph on semilog paper. The slope and intercept of the line are calculated and used as constant factors in the operational amplifier density circuit. Regression analysis indicated that snow density can be determined with a standard error of ±0.015 g/cm^3 in the range 0.001 to 0.686 g/cm^3.

Melt of the snow around the access tubes is another possible source of error. We have found the effect of suncupping to be insignificant except at the end of the snow season. By this time general snow cover is discontinuous over the watershed. This condition creates more error in snowmelt prediction than that induced by suncups around the access tubes. We do not consider melt around the tubes as significant provided tube diameters do not exceed present sizes.

INFORMATION AVAILABLE WITH PROFILING SNOW GAGE

With the gamma-transmission profiling snow gage, one may measure 8 factors important to understanding snow hydrology: total snow depth; snow density at ⅓- to ½-in. increments throughout the pack, and the average density of the entire pack; total water content of the pack; water content increase or decrease and the section of the pack where the changes are occurring; amount of snow that has fallen since the last measurement; rainfall amount and intensity until such time as the snowpack begins to discharge water; melt rate between measurements if melt is occurring; and moisture changes in the soil (with a closer source-detector spacing).

Since 1964 we have measured snow density with the profiling snow gage at intervals varying from once to several times per day. In addition, we have studied water movement through snowpacks from snowmelt, from natural rain falling on snowpacks, and from artificially applied rain on snow. New theories about water-holding capacities of snow, water transmission rates, and the factors affecting water transmission have come from these studies (15).

The following case histories serve as illustrations of the utility of the snow gage.

1. Melt rate of a pack can be determined. On March 29, 1966, 3 profiles were made at 8:40 a.m., 1:25 p.m., and 5:11 p.m., Pacific standard time (Fig. 3). Pack depth decreased by 1 in. (2.54 cm). The melt water moving through the pack can be seen as increased density of the 2 latter profiles over the 8:40 a.m. profile.

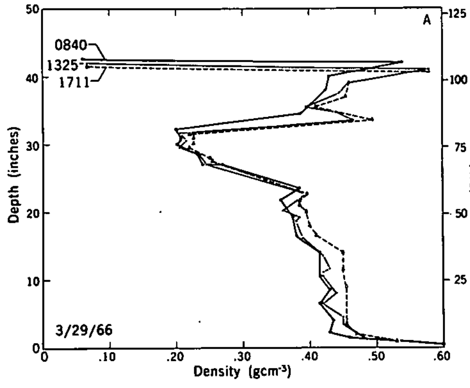


Figure 3. Three profiles of same snowpack showing melt. Note the 2 ice lenses at surface and at 33-in. depth.

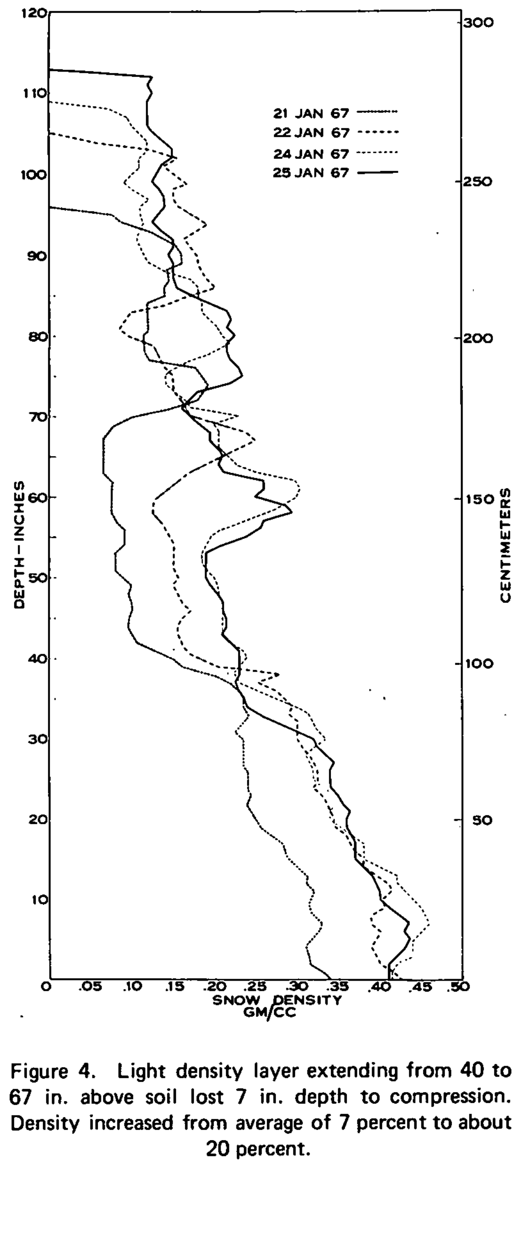


Figure 4. Light density layer extending from 40 to 67 in. above soil lost 7 in. depth to compression. Density increased from average of 7 percent to about 20 percent.

2. Compaction and settling of the snowpack can be determined. This is shown in Figure 4. A 27-in. (68.58 cm) layer of 10 percent density snow, overlaid by a 5-in. (12.70 cm) layer of 23 percent density snow, was able to support an overburden of 20 in. (50.80 cm) of approximately 12 percent density snow. Snowfalls during the following 4 days increased the density of the entire mass. Density of the 27-in. (68.58 cm) layer increased progressively from 10 to 25 percent.

Density alone is not always a reliable index of snow strength. Air temperature increase can cause snowmelt and structural alteration and thus decrease strength. However, a higher density snow will usually have a higher strength (16). It may be possible to estimate the strength of snow by analyzing the history of density changes recorded by the snow gage in conjunction with the meteorological record.

3. The amount of rainfall absorbed by a snowpack may be determined. On March 1, 1967, a study was initiated on a 71-in. (180.34 cm) snowpack containing 19.9 in. (50.55 cm) of water. A total of 10.56 in. (26.82 cm) of water was sprinkled onto the snowpack at the rate of 0.33 in. (0.838 cm) per hour. Profiles were obtained at regular intervals throughout the study period. The amount of water held in the pack and its location could be determined at any time. After drainage, the pack contained 28.8 in. (73.15 cm) of water, an increase of 8.9 in. (22.61 cm) (Fig. 5).

We believe that the amount of water retained by snow can be determined through research. We further believe that, if one knows the day-to-day history of a snowpack from study of daily profiles, he can determine the amount of new water that the pack will hold at any time. This information is vital to prediction of floods that are caused by rain falling on and melting snowpacks.

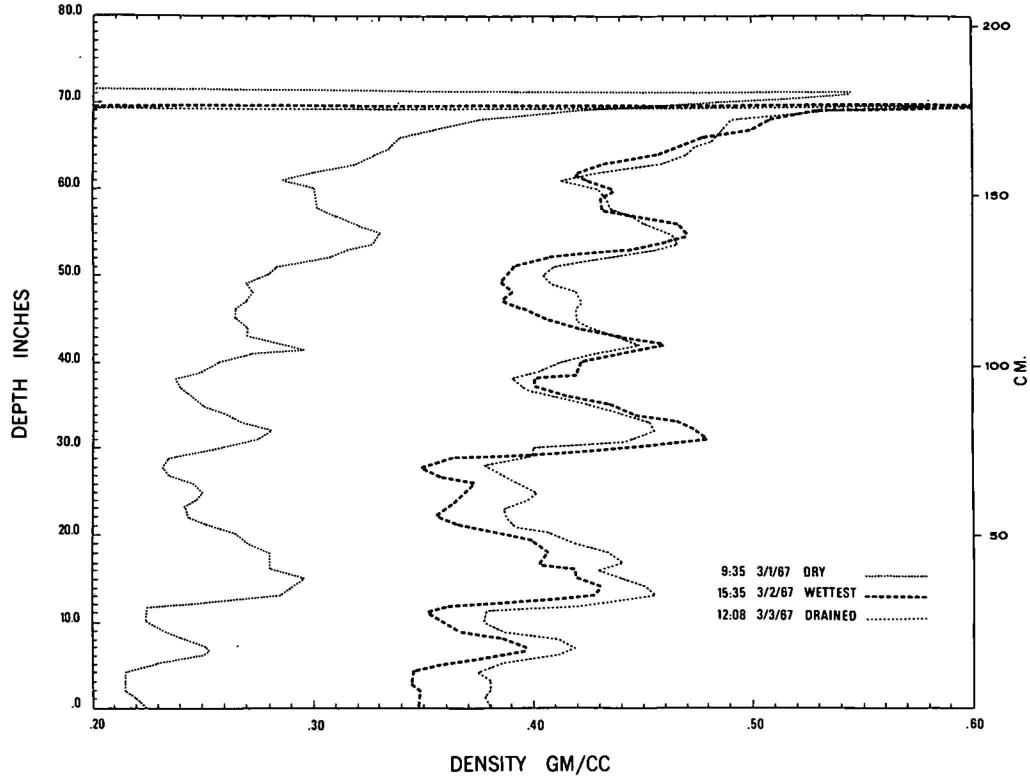


Figure 5. Density increased after water was applied to light density snowpack.

A natural rain on snow event occurred during the period January 17 to January 23, 1969. A 79-in. (200.66 cm) snowpack containing 29.95 in. (76.07 cm) of water received 12.30 in. (31.24 cm) of water as snow and rain. Of the total precipitation, 7 in. (17.78 cm) fell as rain or as snow of 30 percent density, which melted within a few hours.

The original pack had a uniform density ranging from 30 to 38 percent from ground line to 40 in. (101.6 cm) (Fig. 6). Densities from 40 in. (101.6 cm) to 79 in. (200.66 cm) decreased gradually to 15 percent near the snow-air interface. The snow in this pack had accumulated from frequent storms with no intervening melt and refreezing. Thus, no ice lenses were present. Free water content as determined by freezing calorimetry was 3 percent or less. The pack had densified by compression alone. It was in an ideal condition to hold more water. After the rain stopped, new snow increased pack depth to 100 in. (279.4 cm).

The 79-in. (200.66 cm) snowpack absorbed 6.44 in. (16.36 cm) of new water between January 18 and 21. Later it absorbed 0.56 in. (1.42 cm) of rain that fell mixed with the 27 in. (68.58 cm) of new snow on January 23. Another inch (2.54 cm) of rain was held in the new snow. The original pack increased in density by an average of 9 percent. Density increases for different snow layers ranged from 3 to 24 percent (0.03 to 0.24 g/cm^3) over those prevailing at the beginning of the storm. As a result of our studies we were able to predict prior to rainfall the amount of water this snowpack would hold.

POSSIBLE APPLICATION OF PROFILING SNOW GAGE DATA

With the availability of the profiling snow gage, snow scientists should be able to re-examine current theories in snow hydrology. Where these are deficient it may be

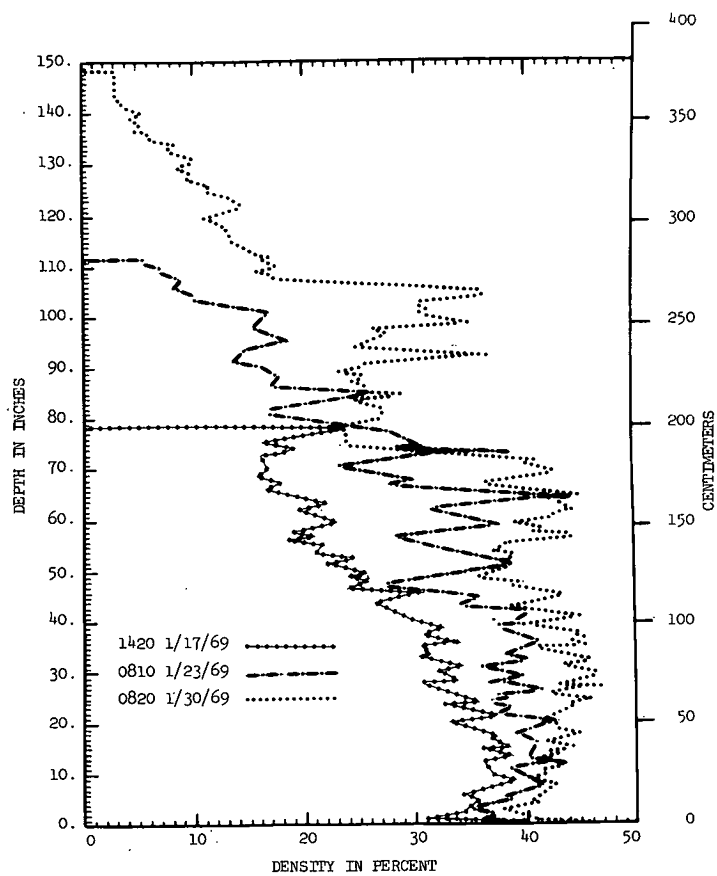


Figure 6. Snow profiles of snowpack at Central Sierra Snow Laboratory for storm of January 18-30, 1969.

possible to develop new theories from which more precise snowmelt equations can be formulated.

In operational snow hydrology, the use of data from the profiling snow gage opens a new dimension to streamflow forecasting. With the knowledge of the pack gained from study of profiles obtained throughout the accumulation and melt season, one should now be able to predict the reaction of the pack to meltwater or rainwater moving into the profile. Accurate predictions may be made of the effect of such events on water delivery from the snowpack and to streamflow increases.

More accurate streamflow predictions from snowmelt could result in better scheduling of reservoir operations and in less "reservoir spillage." In some flood situations such knowledge could conceivably save lives and property, including highway structures.

Avalanches are claiming a progressively greater toll of life and property as greater leisure time enables more people to participate in winter sports. Many ski resorts are situated in prime avalanche hazard areas. Most alpine roads pass under avalanche paths.

The causes of avalanches are still not fully understood. Basically, they are believed to be caused by movement of a snow overburden overlying a slippage plane in the snow. The reason for development of this slippage plane may be related to the development of depth hoar. We believe the development of this layer can be monitored with the snow gage because it normally consists of a change in density. Increase in weight of the snow above a slip plane can be caused by water absorption by the snow from rain falling on snowpacks. This increase in weight can be determined through monitoring of density.

With the discovery of oil in the Arctic has come an increased need for remote landing strips and roads. Some of these will probably be unattended for long periods of time. It should be possible to monitor snow strength and new snow depth on these improvements with the profiling gage.

The gage should fill a need for highway departments that must keep seldom used, remote mountain roads passable. With use of the telemetered snow gage data, highway personnel can determine whether snow or rain is falling, the amount of snow already on the ground, and its condition.

The current snow gage is an experimental model and requires an operator. Plans call for development and fabrication of a remotely operated, telemetered gage. We hope to have the first prototype gage installed before snow falls in the fall of 1970. Commercial gages should be available within another 1 to 2 years.

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Informal Discussion

L. G. Byrd

What is the nature of the system? Is it designed for permanent installation, or can it be moved as required?

Smith

We have both a portable system and a permanent installation. The package that is being prepared now is going to be modular, such that you could break it off at any point. It is a portable system that a man should be able to carry in a backpack on skis.