EVALUATION OF STREAMFLOW FORECASTS FOR MULTIPLE BASINS IN THE PACIFIC NORTHWEST USING AN ENHANCED VERSION OF THE SNOWMELT RUNOFF MODEL

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ABSTRACT

Runoff in mountainous areas of the Pacific Northwest is largely dominated by snowmelt. Thus accurate streamflow forecasts are critical for the management of water resource systems. The objective of this project is to develop a short to medium range streamflow prediction system (1 to 15 days) based on the Snowmelt Runoff Model (SRM) for mountainous basins in the Pacific Northwest. Enhancements were made to the model to optimize model efficiency and aid in its operational implementation. Results from retrospective forecast model runs, using statistically downscaled temperature and precipitation forecasts from the NCEP Global Forecasting System (GFS) model (2003-2006) will be examined.

INTRODUCTION

Snowmelt runoff forecasts are important for the management of water resource systems, which are designed for the purposes of irrigation, flood control, and the generation of hydropower. The hydrologic model used in this study is the Snowmelt Runoff Model (SRM), which was designed to simulate and forecast streamflow in mountainous areas where snowmelt is the major contributing factor to runoff (Martinec et al., 1994; Mitchell and Dewalle, 1998). Although SRM has been successfully tested in numerous mountainous watersheds around the world (e.g. Rango and Martinec, 1979; Shafer et al., 1982; Martinec, 1985; Hall and Martinec, 1985; Dey et al., 1989; Rango and Katwijk, 1990; Martinec et al., 1994; Rango and Martinec, 1997; Mitchell and Dewalle, 1998; Ferguson, 1999; Wang and Li, 2001; Gomez-Landesa and Rango, 2002; Huong and Guodong, 2003), it has only been used on a limited basis to create streamflow forecasts (Rango and Martinec, 1994; Nagler et al., 2000).

In this research, we describe a methodology for the generation of short to medium range (1 to 15 days) streamflow forecasts using an enhanced version of SRM. This research is highly applied and is designed to provide improved tools for use by operational forecasters. To optimize model efficiency and aid in its operational implementation, two enhancements have been made to SRM: 1) the use of an antecedent temperature index method to track snowpack cold-content and account for the delay in melt associated with diurnal refreezing, and 2) the use of both maximum and minimum critical temperatures to partition precipitation into rain, snow, or rain/snow mixed. Streamflow forecasts were generated for the Big Wood, South Fork of the Boise, and North Fork of the Clearwater basins in the state of Idaho (Figure 1). Detailed characteristics for each of the three test basins can be found in Table 1. Forecast results for the 2003–2006 snowmelt seasons are evaluated

DATA AND METHODOLOGY

Model Description

SRM, used in this study, is a conceptually based, degree-day (temperature index) model (Martinec et al., 1994). Like most degree-day models, SRM is run in a semi-distributed manner. Model Input variables are distributed among elevation zones (each with approximately 500 m of relief), and include daily average air temperature, daily total precipitation, and snow-covered area (SCA). The following equation is used in SRM to simulate daily streamflow discharge:

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

where Q ($m^3 s^{-1}$) is the average daily stream discharge, C_S and C_R are runoff coefficients for snow and rain, a (cm $^oC^{-1}$ day^{-1}) is the degree-day factor (melt factor), T (^oC) is the number of degree-days, ΔT (^oC/100 m) 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 $m^3 s^{-1}$.

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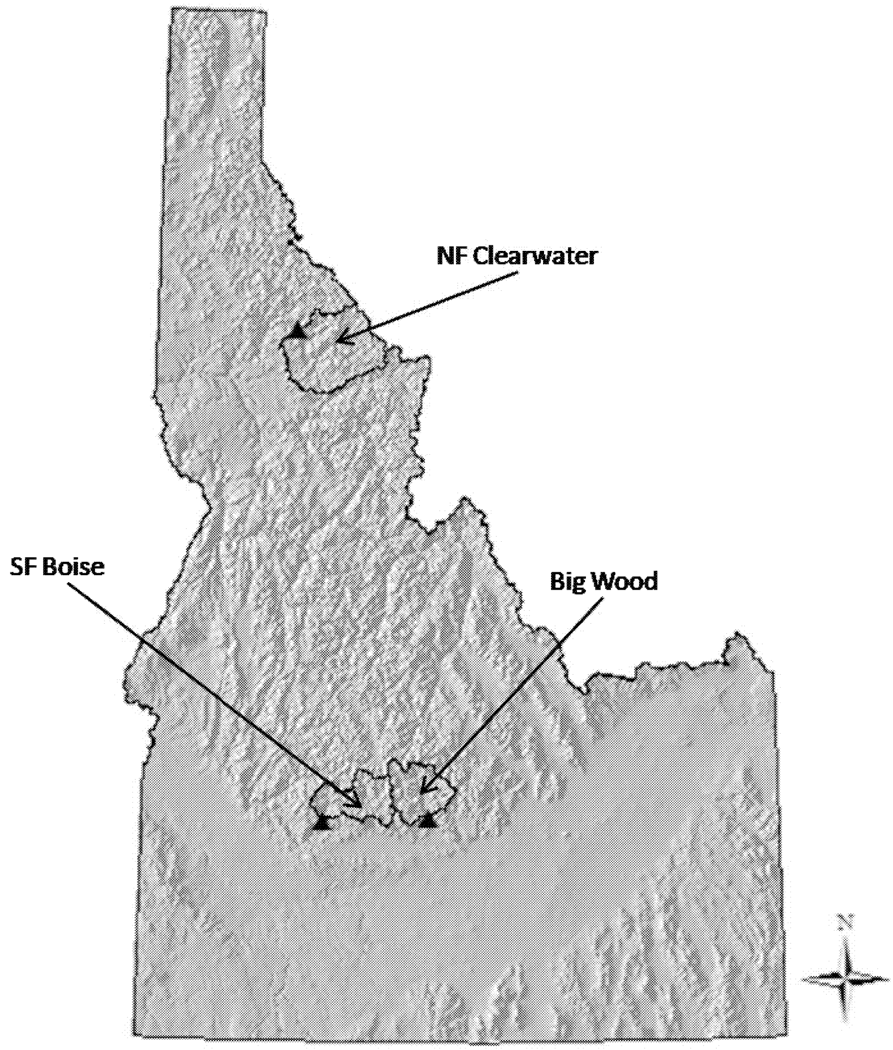

Figure 1. Map of Idaho showing the location of the basins modeled in this study. The triangles represent the locations of the stream gauges.

Table 1. Characteristics for the 3 test basins modeled in this study.

Basin	*Contributing Area (km)*	*Elevation Range (m)*
Big Wood	1,625	1,618-3,630
South Fork of the Boise	1,639	1,316-3,159
North Fork of the Boise	3,520	504-2,407

Model Inputs

Forecasted values of maximum (T_{max}) and minimum (T_{min}) temperature are obtained from the Global Forecasting System (GFS) model (2.5 degree grid cells) produced by the National Center for Environmental Prediction (NCEP). These forecasts are generated on a daily basis and extend out 1 to 15 days in advance. To account for the coarse spatial resolution of the forecast data, the forecasted values are downscaled to the locations of Snow Telemetry (SNOTEL) stations located within or surrounding each test basin. A full description of the downscaling process can be found in Clark et al. (2004) and Moore et al. (2006). The downscaled T_{max} and T_{min} forecast values are converted to forecasted values of daily average temperature by taking the simple average of them. The station data are then averaged to create a synthetic station and are extrapolated to the hypsometric mean elevation of each elevation zone using mean monthly lapse rates. The elevation of the synthetic station is the mean elevation of all of the SNOTEL stations used to model each basin.

Forecasted daily precipitation values (1 to 15 days) are also obtained from the GFS model. However, unlike the temperature forecast data, statistical downscaling procedures are not applied to the data. Instead, the precipitation forecast data values are interpolated directly to the locations of the SNOTEL stations using inverse distance weighting. Once values are obtained for each SNOTEL station, they are averaged to create a synthetic station. This is identical to the methodology applied to the temperature forecast data, however, the forecasted precipitation values from synthetic station are then applied to directly to each elevation zone. No adjustment is made to the data to account for changes in precipitation with elevation.

SCA data is obtained from the MODIS 8-day composite snow cover data product (MOD10A2). This data is produced operationally and is disseminated by the National Snow and Ice Data Center (NSIDC). Since the SCA data is only available every 8 days, modified snow depletion curves (MDCs) are generated from the raw SCA data. MDCs relate the daily reduction in SCA to the cumulative melted depth. A gaussian distribution is used to fit a curve to the data and individual curves are generated for each elevation zone and year. Using the equation obtained from the gaussian fit, forecasted values of snow-covered area (extending out 1 to 15 days in advance) can be obtained using the forecasted melted depth.

Model Updating

Real-time model updating is used to avoid the propagation of errors in the streamflow forecasts. Since a new 15-day streamflow forecast is generated every day, the model is updated with observed temperature and precipitation values from the previous day. This data is obtained from the same SNOTEL sites that are used to model each test basin and is handled in the same manner as the forecasted model inputs (e.g. generation of a synthetic station). The SNOTEL data were provided by the Natural Resources Conservation Service (NRCS). Replacement of forecasted model inputs with actual temperature and precipitation values is vital since SRM temporarily stores new snow in areas deemed non-snow covered from the SCA imagery. Thus, updating the model with actual temperature and precipitation data ensures that the amount of new snow stored in the model is as accurate as possible at the beginning of each forecast period. In addition to updating the model with observed SNOTEL data, the model is also updated with actual streamflow values from the previous day. This data is obtained from the United States Geological Survey (USGS). The observed streamflow data is also used to evaluate the accuracy of the streamflow forecasts.

RESULTS AND DISCUSSION

In order to assess the performance of the streamflow predictions, forecast hydrographs are generated to visually compare the actual (measured) stream discharge with the forecasted values at lead times of 1, 4, 7, and 10 days. Since four years (2003-2006) of streamflow forecasts were generated for each of the three basins, only one set of forecast plots are shown here. Figure 2 shows the forecast results for the Big Wood during the 2006 snowmelt season (April 1-July 31), which was an abnormally high flow year. As can be seen in figure 2, the forecasted discharge follows the measured flow fairly well, although there are small differences in the timing and magnitude of the flow. The quality of the streamflow forecasts also degrades with increasing leadtime, which can be attributed to the fact that the accuracy of the meteorological forecasts decrease as you move out in time. Even though there are small timing issues in the streamflow forecasts, the model correctly forecasted the timing of the peak flow out 6 days in advance. The forecasts only missed the peak by 1 day at a lead time of 7 days (Figure 2c) and 2 days at a lead time of 10 days. (Figure 2d). Although the timing of the peak flow was predicted with some precision, the magnitude of the peak was slightly underpredicted at all 4 of the forecast lead-times illustrated here (Figure 2). This can be attributed to errors in the meteorological forecasts and the fact that the weather forecasts often do not always capture the extreme conditions which are often responsible for producing the peak flow.

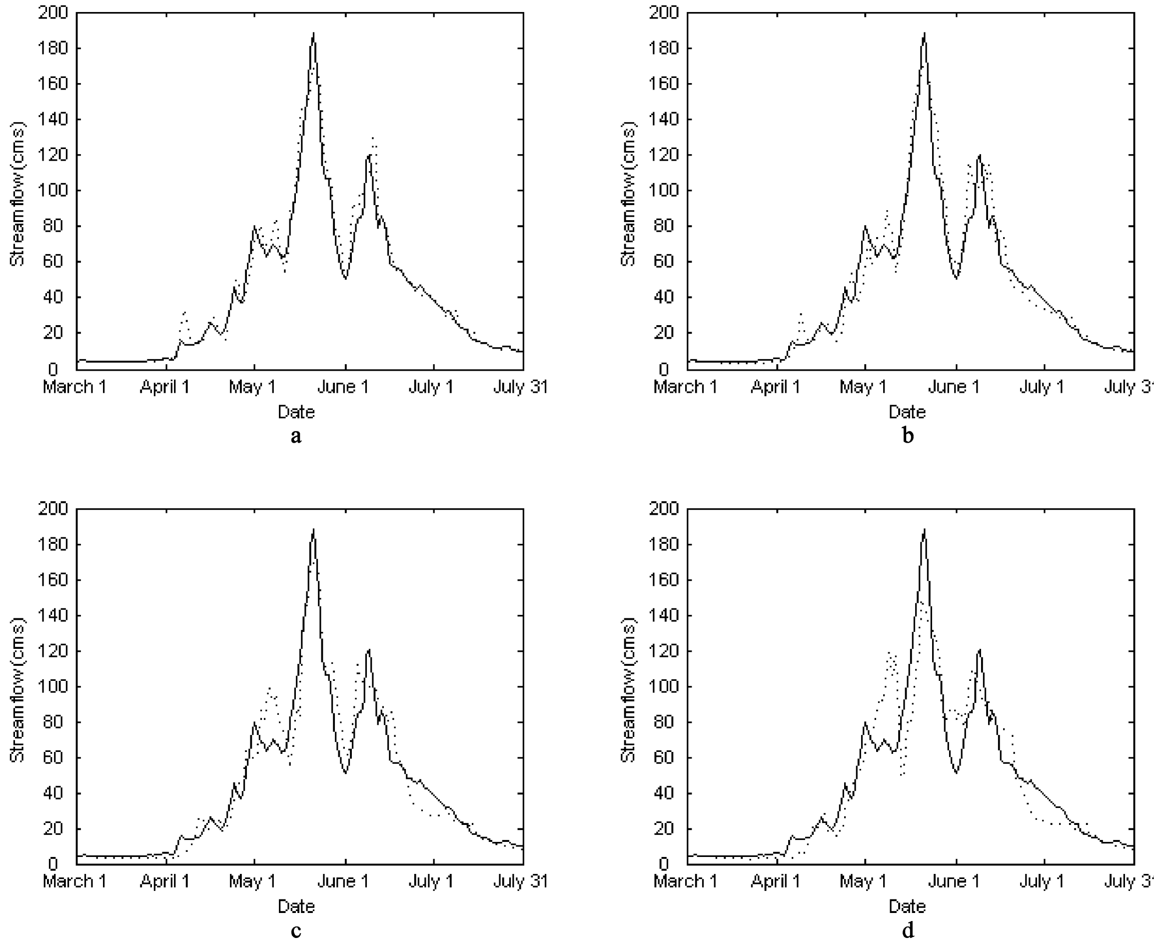

Figure 2. Forecast hydrographs showing the actual (solid line) and forecasted (dashed line) streamflow discharge values for the Big Wood (2006) at lead times of: (a) 1 day, (b) 3 days, (c) 7 days, and (d) 10 days.

In addition to the forecast hydrographs, the coefficient of determination (R^2) and root mean squared error (RMSE) are used to assess the accuracy of the streamflow forecasts. Average R^2 and RMSE values for each of the 3 basins are listed in tables 2 and 3. Values are provided for each of the 15 forecast leadtimes. Average values for the 4 forecast years were used to limit the amount of data presented in the table. The average R^2 values are within acceptable limits at leadtimes up to about 10 days and generally decrease with increasing leadtime (Table 2). The values very comparable for all three stations, however, the values are higher for the North Fork of the Clearwater than for the other 2 basins at leadtimes greater than 9 days (Table 2). This can be attributed to the fact that the Big Wood and South Fork of the Boise had very low R^2 values for the 2004 snowmelt season, which was a low flow year. The RMSE values for the Big Wood and South Fork of the Boise are very similar, however, the values for the North Fork of the Clearwater are much larger at every forecast leadtime (Table 3). This can be attributed to the fact that the North Fork of the Clearwater is much larger in area than the other 2 basins (Table 1) and experiences much larger flows. To adjust for this, the RMSE values were weighted by the total annual discharge volume to allow for the intercomparison between basins and individual years (Figure 3). Separate plots were generated for each of the 3 basins with each line representing a different forecast year. The results indicate that the model generally performed the same if not better in the North Fork of the Clearwater at every forecast leadtime (Figure 3c) than in the other 2 basins (Figures 3a and 3b). The weighted RMSE values also had less annual variability than (Figure 3c) for the other 2 basins (Figures 3a and 3b). This result is interesting and will require further investigation.

Table 2. Average coefficient of determination (R^2) values by forecast leadtime (in days).

Basin	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***
Big Wood	0.92	0.88	0.83	0.79	0.74	0.71	0.67	0.65	0.62	0.58	0.53	0.48	0.44	0.40	0.36
SF Boise	0.95	0.91	0.88	0.85	0.81	0.78	0.76	0.73	0.70	0.67	0.63	0.60	0.57	0.54	0.50
NF Boise	0.91	0.88	0.87	0.84	0.81	0.78	0.75	0.73	0.71	0.70	0.67	0.65	0.65	0.64	0.63

Table 3. Average RMSE values by forecast leadtime (in days).

Basin	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***
Big Wood	5.3	6.5	7.4	8.0	8.5	8.9	9.5	10.2	10.8	11.4	11.8	12.4	13.0	13.5	13.8
SF Boise	6.9	9.1	10.3	11.4	12.4	13.1	13.7	14.5	15.2	15.9	16.6	17.3	17.6	17.9	18.3
NF Boise	27.1	31.7	34.0	36.8	39.8	43.0	46.3	48.4	50.1	52.1	54.2	55.8	56.3	56.9	57.4

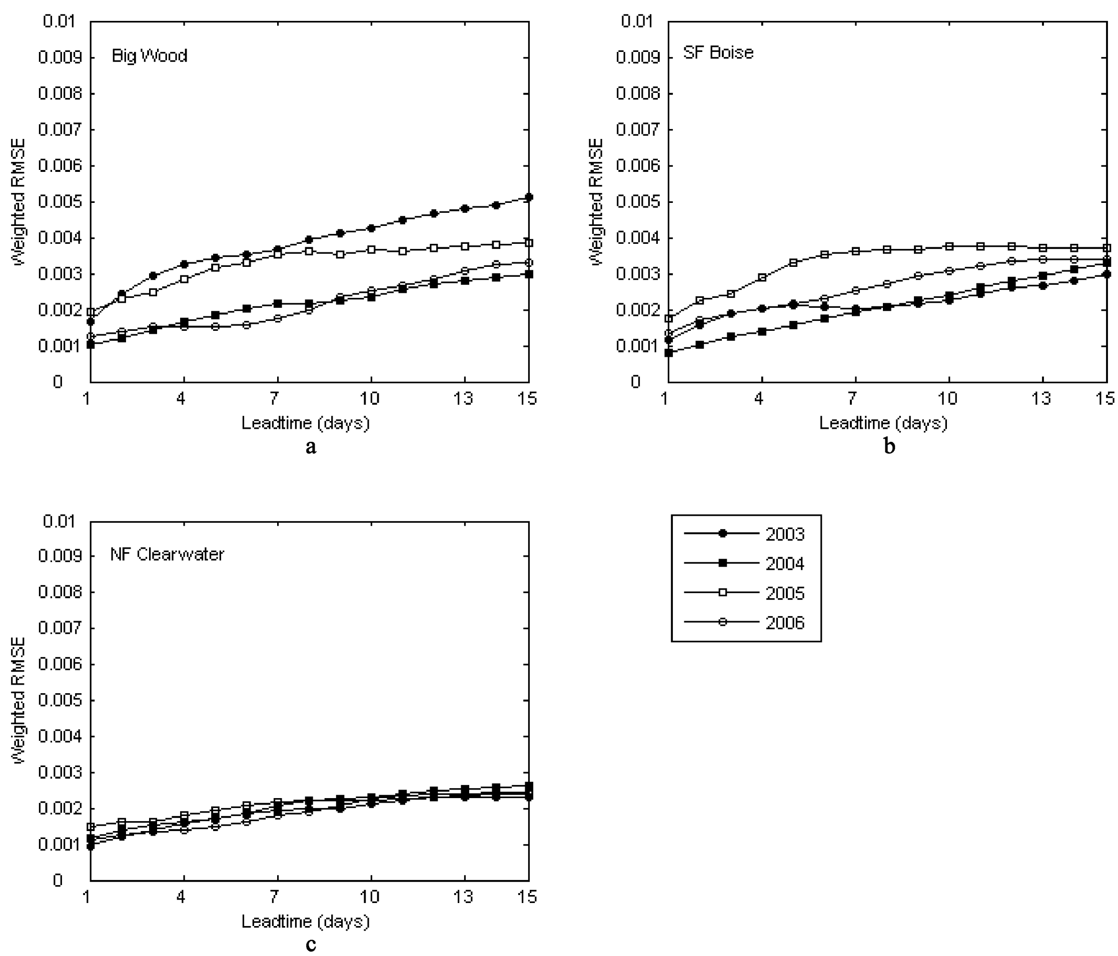

Figure 3. Plots showing weighted RMSE values by forecast leadtime for the: (a) Big Wood, (b) South Fork of the Boise, and (c) North Fork of the Clearwater.

CONCLUSIONS

A new methodology was developed and tested for the generation of short to medium range streamflow forecasts (1 to 15 days) using an enhanced version of SRM. Enhancements were made to the model to optimize model efficiency and aid in its operational implementation. The results indicate that the model performed very well at leadtimes up to about 7 days, however there was still some predictability at the longer leadtimes (average R^2 value of 0.65 at a leadtime of 10 days). The model performed well in years with average to above average flows, however did not perform quite as well during low flow years. Given that the model was successfully tested in 3 basins for 4 separate years, we believe that there is potential for these methods to be applied in other snowmelt-dominated basins around the world.

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