EOS, Transactions, American Geophysical Union, Vol. 60, No. 21, pp. 464-471, May 22, 1979.

SNOW ACCUMULATION, DISTRIBUTION, MELT, AND RUNOFF

S. C. Colbeck, E. A. Anderson, V. C. Bissell, A. G. Crook, D. H. Male, C. W. Slaughter, and D. R. Wiesnet

Introduction

During recent winters the news media frequently reported very large snowfalls in the midwestern and northeastern states coincident with greatly reduced snowfalls in the Rocky Mountain and western states. The dangers of large snowmelt floods and restricted transportation in the Midwest and Northeast and the water management problems arising from the extended drought in the West brought national attention to the economic importance of the seasonal snow cover. Although we cannot eliminate the immediate problems of heavy snowfalls in areas such as Buffalo, New York, or water shortages in California, as snow hydrologists we should reconsider our research objectives in view of these serious national problems. In this article we outline our ideas about the current status and needs in snow hydrology in order to provide some guidance for the multitude of national and local organizations that are affected by these problems.

Collection and processing of snow survey data

In the last two decades, snow measurement technology has advanced from the manual survey methods to the use of automated equipment as well as aircraft and satellites. In addition to the water equivalent, other physical characteristics of snow, such as density and temperature profiles, free water content, albedo, and various mechanical indexes, are now being measured. The following discussion addresses current development work and research needed, in order of application priority.

Data collection. Point measurements of the water equivalent of snow are the most valuable and most widely used of all snow measurements. Snow pillows have been used for this purpose for many years, with recent emphasis shifting from the butyl rubber pillows to metal pressure tanks. Metal tanks are easier to manufacture, less prone to leakage, and more durable, although slightly less sensitive than the rubber pillows. The accuracy of pressure-sensing devices depends on the accuracy of the readout device (about 1.5% error) and the presence of ice layers of high flexural strength within the snowpack, which cause a registration time lag for newly deposited snow of up to several days. Areas of varying weight often develop in snowpacks; hence, pillow surface areas in deep snow are increased to as much as 11 m^2.

Isotopic measurements of point water equivalent for snow of shallow to moderate depths use a single detector with either natural soil radiation [*Bissell and Peck*, 1973] or a single artificial source [*Department of the Army*, 1955]. Owing to reduced signal strength with increased water equivalent, the most promising configurations for deeper snow consist of multiple sources and detectors, such as the 'zig-zag' gages shown in Figure 1 [*Shreve and Brown*, 1974]. The error with this type of configuration appears to be less than 10% except when located close to the snow surface, where melting by solar radiation can occur around the support poles. Most of the error is due to calibration uncertainties and may be reduced substantially through future testing. Besides total water equivalent, the zig-zag gage also provides information on the layering of the snow cover.

For extremely deep snow, a cosmic ray detector can be placed at ground level to indicate the snow's water equivalent, by measuring the reduction of cosmic flux by the snow [*Bissell and Burson*, 1974]. In this method, which has been tested in the USSR, the measurement error is relatively insensitive to water equivalent and thus becomes relatively small in deeper snow.

Improvements in pressure sensors should include developments in sensor material, fabrication, multiple sensor configurations, sensor-snow interactions, and reliability in severe environments. Single-detector gages which measure natural soil radioactivity also require further development to eliminate anomalous readings during significant precipitation events, to improve the soil moisture corrections, to define the radioactive gas dynamics within the snowpack, and to stabilize the detector gain. The error of the natural radiation method could be less than 10% in snow covers with up to 0.4 m of water equivalent; moreover, this method is inexpensive and the equipment is easily installed. Multiple source and detector configurations are in use at the present time but investigations are required to establish the influence of natural radiation on detector output and, most importantly, to refine the source-detector configuration by evaluating trade offs of accuracy and reliability versus safety and cost. Research in the cosmic attenuation method has a less certain payoff, partly because of the large errors introduced by any shift in calibration, but should include evaluation of cosmic flux variations related to season and atmospheric pressure. Although this method will never be widely applied, there are some areas of very deep snow accumulation where it may be the only practical approach.

Areal surveys for the water equivalent of snow are being made over terrain of little relief by low-elevation overflights of aircraft carrying gamma ray detectors which monitor natural radiation from the soil [*Larson*, 1975; *Dimitriev et al.*, 1972]. Such measurements eliminate sampling problems due to mesoscale variations in the snow cover, but in the United States, gamma flights are only well suited to the upper Midwest, where hundreds of kilometers can be traversed in a single day. For well-calibrated flight lines, the accuracy of this method is about 1 cm of water equivalent, but further work is needed to develop methods for removal of atmospheric radioactivity effects, to design efficient networks of flight lines, and to improve the use of simulation values from a hydrologic computer model to assist in interpretation of the measured spectrum.

Short-term measurements of frozen precipitation are

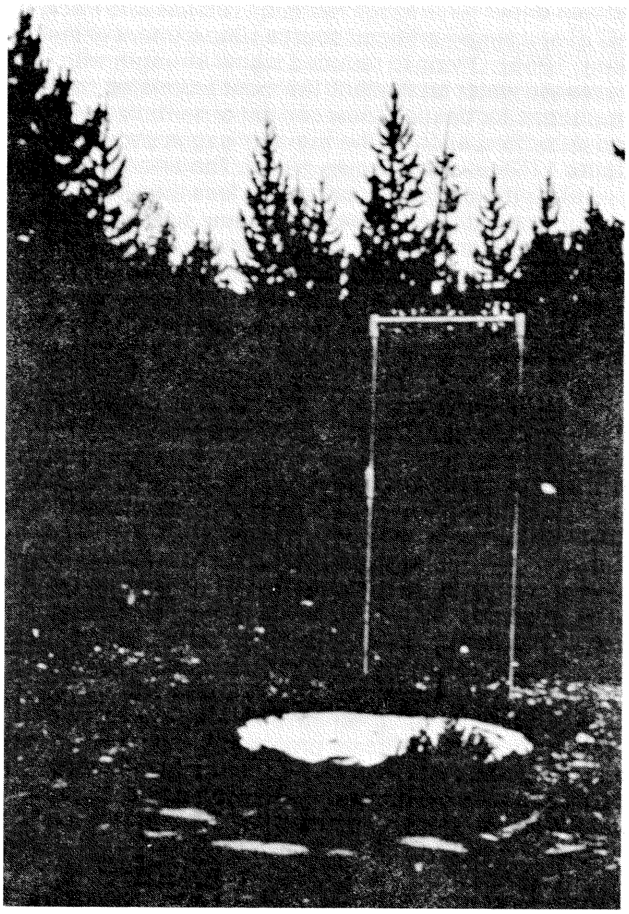


Fig. 1. Three snow sensors are shown: a multisource or 'zig-zag' gage in the background, a 6-ft-diameter rubber pillow in the middle, and two 4 × 5 ft metal pressure tanks in the foreground.

also necessary, but really good methods are not yet available, particularly at windy or remote locations. Radar has been used for snow measurements over large, inaccessible areas such as Lake Ontario, but the accuracy of present technology is not sufficient to replace conventional methods. The development of helium bubblers for fluid mixing has increased the reliability of data telemetered from precipitation storage gages, but storage gages are still relatively insensitive to small increments of precipitation. In response to this problem, the National Weather Service is testing a precipitation overflow gage in which solid or liquid precipitation entering a constant level, nonfreezing fluid mixture would force an equal volume of fluid out through a discharge orifice. Another device, the radiometric storage precipitation gage, is very sensitive in theory, but its accuracy has not been demonstrated operationally. Recent improvements have reduced snow gage catch deficiency through the use of multiple gages or fencing configurations, such as the Wyoming shield, but the improved measurement of increments of snowfall continues to be a primary research need.

The design of snow survey systems in the future will be dictated by the requirements of new methods of forecasting and analysis. For example, the application of energy models would require new and better input data such as solar radiation, albedo, dew point, and some details of density, temperature, and free water profiles in the snow. One of the most important of these, the measurement of areal albedo from remote platforms, is discussed later. Data needed for a complete energy budget analysis on an operational scale will be delayed until it can be shown that benefits of the energy budget approach outweigh the considerably increased costs and problems of data collection.

Data transmission. The rapid transmission of snow data from remote stations to central collection points has been too expensive for many sites until the last few years. With the advent of meteor burst communication, now in use with the Soil Conservation Service's west-wide Snotel system, and satellite relay stations such as NASA's Landsat and NOAA's Geostationary Operational Environmental Satellite (GOES), data are now coming in rapidly from heretofore inaccessible locations. Much testing and evaluating of telemetry and equipment configurations remains to be done under severe environmental conditions but the 'line of sight' problem for ground-based radio has been greatly reduced.

Data storage and processing. At present there is no central records center to maintain snow measurement archives from all U.S. sources, although snow depth and water equivalent data from weather stations are maintained at the National Climatic Center in Asheville, North Carolina. Snow course data from the Soil Conservation Service are maintained by state offices but will soon be centralized at the U.S. Department of Agriculture computer center at Fort Collins, Colorado. This configuration will allow users easy access to a comprehensive snow data bank covering nearly all mountainous regions of the western U.S. Under the auspices of the Eastern Snow Conference since 1941, New England and New York snow data from a variety of federal, state, local, and private interests have been compiled by the U.S. Geological Survey and published by the National Climatic Center. Mountain snow data in California can be obtained from state publications, but in some areas of the country no centralized snow data base of any kind exists to centralize the measurements of many diverse groups.

The entire problem of snow data collection and archiving should have some national coordination and review, in order to achieve standardization of data collection methods, automatic data processing, and station identification. This would help the processing of data for producing nationwide snow depth and water equivalent frequency and duration atlases for such worthwhile applications as optimal cropping studies, snow load design criteria, transportation and facilities siting, avalanche zoning, snow removal planning, resource retrieval feasibilities, and water resource and recreation management.

Other major problems with the interpretation and use of snow data include the development of adequate frequency distribution functions and the fitting of conflicting measurements from one area. A log normal distribution has been used in the nationwide studies of snow distribution, and atmospheric models for the distribution of precipitation in mountainous areas have been used to interpolate snow information between measurement sites [*Colton,* 1976]. Snow frequency data are also needed for snow cover redistribution studies for transportation analyses [*Tabler*, 1975], and it is not clear what frequency distribution functions are appropriate for these and other purposes. Likewise, fitting a number of different observations is a major data processing task in operational applications of snow measurements. This task requires knowledge of the error and correlation characteristics of the measurements involved and of the requirements of the applications. For example, automated map production for the upper Midwest snow cover would require the analysis of error and correlation characteristics of first-order and cooperative ground station measurements, airborne gamma surveys, and computer simulated values.

Electromagnetic radiation at microwave frequencies can also be used to inventory the snow cover with either passive [*Meier*, 1973] or active [*Linlor*, 1973] systems. These techniques offer the important advantage of being able to distinguish the solid and liquid phases of water [*Sweeny and Colbeck*, 1974] and hence can provide information about both the seasonal runoff and daily flows. In spite of the promising theoretical possibilities of the active microwave system, its potential can only be realized after considerably more development, and then the application is likely to be expensive and require considerable technical expertise for operation and data interpretation. In view of the sophisticated nature of this work, it is not too surprising that the simpler methods of data gathering are still in widespread use.

Energy exchange at the snow surface

The central problem in forecasting the melting rate of snow cover is knowing the magnitude of the energy fluxes at the snow surface and the associated changes in internal energy within the pack. The major energy sources available for melting of snow at the upper surface are solar radiation, longwave radiation (most important at night), sensible heat transfer from the air to the snow by convection and conduction, and latent heat transfer by evaporation and condensation at the snow surface (rain is also important at times). The heat flow by conduction from the ground to the bottom layer of the snow is of minor importance although this flux can influence the crystal structure over the winter months. Although shortwave radiation is strongest at the surface, it does penetrate the first few centimeters of the snow cover, and rain penetrates to considerable depths, thereby introducing distirbuted energy sources. Nevertheless, meltwater is predominantly generated at the upper snow surface, as is shown by sequential density profiles of melting snow covers.

The magnitude of each energy flux is influenced by various properties of the snow and atmosphere. For example, longwave radiation is influenced by the snow surface temperature, the air temperature, the moisture content of the air, and variations in air temperature in the first few kilometers above the surface. In addition to sun angle, the solar radiation input is strongly influenced by cloud cover and albedo of the snow surface. Sensible and latent heat fluxes both depend on turbulent mixing in the first few meters above the snow surface and therefore are influenced by the wind speed and the air temperature gradients. In addition, the latent heat flux is governed by the vapor pressure gradient above the snow. Some of these parameters are measured on a routine basis at meteorological stations across the continent, while others can be obtained only through elaborate field studies. Field stations designed to monitor all energy fluxes important to snowmelt contain numerous instruments which must operate under adverse conditions, and they require a considerable investment to obtain accurate data. Although a few such stations are in operation in North America, there are not sufficient data to undertake quantitative comparisons of the magnitudes of the various energy terms according to the major climatic and physiographic factors typical of the continent.

Open snow surfaces. Analysis and interpretation of the energy exchange process at the upper snow surface is greatly simplified if vegetation does not protrude above the snow. This situation is common to the prairies, the Arctic, and some rural areas in the eastern U.S. and Canada. Figure 2 shows a representative set of measurements on the prairies for this condition during the initial melt period when the snow cover is continuous. These types of measurements show that (1) net radiation (sum of all shortwave and longwave components) is the dominant energy flux for a continuous snow cover; (2) where the snow cover becomes patchy the sensible energy flux is much larger than that for a continuous snow cover; (For many seasonal snow covers it is during this period of discontinuous coverage that the bulk of the runoff occurs.) (3) warm, dry winds are relatively rare during the melt period, and evaporation from a continuous snow cover is not significant [*Male and Gray*, 1975]; and (4) total evaporation from an isolated patch may be as high as 20% of its initial water content.

Forested areas. In forested areas or other settings where vegetation protrudes above the snow, the energy exchange is very complicated. In effect, there are two insulating zones above the ground, i.e., the snow layer and the air layer between the tree crowns and the snow. Few quantitative measurements have been made of the energy exchange at the forest canopy or between the canopy and the snow surface. Our inability to adequately define the forest cover for purposes of a heat exchange calculation is one of the major difficulties. Before measurements can be compared between sites and in order to develop useful generalizations, the nonuniform distribution of trees, the presence or absence

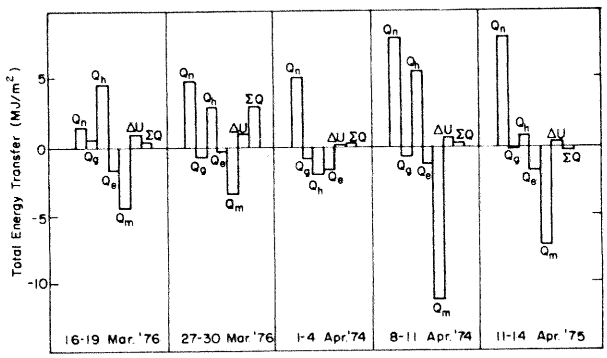


Fig. 2. Energy budget totals measured during the first 4 days of melt in a prairie environment. Note progressive increase in net radiation (Q_n). Q_g is ground heat, Q_h is sensible heat, Q_e is latent heat, Q_m is melt, ΔU is change in internal energy, and ΣQ is the total flux [from *Granger and Male*, 1977].

of undergrowth, and the density of foliage must all be classified.

Of the three major energy exchange processes, radiation has received the most attention. Albedo and absorptivity values have been reported by several investigators as have longwave emissivity values. In recent years, attempts have been made to apply the equations of radiative transfer to a forest canopy. Some type of simplified description of a forest canopy is necessary and *Bohren* [1973], who idealized the canopy as a homogeneous slab, has made a promising first attempt.

The sensible heat transfer to the snow in a forest environment is almost impossible to measure accurately. It is obviously a function of the profiles of temperature and wind through the canopy, but as yet there is no practical means of relating the two profiles. Evaporation from the snow in a forest has received a great deal of attention, with many investigators concluding that it is small. However, interception of snow by a forest canopy further complicates the exchange process, and the extent to which this snow is subject to evaporation is not clear. Although there are many reports of high evaporative losses from forests, these results have not been verified from heat balance considerations. In summary, the energy exchange processes between snow and a forest cover are not well enough understood to allow detailed modeling of the melt process through use of the energy equation. Any attempts to measure directly the individual energy fluxes in a forest environment would involve the solution of formidable problems in instrumentation and data collection.

Areal estimates of energy fluxes. It is only possible to measure energy fluxes at a point. If these data are to be applied to management problems such as flood forecasts or soil moisture forecasts, ways must be found to apply point measurements to areas of several hundred square kilometers. The radiation flux has received the most attention. For example, *O'Neill and Gray* [1973] have established experimentally that temporal variations of point and spatially averaged albedo values are in close agreement for prairie conditions. In mountainous watersheds, *Storr* [1972] suggests a relatively simple procedure for estimating net radiation over a watershed. The procedure considers types of vegetation as well as topographic factors. Similarly, *Derikx and Loijens* [1971] suggest a method of adjusting shortwave radiation for slope and aspect on glaciers, which may be used in computer simulation models.

The problem of extrapolating point measurements of longwave radiation has not received adequate study. Although a theoretical framework does exist by which values averaged areally could be estimated in terms of local terrain features, the calculations are extremely involved. Simplified procedures must be developed for estimating this component. Likewise, no criteria exist by which the sensible and latent heat fluxes can be estimated over an area, although some experimental work has been reported. For example, *Hutchison* [1966] investigated evaporation rates from adjacent snow and soil surfaces in a forested region and concluded that evaporation from the wet soil surfaces greatly exceeds evaporation from the snow. On a much larger scale, *Treidl* [1970] has examined the modifying effect of a snow surface on the air mass moving over it. Attempts are currently being made to describe the airflow above changes in surface heat flux, temperature, or roughness, but the underlying assumptions of such analyses have yet to be confirmed in the field. These analyses need to be simplified considerably before they can be incorporated into a predictive model.

Water movement and snow properties

The timing of water runoff from snow covers is greatly affected by the mode of flow through the snow itself and is an important part of forecasting the intensity and time of peak runoff from snowmelt or rain-on-snow events. As a result of investigations made during the late 1940's and early 1950's [e.g., *Department of the Army,* 1956], a practical understanding of the metamorphism of snow in the presence of liquid water was achieved, and a data base was established for routing water through the thickness of a snow cover. However, at the conclusion of these investigations, several major problems remained. First, accurate water routing could only be achieved if the snowcover had already experienced 'melt metamorphism.' Second, the coupled effects of liquid movement and melt metamorphism were not understood and could not be included in forecasting schemes. Third, the effect of deviations in snow properties such as snow density and permeability could not be identified. Fourth, the movement of the water along the base of the snow cover could not be considered in forecasting runoff. Fifth, the flow through the snow and soil could not be physically coupled. These limitations are still largely in effect today, but research on the physical properties of wetted snow is providing a basis for understanding the underlying phenomena [e.g., *Colbeck,* 1978] and hopefully will provide a basis for dealing explicitly with water movement through snow in hydrological forecasting.

Water passing the snow surface moves more or less vertically downward through well-aged snow, much as it would through a large-grained (~ 1 mm) soil. This mode of flow can be accurately described as unsaturated flow controlled by gravity forces, since capillary forces are relatively small in snow which has undergone melt metamorphism [*Wankiewicz,* 1978]. The major problem with applying a simple flow theory to unsaturated flow, in this case, is the layered nature of most snowcovers. The layering arises from the sequential nature of snow deposition and/or the preferential retention and refreezing of water in fine-grained layers such as wind crusts. The layers divert the percolating water such that complicated flow paths occur; thus the water discharge hydrograph is diffused in much the same way as would be expected for multiple flow paths. This 'diffusion' could be treated in several ways. First, a diffusion term could be added to the flow equation, but the diffusion constant would be a highly complicated function of the particular properties of the snow cover at any particular place and time. Second, the flow could be characterized by assigning a distribution function to the snow depth to account for the multiple path lengths that exist in a typical snow cover. Again, the distribution function would be difficult to identify, partly because of our lack of knowledge of the detailed structure of a melting snow cover. There is almost a complete lack of statistical information on the size, shape, and distribution of the ice layers and drainage channels which cause the large spatial variations in the flow field. When one thinks about the difficulties of gathering such information on a fragile snow cover, it is easy to see why the information is not already available!

The basic thermodynamic processes of melt metamorphism, especially grain growth, densification, and ice layer decomposition, are well known. In principle, it is possible to include these effects in a coupled water flow-melt metamorphism model to account for such things as the positive feedback relationship between grain growth and water flow through the relationship between permeability and grain size. Such a model would be very useful in understanding the role of melt metamorphism in water runoff during the period of active metamorphism. Melt metamorphism begins when liquid water enters a dry snow cover for the first time. This infiltration of water into a previously unwetted snow cover is a phenomenon of great interest because of the difficulties of forecasting rain-on-snow events. If the capillary requirements of the snow are not exceeded by the rainfall, it is possible that no discharge will occur at all. Certainly the discharge will be somewhat delayed compared to the discharge from a well-metamorphosed snow, but the delay to runoff is generally somewhat less than predicted if the snow is assumed to be homogeneous. The apparent explanation is the development of distinct flow channels which conduct away a large portion of the rain water, thus bypassing large areas of dry snow. The initiation of the flow channels is probably controlled by the detailed structure of the snow cover rather than by the inherently unstable flow known as 'fingering.' Once distinct flow channels are established, they become preferential sites for grain growth, and thus they develop a higher permeability than the surrounding snow. Accordingly, once preferential drainage routes are initiated, they are self-perpetuating. While these ideas about the development of flow channels seem physically reasonable, much remains to be learned about their development and their influence on the timing and intensity of water infiltrating into the snow cover.

Similar problems exist with the routing of water along the base of snow cover because of the development of open melt channels through which preferential water flow occurs. Early in the melt season before the open channels develop, the water moves through a saturated layer overlying the soil and a simple description of the flow is possible. However, as the melt channels develop, more rapid drainage of the snow cover occurs because the average path length for flow through the layer of saturated snow is greatly reduced. Effectively, a snow-covered watershed makes a gradual transition from snow-controlled to terrain-controlled water movement. All stages occur between these two extremes, and the development of open melt channels is one aspect of this transition about which we have very little knowledge. Again, it is apparent that measurements of the size of the open channels beneath a snow cover would be difficult, and information obtained from one study could not be generalized to other situations. However, it is surprising that virtually no information exists about the temporal and spatial distributions of these features of the snow cover.

Snow accumulation and ablation models

In a conceptual snow accumulation and ablation model, each of the significant physical processes affecting the formation and disappearance of a snow cover is represented mathematically. These processes include the distribution of new snow, energy and mass exchanges between the snow and the air, heat transfer within the snow cover, heat transfer between the soil and the ground, the retention and transmission of liquid water through the snow, and the areal extent of the snow cover. Such models can be used to simulate a snow cover at a point or over an area. When used to simulate an areal snow cover, the snow accumulation and ablation model is usually coupled with models of the land (which include soil moisture storage, evapotranspiration, and runoff generation mechanisms) and the stream channel portions of the hydrologic cycle. The output from this combination of models is streamflow. These models are used for river forecasting, watershed management investigations, and water resource planning and design studies.

Snow cover models can be classified into three categories, which are based on the method used to compute energy exchange between the snow and the air. Three categories are index models, pseudo energy balance models, and energy balance models. Index models use one or more variables as an index to surface energy exchange, with air temperature being the most commonly used index. Pseudo energy balance models use an energy balance equation to compute snowmelt, but they use an index method to compute energy exchange during nonmelt periods. An energy balance model couples the equation for energy exchange between the snow and the air with the equation for heat transfer within the snow cover. The solution of these equations requires an iterative technique.

A large number of these models have existed for some time and are used to simulate the snow cover at a point or over an area. Point models are commonly used for areal applications, by assigning a portion of the area to each of a number of points. Index models are primarily used for river forecasting and certain types of water resource planning and design studies. They have the advantage of requiring only readily available data, such as precipitation and air temperature, for both calibration and application. Index models have been shown to give good results over a wide range of climatic and physiographic conditions. The best results have been obtained in heavily forested areas and in areas which experience reasonably consistent meteorological conditions during the snowmelt season. Sometimes index models do not provide good estimates of energy exchange in open areas. This is especially true during extreme or abnormal snowmelt situations and during nonmelt periods.

Because pseudo energy balance models are more physically based, they are used for watershed management investigations in addition to river forecasting and planning and design studies. These models allow the user to predict more realistically the effects of land use changes on snowmelt rates and streamflow. Streamflow simulations using pseudo energy balance models have not proved to be any more accurate than those from index models, probably because of deficiencies in the models and in the input data.

Several snow cover energy balance models have been developed in recent years, but all have been point models [e.g., *Anderson*, 1976; *Obled and Rosse*, 1977]. The results from these models are very good, as long as high quality input data are available. Energy balance models are still in the research stage and have not been used for any extensive applications.

Adequate snow accumulation and ablation models are currently available for many types of applications. These models provide good estimates of the behavior of a snow cover under a wide variety of conditions. The major research needs for improving snow cover models and their applications are identified below:

Model improvement. There is some need to improve the representations of certain components of index models. However, the main research goal in terms of model improvement should be to develop areal energy balance snow cover models. Many of the building blocks are available, such as point energy balance models and techniques to modify point input data, to account for areal variations in vegetation cover and topography. Techniques need to be developed for areal estimates of variables, such as snow albedo, which are relatively easy to measure at a point, but can be highly variable over an area. One of the factors impeding the development of areal energy balance models is a lack of the high quality data needed for model testing.

Ungaged areas and land use applications. Most current snow models contain parameters which must be determined by calibration, for a particular location, through the use of historical data. This presents no problem for most river forecasting and many planning and design applications. However, for other planning and design studies, for investigations of watershed management on ungaged areas, or where the effects of land use changes are being evaluated the parameters cannot be established by calibration. Energy balance models are probably best suited for such applications since they are more physically based. The user can predict, with reasonable accuracy, the value of a model parameter or how a parameter will change as land use is altered. However, the absence of essential input data will prevent the use of energy balance models in both ungaged areas and for the study of land use changes in many situations. In such cases, index models provide adequate answers if the relationships between the model parameters and various climatic and physiographic characteristics were known.

Updating state variables. Areal snow cover models require continuous input data for basic variables such as air temperature and precipitation for index models and additional variables such as radiation, dew point, and wind data for energy balance models. From these data, the models compute the current state of the snow cover, which is defined by certain state variables such as water equivalent, heat deficit, liquid water content, rate of energy exchange, and areal extent. Energy balance models also include such state variables as snow surface temperature and albedo. These computed state variables are obviously imperfect estimates of the true state of the snow cover over the area. However, many of these variables are periodically measured at points, over designated lines, or over areas. These measurements which vary from manual snow course measurements to measurements by various remote sensing techniques, are also imperfect estimates of the true state of the snow cover. What is needed are objective methods for combining the computed and measured estimates of the state of the snow cover, in order to obtain an improved estimate of the state variables. Such objective updating methods will require information on the error distributions of both the computed variables and the areal estimates based on measured values, in order to determine an optimum estimate of the current state of the snow cover.

Objective updating methods are particularly needed for river forecasting applications. This includes both short-term forecasts and extended predictions of runoff volumes or peak flow rates. It is especially critical to have the best possible estimate of the current areal water equivalent for extended streamflow predictions. The snow cover models, measurements of the state variables, and techniques for combining several estimates of a quantity to get an improved estimate of the true value are available, but only a limited amount of information has been compiled on the error distributions of the computed and measured snow cover state variables.

Guidelines on model use. Since the advent of conceptual snow cover models, there have been few intercomparisons of model performance. Such intercomparisons are needed to provide information for users as to the suitability and relative accuracy of the various types of snow models for a certain application, given the data base and the climatic and physiographic conditions. Undoubtedly, no single study will provide a complete set of guidelines. Some intercomparisons should be made as a part of research projects aimed at developing new models. With the number of snow models currently available, the mere ability of a model to reasonably reproduce historical records is not an adequate test of the model. A current World Meteorological Association (WMO) project on the intercomparison of snowmelt models used in hydrological forecasting should provide some of this information.

Arctic and subarctic hydrology

The arctic and subarctic regions have experienced intense development in recent years. Much of this development is directly affected by the snow cover and snowmelt runoff, but critical engineering decisions are often made without a sufficient data base because of the paucity of hydrological records in many northern areas. Accordingly, special attention should be given to the snow hydrology of these regions. While this discussion is oriented toward the permafrost landscapes of Alaska, the statements can usually be applied to the permafrost affected regions of Canada and Asia.

The snow cover, rivers, lakes, and soils of the arctic and subarctic regions have special characteristics because of the intense cold during the winter months. Likewise, data collection and other field observations are particularly difficult and expensive in these regions. The resulting lack of basic hydrometeorologic data is a fundamental problem. While the streamflow of most major rivers draining the permafrost landscapes of Alaska is fairly well known, details of headwaters or uplands precipitation-runoff relations are largely unknown. Apportioning incoming precipitation is extremely difficult on either a seasonal or annual basis. Further, incoming precipitation is measured on a regular basis in relatively few locations, largely in lowland areas, while precipitation or snow cover data from remote sites or upper elevations are largely sporadic or

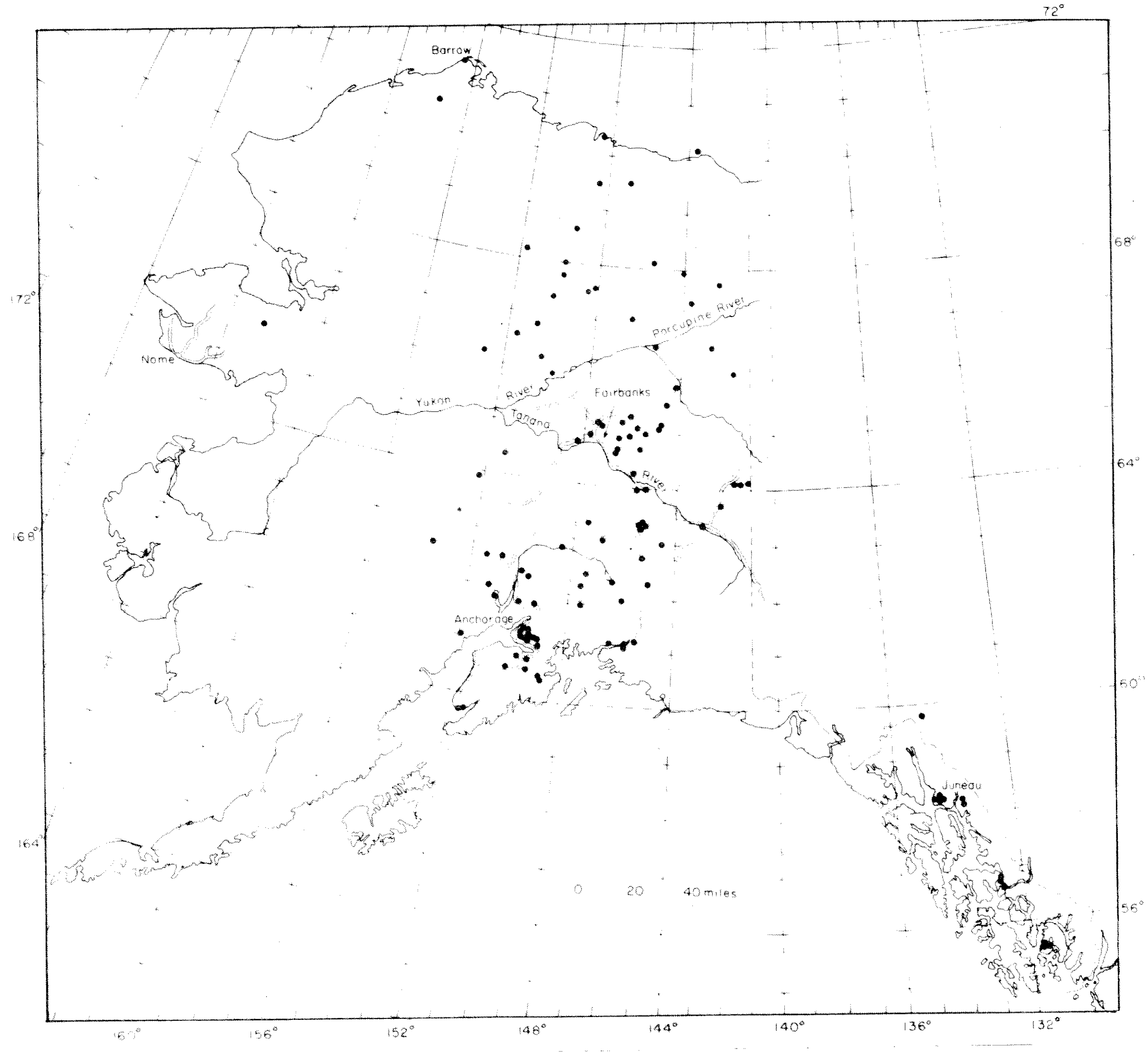


Fig. 3. Alaskan snow measuring sites.

unavailable. As an example, within the past decade the Alaska Snow Survey network has been expanded from 13 to 135 snow courses (Figure 3), but even this major upgrading effort leaves northern and western Alaska with almost no systematic snow cover information. Similarly, the stream-gaging program has been substantially expanded in Alaska over the past 10 years, and a reasonable coverage of major river systems has been achieved, but few upland or headwater catchments are currently gaged on a systematic basis. Thus data suitable for isolating the hydrologic influences of varying topography, geology, vegetative cover, land use, and related factors are almost entirely lacking.

The development of reliable instruments which can operate unattended throughout the year in cold regions is one of the biggest needs. Experience to date indicates that summer data acquisition in cold regions poses no unique problems, but for winter operations in locations without line power and ready access, relatively simple instruments are more reliable and more useful than more sophisticated and complex machinery. In high latitudes north of the boreal forests, some aspects of high-altitude and satellite-based remote sensing are particularly appropriate because of the vast expanses and minimal influence of forest vegetation.

Remote Sensing

It has been shown that our ability to forecast snow runoff, either on a short-term or seasonal basis, is often limited by the availability of reliable data on the snow cover or prevailing atmospheric conditions. The advent of operational satellite monitoring with high spatial resolution has greatly improved our data collection capability. In the most important example of this, 10 countries are currently mapping the snow cover from various satellites. Snow hydrologists now use snow line and snow cover measurements from NOAA and Landsat satellites because, with the 900-m-resolution images from NOAA satellites, changes of as little as 2–3% of snow coverage can be detected in small watersheds [*Wiesnet*, 1974]. In the U.S., NOAA's National Environmental Satellite Service has expanded its quasi-operational river basin snow-mapping program. Currently, 24 basins are snow mapped using NOAA-5 Very High Resolution Radiometer images. The percentage of snow cover in the basin is teletyped within 36 hours to NOAA

River Forecast Centers for use in operational streamflow forecasting models. Similar programs using Landsat data have been established and snow-covered basins as small as 6 km^2 have been mapped. Recent work based on older visible band data and the newer NOAA radiometric data has been used to examine the limits of the global snow cover as far back as 1966 [*Wiesnet and Matson,* 1976]. The results of this work have important climatic implications and point out the potential applications of remote sensing methods.

Unlike areal coverage, attempts to determine snow depth and water equivalent via satellite have had very little success. As described earlier, low-level aircraft gamma ray flights have been used to measure the water equivalent of snow in Norway, the USSR, Canada, and the U.S. These flights must be made at a low level (150 m) to minimize attenuation of the gamma rays; thus rough or mountainous terrain is not suitable for overflights. Microwave techniques, with possible application to the determination of snow water equivalent, continue to be developed for remote sensing applications.

Areal estimates of albedo, the ratio of reflected to incident radiation over the entire solar spectrum, are needed for input to energy balance snow cover models. Because remote sensors are directional, limited to certain parts of the solar spectrum, and subject to atmospheric scattering and attenuation effects, the direct measurement of albedo by remote sensors is not likely. Furthermore, it will be difficult to relate measured reflectance to physical properties of the snow cover without better knowledge of the variation of spectral reflectance with such fundamental parameters as the substrate, depth, density, layering, wetness, grain size, and impurity content.

The main purpose of current research into the earth atmosphere albedo [*Gruber,* 1976] is the study of the earth's radiation budget for general circulation studies and climatological monitoring. Planetary albedos are mapped daily as part of this program but snow and ice areas are not specific targets. The needs of remote sensing in snow covered areas are very stringent and will require more detailed work. Ideally, a program of coordinated studies will be undertaken on the physical, reflective, and radiative properties of snow under natural conditions from ground, aircraft, and satellite sensors.

Many other snow variables besides water equivalent and areal extent are useful. For example, discrimination between old and new snow by remote methods can assist in making trafficability estimates that might be required in resource recovery applications, and side-looking K-band radar has already been shown to penetrate shallow new snow to detect underlying older snow [*Waite and McDonald,* 1970]. The use of microwave techniques has been investigated to a limited degree, but much more basic research is justified by the promising capabilities of these methods. The ability to remotely detect snow depth, water equivalent, density profiles, liquid profiles, and soil wetness has enormous implications for crop forecasting, as well as for more conventional applications such as river and water supply forecasting. Much of the research required for remote microwave imagery and data interpretation will also benefit ground-based applications, for example, in free water profiling within a snowpack. Recent work includes signature codification for various wavelength observations of wet and dry snow, as well as for various density and free water content profiles [*Schanda and Hofer,* 1977]. Research is very expensive in this area but it is hoped that much progress will be made in the next 3 to 5 years.

Conclusions

A detailed understanding of the properties and processes of snow is crucial to the development of adequate models of the snow cover to meet the requirements of today's society. However, it is clear that these models can only represent the snow cover through knowledge generated by the appropriate research. It is also clear that the usefulness of these models is greatly limited by our ability to provide the quality and quantity of the necessary input data. While major advances are being made in this respect by remote sensing, a large number of 'weak links' have been identified in the system. A particular 'weak link' depends upon the problem being studied, the accuracy desired, the geographical area, and prevailing conditions at that moment. The polar and subpolar regions are special in this regard because of the lack of background data, the harsh environment, and the inaccessibility of many sites.

Nevertheless, no one should be discouraged by the scope of the problems identified in this article, because the amount of progress and the hope for the future are at least equally impressive. Current work on the electromagnetic properties of snow may provide vast improvements in our ability to determine the quantity and quality of snow on the ground. Likewise, improvements in our modeling ability can reshape the difficult task of gathering data on a highly variable and rapidly changing snow cover. The degree of interest in the snow cover (e.g., *Time,* February 14, 1977) is a reflection of snow's impact on our society, and our response should be equal to the scientific and engineering challenges offered by snow.

References

Anderson, Eric A., A point energy and mass balance model of a snow cover, *NOAA Tech. Rep. NWS 19,* 150 pp., U.S. Dep. Commer., Silver Spring, Md., 1976.

Bissell, V. C., and Z. G. Burson, Deep snow measurement suggested using cosmic radiation, *Water Resour. Res., 10*(6), 1243–1244, 1974.

Bissell, V. C., and E. L. Peck, Monitoring snow water equivalent by using natural soil radioactivity, *Water Resour. Res., 9*(4), 885–890, 1973.

Bohren, C. F., Theory of radiation heat transfer between forest canopy and snowpacks, Proceedings of the Banff Symposia, *The Role of Snow and Ice in Hydrology, Publ. 107,* pp. 165–175, UNESCO-WMO-IASH, Paris-Geneva-Budapest, 1973.

Colbeck, S. C., The physical aspects of water flow through snow, in *Advances in Hydroscience,* vol. 11, edited by V. T. Chow, pp. 165–206, Academic, New York, 1978.

Colton, D. E., Numerical simulation of the orographically induced precipitation distribution for use in hydrologic analysis, *J. Appl. Meteorol., 15*(12), 1241–1251, 1976.

Department of the Army, Development and test performance of radioisotope-radiotelemetering of snow gage equipment, Civil Works Invest. Proj. CWI-170, p. 74 and Appendix, S. Pac. Div., U.S. Army Corps of Eng., San Francisco, Calif., 1955.

Department of the Army, *Snow Hydrology,* North Pacific Division, U.S. Army Corps of Engineers, Portland, Oreg., 1956.

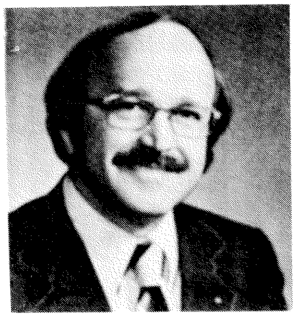
Derikx, A. L., and H. Loijens, Model of runoff from glaciers, in

Eighth Canadian Hydrology Symposium, Runoff from Snow and Ice, pp. 153–159, Inland Waters Branch, Department of Energy, Mines and Resources, Ottawa, Ont., 1971.

Dimitriev, A. V., R. M. Kogan, M. V. Nikiforov, and Sh. D. Fridman, 1972: The experience and practical use of aircraft gamma ray surveys of snow cover in the USSR, Proceedings of the Banff Symposia, *The Role of Snow and Ice in Hyrology, Publ. 107*, pp. 702–712, UNESCO-WMO-IASH, Paris-Geneva-Budapest, 1973.

Granger, R. J., and D. H. Male, Melting of a prairie snowpack, *Second Conference on Hydrometeorology*, pp. 261–267, Amer. Meteorol. Soc., Boston, Mass., 1977.

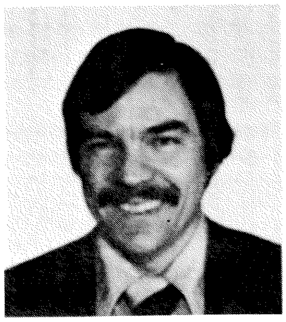
Samuel Colbeck has been with CRREL since receiving a Ph.D. in geophysics at the University of Washington in 1970. His research interests include many aspects of snow and ice, especially the physical properties of wet snow. In addition to his research, he has held the position of adjunct professor at Dartmouth College and has been active in a number of professional organizations. He is currently chairman of the Committee for Snow and Ice of AGU, associate editor of *Water Resources Research*, member of the Council of the International Glaciological Society, member of the Committee on Glaciology of the National Research Council and cochairman of its Study Group on Snow Resources. He is also a member of the U.S. National Committee for IASH.



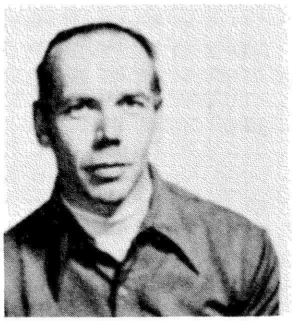
Arthur G. Crook is currently serving as hydrologist in the Soil Conservation Service Water Supply Forecasting Staff in Portland, Oregon. He has been with the SCS for 21 years, serving as range conservationist and district conservationist in Colorado prior to entering the snow hydrology discipline in Wyoming in 1966. He was snow survey supervisor for Alaska for 4 years prior to assuming his present position in 1975. A graduate of Colorado State University with a B.S. in forest-range management, he has authored several technical papers in the snow survey and water supply forecasting field.

Eric Anderson received his B.S. in civil engineering from the University of Wisconsin and his M.S. and Ph.D. from Stanford University. For the past 15 years he has been a research hydrologist for the Hydrologic Research Laboratory of the National Weather Service, NOAA, with a special emphasis on snow and soil moisture accounting models.

David Male graduated from McMaster University in 1962 with a B. E. in Mechanical Engineering. He spent the next 2 years in the U.K. as an Athlone Fellow, the last year at the Graduate School of Thermodynamics, University of Birmingham where he obtained a M. Sc. He then went to the University of Saskatchewan in 1964 and received a Ph.D. in gas dynamics in 1967. He was appointed to the staff in mechanical engineering the same year and began work with the Division of Hydrology in 1969. His major interest is in the area of snowmelt, although he is lately involved in the study of the physics of infiltration into frozen ground. He is presently a professor of mechanical engineering.



Vernon Bissell received his Bachelor's degree in mathematics and physics from Pepperdine University in 1967. He received his Master's (1970) and Ph.D. (1975) from the University of Maryland in water resources engineering. After a brief stint with the Agricultural Research Service Hydrograph Laboratory in Beltsville, Maryland, Bissell served as a research hydrologist with the National Weather Service Hydrologic Research Laboratory in Silver Spring, Maryland. During this tenure his primary responsibility was development of operational snow measurement techniques for river forecasting. He has been a hydrologist in the National Weather Service River Forecast Center, Portland, Oregon, since 1974. The author of a number of conference and professional journal articles, Bissell has also served as an AGU delegate to the XV Assembly of The International Union of Geodesy and Geophysics and is a registered professional engineer in the state of Oregon.



Charles W. Slaughter received his Ph.D. in watershed management from Colorado State University. He is presently the principal watershed scientist at the Institute of Northern Forestry, USDA Forest Service, Fairbanks, Alaska.

Donald R. Wiesnet has been a senior research hydrologis at the National Oceanic and Atmospheric Administration/National Environmental Satellite Service for the past 8 years. Prior to 1971 he served for 14 years with the U.S. Geological Survey and for 4 years with the U.S. Naval Oceanographic Office. He is a fellow of the Geological Society of America and has served on a number of advisory committees and panels to the National Astronautics and Space Administration and National Academy of Sciences. He is a former Rapporteur for the Remote Sensing of Hydrological Elements to the World Meteorological Organization. He has written many papers on applications of satellite data to hydrology and has contributed a chapter to the book *Facets of Hydrology*

Gruber, A., Determination of the earth-atmosphere radiation balance from NOAA satellites, in *Proceedings of the Symposium on Meteorological Observations from Space*, pp. 265-269, 19th COSPAR Meeting, Philadelphia, 1976.

Hutchison, B. A., A comparison of evaporation from snow and soil surfaces, *Int. Ass. Sci. Hydrol., 11*(1), 34-42, 1966.

Larson, L. W., An application of the aerial gamma monitoring technique for measuring snow cover water equivalent on the Great Plains, *Proceedings of Symposium on Snow Management on the Great Plains, Great Plains Agr. Counc. Publ. 73*, Agr. Exp. Sta., Univ. of Nebr., Lincoln, 1975.

Linlor, W. I., Measurement of snow cover using passive microwave radiation, Proceedings of the Banff Symposia, *The Role of Snow and Ice in Hydrology, 1, Publ. 107*, pp. 713-726, UNESCO-WMO-IASH, Paris-Geneva-Budapest, 1973.

Male, D. H., and D. M. Gray, Problems in developing a physically based snowmelt model, *Can. J. of Civil Eng., 2* (4), 474-488, 1975.

Meier, M. F., Measurement of snow cover using passive microwave radiation, Proceedings of the Banff Symposia, *The Role of Snow and Ice in Hydrology, 1, Publ. 107*, pp. 739-750, 1973.

Obled, C., and B. Rosse, Mathematical models of a melting snowpack at an index plot, *J. Hydrol., 32*, 139-163, 1977.

O'Neill, A. D. J., and D. M. Gray, Spatial and temporal variations of the albedo of prairie snowpack, Proceedings of the Banff Symposia, *The Role of Snow and Ice In Hydrology, Publ. 107*, 176-186, UNESCO-WMO-IASH, Paris-Geneva-Budapest, 1973.

Schanda, E., and R. Hofer, Microwave multispectral investigations of snow, in *Proceedings of 11th International Symposium on Remote Sensing of Environment*, Environmental Research Institute of Michigan, Ann Arbor, 1977.

Shreve, D. C., and A. J. Brown, Development and field testing of a remote radioisotopic snow gage, in *Advanced Concepts and Techniques in the Study of Snow and Ice Resources*, pp. 661-673, National Academy of Sciences, Washington, D. C., 1974.

Storr, D., Estimating effective net radiation for a mountainous watershed, in *Boundary Layer Meteorol., 3*, 3-14, 1972.

Sweeny, B. D., and S. C. Colbeck, Measurements of the dielectric properties of wet snow using a microwave technique, *Res. Rep. 325*, Cold Reg. Res. and Eng. Lab., Hanover, N.H., 1974.

Tabler, R. D., Predicting profiles of snowdrifts in topographic catchments, in *Proceedings of the 43rd Annual Meeting of the Western Snow Conference*, pp. 87-97, Western Snow Conference, Spokane, Wash., 1975.

Treidl, R. A., A case study of warm air advection over a melting snow surface, *Boundary Layer Meteorol., 1*, 155-168, 1970.

Waite, W. P., and H. C. McDonald, Snow field mapping with K-band radar, *Remote Sensing Earth Resour. Environ., 1*, 143-150, 1970.

Wankiewicz, A. C., Water pressure in ripe snowpacks, *Water Resour. Res., 14* (4), 593-600, 1978.

Wiesnet, D. R., The role of satellites in snow and ice measurement, *NOAA/NESS Tech. Memo. NESS 58*, 12 pp., Dep. of Commer., Washington, D. C., 1974.

Wiesnet, D. R., and M. Matson, A possible forecasting technique for winter snow cover in the Northern Hemisphere and Eurasia, *Mon. Weather Rev., 104* (7), 828-835, 1976.

EOS, Vol. 60, Pages 465-468

0096-3941/79/6021-0465$01.00