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Progress in Developing an Operational Snowmelt-Runoff Forecast Model with Remote Sensing Input

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In order to apply the snowmelt-runoff model (SRM) or any snowmelt model operationally, a logical progression is required from utilization in the pure simulation mode when all data are known to the pure forecasting mode when no future data are known. Significant progress has been made and results are presented which include pure simulation, simulation when the actual output data are unknown, simulation when estimated or forecasted snow cover input data are employed, simulations or forecasts with updating using observed streamflow, and first attempts at true forecasts. Based on these results, an objective method for forecasting with SRM is being developed.

Introduction

The snowmelt-runoff model (SRM) is one of a very few models that requires remote sensing-derived input (in the form of areal extent of snow cover). SRM has been successfully run with different types of snow cover data including those derived from ground based, aircraft, and satellite observations. The basic model is described by Martinec *et al.* (1983) and a recent microcomputer version of SRM is explained in detail by Rango and Roberts (1987).

Most work thus far with SRM has not been in real time but rather has been conducted after the fact in attempts to duplicate (simulate) the observed hydro-

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graph. Although most SRM testing has been in the simulation mode, considerable effort has also been expended in developing a forecast procedure. The various stages in development of a forecast approach, the first of which is simulation, have yielded positive results that may be useful for other snowmelt-runoff modelling and forecasting efforts.

Regular Simulations

A model is usually verified and, if necessary, modified as a result of a series of simulations conducted on a variety of basins. In the case of snowmelt-runoff models, the most useful simulation period is the entire snowmelt-runoff season. By conducting these simulations under a variety of conditions, the applicability of the model in different snowmelt situations can be assessed. For SRM, a comprehensive record of quantitative model performance on a large number of basins has been kept. These records were published by Martinec and Rango (1986). The average seasonal runoff volume difference was 4.4 % and the average R^2 value measuring the correspondence of the daily flows was 0.84. R^2 is the Nash-Sutcliffe coefficient

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (Q_i - Q_i')^2}{\sum_{i=1}^{n} (Q_i - \bar{Q})^2}$$

where

Q_i – the measured daily discharge,
Q_i – the computed daily daily discharge,
$\bar{Q}_i$ – the average measured discharge, referring in this case to the year or snowmelt season in question,
n – the number of daily discharge values (Nash and Sutcliffe 1970).

When running a model in the simulation mode, all input (temperature, precipitation, and snow cover in the case of SRM) and output (streamflow) data are known. The modeller must predetermine the model parameters for a particular basin and year. After the simulated flow is generated, it must be compared with the observed streamflow and the performance evaluated. Some models can automatically optimize model parameters without constraint to improve the fit whereas other models (like SRM) restrict modifications to physically reasonable values. In either approach, a set of parameters can be established for each simulation. The values of these parameters are reported by Martinec and Rango (1986) for all the SRM simulations available. A recent simulation employing SRM is shown for the Henry's Fork basin in Idaho, U.S.A. in Fig. 1.

The simulation phase is valuable because much is learned about the strengths

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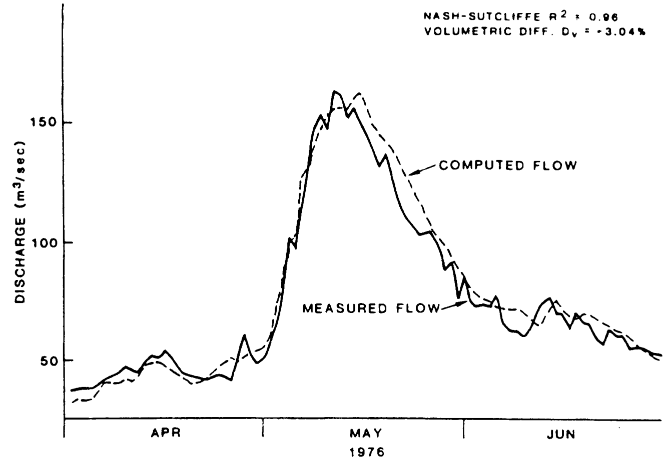

Fig. 1. Example of snowmelt runoff simulation for the Henry's Fork basin (2,694 km^2) in Idaho, U.S.A. using the snowmelt-runoff model (SRM).

and weaknesses of a model and how to apply it in various situations. Utilizing a model in the simulation phase is also the easiest situation because all data are known. The results of the simulations are really just the first step in making progress towards employing the model for forecasting.

Simulation without Adjustments

Although simulation without knowledge of measured output data (streamflow) should be similar to simulations when streamflow is known, results are not as good because most model operators will make adjustments during the snowmelt season when streamflow data are available in order to improve the correspondence between computed and observed values. These adjustments may not be as formal as some of the updating procedures to be discussed later, but they definitely can improve model performance. Simulation without knowledge of the output is the next step towards being able to forecast with a model, and it also has direct applications to estimating flow on ungauged watersheds.

An example of a test to see how a model performs in this kind of simulation mode was conducted by the World Meteorological Organization (1986). Data sets for six basins were established with two separate periods available, namely, a calibration period and a verification period. During the calibration period, the complete input and the output (streamflow) data are known. The parameters for the various calibration years are established (and for most models optimized) based on the streamflow data. During the verification period, the input data are again available, but the streamflow data are withheld from the model operator.

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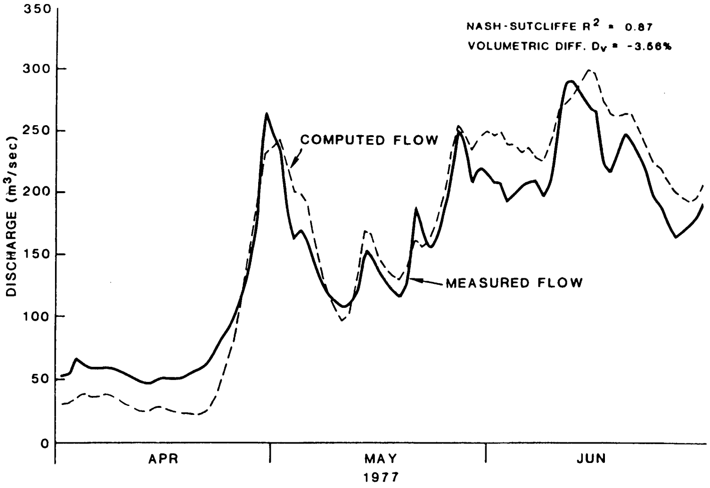

Fig. 2. Snowmelt-runoff simulation (1977) in the verification period for the Durance River basin (2,170 km^2) in France using SRM.

The major differences between this situation and forecasting are that you have to simulate runoff for the entire snowmelt season with no knowledge of the actual flow, and that you have perfect knowledge of the input data during the period, neither of which is true for real-time forecasting.

In this type of operation, the coefficients have to be predetermined and should not be modified during the simulation because we have no knowledge of streamflow until the entire simulation period is over. It is of course possible that some models might institute changes in coefficients as the input data become available if it could be established that there was a strong connection between the input data or some intermediate value and the output. In this case all input data for the snowmelt season are known so no coefficient changes should be necessary.

The previously mentioned World Meteorological Organization (WMO) project on Intercomparison of Models of Snowmelt Runoff (World Meteorological Organization 1986) produced valuable data for comparing model results. SRM, which was the only model of the 11 tested using remote sensing data, performed without problem on those basins with remote sensing data available. Figs. 2 and 3 are examples of simulations produced during the verification period for the Durance River basin in France. The performance statistics were calculated after the simulated values were delivered to WMO. The results obtained from SRM in the WMO project indicate that the verification period performance criteria are in the general range of prior simulations, but that when compared with results during the calibration period, they are somewhat degraded as would be expected. At the same time, a number of the tested models delivered surprisingly better results in the verification period than in the calibration period.

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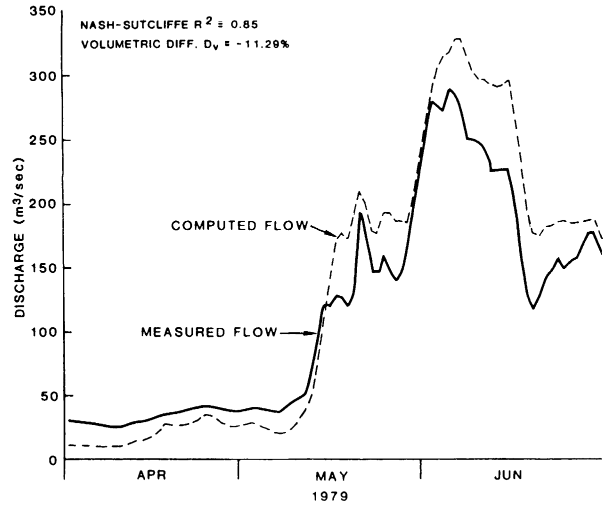

Fig. 3.
Snowmelt-runoff simulation (1979) in the verification period for the Durance River basin (2,170 km^2) in France using SRM.

Simulations/Forecasts with some Unknown Input Data

For forecasting, input data are known up to the time of forecast, but not for the future forecast period. In the case of SRM, one of the three major inputs is the percentage of a basin elevation zone covered by snow. In the true simulation mode, the model operator has a complete knowledge of the basin snow cover values throughout the snowmelt season. In a real-time situation, snow cover data up to the start of the forecast period would be available, but then an estimate of the depletion of the snow cover during the entire forecast period has to be made. According to Martinec (1985), this future depletion can be estimated for example in weekly steps by taking into account the initial snow reserves (snow water equivalent), future temperature, and future precipitation. Martinec and Rango (1987) suggest development of a family of historical snow cover depletion curves or nomographs for a specific elevation zone with each curve indicative of a particular snow water equivalent at the beginning of the snowmelt season. Using a measurement of snow water equivalent on April 1, a depletion curve to use throughout the snowmelt season can be selected. The specific curve being used can then be updated when actual snow cover data become available during the snowmelt season.

To approximate a forecasting situation, simulations starting on April 1 were performed with forecasts or estimates of the snowmelt season snow cover values. All other input data were known. This approach was first employed with SRM on the South Fork of the Rio Grande basin (559 km^2) in Colorado, U.S.A. for 1980 (Shafer *et al.* 1982). In this first attempt only an average snow cover depletion type curve for the South Fork basin was used with no attempt to account for annual

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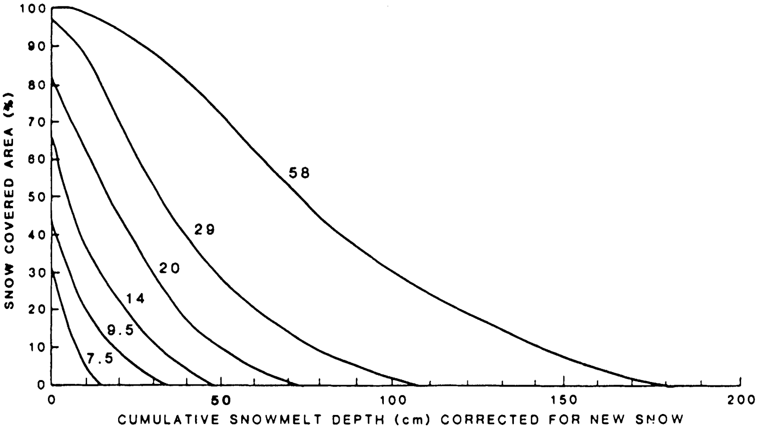

Fig. 4. Nomograph for selecting a snow cover depletion curve for zone B(2,925-3,353 m) of the Rio Grande basin above Del Norte, Colorado, U.S.A. based on the April 1 estimated snow water equivalent in cm.

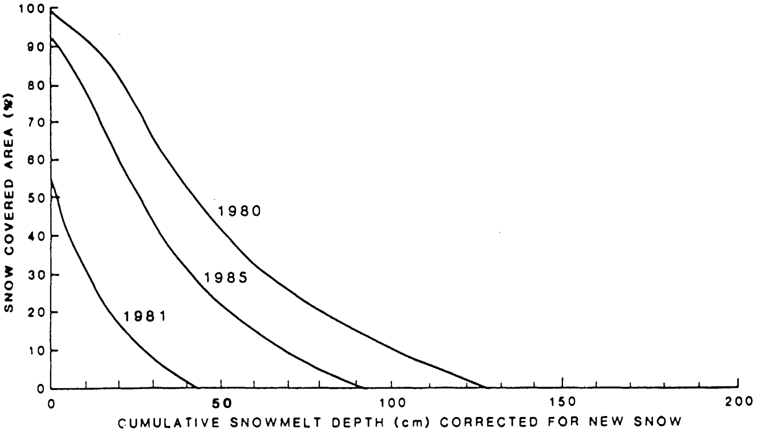

Fig. 5. Snow cover depletion curves for three years selected using averaged snow water equivalent (snow course) values for zone B of the Rio Grande basin and Fig. 4.

differences in snow water equivalent. The second time it was used was a matter of necessity. It was necessary to simulate flow in the upper Rio Grande basin for several years. In certain years (1980, 1981, and 1985) not enough snow cover data during the snowmelt season were available for constructing an observed depletion curve. As a result the nomographs referred to above were constructed and used to select the appropriate curve. Fig. 4 is an example of the nomograph of depletion curves for the zone B (2,925-3,353 m) of the Rio Grande basin. Each curve is labeled with a representative snow water equivalent value in cm. When the snow water equivalents for the years 1980, 1981, and 1985 were calculated, the snow

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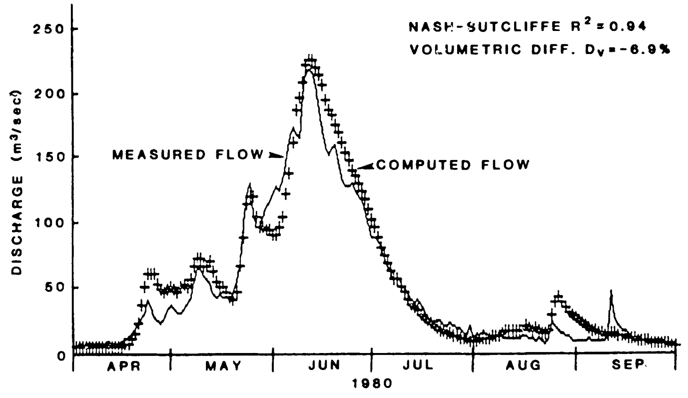

Fig. 6. Snowmelt-runoff simulation for 1980 on the Rio Grande basin (3,419 km^2) above Del Norte, Colorado using estimated (forecast) snow cover input data and SRM.

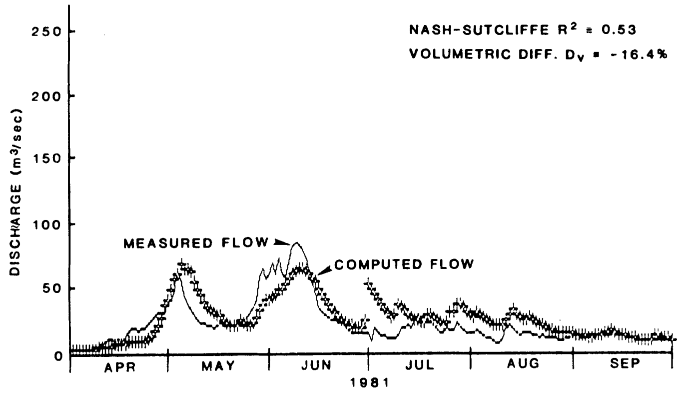

Fig. 7. Snowmelt-runoff simulation for 1981 on the Rio Grande basin (3,419 km^2) above Del Norte, Colorado using estimated (forecast) snow cover input data and SRM.

cover depletion curves in Fig. 5 result. These curves were then utilized to provide the snow cover input data used to forecast the snowmelt-runoff for the three years in question. Table 1 presents the summarized statistics for the four years in which the snow cover input was estimated (or forecast) and not observed. The results for 1980 (see Fig. 6) and 1985 for the Rio Grande basin were excellent, and the result for the low runoff year of 1981 (see Fig. 7) was also quite reasonable when compared to simulation results from other low runoff years on the Rio Grande and other basins.

No updating with actual snow cover data were used in these simulations. If updating was employed in these years, an improvement in simulation or forecast accuracy would be expected. The results are very encouraging and further effort needs to be expended in order to better define the method for selecting the curves

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Table 1 – Performance statistics for SRM snowmelt runoff season simulations using estimated (forecasted) snow cover input data.

Basin	Year	R^2	*Dv*
South Fork of Rio Grande	1980	0.83	-14.7%
Rio Grande above Del Norte	1980	0.94	- 6.9%
Rio Grande above Del Norte	1981	0.53	-16.4%
Rio Grande above Del Norte	1985	0.91	- 3.6%
	Average	0.80	-10.4%

and then to update them as the season progresses. This research is currently ongoing.

Simulations/Forecasts with Updating

The WMO has attempted to create a real-time forecasting situation as a follow-up to the previously mentioned WMO project. This ongoing project is entitled "Simulated Real-Time Intercomparison of Hydrological Models" and operates as follows: In this project model owners assemble with their models at a common test site. Calibration period data have been released for prior testing and optimization of parameters. Most verification period data including streamflow, temperature, and precipitation have been withheld. Additionally, periods shorter than the entire snowmelt season are used for forecasting, and there may be several overlapping forecast periods in the snowmelt season. The input data are released to the modellers just before they are to make their forecasts in order to approximate a real-time situation. In this project the input data are the actually observed data for the forecast period.

As in prior tests, however, all input data were perfect, *i.e.,* no forecasting of input data was necessary. The only differences from prior simulation projects were that the modellers didn't get input data to process or examine until the operational phase of the project was begun and that updating could be performed according to each individual model's updating methods. Because all input data were known perfectly, the only possible discrepancies were those that may have been caused by human errors during processing of the data. Because updating is allowed, one might expect better performance than prior simulations with no updating. This may be counterbalanced by the use of shorter periods of time which typically result in lower performance evaluation statistics.

SRM has an option that performs only a very simple form of automatic updating, namely, every 7th day updating of the computed flow with the actual observed flow. At the moment, the frequency of updating is arbitrary and it could be changed in the future to match the frequencies of input variable forecasts, such as

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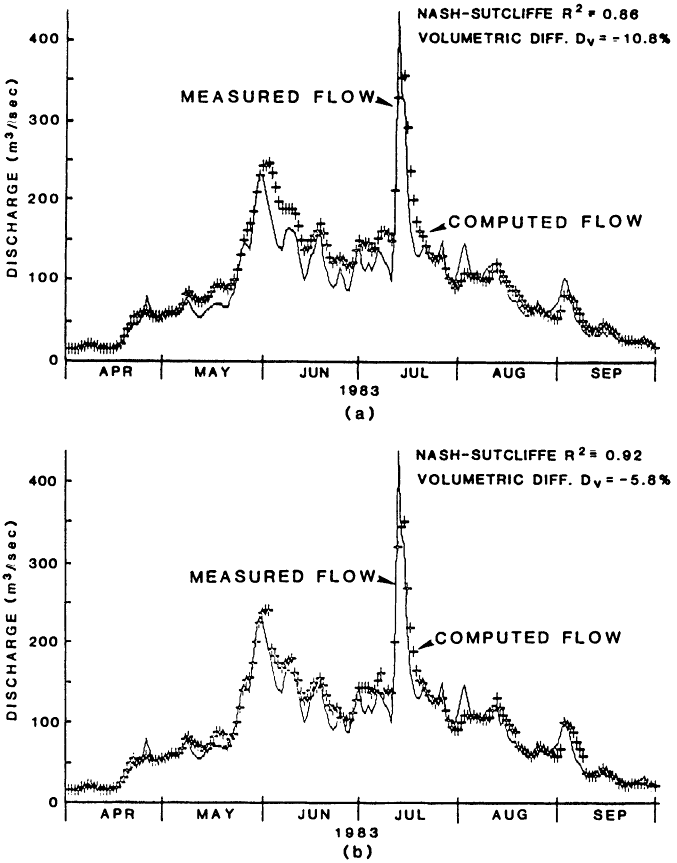

Fig. 8. Snowmelt-runoff simulation for 1983 on the Illecillewaet River basin (1,155 km^2), Canada, using the (a) nonupdated and (b) updated versions of SRM.

3-5 days. Because prior SRM simulations had been characterized as extremely good, the updating option in SRM was never employed. Recently, however, this automatic updating has been attempted in several specific situations. The first attempt at updating was performed on the South Fork of the Rio Grande for 1977. This was an extreme drought year. Low flow years result in low performance statistics and this year was no exception. The every 7th day updating with actual streamflow provided a R^2 improvement from 0.69 to 0.78. In the second WMO project, simulations were requested for the entire snowmelt season with no updating and with normal model updating. This test was performed on the Illecillewaet River in Canada for the years 1983 and 1984. Fig. 8 shows the 1983 nonupdated versus the updated hydrograph. For this second WMO project, updating was tested for shorter forecast periods on the Illecillewaet River basin for the same 2 years. Table 2 presents the statistical results of the SRM updating.

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Table 2 – SRM updating results using the Nash-Sutcliffe R^2 and volumetric difference, *Dv*, values.

	No updating		Updating		Simulation period
	R^2	*Dv*	R^2	*Dv*	*d*
1977 South Fork Rio Grande	0.69	- 0.5	0.78	- 0.9	183
1983 Illecillewaet	0.86	-10.8	0.92	- 5.8	183
1984 Illecillewaet	0.84	-10.5	0.89	- 4.4	183
1983 Illecillewaet	0.71	-15.4	0.82	- 8.0	50
1984 Illecillewaet	0.61	-14.1	0.66	-11.3	50

It is obvious that updating, even in a simple algorithm, has positive benefits for improving simulations or forecasts. Where it is possible, simple and objective forms of updating should be used. This updating should be of a type that can be easily duplicated by a user other than the model developer. The most logical and easiest variable to update would be the streamflow, however, updating may be performed on other input (*e.g.* precipitation) or state (*e.g.* soil moisture) variables as well as model parameters (*e.g.* the runoff coefficient). Also, the areal extent of snow cover can be updated using incoming satellite data. Whatever method is used, it should be objectively defined as opposed to some form of manual subjective updating that will be hard to transfer to interested users.

Forecasting without Prior Knowledge

In a true forecast situation, the modeller has no prior knowledge of any future input or output variable, and the forecast must be performed in real time. Each model developer should be aiming for effective model operation under these conditions. In addition, modelling in the forecast mode should be able to be duplicated by users other than the model developer.

Potential errors are introduced into the forecast procedure by the necessity to use forecasts of temperature, precipitation, and snow cover extent for the forecast period. The longer the forecast period, the greater the chance for error. The same potential for error exists when historical or synthetic data inputs are used.

While these methods are still being developed, it is sometimes necessary to perform forecasts on an ad-hoc basis. Jones *et al.* (1984) used SRM to forecast snowmelt runoff on the Cache La Poudre River in Colorado in 1983 for flood potential predictions. The period of operation was the second half of June at the time of peak runoff. SRM was used to provide 1-3 day forecasts during the period of operation. Special meteorological forecasts of temperature and precipitation were prepared and light aircraft flights over the basin were used to obtain snow-

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covered area by elevation zone. The data produced by SRM were quite useful for flood prevention decisions. The authors reported that their daily forecast runoff values were within 20 percent of observed streamflow values.

Forecasts were also prepared on the Rio Grande basin in Colorado for 1987 using SRM. Early results were very close to actual streamflow, however, the forecast evaluation is still ongoing. It was apparent that the correspondence of forecast and observed streamflow was heavily dependent on the future temperatures and the snow cover depletion curve chosen. Because precipitation is generally not significant during the snowmelt season in these areas, it is only of secondary importance except when an extraordinary summer precipitation event occurs.

In addition to finalizing the forecast procedure to use with SRM, it is extremely important to resolve how input variables such as temperature should be forecast. The use of updating tied to input variables, as well as to streamflow, must also be addressed in order to provide accurate forecasts. The specific steps to use in producing a forecast have to be understandable for those users less experienced than the model developer. Ongoing research to develop expert systems for SRM (Engman *et al.* 1986) may be of great value for forecasting with SRM.

Results and Conclusions

A significant amount of research must be conducted to develop objective forecasting techniques for SRM and other models. Real progress has been made in using SRM for various types of simulations which has helped define the forecasting procedures. There are several steps in the transition from the pure simulation mode to the forecasting situation. Each of these steps has been valuable and led to important accomplishments such as selection of future snow cover depletion curves and rational updating methods.

To put SRM in an operational forecast mode, certain progress is needed. A method must be developed to objectively select future snow cover depletion curves and to modify the curves based on actual observations. Rational, physically-based, and objective ways to employ updating methods should be applied to input variables and model coefficients as a supplement to updating with actual streamflow. Decisions have to be made on how to employ forecasted or assumed meteorological input variables that are likely to have significant errors. It may also be necessary to provide measures of reliability of SRM forecasts based upon the kind of input data used.

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