Comparison of hydrologic predictions from the Variable Infiltration Capacity (VIC) model and the MC1 model to observed gage data in the region around the Shoshone National Forest

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Introduction

Flow regimes in most of the Northern Rockies are snowmelt-driven, characterized by high flows in the late spring and summer and low flows for much of the rest of the year. Although there is considerable natural variability in the timing of the runoff peak (Gillan et al. 2010), there has been a trend toward earlier snowmelt over the course of recent decades (Regonda et al. 2005, Stewart et al. 2005, Moore et al. 2007), accompanied by a decline in low flows (Rood et al. 2005, Luce and Holden 2009). These changes have been attributed to both declining precipitation (Luce and Holden 2009) and increasing temperatures (Mote 2003, Barnett et al. 2008, Hidalgo et al. 2009). Further increases of atmospheric greenhouse gases are expected to cause additional changes to hydrologic regimes (Stewart et al. 2004, Adam et al. 2009), with potential consequences for aquatic ecosystems.

Physically-based hydrologic models are useful tools for studying and predicting changes to flow regimes because they can be forced by both historical weather station data and by outputs from climate models. One such model is the Variable Infiltration Capacity (VIC) model (Liang et al. 1994, Liang et al. 1996), which has been widely employed in the western US to study the effects of droughts [*Luo and Wood*, 2007], changes in snowpack [*Hamlet et al.*, 2005], and impacts to water resources [*Hamlet et al.*, 2009; *Vano et al. 2009a,b*]. For simulation of daily flows, the VIC model is typically coupled with a flow routing model to accommodate downstream transport time [*Lohmann et al.*, 1996; *Lohmann et al.*, 1998] and simulate hydrographs [e.g., *Hamlet and Lettenmaier*, 2007; *Hidalgo et al.*, 2009; *Hurkmans et al.*, 2008; *Maurer et al.*, 2002]. Recently, a simplified pseudo-routing method was developed for rapidly generating hydrographs for small to mid-sized streams from VIC model output (Wenger et al. 2010). A validation study in the Pacific Northwest found that the resulting hydrographs provide reasonably good fits to observed data in many cases, with good predictive ability for some biologically relevant flow metrics such as frequency of high winter flows, but poor accuracy for others (such as low flow events; Wenger et al. 2010). There quality of predictions varied spatially, with poor predictions in regions of high groundwater influx.

Our objective in this study was to conduct additional validations of the VIC model outputs for the region around the Shoshone National Forest by comparing modeled predictions to observed USGS gage data at selected locations. In addition, we compared model performance to that of hydrologic outputs from MC1 (Daly et al. 2000, Bachelet et al. 2001), a dynamic model that simulates vegetation, carbon, hydrology and fire processes.

Methods

VIC is a fully distributed and largely physically-based surface energy and water balance model. Infiltration, runoff, and baseflow processes are based on empirically derived relationships (Liang et al. 1994) and characterize the average conditions over the macro-scale grid cell. For historical simulations, meteorological forcing data for the model are produced using hybrid methods that combine both low elevation station observations and statistically derived estimates of high elevation temperature and precipitation (Daly et al. 1994, Maurer et al. 2002, Hamlet and Lettenmaier 2005). The physically based energy-balance snow model in VIC is shared with the fine-scale Distributed Hydrology Soil Vegetation Model (DHSVM) (Wigmosta et al. 1994, 2002) and explicitly accounts for canopy processes that strongly affect snow accumulation and melt in the PNW. Snow simulations from VIC were validated over the western U.S. by Mote et al. (2005).

The University of Washington Climate Impacts Group ran the VIC model for the Upper Missouri (UM) basin at a 1/16 degree grid scale. The model had been previously calibrated for the Pacific Northwest (Matheussen et al. 2000), and these same settings were used in the UM run. Calibration consisted of adjustment of soil parameters, especially three parameters to which the model showed the greatest sensitivity: the infiltration capacity shape factor, the soil moisture threshold separating linear and nonlinear baseflow, and the linear baseflow storage constant (Matheussen et al. 2000). Runs were made on a daily timestep, except for the snowmelt model, which was run on a 3-hour timestep. The model was first forced with historical data (1916-2006), producing outputs that we validated. The VIC model was then forced with forecast data from general circulation models using a “modified delta” approach. This method uses the monthly predicted changes (deltas) to temperature and precipitation from general circulation models (GCMs) to perturb the historical data series, applying different delta values from each GCM cell. The traditional delta method uses a single average delta value for the whole domain, whereas the modified delta method preserves the spatial variability in GCM output. The advantage of all versions of the delta method is that the temporal variability of the observed data is preserved, providing apples-to-apples comparisons of the full 91-year hydrograph under historical and forecast conditions. Six scenario/model combinations were run, as listed in Table 1.

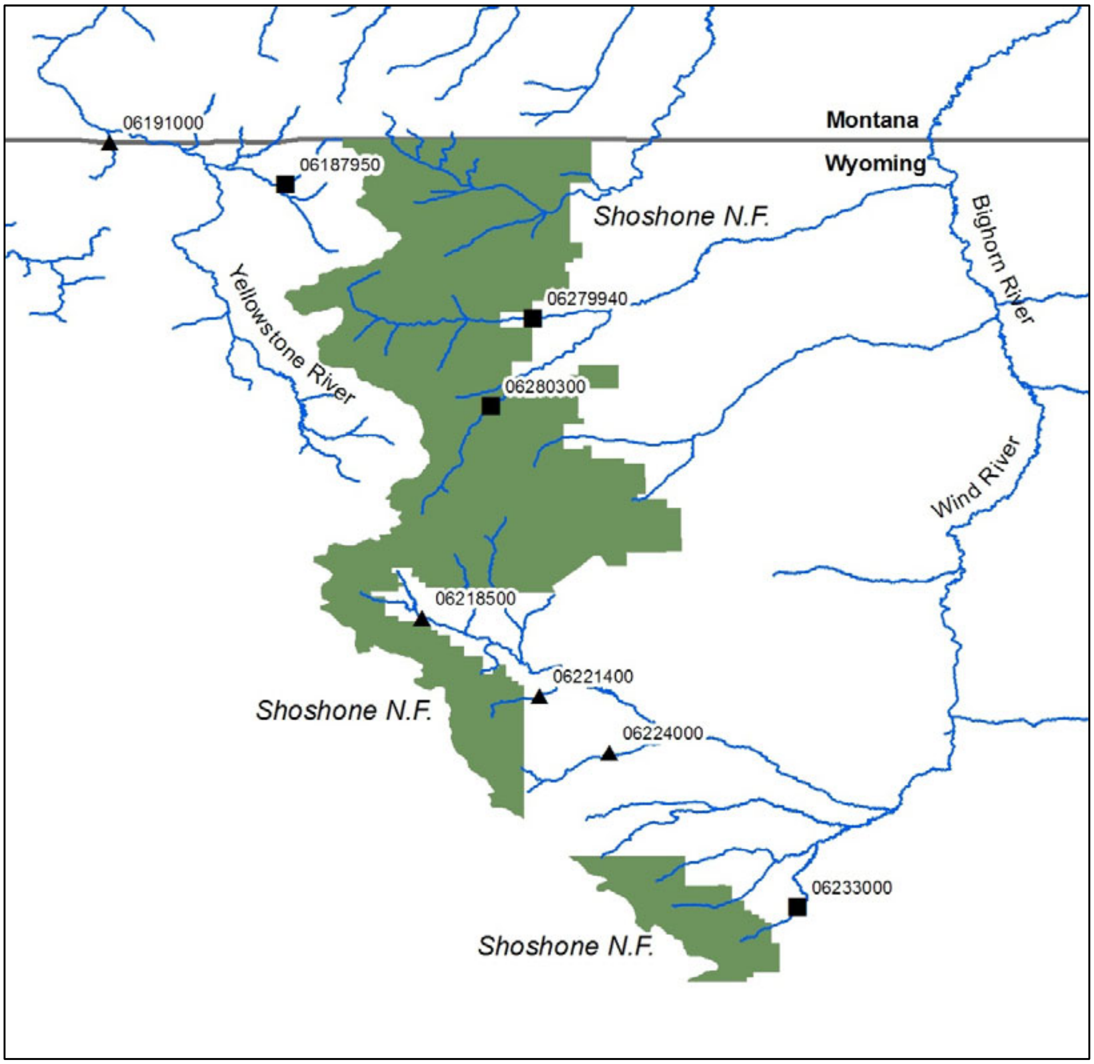
Table 1. Combinations of climate scenarios and GCMs used in forecasts. MIROC =Model for Interdisciplinary Research on Climate. PCM= Parallel Climate Model.

Model	**Scenario**	**Notes**
MIROC	2040s A1B	
PCM	2040s A1B	
Composite	2040s A1B	Mean output from suite of 10 GCMs
MIROC	2080s A1B	
PCM	2080s A1B	
Composite	2080s A1B	Mean output from suite of 10 GCMs

We assigned outputs from the VIC modeling to every stream segment in the National Hydrography Database Plus datast (NHD Plus; http://www.horizon-systems.com/nhdplus/) in the upper Missouri basin (consisting of hydrologic production units 10g and 10h) that had watersheds < 2500 km^2, using the methods of Wenger et al. (2010). We excluded large rivers because the pseudo-routing approach is less appropriate for these than a formal routing method (Wenger et al. 2010).

For validation, we identified eight USGS gaging stations in the vicinity of the Shoshone National Forest that were inside the Missouri Basin (Figure 1, Table 2) and that had minimal upstream anthropogenic flow modifications. Six of these were part of the Hydro-Climatic Data Network (HCDN; Slack et al. 1993) and the remaining two met HCDN criteria except for record length; however, they had sufficient recent records for our purposes and so were included. For each station we downloaded monthly discharge records for water years 1990 to 2006, inclusive. We compared predicted monthly discharge values from VIC to the observed values, calculating the Nash-Sutcliffe Efficiency Index (Ef; Nash and Sutcliffe 1970) as a metric of model skill.

Figure 1. Map of validation gages used in this study. Gages are labeled with their station number (see Table 2 for names).Stations marked with a square have both VIC and MC1 output; those marked with triangles have only VIC output.

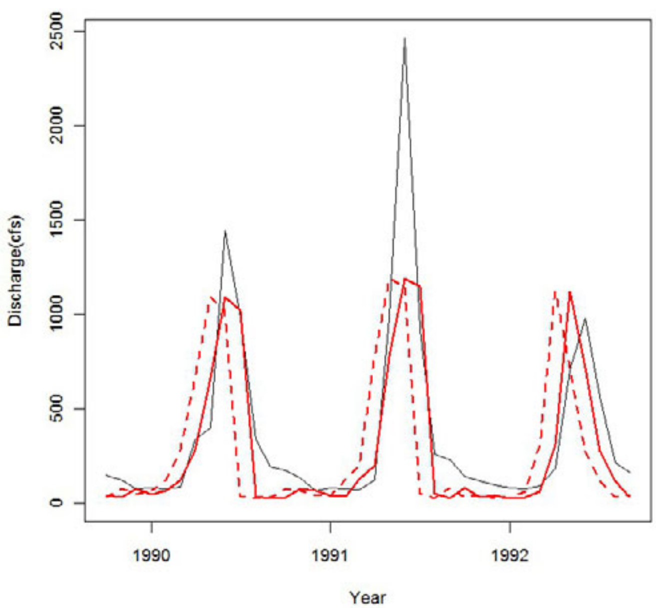


Monthly MC1 model outputs were provided for four gaging stations (Table 2), as well as a fifth station (Yellowstone River at Corwin Springs) that exceeded the size cutoff for the VIC model and so was not included in the comparison. We calculated Ef scores for the MC1 model predictions at the four stations.

Results and Discussion

Raw outputs from both the VIC model and the MC1 model showed considerable bias in the prediction of the timing of the snowmelt peak (Figure 2). For all sites, snowmelt-induced runoff was predicted to begin about a month prior to the observed date. In previous validation work (Wenger et al. 2010), we found a linear bias to predictions of the timing of the center of flow mass such that snowmelt sites were predicted too early, while rain-dominated sites were predicted too late. This suggests that the error was not caused by a lack of formal routing, which would have produced a consistent bias for all sites, and furthermore could not have explained bias of the magnitude observed. Rather, we suspect that the error is a result of either inaccurate snowmelt or soil modeling/calibration. The source of the error for the MC1 simulations is unknown, but the character of the bias was very similar to that observed for the VIC outputs.

Figure 2. Uncorrected VIC output (red, dashed line) vs. corrected (red, solid line) and observed data(black line) at South Fork Shoshone River (gage 6280300).Note that the uncorrected predictions of snowmelt runoff are about 1 month early.



We performed a simplistic post-hoc bias correction by adjusting all VIC and MC1 values back by one month (Figure 2). More sophisticated bias corrections could be employed; one possible approach is to use a linear statistical correction based on the regression of predicted and observed hydrographs for a broad region that encompasses a range of snowmelt conditions. This relationship could be generated, for example, using the same gage data used in the Wenger et al. (2010) validation, supplemented by the gage data used here. However, any such post-hoc adjustments are less desirable than correction of the source of the problem in the model itself. For purposes of this analysis we examine the output using just the simple one-month shift, assuming that future results with better corrections will be at least as good as what is produced here.

After correction, the Ef scores were reasonably high for most stations (Table 2; Ef>0.5 is considered good) and comparable between the two models. The low score for the Wind River station appears to be a product of the short data record and relatively low variability of observed data for this station, rather than genuinely poor performance (see Figure 3). The full monthly hydrographs are shown in Figure 3. For the VIC data there was no consistent pattern of errors, other than the issue of timing described above. In many cases peak flow magnitude was overestimated or underestimated. Baseflow estimates were reasonable with the exception of Gardner River near Mammoth, in which baseflow was underestimated. This is likely due to groundwater inputs; like most macroscale hydrologic models, VIC does not include a groundwater component and cannot account for exchange of surface and groundwater.

Although our focus here was on monthly hydrographs (for consistency with MC1 output), we also examined daily hydrographs to assess whether VIC correctly predicted winter high flow frequency, a metric of potential ecological interest. The eight stations used for validation here were all strongly snow-dominated, with very few high flows occurring during the winter. This was accurately predicted by VIC modeling.

Full analysis of forecast data was beyond the scope of this validation exercise. We nevertheless produced three sets of figures showing VIC outputs from the forecasts: (1) a comparison of historical and 2080 composite forecast hydrographs for each station; (2) a figure showing the change in discharge between the 2080 composite and the historical hydrographs; and (3) a comparison of hydrographs from the 2080 composite, 2080 MIROC and 2080 PCM model. The latter gives a sense of the variability in forecasts. An example of these figures is shown for the North Fork Shoshone gage (Figure 3). Notable in these results is what appears to be a winter rain event in 1997 that produed a minor increase in flow. Under 2080 conditions, such an event is projected to produce a major rain-on-snow flood. The full set of forecast figures is included in an electronic supplement, ”Forecasts.zip.”

Table 2. Monthly Nash-Sutcliffe scores for VIC and MC1 outputs for each validation gage station.

Gage No	Name	NS-Vic	NS-MC1
6279940	North Fork Shoshone River	0.71	0.7
6233000	Little Popo Agie River	0.55	0.45
6280300	South Fork Shoshone River	0.69	0.57
6187950	Soda Butte Creek	0.49	0.74
6191000	Gardner River nr Mammoth	0.45	x
6218500	Wind River nr Dubois	0.12	x
6221400	Dinwoody Creek ab lakes	0.35	x
6224000	Bull Lake Creek ab Bull Lake	0.63	x

Conclusions

Once adjusted for bias in snowmelt runoff timing, both VIC and MC1 produced predicted hydrographs that appeared accurate enough to have utility, based on Nash-Sutcliffe scores and visual inspection. The bias in runoff timing does not affect some metrics, such as winter high flow frequency, and can be ignored if only such metrics are of interest. If runoff timing is itself of interest, however, either the models must be corrected and re-run or a more sophisticated post-hoc correction must be employed.

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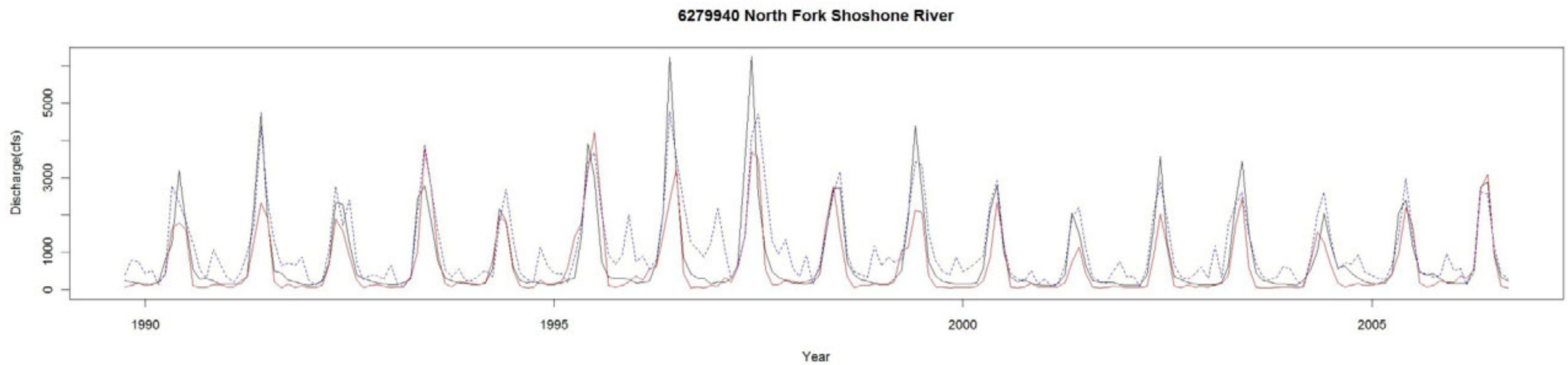
Figure 3. Predicted vs. observed monthly hydrographs for each validation station after applying an x day shift to the modeled hydrographs. Black = observed; red solid = VIC; blue dashed = MC1. This figure is best viewed electronically.



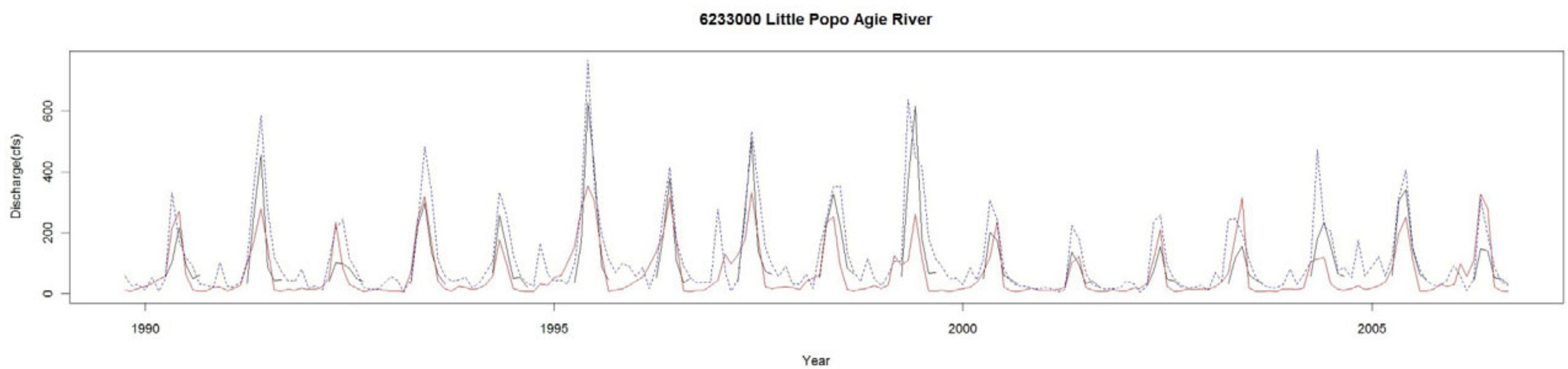
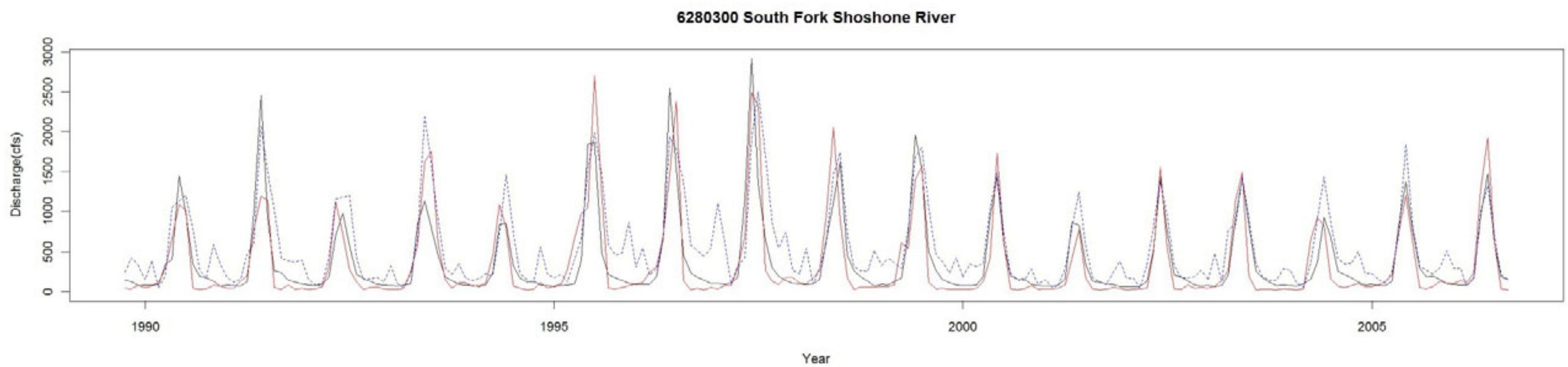


Figure 3, continued. Black = observed; red solid = VIC; blue dashed = MC1.



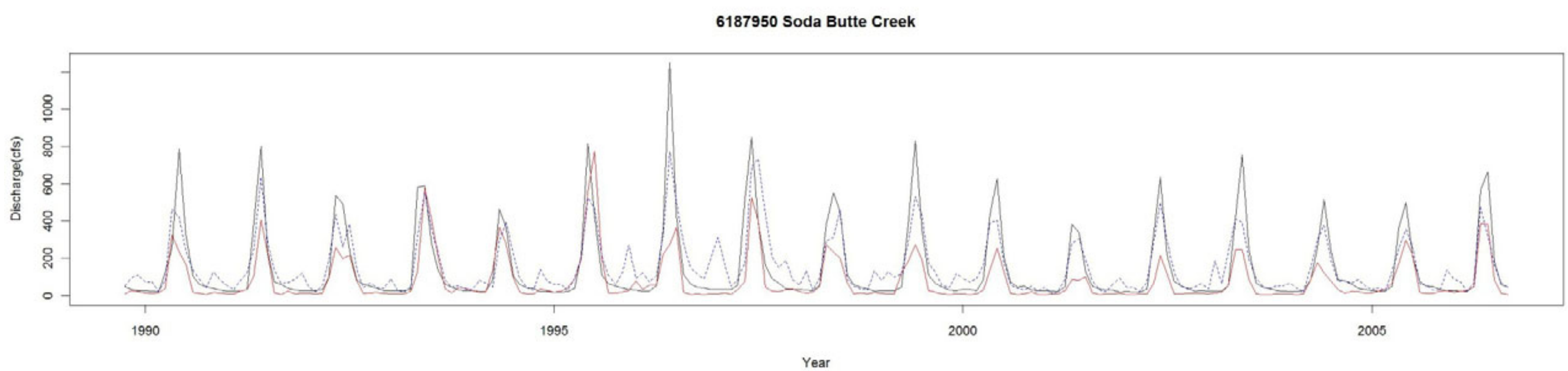
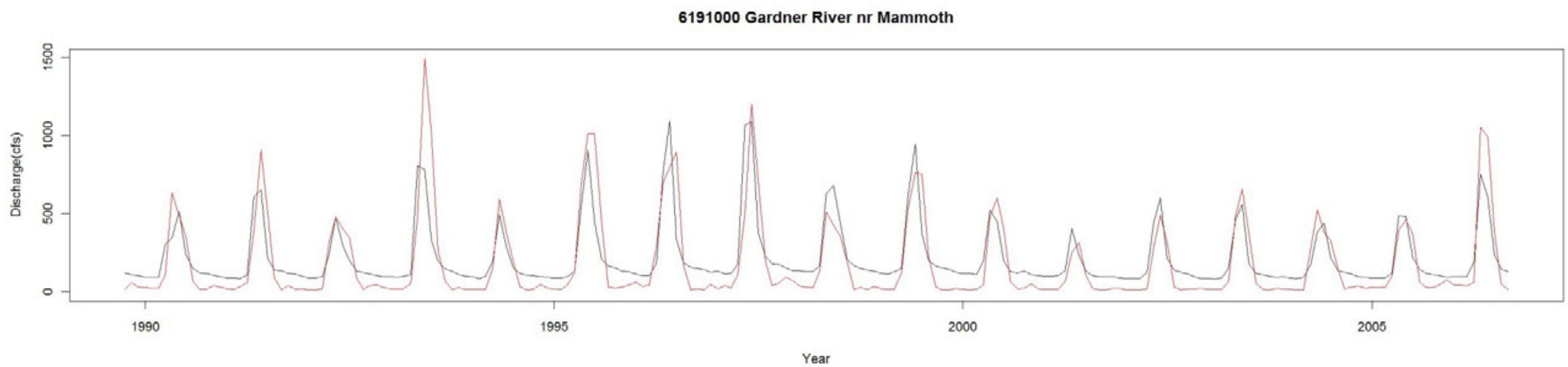
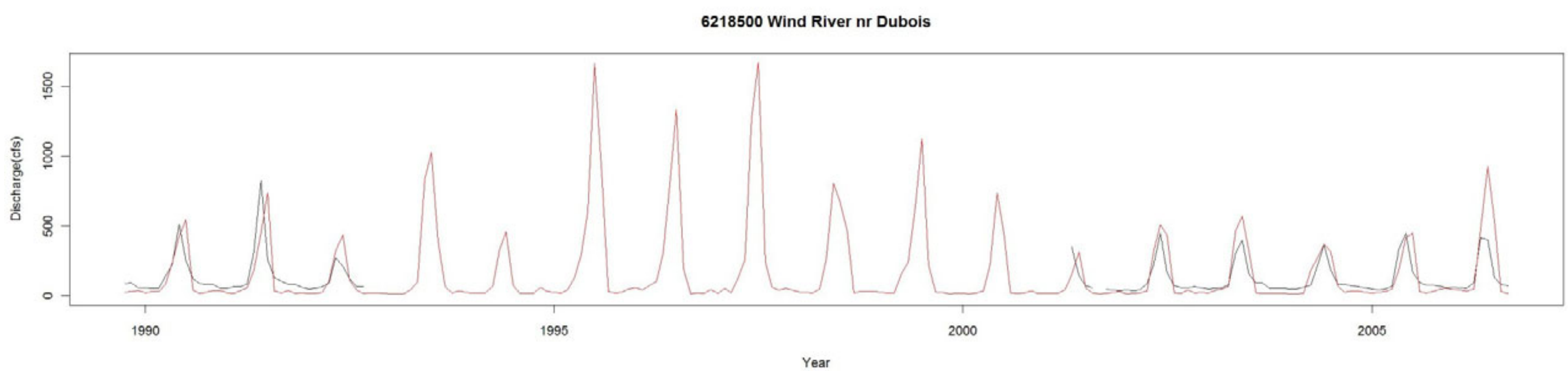


Figure 3, continued. Black = observed; red solid = VIC. MC1 data not available for the stations below.





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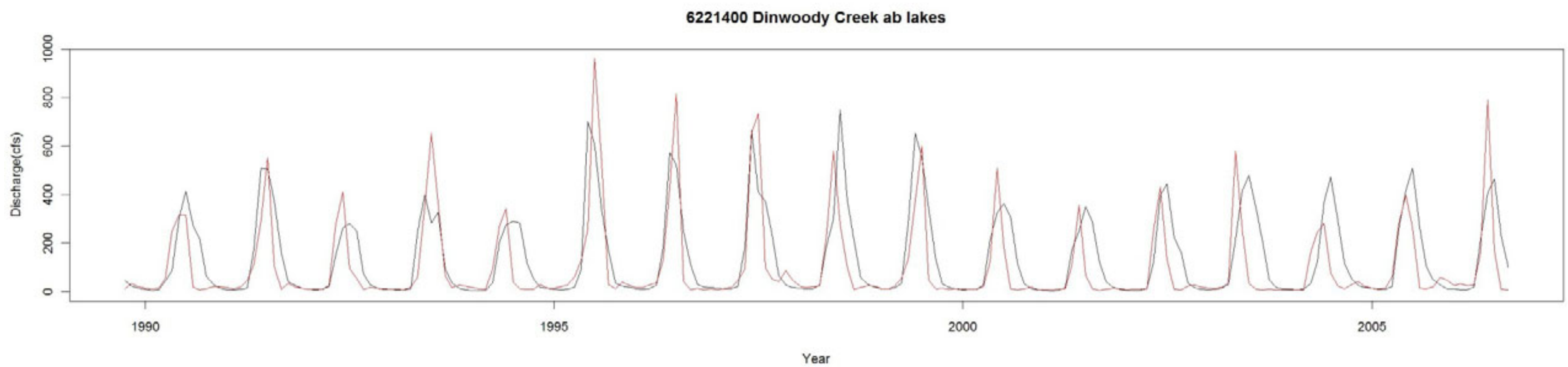


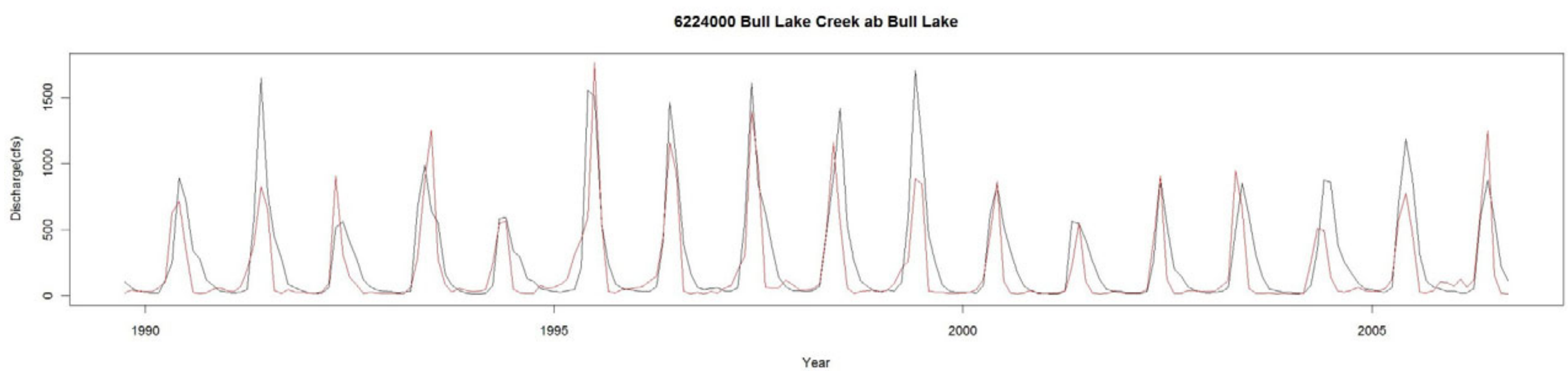
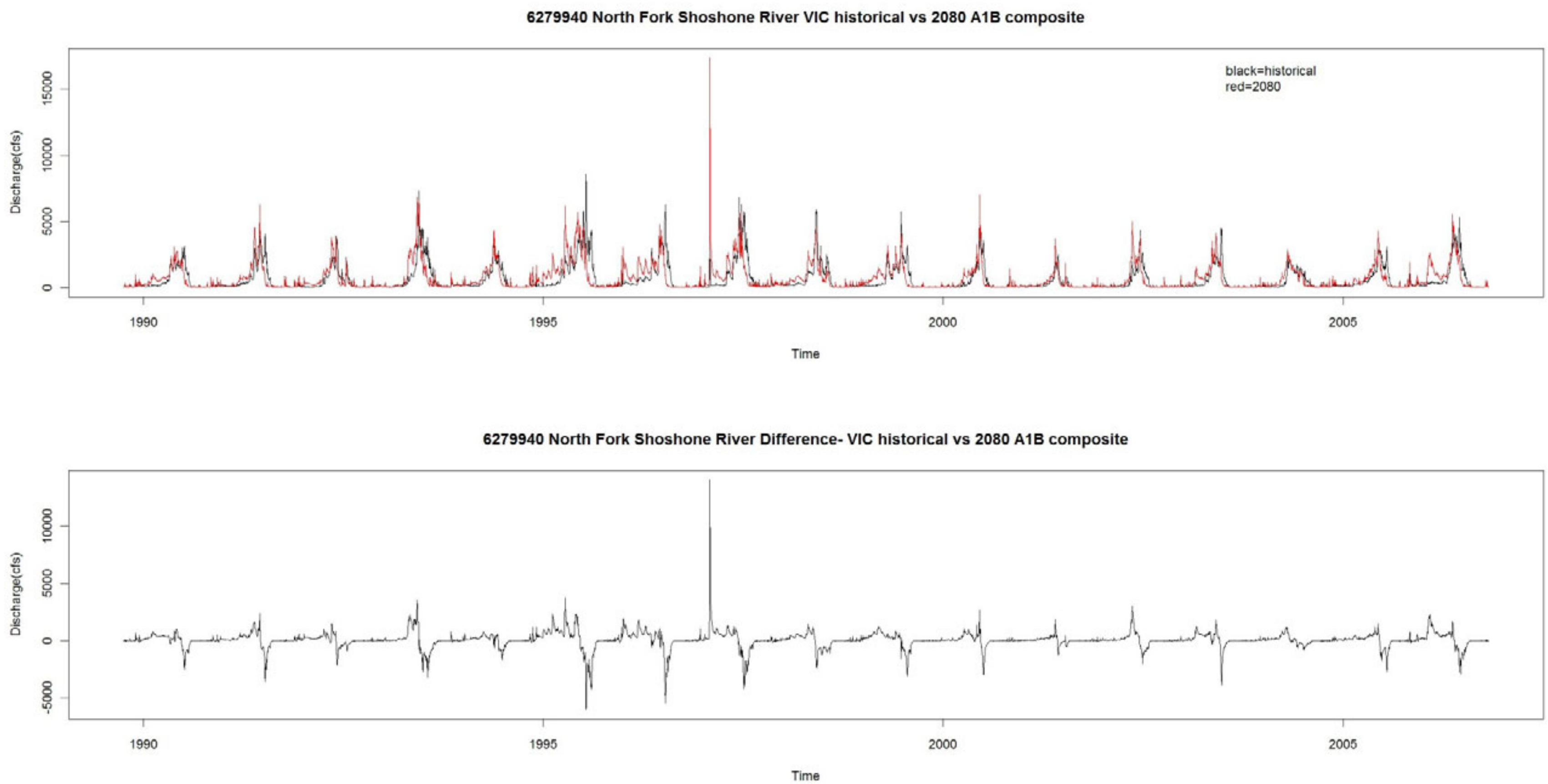
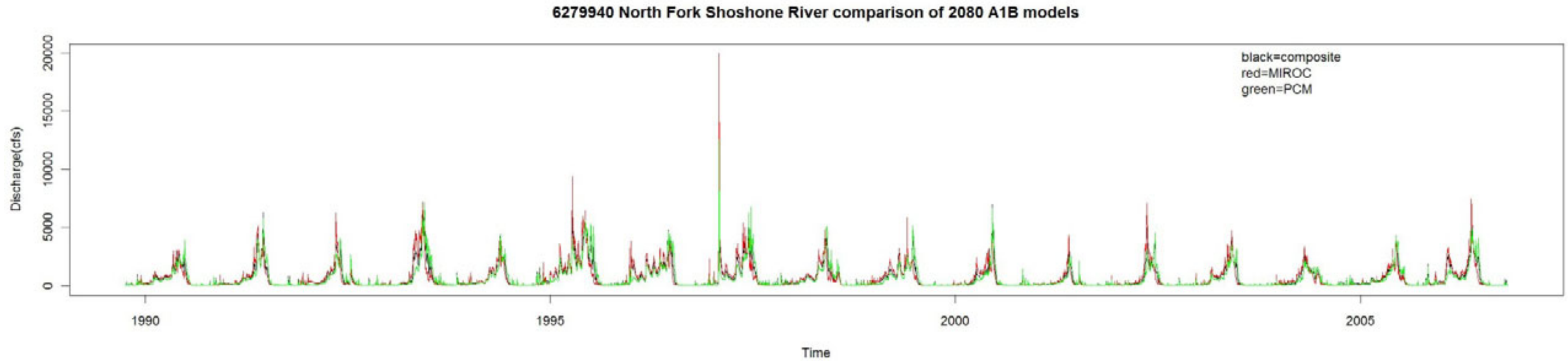


Figure 4. Forecast results for the North Fork Shoshone gage site.




6279940 North Fork Shoshone River comparison of 2080 A1B models
black=composite
red=MIROC
green=PCM
Discharge(cfs)
0
5000
10000
15000
20000
1990
1995
2000
2005
Time