STREAMFLOW SIMULATION MODELS FOR USE ON SNOW-COVERED WATERSHEDS

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ABSTRACT. A set of principles to govern the use of conceptual models in snow-covered areas has evolved over the last 15 years within the Office of Hydrology of the National Weather Service. These principles are concerned with model structure, data input, model calibration, and the operational use of the models. A number of elements have been found to be needed in the structure of a model to adequately simulate snow accumulation and ablation. Other suggestions for using conceptual models in snow-covered areas pertain to the type of data required, the method of processing the data, the calibration method, and ways to update the model to correct the major sources of error.

Reasonably accurate simulation models are now available. Thus, further research on model structure is not as urgent and should be generally restricted to those components which contribute the most error. More accurate and reliable data are still needed for model input and for updating models used for real-time applications. The use of objective update techniques is virtually nonexistent. In many cases good update procedures could significantly increase the utility of streamflow simulation models in snow-covered areas.

INTRODUCTION

The use of streamflow simulation models has expanded significantly in the last 10 to 20 years. Within the context of this paper, a streamflow simulation model is a mathematical model which will compute discharges for time intervals of one day or less on a continuous basis. Such models are now widely used in hydrology for a variety of applications. The main real-time use of these models is for river forecasting. This includes forecasts of flood levels, inflows for reservoir operations, water available for navigation, and the likely range of future inflows both in terms of volume and timing for water supply, irrigation, and power generation. Streamflow simulation models can also be used for various types of planning, design, and water management studies. This paper is biased towards the use of simulation models for river forecasting.

The purpose of this session is to examine methods of combining unit process studies of various parts of the snow cycle such as accumulation, distribution, surface energy exchange, metamorphism, and water movement into a total model of the snow accumulation and ablation process. In addition, modifications to the rainfall-runoff portion of a simulation model which are needed in snow covered areas because of snow-soil interactions are to be considered. In order to be consistent with the purpose of this session, this paper will basically deal with physically based conceptual models, i.e., models which include representations of unit processes.

The specific objective of this paper is not to review all available models, but to focus on the things that have been learned within the Office of Hydrology (O/H) of the National Weather Service (NWS) concerning the structure and use of streamflow simulation models

To be presented at the Meeting/Workshop on Modeling of Snow Cover Runoff sponsored by AGU, AMS, Corps of Engineers, and NWS to be held at Hanover, N. H. on Sept. 26-29, 1978.

on snow-covered watersheds. This will not be a detailed description of the models that have been developed within O/H, but rather will be a discussion of what has been learned regarding model structure, the complexity of model components, data input for models, and the operational use of models.

BACKGROUND

Prior to the advent of continuous simulation models, NWS (then called the Weather Bureau) was involved in various types of snow studies. These included the development of short-term forecasting techniques [Linsley (1943), McCalister and Johnson (1962)], the development of water supply forecast procedures [Alter (1940), Light and Kohler (1943), Kohler and Linsley (1949)], and several unit process studies [Light (1941), Wilson (1941), Gerdel (1948)]. The Weather Bureau, along with the Corps of Engineers, initiated the Cooperative Snow Investigations which ultimately led to the publication of Snow Hydrology in 1956.

O/H began experimenting with continuous streamflow simulation models in 1964. A considerable effort has been spent in the development of snow accumulation and ablation models. Fig. 1 illustrates the general structure of these models. Areal snow cover models have been developed which use either a temperature index [Anderson and Crawford (1964), Anderson (1973)] or a simplified energy balance approach [Anderson and Crawford (1964), Anderson (1968)] to compute surface energy exchange. In addition, a detailed study of the physics

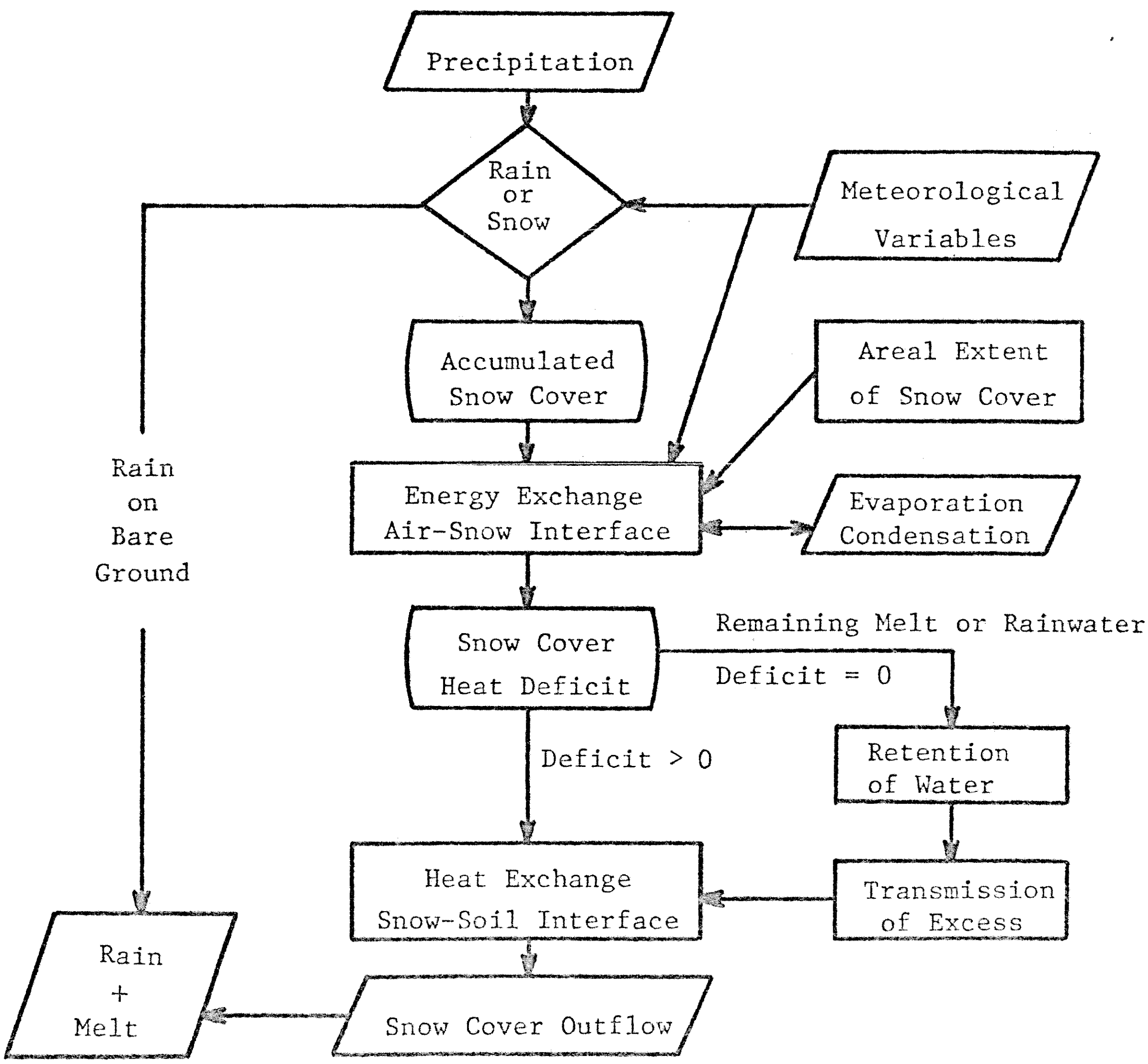

Figure 1. Flowchart of typical snow accumulation and ablation model.

of snow cover energy exchange has been conducted in cooperation with the Science and Education Administration (formerly the Agricultural Research Service) near Danville, Vermont [Anderson, et al (1977)]. This study, in part, led to the development of a comprehensive point snow cover energy balance model [Anderson (1976)]. In addition to the development of snow cover models, O/H has been involved in the testing and application of various soil moisture accounting models and has done one study on the effect of frozen soil on infiltration rates [Farnsworth (1976)].

In order to use continuous conceptual streamflow simulation models for river forecasting, O/H created the National Weather Service River Forecast System (NWSRFS) [Monro and Anderson (1974), Curtis and Smith (1976)]. NWSRFS is a collection of computer programs and the associated documentation which allows for the efficient use of conceptual models for river forecasting. Included are programs for data processing, file management, model calibration, and operational forecasting. The current snow model in NWSRFS uses air temperature as the sole index to snow cover energy exchange [Anderson (1973)]. The soil moisture accounting model is based on the catchment model developed at the NWS Sacramento River Forecast Center (RFC) [Burnash et al (1973)]. No provision is currently included for the effect of frozen ground or any other snow-soil interactions.

O/H is not the only component of NWS working on the development of snow accumulation and ablation models. The Portland RFC has been working with the Corps of Engineers to improve the snow portion of the SSARR model [SSARR Users Manual (1973), Speers et al (1978)]. Snow models have also been developed at the Sacramento RFC and the Cincinnati RFC [Winston (1965)]. This paper is restricted to the studies conducted at O/H.

PRINCIPLES GOVERNING THE USE OF MODELS IN SNOW-COVERED AREAS

Over the period that continuous conceptual models have been used within O/H a general set of principles has evolved concerning the model structure, data input, method of calibration, and the operational use of the models in snow-covered areas. These principles are not time-invariant, but will continue to evolve; however, the point has been reached within O/H where drastic alterations to these general principles are very unlikely.

1. Model structure should be physically based.

The model should have a structure in which all unit processes having a reasonably significant effect on the volume or timing of snow cover runoff should be represented. The inclusion of all significant unit processes keeps the user from having to make subjective guesses as to the effect of processes that are not included in the model (e.g., the user must subjectively decide when the snow cover is ripe if the modeling of the heat deficit and liquid water storage is not included.) It also simplifies the process of adjusting model output when unit processes are separated rather than being lumped together (e.g., it is difficult to decide whether the melt rate or the percent snow cover is in error if the effect of both energy exchange and areal cover are included in the melt factor). In addition to including all significant physical processes in the model, the mathematical representations of these processes, even though simplified, should be good approximations of the physical laws governing the real world. This makes it likely that the parameters in the model will have a physical basis, and also that the model can be extrapolated to estimate extreme events with some degree of confidence. The inclusion of all unit processes results in a modular model in which the modules can be changed as better representations of unit processes become available or as the available data change.

2. Model should require only readily obtainable data.

For a simulation model to be widely applicable, the basic model should require only data that can be readily obtained wherever the model is to be used. For a model which is to be used for river forecasting this means data that are available on a real-time day-by-day basis. In addition, in forecasting an added time advantage can be gained by using forecasted input data along with observed. Thus a consideration is what types of input data can be forecasted with some degree of skill. In the United States the current operational networks and meteorological forecasting capabilities limit the generally available input data for snow models to precipitation and air temperature. Thus, the basic streamflow simulation model for use in snow-covered areas should require only precipitation and air temperature data as input. This does not mean that the model should not have the capability to use other data when available.

3. Data should be unbiased.

It is critical that data used in streamflow simulation models be as unbiased as possible if the true utility of the model is to be realized. A data bias will cause a distortion in one or more parameters. This may still allow for an adequate simulation during the calibration period, but distorted parameters will limit the effectiveness of the model to forecast some future extreme event. While bias data can distort parameter values during calibration, random errors in calibration data do not seem to affect parameter values unless the random errors are very large. Operationally it is critical that the data used should be unbiased compared to the data used during calibration, since the model parameters are based on the calibration data. In addition, operationally it is important to reduce errors to a minimum. Thus, additional data, which are not needed for calibration, can be justified operationally to reduce the random deviations between computed and observed streamflows.

4. Representations of unit processes should be parameterized.

Mathematical representations of unit processes should be expressed in terms of single valued parameters rather than in the form of multi-valued tables whenever possible. Advantages of using single-valued parameters are:

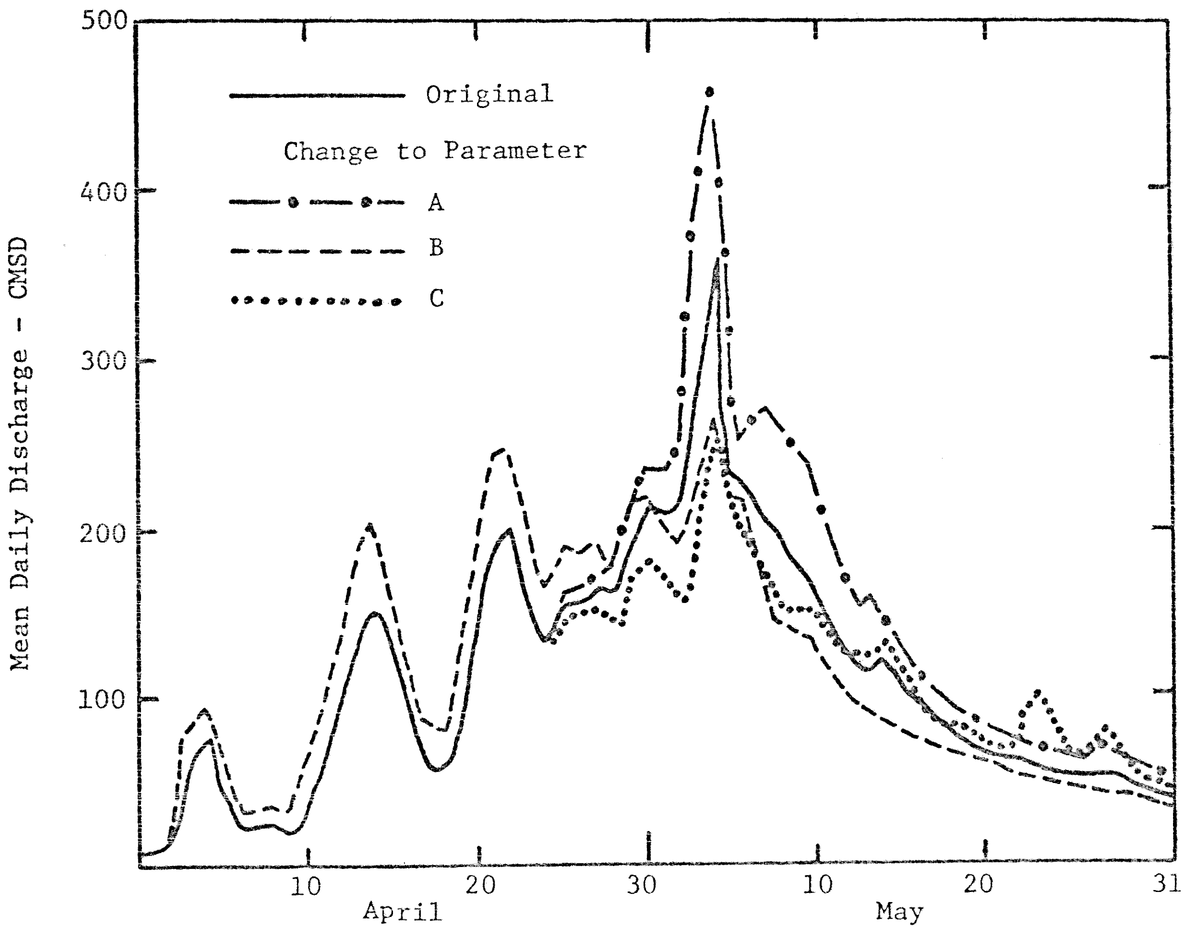

Figure 2. Illustration of different effects that parameters have during the melt season on model response.

a. automatic optimization is much more feasible because the number of values to be altered is greatly reduced,

b. manual calibration is simplified because it is easier to visualize and isolate the effect of an individual parameter, and

c. the chance of curve fitting is reduced because the number of values that can be altered is much smaller.

It also seems like it is easier to relate individual parameter values rather than tabular values to the physical characteristics of the area. Such relationships are important for getting initial estimates of parameters and for using the model in an ungaged area.

5. Parameters should have unique effects on output.

Only parameters that have a reasonably unique effect on model output should be included in the model. Fig. 2 shows an illustration of this concept. In Fig. 2 all three parameters affect runoff during the melt season, but the actual effect of each parameter is unique. Two or more parameters that essentially have the same effect on model response should not be included. This principle also relates to the subdivision of a watershed into several parts and then assigning different parameter values to each subarea. Assigning different parameter values to different subareas should only be done when the effect of the parameter is reasonably unique for each portion of the watershed. It should also be restated that all parameters, whenever possible, should have a physical basis. The total number of parameters, though a consideration, is not the primary goal.

6. Other available real-time information should be used to update the model.

When used for river forecasting, additional information which is available on a real-time basis, though in most cases discontinuous, should be used to update the model whenever it has some significant informational content. Updating should reduce the forecast errors. Currently most updating is done on a subjective basis. There is a need to develop updating techniques that deal with the most significant sources of error in an objective manner. Subjective updates tend to adjust only the output of the model. Objective updating techniques should be developed which also adjust the internal state variables of the model. This should not only tend to improve the current forecast, but should improve subsequent model performance. Even with good objective updating techniques, it should be stressed that a well designed and well calibrated model is still very important. For a given error in the forecast, the better the model the longer the lead time. This concept is illustrated in Fig. 3. Increased lead time is very important in river forecasting.

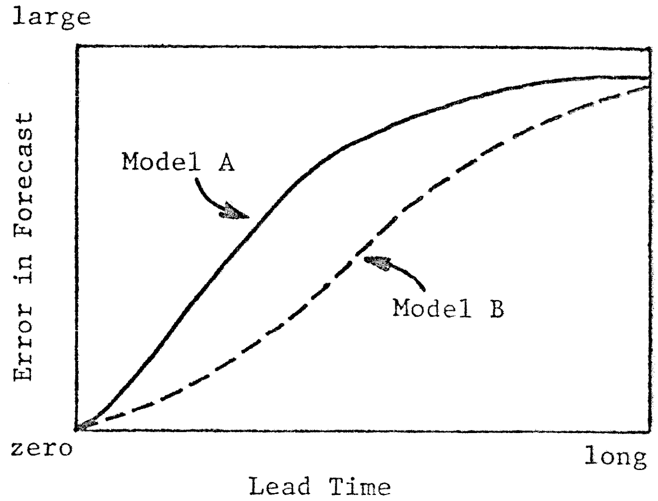

Figure 3. Relationship between error in forecast and lead time for two models using the same update technique. Model B gives a longer lead time for a given level of error in the forecast.

IMPLEMENTATION OF PRINCIPLES

The structure of the models and the recommendations concerning data preparation, model calibration, and operational use that have been developed within O/H attempt to follow the principles outlined in the preceding section. This section describes in more detail how these principles can be implemented when using streamflow simulation models in snow-covered areas.

Data Input

Models developed within O/H use mean areal estimates of the input variables that drive the models. The current basic streamflow simulation model for use in snow-covered areas requires estimates of mean areal precipitation (MAP) and mean areal temperature (MAT). The best way to insure that both calibration and operational estimates of MAP and MAT are reasonably unbiased is to attempt to use the correct scale right from the beginning. The term scale refers to the relationship between the computed and the actual values of the input variables on a long-term basis. The correct scale is a 1:1 relationship. Such a relationship is relatively easy to obtain in flat terrain, but much more difficult in mountainous areas where snow is almost always important.

Estimates of MAP and MAT are computed before model calibration begins. The first step is to check the consistency of the basic point data by double mass analysis. The next step is to determine if the long-term mean at all points within the area can be assumed to be the same. If the long-termed means cannot be assumed to be the same, the area is treated as a mountainous area (whether mountains are present or not). The proper scale for the MAP estimate is determined by an isohyetal analysis [Peck and Brown (1962)], while the scale for MAT is determined by an analysis of temperature versus elevation (and sometimes location). These analyses normally must be done on a seasonal basis because of significant seasonal variations in precipitation patterns [Peck (1964)] and lapse rates. In addition, it is usually difficult to be sure of the pattern if only a few stations are used, thus the analyses should be performed on a regional basis. This procedure should result in initial estimates of MAP and MAT which correspond to the proper scale, as long as a reasonable number of measurement points are available in the region. Adjustments to these MAP and MAT estimates should be kept to a minimum during the calibration process. Estimates of MAP and MAT which do not conform to the proper scale will generally cause model parameter values to be distorted during the calibration process.

There are several advantages operationally of knowing the scale of the input data and having it correspond to the proper scale. The analysis used to determine the scale can be used to help compute seasonal means and station weights for gages which are available operationally, but are not part of the calibration network or for new stations that are added to the operational network. There is also a better chance that additional data, such as upper air and other meteorological data that could be used to help define precipitation patterns, would improve operational data estimates if all data corresponds to the proper scale. No matter what network differences exist, it is critical that the operational input data be unbiased as compared to the calibration data. This is often an overlooked source of error in computed hydrographs during operational runs.

Model Structure

Model structure is of special concern at this meeting. Detailed discussions of several unit processes have been presented in the papers of the previous sessions. Two of the main questions to be discussed at this session are what unit processes need to be included in the snow related portion of a streamflow simulation model and what elements need to be included in the mathematical representations of these processes. Within O/H a number of things have been learned about the structure of a basic snow model and also about the errors associated with different mathematical representations of unit processes. For this discussion the model will be broken up into categories which coincide with the topics discussed in the previous sessions of this meeting.

1. Accumulation. In addition to unbiased estimates of the input data, two other features are needed in a basic snow model to adequately estimate the water-equivalent of the accumulated snow. The first thing needed is a method of determining whether the form of precipitation is liquid or solid. A simple air temperature divider is generally adequate for calibration. Large events that are misclassified by this simple method are usually easy to detect. These misclassifications should be corrected by manually editing the air temperature data since large errors in the form of precipitation make it difficult to determine the proper model parameter values for the watershed. Small random errors in the form of precipitation should not affect the parameter values. Operationally more data should be available, thus, large errors in the computed hydrograph should seldom be the result of incorrectly determining the form of

precipitation.

The second feature needed in the accumulation portion of a snow model is a parameter that indicates the ratio between the increase in water-equivalent of the snow cover and the MAP estimate obtained from precipitation gage measurements during periods of snowfall. This ratio is used to adjust the MAP estimate whenever the precipitation is assumed to be in the form of snow. Such a parameter can be referred to as a snowfall correction factor (SCF). The main reason for the necessity of SCF is to account for catch deficiencies of precipitation gages during periods of snowfall. Unless they are explicitly accounted for in the model, SCF can also implicitly account for factors such as net evaporation -- condensation loss, interception loss, and redistribution of snow across basin boundaries. It has been shown that the effect of an SCF parameter is significant [Larson and Peck (1974)]. If SCF is missing from a model, not only is the accuracy reduced, but the values of some of the other parameters will be distorted. Usually a mean value of SCF is adequate for calibration. The use of a mean value of SCF gives the best results when the number of storms which produce the snow cover are large so that variations in SCF values for individual storms tend to cancel. Operationally attempts to compute SCF for individual storms may be worthwhile, especially in areas with a relatively shallow snow cover.

2. Surface Energy Exchange. Air temperature (ambient) is an adequate index to surface energy exchange in most cases. Several elements are needed in the mathematical expressions used to compute snow cover energy exchange from air temperature.

a. A seasonal variation in the melt factor is essential primarily because of the variation in net available solar energy.

b. The use of a different melt rate during rain-on-snow periods is important in areas where rain-on-snow frequently occurs because different mechanisms dominate the energy exchange process during rain periods than during non-rain periods.

c. A method to compute energy exchange during non-melt periods is especially needed in areas where significant heat deficits can exist just prior to a melt period. The mathematical representation should recognize that energy exchange during non-melt periods is not just a loss of heat, but can be plus or minus.

Even though air temperature is generally a good index of snow cover energy exchange, it is not always adequate. In general air temperature is an inadequate index when meteorological factors affecting the energy balance deviate significantly from normal. Some specific cases when air temperature is not an adequate index to snow cover energy exchange that have been identified [Anderson (1976)] are days with:

a. very warm temperatures and little wind,
b. high dew-points and high winds, and
c. clear skies, but abnormally cool temperatures during the melt season after the snow is ripe.

In the first case a temperature index procedure will overestimate melt, while in the last two cases melt will be underestimated. The use of an energy balance method to estimate snow surface energy exchange should give improved results in these cases, as long as a minimum amount of reliable data are available. Besides air temperature, the minimum data needed for energy balance computations [Anderson (1976)] are dew-point, wind, and incoming solar radiation. These data are available on a real-time basis in some areas. Thus, an energy balance method of computing surface energy exchange could be included as an option in a snow model. It seems like this would be a worthwhile addition because of the potential for increased accuracy during extreme events.

In day-to-day use it is still unclear as to whether an energy balance method of computing surface energy exchange will give improved results over a temperature index procedure even if the minimum data for the energy balance method are available. Some of the reasons why an energy balance method may not give improved overall results are:

a. wind data are hard to extrapolate especially in mountainous areas,
b. incoming solar radiation data are also hard to extrapolate in mountainous areas from low to high elevations,
c. incoming longwave radiation and albedo are not measured and thus,

have to be estimated from other information,

d. methods to estimate radiation exchange in the forest are approximate, plus the needed data on cover density are not available on a wide scale, and

e. turbulent transfer over irregular terrain, with some vegetation cover, and a dynamic snow surface (roughness varies) is not completely understood.

Thus, because of modeling simplifications and data inadequacies an energy balance method of computing energy exchange may contain as much overall error as a temperature index procedure. This author is not aware of any comparisons that have shown otherwise. However, for river forecasting and especially for design studies, energy balance methods could be very beneficial because of the likely improvement in the simulation of extreme events.

3. Water Retention and Movement and Snow Cover Properties. Model components representing liquid water retention and movement are not as critical to the performance of the basic model as are surface energy exchange and accumulation components. However, water retention and movement are still significant components which should be included in a complete model. Liquid water retention is primarily of importance during ripening periods or at the beginning of rain-on-snow events. The effect of water retention is sometimes difficult to separate from the effect of a heat deficit, though by examining several years of record the effects of each process can usually be isolated. A constant water retention capacity is generally completely adequate.

The transmission of meltwater or rain through the snow cover is important in watersheds with relatively deep snow and quick responding hydrographs. In these cases, the absence of a representation of the transmission of water through the snow cover can result in distortions to soil-moisture or channel model parameters. The transmission of water through the snow results in both a lag and an attenuation. It is most important that this process be represented for ripe snow since that is the most common state during the period of snow cover runoff. Transmission of water through fresh snow or thick ice layers can be quite important at times; however, these situations are rare and are difficult to model with the data available for the basic model.

The computation of snow cover properties are needed in some situations. Depth and density need to be known if heat flow through the snow cover is to be computed. Heat flow through the snow might need to be computed to determine if freezing conditions occur in the soil below. Depth, density, and possibly even grain size might be needed to model the transmission of water through fresh snow. Except for purposes such as these, depth, density, and other snow properties do not seem to be necessary in order to adequately simulate streamflow in snow-covered areas.

4. Snow Cover Distribution. The distribution of snow cover over an area is determined by precipitation patterns, redistribution of snow, differential ablation rates, etc., which in turn are determined by such factors as meteorological conditions, terrain features, and vegetation cover. During the melt season, especially the later part, it is critical to know what the distribution of snow is over an area, most importantly what portion of the area is actually covered by snow. There are two basic approaches used in snow cover models to account for distribution and to compute the percentage of the watershed covered by snow. The first can be termed the zonal approach. In this approach the watershed is divided into a number of zones, usually with respect to elevation. Conditions within each zone are considered to be homogeneous, thus each zone is either completely covered by snow or the zone is bare of snow. Usually 5 or more zones are required to represent the distribution of snow over a watershed. The second approach can be termed the depletion curve approach. A curve defines the fraction of the area which is covered by show as a function of water-equivalent or some other index. In this approach a watershed is usually treated as a lump, but can be broken up into parts if the elevation range is very large.

There are advantages and disadvantages to both approaches of modeling snow cover distribution. The zonal approach is not readily applicable to flat terrain, though the area could be subdivided by vegetation zones if distinct differences in vegetation exist. In the depletion curve approach factors such as a reduction in the melt rate as the snow-covered area is decreased are implicitly included in the areal depletion curve. Thus, the computed snow-covered area is not always an approximation of the real snow-covered area, but instead of the effective area. By treating the area as a lump or subdividing into 2 parts as in the depletion curve approach, it is often easier to isolate the effect of a given area and change the proper parameter during calibration. However, the depletion curve approach may not be able to represent the actual extremes in temperature and snow cover that exist in mountainous watersheds with large elevation ranges as easily as the zonal approach. With both approaches care must be taken to avoid curve fitting as much as possible during calibration.

5. Snow-soil interactions. The most important snow-soil interaction in terms of streamflow simulation is the effect of frozen ground on snow cover runoff. Studies within O/H have shown that the effects of frozen ground can be very large. Fig. 4 shows two spring snowmelt periods on the Root River near Lanesboro, Minnesota. In one case, 1971, a deep snow cover had existed since late fall and therefore frozen ground was minimal. The model simulation of that spring is quite reasonable. In 1965, a very deep layer of concrete frost had formed prior to several heavy snowfalls in late winter. In 1965, the effect of the frozen soil on the spring runoff is dramatic. A model simulation study on the Chena River near Fairbanks, Alaska, however, showed the effect of frozen soil to be small even though the basin contains sizable areas of permafrost. Fig. 5 shows a typical simulation of one spring snowmelt period on the Chena. Likely reasons for the minimal effect of frozen ground on the Chena River streamflow simulations are the fact that similar soil conditions persist each spring and the general absence of concrete frost at the snow-soil interface.

Other snow-soil interactions which could have an effect on streamflow simulation are the effect of soil temperature beneath a snow cover on water retention and movement [Peck (1974)], and the migration of water from the soil to the snow by vapor flux [Santeford (1976)]. At the present time snow-soil interactions have only in the simplest form been added to conceptual streamflow simulation models. Thus, it is unclear as to exactly what features need to be added to the structure of a model in order to adequately model the effect of frozen ground and the other interactions.

Model Calibration

The fastest way to calibrate a model to a large number of watersheds would be by automatically optimizing the parameters. This would also permit hydrologists with only a general knowledge of the model to perform the calibration. However, for the models developed within O/H, the recommended calibration procedure is a combination of manual (trial-and-error) and automatic techniques with more emphasis currently placed on manual calibration. The reason for this is simply that the currently available automatic parameter optimization technique used within O/H [Monro (1971)] just is not able to produce an adequate calibration by itself. This is true when snow is not included and is accentuated when the snow model is used. Research into improved methods of automatic parameter optimization is starting, but the development of a completely automatic calibration procedure is not envisioned.

The keys to manual calibration are to have a model in which the effect of each parameter on model response is reasonably unique and for the hydrologist to have a complete understanding of the model. The second key is why the developer of a model tends to be the most proficient at calibrating that model. This calibration expertise is not related to any mystical quality that the person or the model possesses, but just to the time that has been spent developing and working with the model. This amount of time is not needed for a user to become proficient at calibration, but more than a few days of indoctrination is required.

Statistical summaries are important in assessing the overall accuracy of the calibration and in some cases to assist in adjusting parameter values, but no single statistic or combination of statistics can completely reflect the performance of the model. The computed and observed hydrographs are the most important displays to be examined. The calibration is considered complete when all bias (includes overall, seasonal, flow-internal and any other bias) has been reasonably removed from the computed hydrograph.

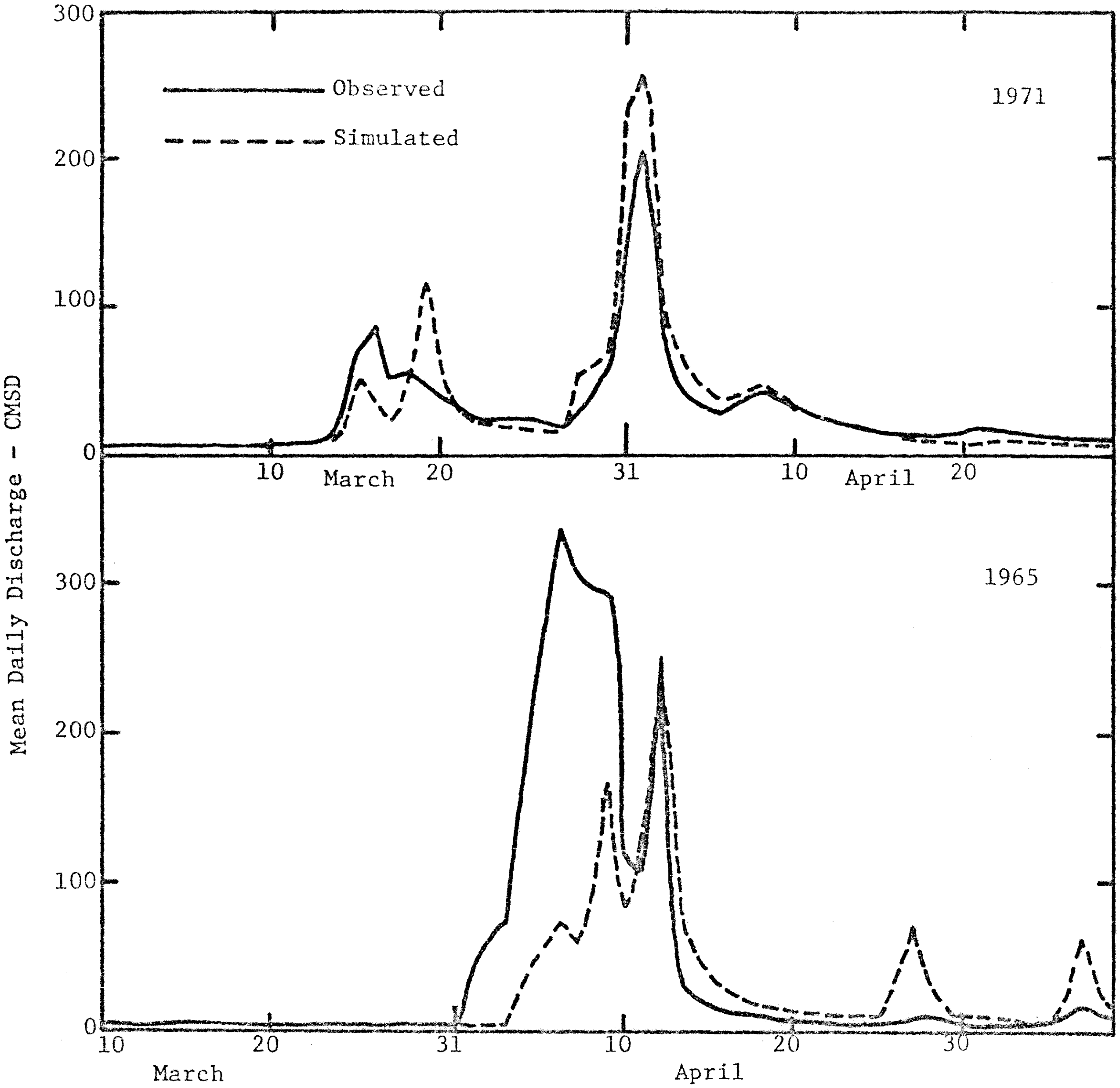

Figure 4. Simulation of spring runoff on the Root River near Lanesboro, Minnesota. In 1971 there was very little frost, while deep concrete frost existed prior to snowmelt in 1965.

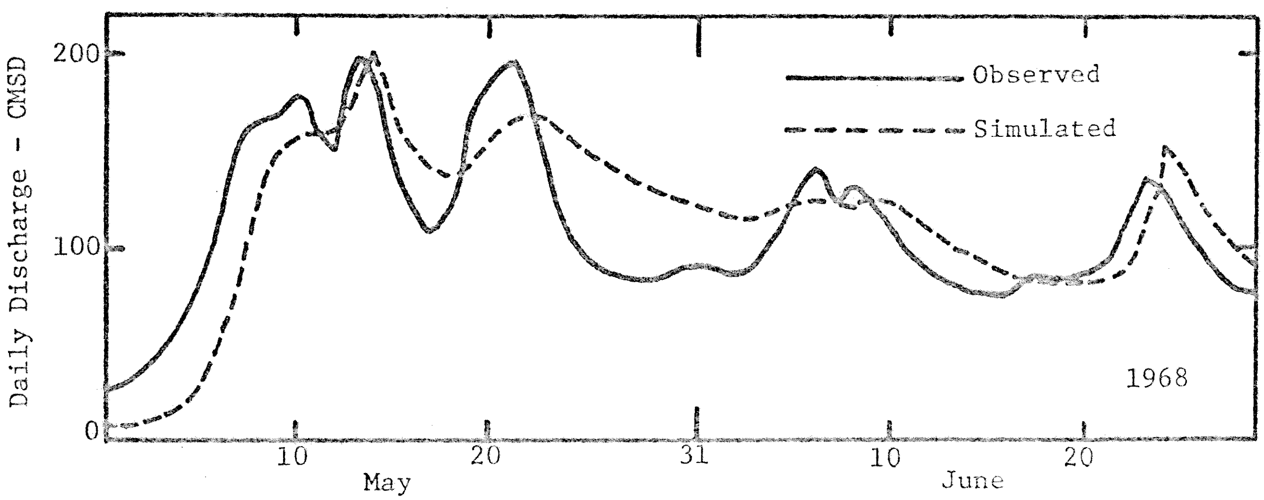

Figure 5. Typical simulation of spring runoff on the Chena River near Fairbanks, Alaska.

All of the mathematical representations of unit processes within the NWSRFS snow and soil-moisture models are expressed in parameterized form except for the snow cover areal depletion curve and an evaporation adjustment curve which are in tabular form. So far it has not been possible to find an equation that would contain the flexibility needed to represent the various shapes of the areal depletion curve. The total number of parameters in the NWSRFS models is quite large (about 13 snow and 17 soil-moisture parameters, depending on what is defined as a parameter). However, the effect of most parameters on model response is reasonably unique. Part of the reason for the relatively large number of parameters is that the objective is to be able to accurately simulate the entire spectrum of streamflows. Another part is that the aim is to be able to simulate streamflow throughout the entire United States. In any one region only a portion of the parameters usually have a significant influence on model performance. Models which are developed for use within a specific hydrologic regime can generally have a simpler structure and fewer parameters and still do a completely adequate job.

Updating the Model

Updating is relevant only to real-time applications of a model such as river forecasting. Updating involves the adjustment of the model output and/or one or more of the state variables of the model based on real-time observations which are in addition to the data required by the basic model. An advantage of a physically based model is that besides the output, a number of internal state variables representing physical quantities which will ultimately affect streamflow are computed. Thus, each of these internal states can be updated. Over the long run, this will improve future model performance. In the case of a snow model, the state of the snow cover can be observed before snow cover runoff even begins. This allows for a state variable like water-equivalent to be adjusted prior to when melt begins and the resulting streamflow can be observed.

It is critical to realize that updating should involve a combination of information by taking into account the uncertainty associated with each quantity. Updating is not merely using one estimate in place of another, such as using a satellite estimate of areal snow cover in place of the value computed by the model. Since all information has some error associated with it, each new piece of information merely adds to that already available. A lot of time and effort is often spent to develop alternative ways to estimate the same quantity using different information, yet even a better answer would be possible if the information was combined. Updating is one method of combining information.

The emphasis in updating streamflow simulation models for use in snow-covered areas should be placed on those components of the basic model which have the most effect on deviations between computed and observed streamflow.

1. Accumulation. Errors in the runoff volume produced by snowmelt are primarily the result of differences between computed and actual areal water-equivalent just prior to the melt season. Two general methods seem to be available to improve the model estimate of areal water-equivalent. The first is to improve MAP estimates by using meteorological data. In flat terrain this may merely involve the use of wind data to adjust for deviations between the actual gage catch deficiency and the mean gage catch deficiency parameter, SCF, used in the basic model. In mountainous areas, upper air soundings and other meteorological information could be combined with raingage data and orographic parameters to adjust for differences between the actual precipitation pattern and the normal pattern. Several studies have already been conducted regarding the use of meteorological information for estimating precipitation patterns in mountainous areas [Coltan (1976), Elliot (1977), Rhea (1978)].

   The other method of reducing runoff volume errors is to update the model estimate of areal water-equivalent based on actual measurements of water-equivalent. Point snow course data or measurements of water-equivalent obtained along a flight line using the aerial gamma radiation method [Peck and Bissell (1973), Peck et al (1977)] could be used for these updates. An estimate of areal water-equivalent could be computed from the measurements and then weighted along with the original model estimate to obtain the updated value. Such a method, using snow course data in mountainous areas, has recently been developed [Carroll (1978)]. The use of actual measurements of water-equivalent for updating may have an advantage over merely improving MAP estimates because variations between actual and computed water-equivalent are only partly the result of errors in precipitation input. However, the reduction in error by either method will largely depend on the available data. A combination of the two methods should produce even better results.

2. Surface Energy Exchange. The main cause of error in the timing of snow cover runoff is the daily variation between actual and computed snowmelt. Two possible methods are suggested to adjust for errors in surface energy exchange during the melt season. The first suggestion is to adjust the melt rate before the resulting runoff is observed in the stream. Updating before the runoff can be observed in the stream would result in an increase in the lead time of the forecast. This could be accomplished by using energy balance computations at points or over small watersheds, where the necessary data are available, to update the melt factor used on other watersheds in the region. The primary purpose of such a procedure would be to adjust for errors in the melt factor during extreme events.

The second suggestion for adjusting errors in snow cover runoff is to update the model based on deviations between observed and computed streamflow. Two such update techniques have been applied to conceptual models when snow is not included. The first makes assumptions as to the most likely cause of error and adjusts those sources of error until the computed hydrograph agrees with the observed within a specified tolerance [Sittner and Krouse (1978)]. The state variables of the model are adjusted in the process. The second approach uses a Kalman filter to adjust the state variables of the model and the computed streamflow [Kitanidis and Bras (1978)]. Both of these approaches could also be applied to a streamflow simulation model which includes snow.

3. Snow Cover Distribution. Probably the second largest source of a timing error during the melt season is deviations from normal in the accumulation and melt patterns. This error primarily shows up in the areal extent of snow cover, thus, this is the quantity to adjust. The most likely update approach would be to combine observations of the areal extent of snow cover, probably from satellites, with the model estimate. Even though a lot of effort has been spent to obtain satellite estimates of areal snow cover, this author knows of no objective update technique which uses these data.

4. Errors due to Processes not in the Basic Model. If processes which are not represented in the basic model, like frozen ground and rain on fresh snow, are the primary source of error, this will cause problems. The update technique will try to alter the state variables of those processes which are included in the model to correct the error. This will result in at least a temporary distortion of some of the state variables. Objective updating techniques should be able to reduce random errors between computed and observed streamflow, but would not be expected to correctly handle a bias which is the result of a unit process not being included in the model. The best solution, if such a problem occurs frequently, is to include a representation of the missing unit process in the basic model.

Whereas, much work has been done in the area of model structure, as evidenced by the large number of conceptual snow models described in the literature, there has been very little work done on objective updating techniques, especially with regard to snow models. This area needs more work. There seems to be a greater awareness of the importance of objective updating and an increased interest in the subject as evidenced by two recent symposiums [IIASA(1976), Univ. of Pittsburgh (1978)]. Most of the initial work has avoided snow, as is usually the case, since snow tends to complicate already difficult problems.

CONCLUSIONS

Much has been accomplished in the last 15-20 years in terms of the development of conceptual streamflow simulation models for use in snow-covered areas. Reasonably accurate continuous simulation models have been available for a number of years. This is not only true within O/H, but in many other countries and organizations. These models are currently used for river forecasting and for various design and watershed management studies. The research goals in snow hydrology which are related to model development and use need to change as the models mature and the use of models expands. In the beginning unit process studies, which are the foundation of good models, and studies to develop and test model structure were of prime importance. Now that reasonably reliable models are available many of these studies are not as urgent. Certain components of the model structure still need improvement, thus, further work in these areas is needed. The main deficiencies of models used in snow-covered regions and therefore the areas which require the most study seem to be snow-soil interactions and energy balance computations on an areal basis. Further work is also needed on better procedures to account for the distribution of snow, represent the movement of water in snow, and determine model parameters for use in ungaged areas. In addition, further research is needed to improve calibration techniques so that models can be implemented faster and more reliably. The development of entirely new models is very questionable in most cases.

Research must also continue on improved measurement techniques for obtaining accurate and reliable data for use with models. This includes not only better input data for the basic model, but also information that can be used to update models which are used for real-time applications such as river forecasting. Objective updating techniques have virtually been neglected in the past. This is an area that needs to be developed and expanded in the future. In many cases, update methods are the main way to fully realize the potential benefits of improved measurement techniques and to increase the utility of the streamflow simulation models.

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