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TECHNIQUES FOR PREDICTING SNOW COVER RUNOFF
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by

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TECHNIQUES FOR PREDICTING SNOW COVER RUNOFF

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SUMMARY

The paper identifies the dominant variables in snow hydrology that affect river forecasts and discusses each in terms of areal variability as related to geographical factors. The two basic types of forecasts, short-term and seasonal yield forecasts, are discussed. In the past, seasonal yield forecasts have relied solely on correlation methods. The use of simulation models to isolate and evaluate relationships between variables and the use of more advanced statistical methods to define future probabilities seem likely to result in more reliable forecasts in the future. Improved simulation models offer a great potential as both a forecasting tool and as a means to improve our understanding of the snow process. The paper discusses approaches to simulation modeling and problems which arise, plus showing typical results from several recent models of the snow process.

RESUME

Dans cette communication, on identifie les variables principales de l'hydrologie des neiges qui affectent les prévisions pour les rivières et l'on discute de chacune d'elles en fonction des variations des surfaces couvertes par rapport aux facteurs géographiques. On traite des deux types de prévisions fondamentales: les prévisions à court terme et celles de l'apport global saisonnier. Par le passé, les prévisions de cet apport ont été entièrement basées sur des corrélations. L'utilisation des méthodes de simulation pour isoler et évaluer les rapports entre les variables et l'utilisation des méthodes statistiques plus avancées pour définir les probabilités sont susceptibles de donner des résultats plus sûrs. Les modèles de simulation améliorés offrent un grand potentiel à la fois comme outil de prévision et comme moyen d'augmenter notre compréhension des processus liés à la neige. Dans cette communication, nous discutons de la manière de concevoir des modèles de simulation et des problèmes qui apparaissent; de plus, nous montrons des résultats types donnés par plusieurs modèles récents des processus des neiges.

INTRODUCTION

The river forecasting problem in snow hydrology includes two basic types of forecasts. First, the short term forecast which utilizes current data on snow cover and observed plus predicted meteorological conditions to estimate discharge for a day to a week (in some cases longer) into the future. Second is the forecast of seasonal water yield which uses current snow cover conditions plus probable future climatic patterns to predict the volume of runoff for the season. In addition, seasonal water yield estimates may contain statements as to the probable distribution of the runoff with time and peak rates of discharge.

VARIABLES AFFECTING SNOW COVER RUNOFF

The two most important groups of variables affecting snow cover runoff are those that describe the existing state of the snow cover and those meteorological variables that determine its future melt or accumulation. In river forecasting the most important information about the snow cover is its water equivalent. The areal mean and its distribution are needed. For seasonal water yield forecasts, the mean water equivalent is the critical piece of information. In the case of the short term forecast the distribution of the snow cover becomes very important, as it determines which portions of a watershed are potential contributors to runoff.

The following factors affect the distribution of water equivalent over an area.

1. Topography affects the initial accumulation of snow since it has a significant influence on the variations of precipitation (1). Topography also plays an important role in determining how significant the following factors are for a particular watershed.

2. Storm characteristics can influence the distribution of precipitation with elevation. Synoptic situations determine the increase or in some cases decrease of precipitation with elevation (2). Storm direction, for example, can result in distribution of more snow on south slopes one year while more on north slopes the next. In areas of flat topography such as the Great Plains of the U.S. and Canada, weather patterns are the dominant factor in the distribution of snow cover on a macro scale.

3. Wind can have a significant effect on the redistribution of snow cover (3). This is particularly true in exposed non-forested areas.

4. Areas with significant forest cover tend to have a more uniform distribution of snow cover. Forest openings tend to accumulate more snow than inside the forest (3). Forest management practices may alter the distribution of snow cover over an area and thus change the seasonal snowmelt runoff pattern (4).

5. In the process of melting, the distribution of a snow cover is changed. Snow at low elevations melts more rapidly than at high elevations. Snow on south facing slopes melts faster than on north facing slopes (in the northern hemisphere). Snow in open areas melts at a different rate than snow in the forest. All of these differential rates of melting produce a continual change in the distribution of the water equivalent of the snow cover.

These factors affecting the distribution of snow have a tremendous influence on the hydrograph produced by the depletion of the snow cover. For example, during the winter of 1968-69 record snow cover accumulated in both the upper New England and upper midwest areas of the United States. Hendrick (5) reported that on the Sleepers River Watershed snow water equivalent ranged from 200 to 500 mm. with a mean of 300 mm. This watershed is typical of the glaciated uplands of northern New England and is 67% forested. On the Sleepers River snowmelt occurred without flooding despite normal spring temperatures and rainfall. On the Rock River watershed above Rock Rapids, Iowa, accumulation varied from 100 to 225 mm water equivalent with a mean of only 155 mm, yet record flooding occurred with normal temperatures and below normal rainfall (6). The major reason for this difference is that the Rock River watershed is flat, with negligible forest cover, thus there was very little differential melting and the entire snow cover was depleted in 6 days. In New England the melt season lasted approximately one month.

It was previously mentioned that melt is a major factor influencing the distribution of snow cover. The rate of melt is the most important factor in determining the runoff from a snow cover. The most important variables affecting melt at the snow-air interface are air temperature, vapor pressure, wind, incident solar radiation, albedo, incident longwave radiation and the condition of the surface layer of the snow cover.

1. Air temperature can vary considerably on a micro scale. These variations are created by the interaction of other meteorological variables with the topography and vegetation. However, over a watershed of more than a few square kilometers, temperature may be assumed uniform for most hydrological forecasting purposes. Point values of air temperature, measured at a representative location, are applicable over large areas in flat terrain. In the case of mountainous terrain, temperature data should be observed for various elevation zones, or if this is not possible, an appropriate lapse rate should be used to adjust data observed at one elevation to the required elevation.

2. Vapor pressure is a reasonably conservative variable over a watershed, except within the boundary layer of evaporating surfaces. Therefore, the use of point data should be adequate. The appropriate density of an air temperature-vapor pressure network is not known, but a network in the order of 2 to 3 stations per headwater basin or local area should be adequate in relatively flat terrain. In small watersheds (less than 100 km^2) one station is probably adequate. Where elevation varies significantly and vapor pressure data are not available for selected zones, a lapse rate can be used to adjust the point data. However, the relationship between elevation and vapor pressure is more complex than that between elevation and air temperature (7). Ideally, in mountainous terrain, the appropriate lapse rate for each time period should be obtained from the air temperature-vapor pressure network. This would mean that at least a high elevation and a low elevation station are necessary.

3. Wind is reasonably uniform over areas of flat terrain and uniform forest cover. In a watershed with rough terrain and non-uniform forest cover, wind is highly variable (8). Thus point wind data are, in general, merely an index to area wind. The selection of an index wind station should be made with considerable care as the relationship between mean areal wind and point wind can vary considerably with wind speed and direction (8). A good index to areal wind should be wind velocity several hundred meters up in the

atmosphere. In this case the effects of topography and forest cover near a ground anemometer would be removed.

4. Incident solar radiation and atmospheric longwave radiation tend to be reasonably uniform over a watershed as long as areas are not so large that sky cover conditions vary significantly. Thus, point radiation measurements should be adequate to determine radiation input from the sun and the atmosphere on reasonably flat watersheds with uniform sky cover. However, problems arise when point measurements have to be adjusted for the effects of topography and forest cover.

   It is possible, knowing slope, aspect and latitude, to calculate the direct solar radiation received by a surface of any orientation as compared to that received by a horizontal surface such as a pyranometer (9). The percentage of direct solar radiation can be obtained from a relationship of direct solar radiation to the measured solar divided by clear sky solar (10). Since the amount of diffuse radiation received is not influenced by orientation of the surface, the amount of solar radiation received by any surface can be computed. Atmospheric longwave radiation is diffuse and is thus not affected by topography.

   Forest cover presents even more of a problem. A certain percentage of incoming solar radiation penetrates the forest canopy and is incident on the snow cover (11). This percentage is affected by many factors including solar angle, amount of direct solar radiation, type of vegetation and the amount of foliage on the trees. The longwave radiation received by the snow is comprised of atmospheric longwave radiation which penetrates the forest canopy plus the longwave radiation emitted by the forest itself. Although the temperature of the forest canopy varies from leaf to leaf and to the trunks of the trees, air temperature is probably a reasonably good index of the radiating temperature of the forest.

5. The upper layer of the snow cover is most important in the heat exchange process. The majority of heat added to or taken from the snow is at the snow-air interface. The most

important properties of the surface layer are those controlling the reflectivity, absorption and penetration of radiation and those controlling heat flow into or out of the snow.

In the longwave portion of the spectrum, most studies show snow to be a nearly perfect absorber of radiation with an emmissivity of about 0.99 (11)(12). In the shortwave portion of the spectrum, snow is a good reflector. However, its reflectivity (albedo) varies considerably with the condition of the surface layer. New fresh dry snow has an albedo near 0.90, while old moist snow approaches 0.40 (11). Figure 1 shows the seasonal variation in albedo over a 20 km^2 watershed in northern Vermont. This figure shows that the variability of albedo becomes greater as the season progresses because of differential melt rates and snowfall patterns. Thus it may be difficult to use point albedo measurements over an area. Very little research has been done on the areal variability of snow albedo and methods of estimating the mean value over an area. Albedo has been related to such things as summation of degree-days or time since the last snowfall (11). A procedure based on these studies may be adequate to estimate areal albedo. Figure 2 shows a plot of surface layer snow density versus albedo. Such a relationship might also be useful in estimating areal albedo.

The upper layer of the snow controls the heat flow into and out of the snow cover. The physical characteristics of this layer, especially density, affect such things as air and vapor movement within the snow and the penetration of solar radiation (13). Density is also the major variable affecting the variation in thermal conductivity (14). Surface layer density undoubtedly can vary considerably over an area. How precisely it needs to be determined to compute a reasonable areal heat-exchange is not known. It probably does not need to be known with great precision since the transfer of heat from the atmosphere to the snow surface or vice-versa is much greater than that transferred from within the snow cover to the surface. This is due to the good insulating properties of snow.

6. The interaction of all of the variables affecting melt, through the heat exchange processes of radiation, sensible heat, latent heat and conduction, produce another variable, snow surface temperature. Surface temperature normally will be highly variable over an area except under the most uniform conditions, or in the case of area wide melt, when the snow surface is at zero degrees centigrade. Therefore, if snow surface temperature is needed (as in continuous energy balance computations) it should probably be estimated from other variables affecting the energy balance. It would be very difficult to use a point measurement of snow surface temperature to estimate its areal mean. In the future airborne or satellite remote sensing equipment may be able to measure areal snow surface temperature.

PROCEDURES FOR FORECASTING

There are two basic approaches to the forecasting problem. They are statistical models and simulation models.

Statistical correlation models are the predominate method used in seasonal yield forecasting. The basic method uses correlation analysis to relate the current measured snow cover or the past precipitation or combinations thereof, to observed seasonal runoff (11)(15). Other variables have been added to the analysis in an attempt to improve results. These include base flow (16), soil moisture (17), wind (18), high elevation-low elevation water equivalent or precipitation ratios (19) and areal extent of snow cover (20). In recent years papers such as those by Hannaford (21) (22) and Tarble and Burnash (23) have emphasized the need to use simulation models to help isolate and evaluate those hydrologic relationships important to the forecasting of seasonal volume and its distribution. They point out that simulation models can be an important tool in determining the effect upon runoff of any probable sequence of temperature or precipitation with respect to current hydrologic conditions. Thus it seems that future improvement in seasonal yield forecasting will come through the use of simulation models, plus the incorporation of more advanced statistical methods, such as stochastic processes, which will allow more accurate statements as to the probability of future runoff volume and its distribution.

Simulation models have advanced considerably over the past twenty years. Much of the development of simulation models is due to the increased use, speed and capacity of digital computers. Hydrologic simulation models which include snow are generally divided into three basic components: the snow cover, a precipitation-runoff relationship, and a runoff distribution and routing procedure. It is difficult to classify simulation models. One possible way is to differentiate between those that represent each basic component as a single relationship and those which simulate the unit processes involved in the basic components. All of the models in the first category described in the literature (15)(11)(24)(25)(26)(27)(28) simulate the melt season only. Snow cover runoff is normally related to a temperature index which varies seasonally. In several of the models (11)(26)(27), other meteorological variables are used to estimate snow cover runoff. The precipitation-runoff relationship varies from a simple constant loss to relationships which use antecedent moisture, season of year, duration of storm and other factors as indices. Distribution and routing is accomplished by a transformation function which relates runoff volume to a discharge hydrograph. The most common transformation function is the unit hydrograph. For downstream channel reaches, routing may be accomplished by a number of hydrologic routine techniques. Results from this type of simulation model are generally quite good and are currently the primary method used for short-term river forecasting.

Most simulation models which can be grouped into the second category simulate the entire snow accumulation and melt season (29)(30)(31)(32)(33)(34). Some of these models only simulate the snow process (30)(33)(34)while the others are used in conjunction with models of the soil-moisture accounting and channel routing processes. While most of the category two simulation models are in the research stage, models of this type are used for operational short-term forecasting in the United States (32) and the Soviet Union (35)(36). Since the category two type simulation models are relatively recent innovations and seem to offer great potential as both a forecasting tool and a means to improve our understanding of the snow process, the remainder of this paper will be devoted to this topic.

SYSTEMS SIMULATION MODELS OF THE SNOW ACCUMULATION AND MELTING PROCESS

Several simulation models of the snow accumulation and melting process have been developed which attempt to mathematically represent each of the components of the total process. The literature on snow hydrology seems to agree on the components of the snow process. This is reflected in the similarity in basic structure of the models developed. A typical flow-diagram of such a model is shown in Figure 3. The differences between models are the mathematical relationships used for each component. Thus it is undoubtedly true that further improvements in this type of systems model will come through improved representations of individual components rather than from changes in basic structure.

In the development of a systems model first the basic structure is established and then the initial mathematical relationships of each component are added. Next data is obtained to test the model. In developing a model, data should be of the highest possible quality and cover at least several snow seasons so that data errors can be minimized. In operational use the errors will, in most cases, be greater; however, this should be because of data deficiencies and not model logic. Not only should high quality data be used in development, but observations of variables not normally required for operation of the model should be available to check, as completely as possible, the validity of the model.

The next step in model development is a cyclic process consisting of:

1. Fit the model to the observed data by means of adjusting parameter values. The adjustment of parameters should continue until an "optimal" fit is obtained. The criteria for optimization are usually based on the most important variables such as water equivalent or the discharge hydrograph. However, other variables such as snow cover depth, density, temperature and areal extent should be compared to observed conditions so that some insight into the validity of the individual components is also obtained.

2. Evaluate the errors to determine which components are not adequately represented. Also perform sensitivity analysis on parameters so that very insensitive parameters can be eliminated. In general, the fewer parameters that are used the easier it is to get an "optimal" fit.

3. Change the representations of model components based on the prior evaluation of errors. The process of fitting, evaluating, and changing is then repeated until a reasonable reproduction of observed conditions is obtained. If the simulation model is to be of general applicability the process is then repeated on watersheds or snow data representing other geographic conditions.

Before showing some typical results of simulation models of the snow process, a brief discussion of each of the major components of such models is needed.

1. The water equivalent and possibly other properties of the snow cover are available for some watersheds, but in most

cases it is necessary to simulate the accumulation of snow cover. To accomplish this the type of precipitation needs to be estimated. Sometimes such observations are available, but normally the hydrologist must depend on meteorological information. Air temperature provides a reasonable estimate as to type of precipitation (11), with a ground level temperature of about 0.5°C being a good delineation between rain and snow. Wet-bulb temperature or upper air temperature are probably even better indicators.

2. Interception of snow and any subsequent loss are complex processes (37). During a storm interception storage increases until some maximum is reached. After the storm some of the intercepted snow falls to the ground, some melts and runs down the trunk and some sublimates. Many studies have represented the seasonal loss by interception as a percentage of the total seasonal snowfall(11). The simulation models developed to date have used this simplified approach if they have included interception at all. The one exception is Willen et al (34) who represent interception as a function of precipitation and canopy density.

3. The heat exchange at the surface of the snow cover is the most critical part of a simulation model. To simulate the snow process continuously, heat exchange must be estimated under all conditions, not just when melt occurs. Two basic methods have been used, the temperature index method and energy balance method.

   (a) The temperature index method is similar to degree-day type melt equations, except that heat exchange is also estimated when melt is not occurring. It should also be made clear that the heat exchange through the air-snow interface is being estimated and not snow cover runoff as in many of the degree-day melt equations.

   The estimation of heat exchange when using the temperature index method depends on whether the air temperature is above or below a base value (usually 0°C). When air temperature is above the base, the air temperature is multiplied by a melt factor to estimate surface melt. There seems to be agreement that this melt factor should vary seasonally because of the changing relationship between air temperature and other meteorological variables, especially solar radiation. The melt factor also varies from area to area because of forest cover and other geographic variables. Eggleston, et al (33) have tried to identify the major variables affecting the melt factor and express them in mathematical form. Eggleston's basic melt factor (F) is:

$$F = k_m \cdot k_v \cdot \frac{RI_s}{RI_h} \cdot (1 - A) \qquad \text{(Eq. 1)}$$

where k_m = proportionality constant

k_v = vegetation transmission coefficient for radiation

RI_s = radiation index for a particular area of known slope and aspect

RI_h = radiation index for a horizontal surface at the same latitude

A = Albedo

When air temperature is less than the base temperature the rate of heat exchange is different than during a melt situation. Several methods have been tried to estimate heat exchange during non-melt periods. Anderson and Crawford (29) used air temperature and the negative heat storage of the snow cover as indices. Negative heat storage is a combination of refrozen liquid water and snow that is less than 0°C. Thus it is the amount of heat that must be added before liquid water storage within the snow cover can be increased. Eggleston, et al (33) assume that snow surface temperature is equal to air temperature and calculate the heat gain or loss from the snow cover by the heat conduction equation. The U. S. National Weather Service is currently using the difference between the air temperature and an antecedent temperature index, multiplied by a heat exchange factor to estimate heat exchange during non-melt periods. The antecedent index is an estimation of the temperature of the surface layer of the snow cover.

In addition to an index based only on air temperature, other meteorological variables could be used as indices to the heat exchange at the air-snow interface. Willen et al (34) use solar radiation and albedo in addition to air temperature.

(b) In the energy balance method the basic energy transfer mechanisms are estimated on a continuous basis so that the snow cover heat exchange can be computed. The primary heat exchange mechanisms are radiation transfer, sensible heat transfer, latent heat transfer and the heat content of precipitation.

Anderson and Crawford (29) and Amorocho and Espildora (30) used similar representations of the transfer mechanisms. In both studies the equations for shortwave and longwave radiation, convection and evaporation-condensation as developed during the snow investigations of the Corps of Engineers and U.S. Weather Bureau (11) were relied on. Anderson and Crawford calculated heat exchange by the energy balance only during melt periods. During non-melt periods the index procedure described previously was used.

In the study of evaporation from water the combination method (combination of energy balance and aerodynamic equations) as first described by Penman (38) and since supplemented by Van Bavel (39), Kohler and Parmele (40) and others has given excellent results. This approach assumes that the eddy transfer coefficients for heat and vapor are equal. There has been some question as to the validity of this assumption, but the general opinion in a review by Pruitt and Lourence (41) is that the assumption is valid except possibly under highly unstable conditions. This opinion is further substantiated in a recent report by Morgan et al (42). Since stable or near neutral conditions prevail over a snow cover the combination method should be a good approach to estimate heat exchange. Anderson (31) applied the combination method to data from the Central Sierra Snow Laboratory lysimeter of 1954 (43) and obtained excellent agreement between computed and observed snow cover runoff as shown in figure 4. Good agreement between observed and computed snow surface temperature at night was also obtained. Though the combination method needs more verification regarding its application to a snow cover, the approach seems to offer a theoretically sound method of estimating heat exchange that does not have unreasonable data requirements for operational use.

4. The liquid water retention and transmission properties of snow are not completely understood. Liquid-water retention capacities from 2 percent to 52 percent are reported in the literature (11)(46)(45)(44)(35). The densities, depth and method of measurement vary in each study. Reported variations in liquid-water retention with density also are not similar. Most measurements on "ripe" snow (snow at 0°C, whose liquid-water retention capacity is satisfied) from a deep snow cover (greater than one meter) indicate retention capacities less than 10 percent and in most cases on the order of 2 to 5 percent. Slush layers may be formed at the snow-soil interface or in conjunction with ice layers in the snow cover. Considerable liquid water can be retained within such slush layers. While slush layers can form in deep snow covers their relative effect on the total water retention of the snow is small. However, in shallow snow covers such slush layers will increase the total liquid-water retention significantly.

   Some work has been done on the transmission of water in "ripe" snow, but in the case of a new fresh snow cover only descriptive information exists. This case can significantly affect the forecast of a rain on fresh snow event. During such an event the snow seems to exhibit retention and transmission characteristics which are continually varying as methaphorism of the snow crystals takes place.

   Current models of the snow process treat only the case of retention and transmission in a "ripe" snow cover. The retention and transmission of liquid-water in fresh snow is not modeled because of a lack of quantitative knowledge on these phenomena.

5. The heat exchange at the soil-snow interface is generally small compared to the heat exchange at the air-snow interface. Current models of the snow process either ignore this component or assume a small constant rate of heat flow from the soil to the snow. This constant rate of ground melt is needed in some watersheds to sustain base flow during extended cold periods.

6. An estimation of the areal extent of the snow cover is critical to determining the area contributing to snow cover runoff. Several investigators (11)(47)(19) have found good relationships between percent of seasonal runoff and percent snow cover. Thus such a relationship could be used in conjunction with a seasonal water yield forecast to estimate the areal extent of snow cover for use in a short-term forecast model. Since percent of seasonal runoff is merely an index to remaining snow cover, even better results should be expected by relating areal extent of snow directly to the water equivalent of the snow cover.

RESULTS OF PRESENT SIMULATION MODELS

The simulation models of snow process thus developed have shown that simulation is definitely feasible and should be a very useful tool for river forecasting. Figures 5 through 8 show typical results that have been obtained from several of the simulation models. Models developed by Amorocho and Espildora (30), and Eggleston, et al (33) were not used in conjunction with a soil moisture accounting and channel routing model. The model of Anderson (31) is used with the Stanford Watershed Model (48). The snow simulation model described by Rockwood and Anderson (32) is used with the SSARR model(49).

COMMENTS AND RECOMMENDATIONS ON FUTURE USE OF SYSTEMS SIMULATION MODELS OF THE SNOW PROCESS

To conclude this paper a few comments on current simulation models of the snow process and on possible future modifications and uses of such models are presented.

1. One question that undoubtedly arises when examining snow hydrology literature and especially the results of simulation models is, what is the best method of calculating the heat exchange at the air-snow interface? This would be a relatively easy question to answer if perfect measurements of all variables were available and

the calculations were to be made at a point. In this case the combination method or some other theoretically sound heat transfer approach would give the best results. However, forecasting involves an area rather than a point. There are errors in individual measurements and generally only a limited number of variables are observed. In this case the answer to the question of the proper heat exchange method is not an easy one. Two basic approaches are available. The first is to use an index method such as the melt factor and the second is to use a theoretically sound heat transfer method and attempt to estimate the areal value of each variable from existing observations. The first approach has the advantage that the value of the primary index, air temperature, is commonly observed and its areal variability can be satisfactorily estimated in most cases. Its disadvantage is that it is an index method and there can be significant scatter in the relationship between the index variable and snow cover heat exchange. The advantage of the use of a theoretical heat transfer approach is that this scatter is decreased. The disadvantage of the theoretical heat transfer approach lies in the data requirements. In most cases some of the variables are not observed. If the variables are not observed, they must be estimated. The estimation of solar radiation from percent sunshine or cloud cover, the estimation of atmospheric longwave radiation from air temperature, vapor pressure and an index to sky cover, and the estimation of albedo from days since the last snow or accumulated temperature indices all induce errors. Next comes the problem of adjusting the data for geographical factors as discussed previously which creates additional errors.

Anderson (31) shows results (Figure 5) for two methods of heat exchange calculations using data from the Central Sierra Snow Laboratory. One method used a melt factor approach while the other used a physical heat transfer approach based on the combination method to calculate heat exchange. The physical heat transfer approach gave better results during this comparison though the improvement was not dramatic.

These tests are on a single watershed and general conclusions cannot be drawn from the results. The point is that the observational network and geographical features of the area will determine the accuracy to be expected from various heat exchange methods. With further testing, perhaps conclusions can be reached as to accuracy to be expected knowing the forest cover, terrain, and observational network.

2. In large watersheds, especially those containing significant differences in elevation, forest cover and aspect, results can possibly be improved by sub-dividing the watershed according to geographical characteristics and determining parameter values for each area. Care must be taken in this case to avoid using the additional degrees of freedom purely for curve fitting. In general the fewer inter-related parameters a model has and the longer the period of record, the more probable it is that the parameters will take on values close to the "true" value. Thus sub-dividing of watersheds may be necessary, but it should not be done merely to get a better reproduction of the hydrograph, especially when the record is short.

3. When simulation models of the snow process are used for operational river forecasting, current observations may be available to update the model. However, the forecaster will have to decide whether the observed value of a variable is more accurate than the simulated value before updating the model. For example, areal snow cover from aerial photographs should be more accurate than that simulated by the model, whereas areal snow cover from visual ground observations may not. In the case of water equivalent measurements the decision may be more difficult. It will depend on the errors in the simulated water equivalent, which are heavily dependent on the location and catch characteristics of the precipitation gages, versus the errors in the method of measuring areal water equivalent. A further possible use of measurements to update a simulation model would be to use observations of the change in water equivalent. It is difficult, even at a point, to accurately measure change in water equivalent for short time periods such as several days. Several new snow measurement techniques such as pressure devices and lysimeters (50), isotopic snow gages (50)(51), and natural gamma radiation detectors (52)(53) may make the use of measured change in water equivalent advantageous under certain situations in the future.

4. The present models have produced good results in regard to both reproduction of major snow cover variables and, when used with models of soil moisture and channel processes, reproduction of the discharge hydrograph. Future research in systems simulation models of the snow processes should be aimed at overcoming present deficiencies and should include:

   (a) Testing of models on data from watersheds with different geographic characteristics than those studied to date. Most testing has been on partly to heavily forested mountain watersheds with deep snow covers. Testing is needed in non-mountainous regions and areas of shallow snow cover. Problems that have not been encountered in deep snow mountain areas will be very important in shallow snow areas. One is the effect of capillary slush layers on the retention of liquid-water, which has been discussed already, and another is the effect of frozen ground. Frozen ground will not affect the snow cover except to change the heat exchange at the soil-snow interface. The major effect of frozen ground is how it changes the infiltration characteristics of the soil and thus the volume of runoff and timing of streamflow. Modeling the effect of frozen ground on runoff is pratically non-existent.

   (b) The problem of liquid-water retention and transmission, especially in new fresh snow needs to be examined in more detail. Mathematical relationships of this component of the snow process need to be developed for use in simulation models.

   (c) Results of present simulation models on the snow process have shown they can be a very useful tool for river forecasting. Future research should not only be oriented toward improving simulation models for forecasting purposes, but also as research tools for data requirement and network design problems.

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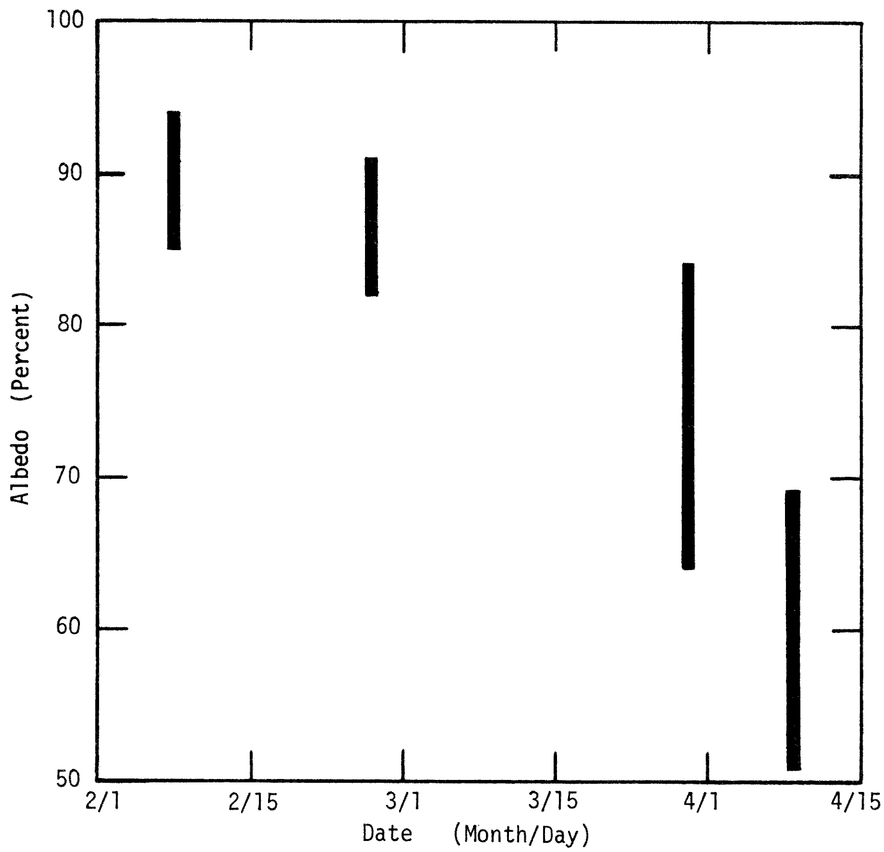

Fig. 1. Areal Variability of Albedo on Sleepers River Watershed near Danville, Vermont — 1969.

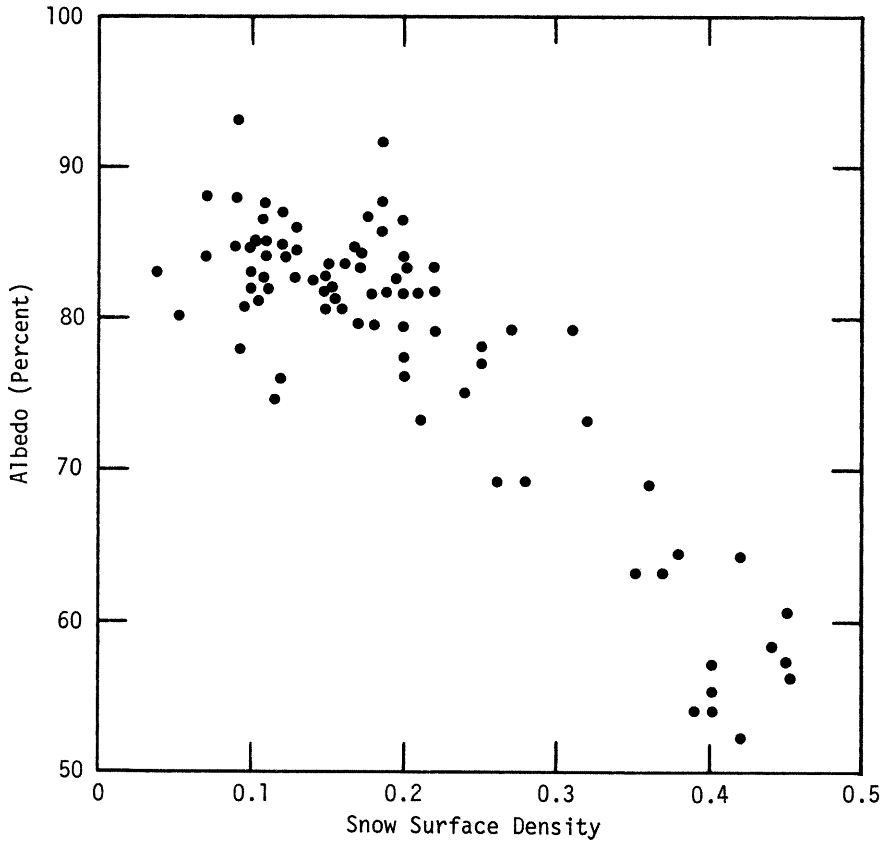

Fig. 2. Snow Surface Density Versus Albedo near Danville, Vermont — 1968-69.

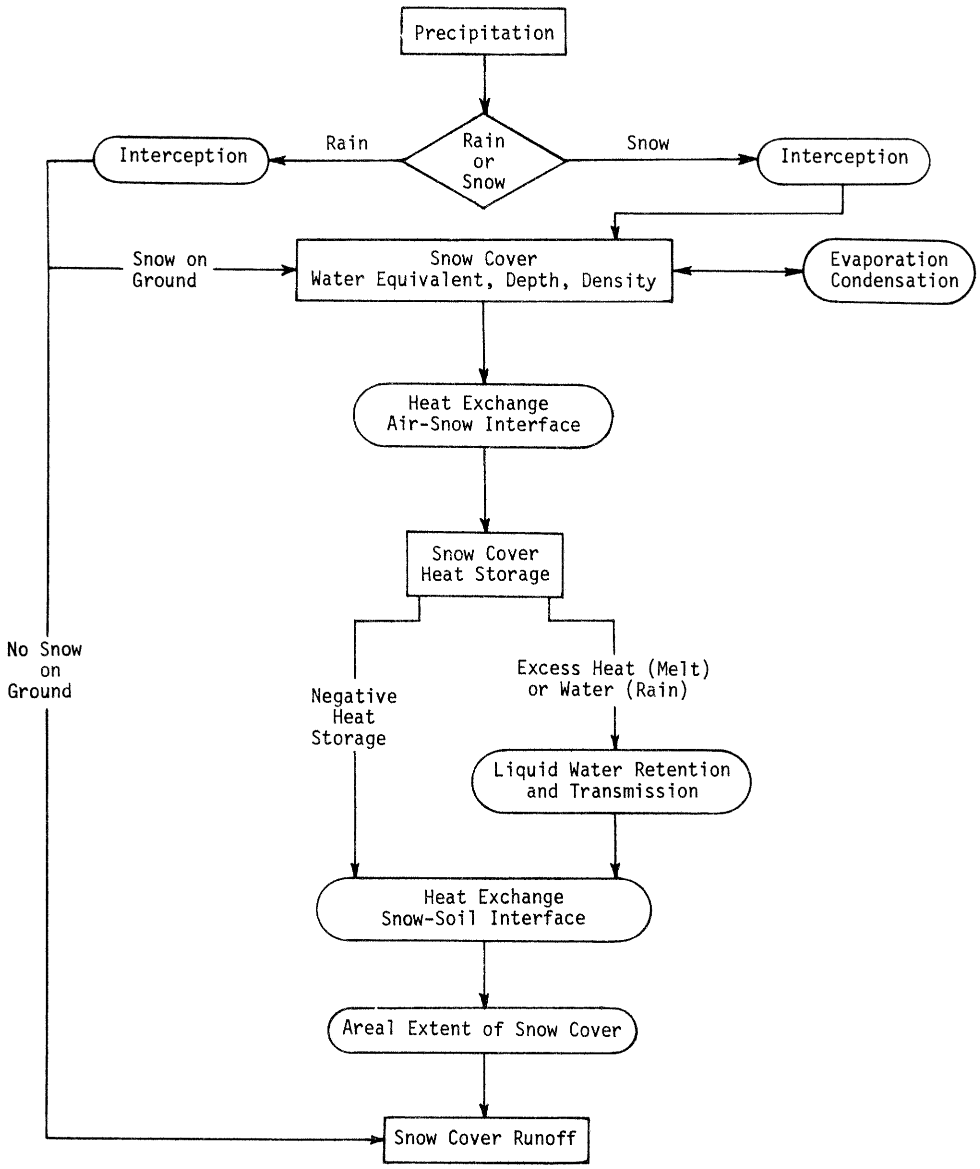

Fig. 3. Flow Chart of Typical Simulation Model.

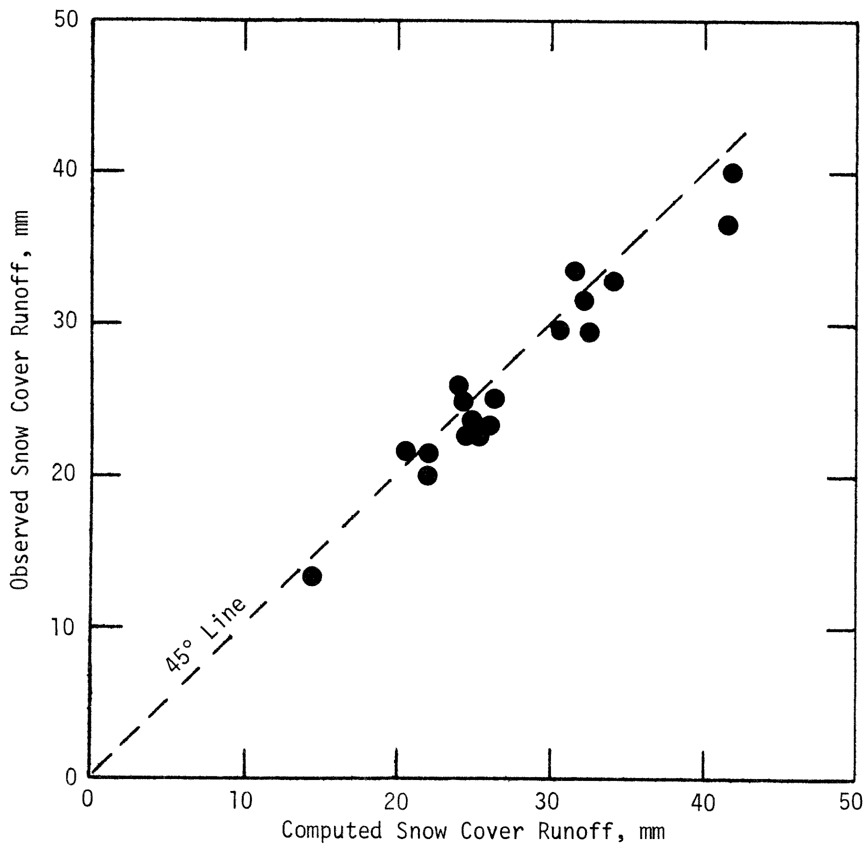

Fig. 4. Computed (Combination Method - Anderson [31]) versus Observed Snow Cover.

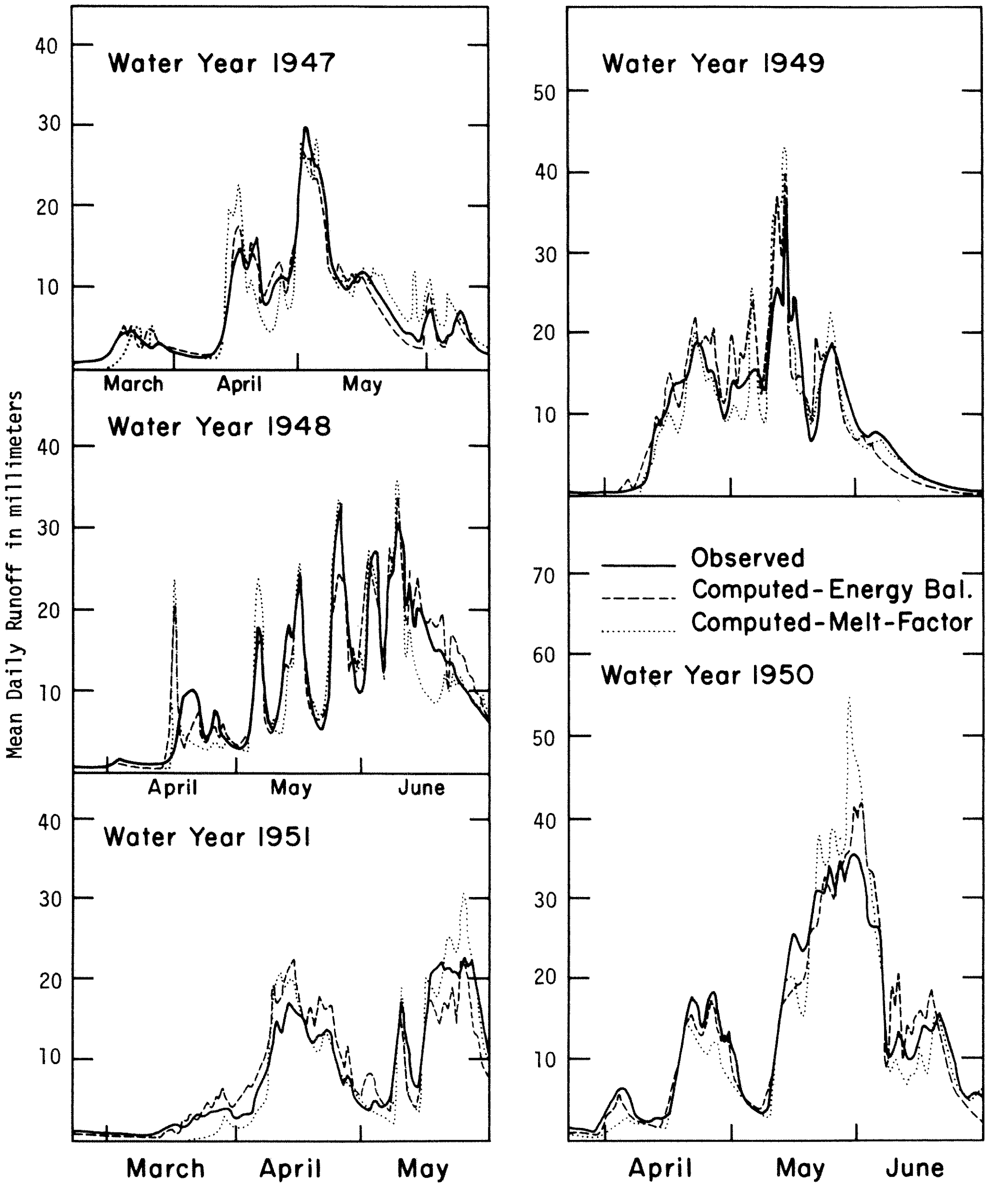

Fig. 5. Comparison of observed streamflow and streamflow computed by energy balance and melt factor methods. Central Sierra Snow Laboratory after Anderson [31].

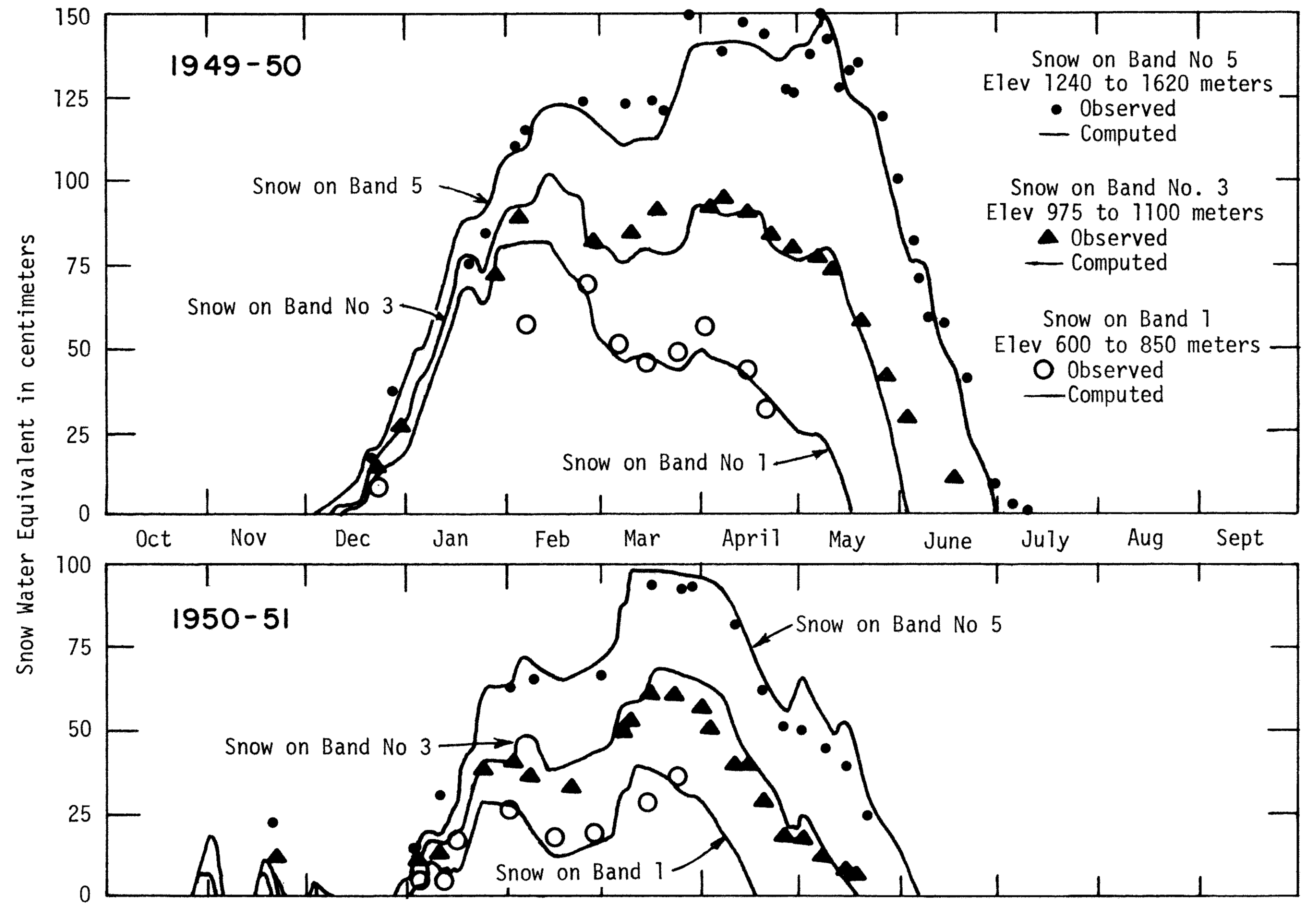

Fig. 6. Zonal Snow Water Equivalent, Computed vs Observed, Willamette Basin Snow Laboratory after Anderson and Rockwood [32].

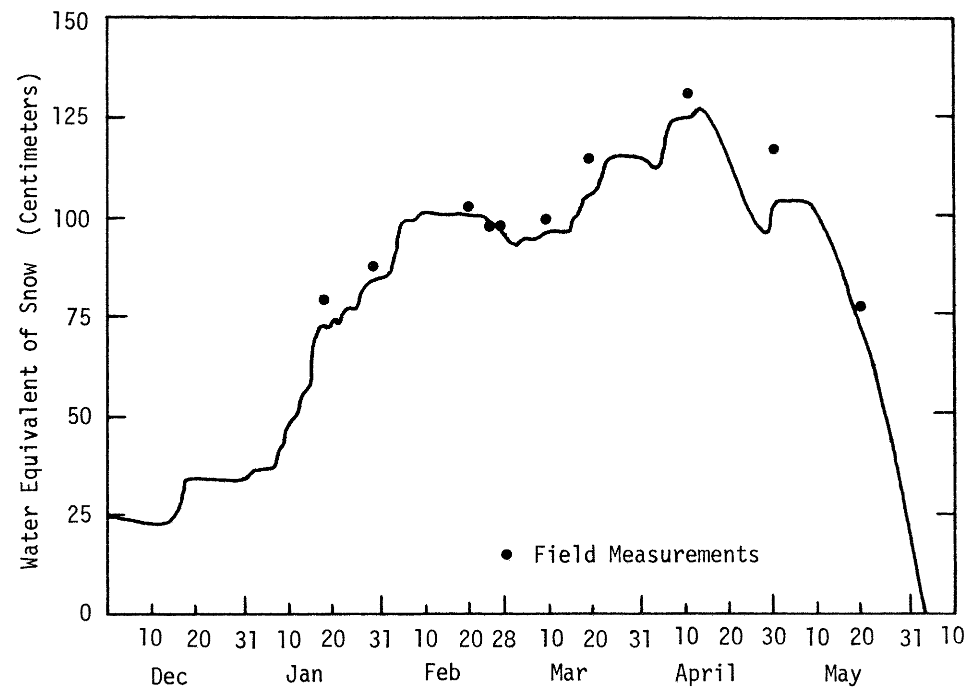

Fig. 7. Calculated Water Equivalent of the Snowpack for the Year 1949-50. Central Sierra Snow Laboratory, after Eggleston et al. [33].

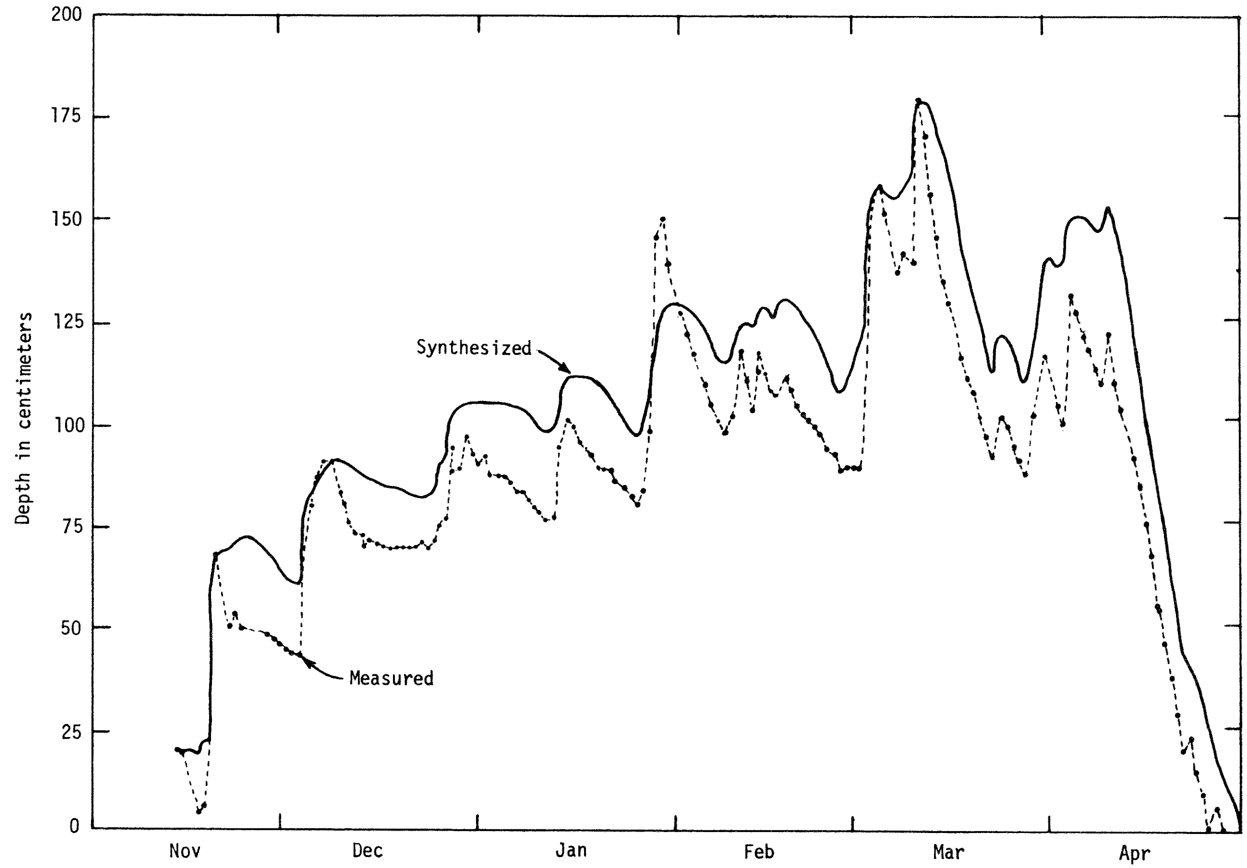

Fig. 8. Synthesized and Measured Snow Cover Depths, Central Sierra Snow Laboratory, 1946-47, after Amorocho and Espildora [30].