REVIEW OF METHODS OF MEASURING SNOW COVER, SNOWMELT, AND STREAMFLOW UNDER WINTER CONDITIONS

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SUMMARY

As a theme paper for the session on measurement in space and time, a brief review of the methods of measuring snow cover, snowmelt and related meteorological parameters, and streamflow under winter conditions is presented. Emphasis is directed to more recently evolved methods, including airborne sensors and satellite techniques. Errors associated with the various methods are discussed as well as the problems of areal representativeness, network efficiency and design.

Résumé

Nous présentons une revue succincte des méthodes de mesure de la couche de neige, des eaux de fonte et des paramètres météorologiques connexes ainsi que de l;écoulement en hiver, dans une communication thématique concernant la session sur les mesures spatio-temporelles. Léaccent est mis sur les nouvelles méthodes comprenant les détecteurs aéroportés et les techniques faisant appel aux satellites. On discute des erreurs liées aux différentes méthodes ainsi que de la représentativité des zones étudiées et de l;efficacité et la conception des réseaux.

INTRODUCTION

Historically snow hydrologists have been limited to the use of point measurements for estimating the areal and temporal variability of snow cover. Even though point measurements are subject to error and are not necessarily representative of the areal conditions, they have proven to be of considerable value when used with proper evaluation and careful analysis in empirical procedures such as those used to predict snowmelt runoff. However, it is recognized that future improvements in hydrologic forecasting depend to a large extent on the ability to accurately measure the magnitude and distribution of the snow cover. The advent of the modern high-speed computer has enabled hydrologists to develop conceptual models which will permit continuous and improved hydrologic forecasts to meet the increased demands for hydrologic forecasting services. Ideally, such models require absolute measurements of the input factors rather than index values which were sufficient for empirical techniques.

The purpose of this paper is to present a brief review of the commonly used methods for measuring snow cover, snowmelt and streamflow under winter conditions, to discuss the errors and representativeness of such measurements and to look at what the future may hold for improvement.

AREAL REPRESENTATIVENESS

When snowfall occurs with strong wind movement, the measured snowfall is generally deficient in comparison with the true amount. Deficiency of snowfall measurements has been extensively discussed in the literature [1,2,3,4] and was a major topic at the IHD/WMO Symposium on Precipitation Distribution in Mountainous Areas held in Geilo, Norway, in August 1972. The snowfall measured in a particular gage may be highly variable compared to the areal average. The degree of variability is dependent upon many factors such as the meteorological conditions associated with the storm, the large-scale physiography of the region, the topography of the local area, and the aerodynamic effects induced by objects in the immediate vicinity of the gage such as trees and buildings, as well as the disturbances caused by the gage itself [5,6]. Thus the relation of the catch in a single gage to areal average snowfall is not consistent and has been shown to vary greatly from storm to storm, season to season, and even from year to year [7,8]. It is difficult to adequately assess how variations in exposure may affect the value of a point measurement as an estimator of the areal average.

Redistribution of the fallen snow is also a major reason why it is difficult to estimate areal average conditions from point measurements. Kuzmin [9] has stated the following pertaining to the representativeness of a snow survey for areal conditions:

"The representativeness of a snow survey depends on the variation of the snow reserves over the area, the correct selection of the traverse, its length, and the number of points at which measurements are taken. The choice of a representative traverse becomes more difficult the smaller its assigned length, the more broken the terrain and the less homogeneous the plant cover. It is impossible to select a short traverse along which the deposition of snow in winter would be characteristic for the whole vicinity. Measurements taken at only one point are even less representative."

Snow surveys or other single location measurements of the snow cover are most reliable as an indicator of the average areal conditions when the site is protected from blowing and drifting of snow [5,8]. Since this is also the criteria that is normally cited as essential for a reliable measurement of snowfall, it may be said that exposure requirements for either a reliable snow cover or snowfall measurement are identical.

Snowfall in some areas has high spatial correlation and therefore single measurements prove to be good indicators of the areal average. Examples of such areas are the western slopes of the Sierra Madres in California and the interior basins in Alaska. In other areas spatial correlations are very low and the problems associated with determination of the areal average are much more difficult. For example, the inter-mountain area of the Western United States is a region where precipitation may occur with greatly different meteorological conditions and the spatial correlation of snowfall and snow cover is very poor.

DEPTH AND AREAL COVERAGE MEASUREMENTS

Knowledge of the temporal and areal variations in the snow cover is important to the snow hydrologist. The extent or areal coverage of the snow can be expressed as an area (i.e., square kilometers) or as a percent-age cover for a given watershed. Many procedures for predicting snowmelt runoff are based on or utilize actual areal coverage or percent of cover as a parameter [10,11,12].

Snow depth measurements are normally made by observers at basic national network stations. In the United States observers obtain the depth by averaging depths at several points in a preselected location as measured by a ruler. At mountainous stations, especially those equipped with totalizing or seasonal gages, snow stakes are installed. A second major source of snow depth measurements are those made during snow surveys. In the Western United States, there are approximately 1,650 regular snow survey stations. At remote sites large poles with graduated cross arms at specific intervals are observed directly or by aerial photography for obtaining the snow depth [13,14]. However as indicated previously because of the variability of the terrain in mountainous areas, snowfall and depth of snow cover measurements must be considered indices to the areal average.

Representative depth measurements are often difficult to obtain in open country due to the drifting and redistribution of the snow by wind action. Since ground roughness is a major factor in determining redistribution of snow, large fields with similar ground cover may have approximately uniform snow depths, with great variation in depths among fields with different types of cover.

A major problem in the hydrologic field is that of network design. Adequate methods are not available to objectively define areal conditions from point measurements of the snow cover. A network of stations which may provide a reasonable estimate under normal snowfall deposition may be entirely inadequate for a period when snowfall, snow density or wind speed deviate greatly from the normal.

Mapping of the snow cover by aerial photography has proven to be effective but expensive [15]. The availability of satellite photographs has led to the development of techniques to map snow cover [16]. In the United States, photographs for snow cover analysis were first used from the Television Infrared Observational Satellite (TIROS) that was launched in 1960 [17]. Later studies continued with data from the Tiros Operational System (TOS) commencing in 1965 and the improved TOS (ITOS) series starting in 1971. Limited use has also been made of photographs from the Nimbus Satellite and also the Geostationary Applications Technology Satellite (ATS).

One of the limiting factors when using satellite photography for snow mapping is the problem of differentiating between snow cover and clouds. The method of composite minimum brightness, which was developed in the United States, is a system suited to repetitive analysis of very large areas and amenable to automation [19]. Composite maps are prepared from the minimum brightness values (digitized data) observed during a five-day period. Snow areas can be distinguished from clouds because the latter tend to change brightness during this period of time. Many countries are using satellite photographs for snow cover mapping,but the techniques are generally subjective and require skilled and experienced anlaysis [20]. A guide for utilizing satellite photographs for mapping snow cover for non-mountainous and relatively unforested areas has been published in the United States [21]. In general, studies indicate that snow cover can be identified reliably from the satellite photographs presently available with snow depths of at least 2-3 cm appearing as continuous snow cover. Snow lines have been mapped with an accuracy of about 32 km with sufficient detail to permit the mapping of individual basins as small as 1100 km^2 [22,23].

Improved sensing equipment on future satellites planned during the next two years will include multispectral scanner and returned beam vidicon capabilities (ERTS-A) and a new infrared sensor called the Very High Resolution Radiometer (VHRR) on the upcoming ITOS-D satellite. The VHRR will have a resolution of half a nautical mile in the 10.5 to 12.5 micrometer thermal IR band and the same resolution in the 0.6 to 0.7 micrometer band of the visible spectrum (red band). This increased resolution will permit the development of techniques for computer enhanced snow surveys that will provide timely and adequate data for many areas of the world. However, the problems associated with delineating snow cover in the forested areas will still be present.

The use of microwave radiometry to measure snow depths and snow cover has proven to be of great interest [24,25,26,27,28,29]. There are still problems as has been noted in the literature due to free water in the snow cover, and it is evident that multi-wave length observations will be required to overcome the various problems associated with measurements in these wave lengths.

Aerial photogrammetry is a practical technique for obtaining detailed information on snow depths and distributions [30]. This method has been used successfully to determine snow depths for several thousand points on an 0.4 km^2 study basin in Idaho. The standard error of the average snow depth for the Idaho study was 0.6 cm and with adequate vertical and horizontal controls, snow depths of less than 15.3 cm could be satisfactorily measured.

The monitoring of an artificial light source has also been utilized to determine snow pack depths. A light source is made to sweep a beam up a vertical photocell ladder by means of a movable mirror. The snow depth at any given time is then indicated by the number of photocells not activated. Five mm^2 silicon photocells will give a vertical accuracy of 0.3 cm in snow depths [3].

MEASUREMENT OF WATER EQUIVALENT OF THE SNOW COVER

The Chinese, as early as 1245AD, used the amount of snow in snow bins in mountain passes to estimate the flood potential of the great rivers in that country [32]. Attempts to measure the water equivalent of the snow cover for use in streamflow forecasting during recent times can be traced to the efforts of several investigators shortly after the turn of the 20th century. A summary of the developments of the standard gravimetric measurements using snow tubes to obtain sample cores has been summarized by Washicheck, et al., [33]. Such snow surveys based on this general approach are now common in many countries. Research has shown that standard snow-tube measurements, such as those obtained by the Federal or Mount Rose types, tend to overestimate the water equivalent of the snow cover by about 7 to 12 percent depending upon the snow depth and density. Improved accuracy for light snow cover, less than 15 cm of water equivalent, may be obtained by the use of samplers with larger diameters such as the Adirondack snow tube [34]. However, such larger diameter tubes are not satisfactory for use with depths greater than about 1 meter.

Increased costs for obtaining samples by having personnel travel to the snow areas and the need for more rapid acquisition of the information has led to the development of sensors that can be read remotely and automatically. One of these newer sensors is the pressure snow pillow. Beaumont [35] has described its use in the United States and Tollan [36], its use in other countires. The snow pillow assumes that snow acts as a perfect fluid and unusual conditions can affect the accuracy of the measurements. In light snow areas, where there may be periods of alternate freezing and thawing, ice lenses in the snow pack or at the surface interface can materially affect the readings. Pooling of water on the top of the pillow can also be a factor. The pressure pillow has proven in many heavier snow areas to be a fair indicator of the actual water equivalent of the snow cover, especially during the primary snow accumulation period. Other investigators have used pressure plates rather than the original butyl rubber pillow [37]. The size of the pressure plate or snow pillow necessary for best accuracy depends on the amount of snow cover normally expected, the greater the depth, the larger the pillow needed!

It is possible to measure the water equivalent of snow by an electrical method which utilizes the capacitance properties of snow [38]. The capacitance of snow which accumulates between two electrodes is related (a linear relation) to water equivalent in centimeters. This method, however, appears to have too much variability to be of practical value.

Radioisotope Snow Gages

Many gages have been designed in the past few years based on the principle of attenuation of radiation by the mass of the snow cover as a means of measurement. The earliest developments were by placing a radiation source (^{60}Co or ^{137}Ci) on the ground with a detector overhead. As the snow accumulated the reduction in radiation received by the detector, e.g., a Geiger-Muller tube, mounted above the snow cover was a measure of the water equivalent of the snow cover [39,40,41]. Some researchers reversed the position of the source and counter [42]. Radioisotope snow gages which are designed to read directly the total water equivalent of the snowcover are referred to as vertical type gages. They can be used for depths of water equivalent up to about 100 cm with a standard error of 1.8 cm using radiation sources of permissible strength [43]. Increasing the strength of the radiation source permits readout from an aircraft [44] but requires considerable protection for environmental safety.

Radioisotope Snow Gage (Horizontal Type)

A profiling radioisotope snow gage which measures the density profile of the snow cover between two vertical poles at selected space intervals has been developed in France, the United States, and in Canada [45,46,47,48,49]. The water equivalent of the snow cover can be calculated from the density profile information. The amount of time required to complete one measurement cycle is dependent upon the total depth of the snow cover and the spacing of the individual readings. Since most operational hydrologic forecast procedures utilize only the total water equivalent, it may be some time before the additional information from such gages will be of wide spread value. As the length of record increases, techniques will be developed to use the density profile information, especially in avalanche forecast studies. However, for operational hydrologic use, there will be many problems in attempting to relate the point measurements of the density profile to areal conditions.

A new gage incorporating some of the features of both the vertical and horizontal type gages has been designed and operated in the field in the United States [50]. The instrument consists of two parallel vertical poles with a radiation source located in one pole at 150 cm vertical intervals and detectors (GM tubes) located in the other pole but offset vertically by 75 cm. Diagonal measurements of the water equivalent between the two vertical tubes are obtained for each 75 cm interval with each source serving for two sections. This instrument has several advantages: there are no moving parts, it has low power requirements, and most important each measurement cycle includes a reference calibration with respect to the radiation source so that a shift in calibration due to radioactive decay is greatly diminished.

The International Atomic Energy Commission, however, reports that the installation of radioactive snow gages in a hydrometeorological network is probably not justified in places with shallow snows where the snow water content can be easily measured by more conventional means. In mountain watersheds the number of nuclear snow gages will also probably not be too great. It is suggested that a limited number of radioactive snow gages can serve as index values for adjacent stations. Thus, a few radioactive snow gages may be sufficient to improve the reliability of the entire conventional gaging network. These conclusions are based mainly on the high costs involved for this type of gage [51].

Natural Radiation Techniques

The use of natural gamma radiation from the earth as a means of measuring the water equivalent of the snow cover was initially developed in the Soviet Union [52,53,54]. Dalh [55] used the same general approach in Norway and the techniques have been modified in the United States [56,57].

Aerial surveys of the gamma radiation, using gross count or spectral analysis, provides a means of estimating the water equivalent of the areal snow cover beneath the flight path. Such areal measurements are a beginning towards eliminating the many problems in representativeness associated with point measurements. In addition, the method has a considerable advantage over many proposed remote sensing systems in that the measurements are not affected by variations in density due to ice lenses or free water in the snow cover. Aerial measurements may be made for water equivalent up to depths of 30 cm. In the Soviet Union, operational aerial surveys are conducted at an altitude of 25 meters above the ground over large expanses of the country. Operational use by aerial survey is planned for the north central United States in an area which is subject to snowmelt flooding from relatively light snow cover (less than 30 cm) but which often covers extensive areas.

Variation in the natural radiation from radon gas daughter products (^{214}Bi) is a problem area that is under study. The gamma radiation technique does have limitations for use in mountainous areas of which the most serious are those of flight safety and exact positioning ability. Although the Soviet Union has reported that the technique has been used over forested areas, little documentation on this use is available in the literature. Ground surveys have been made in the Soviet Union by carrying a Geiger-Muller detector along a selected snow survey course [58]. Research on the use of a NaI scintillation unit mounted on a boom above a standard snow course in a forest opening is being conducted in the United States [59]. Preliminary studies indicate that the water equivalent of the snow cover can be measured with a standard error of four to six percent when compared with snow tube and snow pillow measurements. The measurements reflect the total moisture above the ground surface and in the first few centimeters of the soil beneath the surface and may prove to be of use in conceptual hydrologic modeling.

MEASUREMENT OF SNOWMELT

Snowmelt has been one of the most difficult of snow cover parameters to accurately measure. For most purposes, theoretical estimates or indices of snowmelt, based on meteorological and in some cases snow cover parameters, have been used rather than actual measurements. Many techniques for direct measurement require the placing of foreign material, such as plastic containers, in or near the snow cover which in turn affects radiation and other heat transfer processes [60,61]. Some investigators have used plastic to isolate the snow above a weighing lysimeter, but this technique introduces many possible sources of inaccuracy.

Snow pillows and radioisotope snow gages have provided a more direct method of measuring the water equivalent of the snow cover. Unfortunately, daily changes in the snow cover water equivalent are usually small so that estimates of daily liquid outflow from the pack by this means is not reliable. Some snow pillows, mostly for research purposes, have been modified to include a catchment for a separate measurement of the liquid runoff from the snow cover. Thus, the pillow measures not only the water equivalent but also the daily liquid runoff [62].

The problem associated with error due to interflow along ice lenses within the snow cover still remains. To overcome this problem, experiments are being conducted in the United States to physically isolate the snow above a pressure pillow using a heated coil to cut a cylinder around the vertical projection of the pillow.

METEOROLOGICAL PARAMETERS RELATED TO SNOWMELT

Snowmelt is the end result of many processes including radiation, convective and conductive heat transfer and the latent heat of vaporization. Techniques for using meteorological parameters of air temperature, vapor pressure, wind movement and radiation for estimating the magnitude of the various processes are to be discussed in other sessions of this symposium. There are numerous types of instruments for the measurement of air, snow, and ground temperatures as well as for wind speed and direction. These measurements are sufficient for predicting snowmelt and evaporation on an operational basis except for those techniques which require computations for the vertical flux of moisture and momentum.

For energy budget studies, special care is required to obtain the accuracy needed especially those of radiation transfer. Many of the sensors and integrating recorders for radiation are subject to shifts in calibration [63]. For the purpose of this review, it should be sufficient to state that even under rigorous controls used for research areas, complete information on the heat balance of the snow cover based on radiative measurements is extremely difficult to accomplish. Attention needs to be given to the problem of instrument calibration while redundant measurements should be utilized as check on instrument accuracy. Albedo measurements, or the amount of shortwave radiation that is reflected by the snow, are now being used in operational forecasting. The problem of obtaining areal representativeness from point radiation measurements still confronts the hydrologist, but improvement in the resolution of remote radiation measurement from satellites hold promise for alleviating the problem in the near future.

STREAMFLOW MEASUREMENTS UNDER WINTER CONDITIONS

The presence of ice in a river complicates the stream gaging process in two ways. First, ice cover in a measuring section makes it necessary to suspend the current meter beneath the ice, working through holes cut for this purpose [63]. The second problem is that the presence of ice in the control section usually creates a backwater condition and temporarily invalidates the stage-discharge relation. That is, when a stream is covered with ice, the additional resistance between water and ice must be overcome by the flow. The effect is to reduce the water velocity from what it would normally be in open channel flow. To compensate for the reduction in velocity, the cross-sectional area of the stream must increase, thus necessitating an increase in stage. This increase in stage is termed the backwater effect.

These are two separate problems which can, but do not always occur simultaneously. Open water discharge measurements made during periods of backwater are quite common. On the other hand, measurements must sometimes be made through ice cover when the control section is clear.

Discharge Measurements Through Ice Cover

The first step in making a measurement through ice cover is the cutting of holes across the section. A familiarity with the channel, gained during the summer months, is essential to the selection of a proper measuring site. Reconnaissance cannot be carried out when the channel and water are not visible. In fact, under extreme ice and snow conditions, hydrographers have been known to have trouble finding the river. Because of the adverse conditions involved, the number of measuring points each requiring one hole, should really be somewhat greater than the 25-40 normally used in an open water measurement. In practice, due to the labor involved, it is often less. After the holes have been cut, the process does not differ appreciably from that for an open water measurement. The depth which is recorded is the distance from the bed to the underside of the ice or slush layer. The standard 0.2 - 0.8 D velocity determination technique may be used under ice where depth permits. Where the water is too shallow, a single observation at 0.5 D rather than 0.6 D is usually used. A method coefficient of 0.88 is then applicable.

Computing Continuous Discharge Under Ice Conditions

The computation of continuous discharge records during backwater periods can be very easy or very difficult, depending on circumstances. Very brief periods of backwater such as are caused by anchor ice can usually be detected in the stage record by a skilled eye examination and evaluated without the need for discharge measurements or field observations. For lengthy periods of varying backwater, each discharge measurement provides a point on the time curve. The problem is one of interpolation between these points to define complete and continuous curves of backwater versus time. For usual condition of partial ice cover, the analysis is based on a combination of fragmentary weather data and subjective judgement. Hydrologic comparison among records in the same area is a useful tool.

Rosenberg and Pentland [64] and many others (i.e., Michel [65], Strilaeff [66], Carey [67], Panfilov [68]) have all outlined computational methods for determining discharge of rivers and streams under ice conditions. In general, these methods usually determine the backwater effect, correct the ice stage for it, and thus determine discharge. In particular, Rosenberg outlines three methods used by the Water Resources Branch in Ottawa to compute discharge under ice conditions. They are the Backwater Method, the Interpolation Discharge Method, and the Adjusted Discharge Method. In addition, he mentions three other methods: the Effective Gage - Height Method, the Recession Curve method, and the K-factor method.

The dye-dilution method of measuring discharge has received considerable attention in the past few years [69,70]. Some application of this method for ice conditions has been attempted with reasonable results under certain conditions, but in general, dye techniques for under ice conditions are not considered operational at this time.

FUTURE SNOW COVER SENSING

With the rapid improvement in automation of data acquisition such as the collection of real-time data via the geostationary satellite [71] (Flanders and Schiesl 1972), the operational hydrologist will soon have the ability to collect and process much larger masses of information than at the present time. Increasing the number of point measurements of snow cover parameters will lead to better estimates of the areal distribution. However, the most significant improvement can only be realized with techniques that measure (directly) the areal average or spatial variation. Research in snow cover measurement techniques will concern itself more and more with perfecting operational techniques for surveying from satellite heights. Much of the research effort will be directed towards examining the energy emittance of snow surfaces, measuring the brightness temperatures under varying atmospheric conditions, studying emissivity of various types of snow and ice, and using thermal inertia ratios or multispectral signatures to compare one band with another [72] (Strong McClain and McGuinnis 1971). Snow physics and microstructure micrometorology studies will also be essential to the development of operational snow surveys from space.

Considerable progress is being made on the development of remote sensing techniques for areal measurement of the snow cover and snowmelt. However, it is clear that it will be at least several years before they are operational. Until this goal is achieved, considerable attention should be given to the problem of areal representativeness from point measurements (network design) to provide better tools for the operational hydrologist until the remote sensing of areal parameters is perfected.

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