EVALUATION OF ENHANCEMENTS TO THE SNOWMELT RUNOFF MODEL

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ABSTRACT

As part of a larger effort to develop tools for improved short-term (1-2 week) streamflow forecasting in snowmelt-dominated basins, the Snowmelt Runoff Model (SRM) is used to simulate and forecast streamflow in the Big Wood River basin, Idaho. Several enhancements to SRM will be evaluated: a) a new method to estimate degree-days; b) new techniques used to assign and temporally update model parameters (degree-day factor and runoff coefficients) that make use of data from SNOTEL sites located within the basin and; c) the incorporation of relative humidity and wind speed data into a new (optional) model module designed to improve model performance during rain-on-snow events. Model results will be evaluated to determine the usefulness of these enhancements.

INTRODUCTION

In the Western United States, water supplies are often derived from runoff due to snowmelt. Thus knowledge of the timing and rate of snowmelt is crucial for decision-makers in federal and state agencies, as well as citizens whose livelihoods are directly affected by water availability (for example, farmers and tourism operators). Also as the region's population increases, bringing more industry, there is and will be ever-increasing demands on water resources. Consequently, the objective of this project is to develop a prediction system for short-term streamflow forecasts in the mountainous regions of the Western United States.

Snowmelt runoff may be simulated using either an energy balance approach or a temperature index (degree-day) approach (Singh and Singh, 2001). Energy balance models are physically correct, but demand a lot of data that is often not readily available. Conceptually-based, degree-day models, on the other hand, lack the complexity of energy-balance models and often rely on commonly available input variables, which make them suitable candidates for operational implementation. These models, however, are not without limitations. Degree-day models often use model parameters to simplify hydrologic processes and often ignore the physics behind them. Because of this, there is a desire to include more detail (complexity) in these models, yet maintain their operational feasibility.

This paper is focused on several enhancements to the Snowmelt Runoff Model (SRM), which are designed to optimize model efficiency and to aid in its operational implementation. These enhancements include: 1) the incorporation of relative humidity and wind speed data to increase model accuracy during rain-on-snow events (i.e. condensation melt), 2) the use of SNOwpack TELemetry (SNOTEL) data to assign and update model parameters, and 3) the use of an alternate scheme to estimate daily average temperature.

STUDY AREA

The Big Wood River Basin (Figure 1), located in south-central Idaho, has an elevation range of 250 to 3,630 meters. It's rugged, mountainous landscape and the fact that approximately 50% of the basin's total annual precipitation falls in the form of snow during the winter months, make it a suitable area for the study of snowmelt runoff. Our study area is limited to a subsection of the basin (~1,625 km^2) located upstream of Magic Reservoir. This is important because the model is set up to simulate natural flow, not controlled flow.

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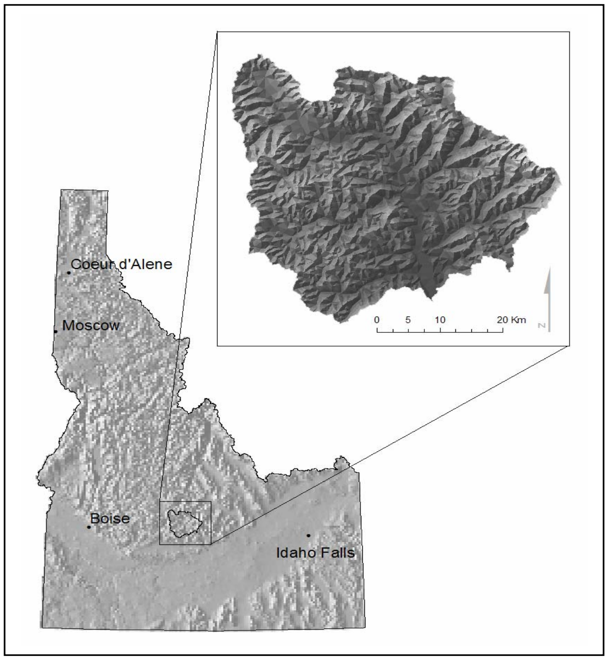


Figure 1. Big Wood River Basin

DATA AND METODOLOGY

SRM, used in this study, is a conceptually based degree-day model designed to simulate and forecast daily streamflow in mountain basins where snowmelt is a major runoff factor (Martinec et al., 1994). Model input variables are distributed among several elevation zones within the watershed, and include daily estimates of temperature, precipitation, and snow-covered area (SCA). The following equation is used in SRM to estimate daily snowmelt:

$$Q_{n+1} = [C_{Sn} * a_n (T_n + \Delta T_n) S_n + C_{Rn} * P_n] A*10{,}000 / 86{,}400 (1-k_{n+1}) + Q_n k_{n+1} \quad (1)$$

where Q ($m^3 s^{-1}$) is the average daily stream discharge, C_S and C_R are runoff coefficients, a (cm $^oC^{-1}$ day^{-1}) is the degree-day factor, T (^oC day^{-1}) is the number of degree-days, ΔT ($^oC/100m$) is the temperature lapse rate, P is the daily total precipitation (cm), S (%) is the snow-covered area (SCA), A (km^2) is the area of the basin, k is the recession coefficient, n is the sequence of days during the simulation period, and 10,000/86,400 is the conversion from cm km^{-2} day^{-1} to $m^3 s^{-1}$. Daily maximum (T_{max}) and minimum (T_{min}) temperature data were obtained from six SNOTEL sites located either within or just outside the basin. These data were then averaged to create a synthetic station and extrapolated to the hypsometric mean elevation of each elevation zone using the standard lapse rate of (0.65 $^oC/100m$). SNOTEL data, including daily total precipitation, was obtained from the Natural Resources Conservation Service (NRCS). The MOD10A1 operational MODIS snow cover product, obtained from the National Snow and Ice Data Center (NSIDC), was used to obtain estimates of SCA for input into the model. This is a daily product with a spatial resolution of 500 meters. Simulated and actual ground-based streamflow measurements (historical streamflow simulations) are compared to assess the performance of these enhancements. Years were chosen so that the model performance could be evaluated during both a relatively wet (2000) and dry year (2001). Actual stream discharge data for the stream gauge at Hailey, ID was obtained from the United States Geological Survey (USGS).

Estimation of Degree-Days

There are several available methods used to convert daily temperature values (T_{max} and T_{min}) to degree-days. A simple average of T_{max} and T_{min} is most common (equation 2), however it may not always result in accurate daily temperature estimates. Problems occur during the early portions of the snowmelt season when the temperatures hovers around the melting point (0^oC). Underestimates of melt may occur, for instance when T_{max} is above 0^oC and

T_{min} is below 0°C. For example if T_{max} was equal to +5 °C and T_{min} was equal to -5°C no melt would be calculated. This situation might occur, but it is more likely that melt will occur during the day-time hours (when T_{max} typically occurs).

$$T_n = [((T_{max} - T_{min}) / 2) - 0] \quad (2)$$

The triangular method, used in this study, weighs T_{max} slightly higher than T_{min} and would result in snowmelt under these conditions. The equation for the triangular method is as follows:

$$T_n = (T_{max} / 2) * (T_{max} / (T_{max} - T_{min})) \quad (3)$$

Estimation and Temporal Updating of Model Parameters

The principal model parameters, found in SRM, are the degree-day factor (*a*) and the runoff coefficients (C_S and C_R). The degree-day factor converts the number of degree-days into the daily snowmelt depth. The runoff coefficients represent the difference between the available water volume (snowfall + rainfall) and the outflow from the basin. These parameters can either be derived from field measurements or estimated by hydrological judgment taking into account the basins characteristics, physical laws, and empirical relationships (Martinec et al., 1994). Without significant knowledge of the basin being modeled, these parameters may be difficult to estimate, and may ultimately result in limited applicability of the model for operational streamflow forecasting. Thus methods need to be developed to accurately assign and temporally update these parameters, while limiting the time and effort spent by the forecaster. Also, available data needs to be utilized sufficiently. In this study the degree-day factor is estimated using the following equation developed by Martinec (1975) for use with SRM:

$$a = 1.1 (\rho_s / \rho_w) \quad (4)$$

where ρ_s is the density of snow and ρ_w (kg m^{-3}) is the density of water (1000 kg m^{-3}). Snow water equivalency (SWE) and snow depth data, obtained from SNOTEL sites, are used to estimate the density of the snowpack. The density of the snowpack is calculated using the following equation:

$$\rho_s = (SWE * \rho_w) / d_s \quad (5)$$

where d_s is the depth of the snowpack (cm). A regression line is fit to the data to smooth out short-term variations (Figure 2). This method can then be repeated for each individual SNOTEL station and the data can be used to determine the degree-day factor for each individual elevation zone. The degree-day factor typically increases during the snowmelt season, in response to seasonal changes in solar insolation and increases in the density of the snowpack (Martinec and Rango, 1986). The calculated degree-day factors should follow a similar trend.

The runoff coefficients are much more difficult to estimate than the degree-day factor. Thus a precipitation index method is used to temporally update the runoff coefficients throughout the snowmelt season. This method requires that the user determine the initial values for the runoff coefficients and automatically adjusts them according to the amount of precipitation and snowmelt that has occurred during the previous three days. This streamlines the process and negates the need for the forecaster to manually update the coefficients on a daily basis. An increase in precipitation and snowmelt results in an increase in the runoff coefficients. During dry periods, without significant amounts of precipitation and snowmelt, the runoff coefficients will decrease to their initial values. The equation for the precipitation index method is as follows:

$$C_n = C_i + (C_i (R/x)) \quad (6)$$

where C_n is the runoff coefficient on day n, C_i is the initial runoff coefficient, R is the total precipitation and snowmelt that occurred during the previous three days, and x is a fit parameter (a value of 5 cm was used in these simulations).

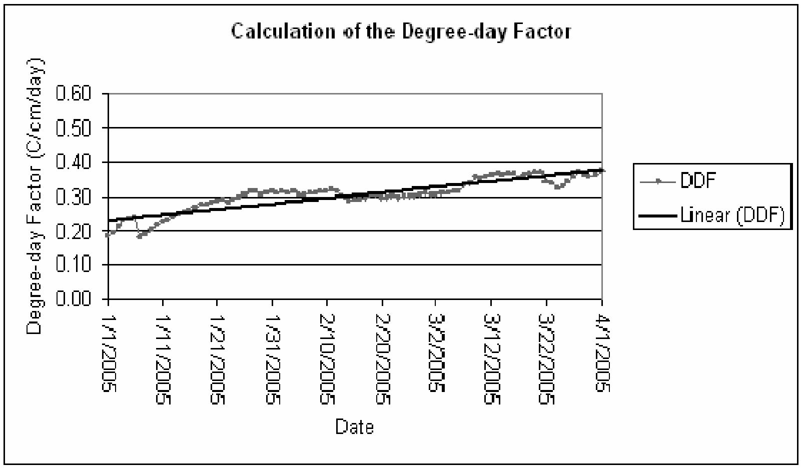


Figure 2. Estimation of the degree-day factor using SWE and snow depth data obtained from SNOTEL sites. The regression line is used to smooth out any daily variability inherent in the data.

Calculation of Snowmelt During Rain-On-Snow Events

Degree-day models, like SRM, have always struggled to accurately simulate snowmelt during rain-on-snow events. Thus enhancements need to be made to the model to account for processes that occur during these conditions. The following equation is added to the right hand portion of equation 1 to account for melt due to condensation on the snowpack:

$$M_c = (0.18642 * T_d * W_s)/10 \quad (7)$$

where M_c is condensation melt (cm), T_d is the dew point temperature (^oC), W_s is the wind speed (km/hr), and 10 is a conversion factor from mm to cm. This equation requires that the relative humidity (RH) and daily temperature (T_n) data be converted to the actual water vapor pressure (e_a) and subsequently to the dew point temperature. This can be accomplished using the following equations:

$$e_s = 0.611 * \exp((17.27*T_n) / (T_n+237.3)) \quad (8)$$

$$e_a = (RH * e_s) /100 \quad (9)$$

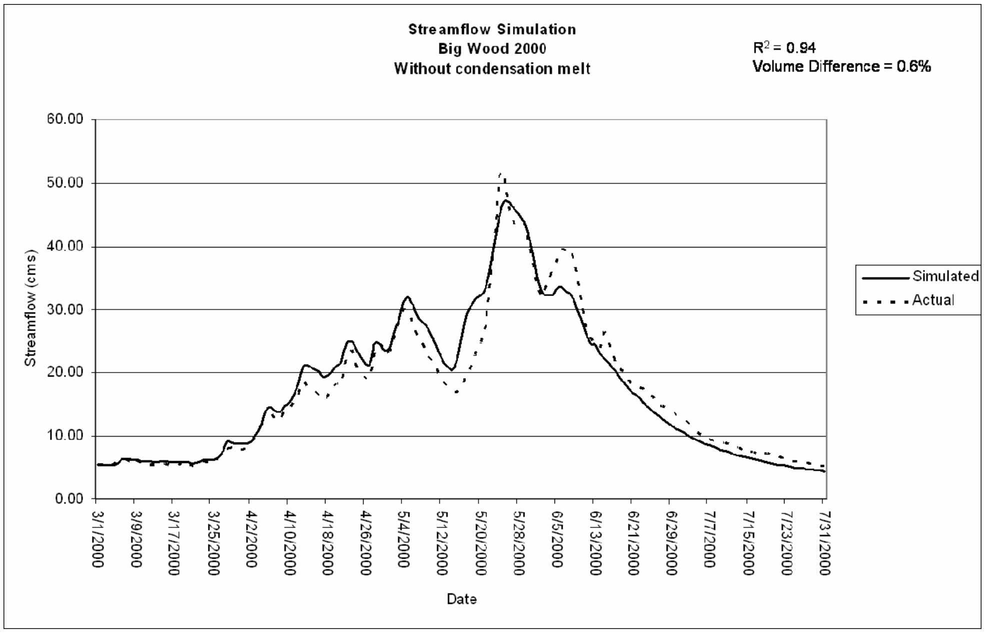
$$T_d = (\ln(e_a) +0.4926) / (0.0708 – (0.00421 * \ln(231))) \quad (10)$$

where e_s is the saturation vapor pressure (mb). Relative humidity and wind speed data, used in this study, were obtained from a single Remote Automated Weather Station (RAWS) located within the basin. These data were downloaded from the Western Regional Climate Center's (WRCC) webpage (http://www.wrcc.dri.edu/). Model runs with and without the inclusion of relative humidity and wind speed data are evaluated.

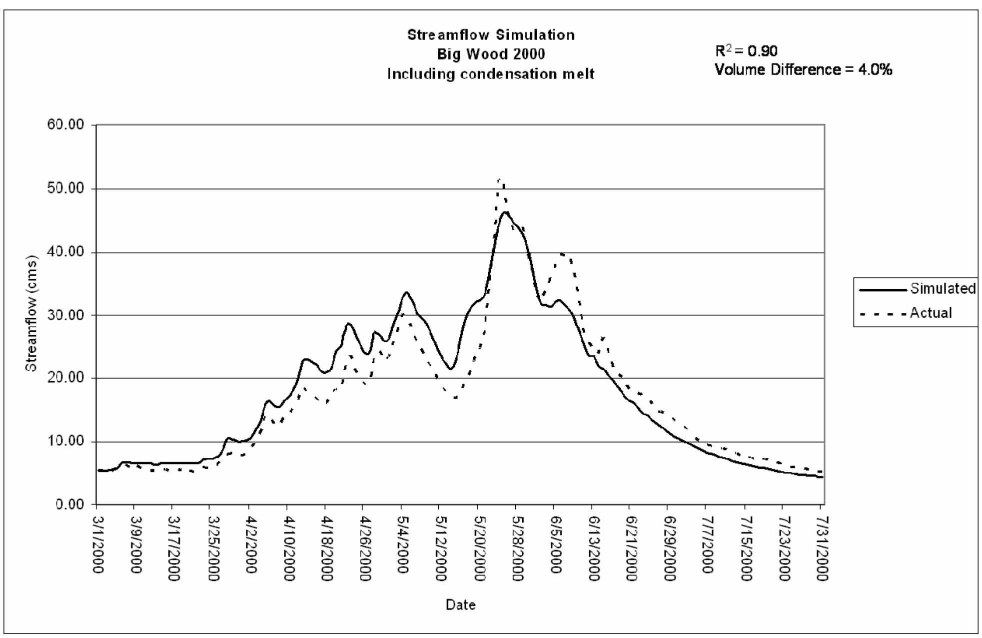
RESULTS AND DISCUSSION

The results from the model simulations indicate that the enhanced version of SRM performs well when simulating the actual stream discharge (Figures 3 and 4). The timing and magnitude of streamflow peaks also are simulated reasonably well. The average R^2 value for the four model simulations is 0.94 and the difference in the average seasonal volume is 2%. These results are comparable to those found in previous studies using the original version of SRM (e.g. Rango and van Katwijk, 1990; Mitchell and DeWalle, 1998), however the enhancements should make it easier for the user to run the model. This is important for operational streamflow forecasting.

The model results with and without the inclusion of relative humidity and wind speed data (condensation melt) are not significantly different. No improvement is shown for either of the two years tested. In fact, the results for this case are slightly inferior when condensation melt is included. This may be due to the fact that rain-on-snow events were not significant contributing factors in determining the stream discharge during the years tested. It is hypothesized that more significant results (differences) may occur if the model is run on a basin where rain-on-snow events are more common. Condensation melt is common under moist, windy conditions, which are more frequently observed in mountainous areas located closer to the coastline (i.e. the Cascade Mountains of Washington and Oregon).

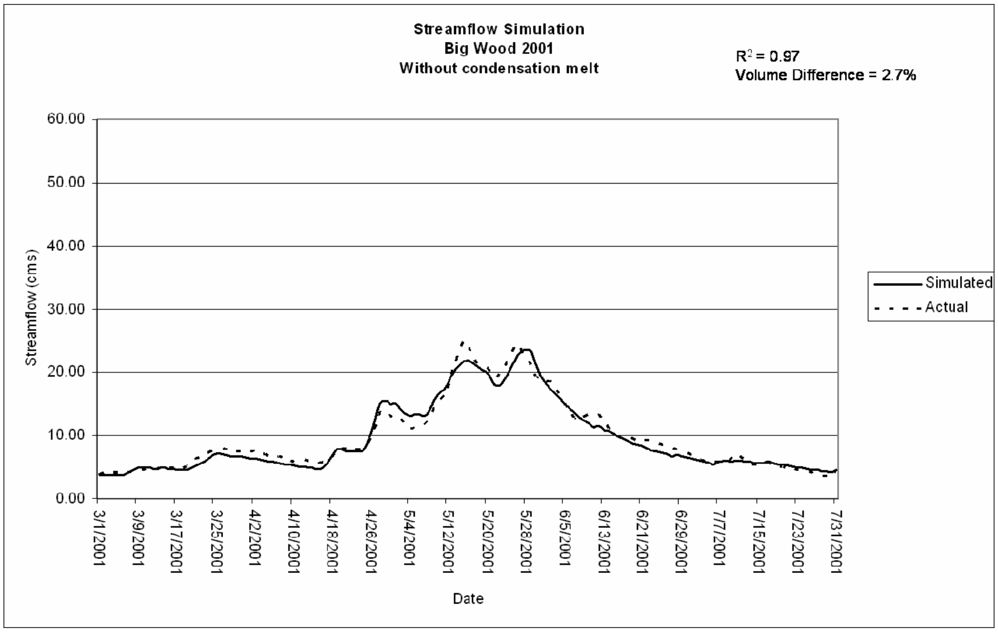


(a)



(b)

Figure 3. Model simulation results for 2000. (a) The enhanced version of SRM, excluding condensation melt. (b) The enhanced version of SRM, including condensation melt.



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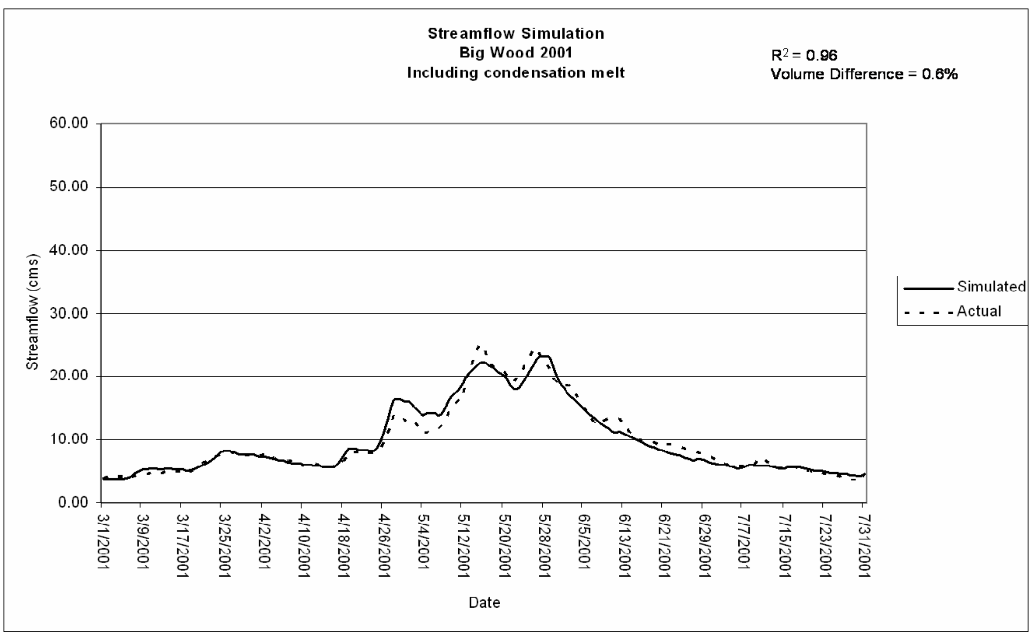

(b)

Figure 4. Model simulation results for 2001. (a) The enhanced version of SRM, excluding condensation melt. (b) The enhanced version of SRM, including condensation melt.

CONCLUSIONS

An enhanced version of the snowmelt runoff model was used to simulate stream discharge in the snowmelt dominated Big Wood River Basin, located in Idaho. Enhancements to the original version of SRM were tested to determine their usefulness. The model results indicate that the enhanced version of SRM did a good job simulating the actual stream discharge. However, the inclusion of relative humidity and wind speed data did not offer any improvement to the model simulations. Different results may occur in locations where condensation melt is more common. Overall the enhancements made to the model should increase its operational applicability and streamline the modeling process.

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