STREAMFLOW AND SNOW CONTRIBUTION TO THE BOULDER CREEK WATERSHED UNDER CLIMATE CHANGE (CLIMATE PERTURBATIONS?)

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ABSTRACT

Hydrological processes in mountainous watersheds control downstream processes, such as ecosystem interactions and groundwater recharge. The impact of climate change on the water cycle in mountainous regions-particularly on snow and ice-is non-linear and requires more detailed research to help quantifying uncertainties in projections related to climate forcing. In this study, the VIC model is applied to the 270 km^2 Boulder Creek Watershed at Orodell, Colorado, to simulate streamflow amount under a meteorological drought condition, and changes in snow water equivalent. The model parameters were first adjusted using current climatic forcings and streamflow measurements. The Nash-Sutcliffe efficiency (NSE) for streamflow from 2006 to 2010 is 0.77, root-mean-square-error (RMSE) is 0.45, and percent bias is 0.1%, which are within acceptable range. Sensitivity analyses show that the effect of 1℃ increase in temperature is the same as 5% ~7% decrease in precipitation on streamflow. With an increased temperature, the timing of peak flow will appear early. Under the condition of decreased precipitation or increased temperature, values of daily streamflow, runoff efficiency, and snow water equivalent will decrease. Understanding the response of streamflow to precipitation and temperature perturbations is significant in regulating water supply, and maintaining water balance in the mountainous areas under future climate change.
(KEYWORDS: Boulder Creek, climate change, Variable Infiltration Model,)

INTRODUCTION

Mountains are water towers and bellwethers of climate change (Williams et al., 2015). Mountainous areas have complex geological features and climatic variability, which limit our ability to simulate and predict hydrologic processes in these areas, especially in face to a changing climate (Bales et al., 2006). Hydrologic models are being applied to understand the land surface water and energy budgets, especially in mountainous areas with limited access to the field with data collections. Hydrologic models can be coupled with general circulation models to depict the interaction between the land surface and atmosphere through water and energy flux exchanges. They are used operationally to forecast floods and droughts, extreme events that have an influence on people’s daily life as well as the economy (Troy et al., 2008).

The Variable Infiltration Capacity (VIC) model is a macro-scale hydrologic model, which is developed by Liang et al. (1994). It uses daily climate forcing data, including wind speed, minimum and maximum temperature, and precipitation, to drive energy and water balance calculations. One outstanding feature is the representation of subgrid variability in precipitation and infiltration (Zhao et al., 2012). Sensitivity analysis of streamflow to climate perturbations is beneficial to water resources management, in which to mitigate or prevent the adverse impacts of excessive runoff or shortage of water (Legesse et al., 2010), especially in a warming climate.

In this study, the VIC model is being applied to the Boulder Creek Watershed at Orodell. It seeks to simulate streamflow at the outlet, using input variables including daily precipitation, maximum and minimum temperature, and wind speed. The outputs that are being analyzed in this study include streamflow and snow water equivalent (SWE). A sensitivity analysis of streamflow to changes in precipitation and temperature will be performed.

METHODS

The Boulder Creek Watershed at Orodell has a drainage area of 270 km^2. The elevation ranges from 1779 m to 4117 m, with a mean elevation of 3139.44 m. The mean annual precipitation is 84.46 cm. There are four headwater

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catchments in the basin: Green Lakes Valley (GLV), Como Creek (CC), Gordon Gulch (GG), and Betasso (BET). Orodell is located downstream of the confluence of Middle and North Boulder Creek at an elevation of 1779 m, with coordinates of 40.006°N and 105.33°W. The geographical location of the watershed is shown in Figure 1.

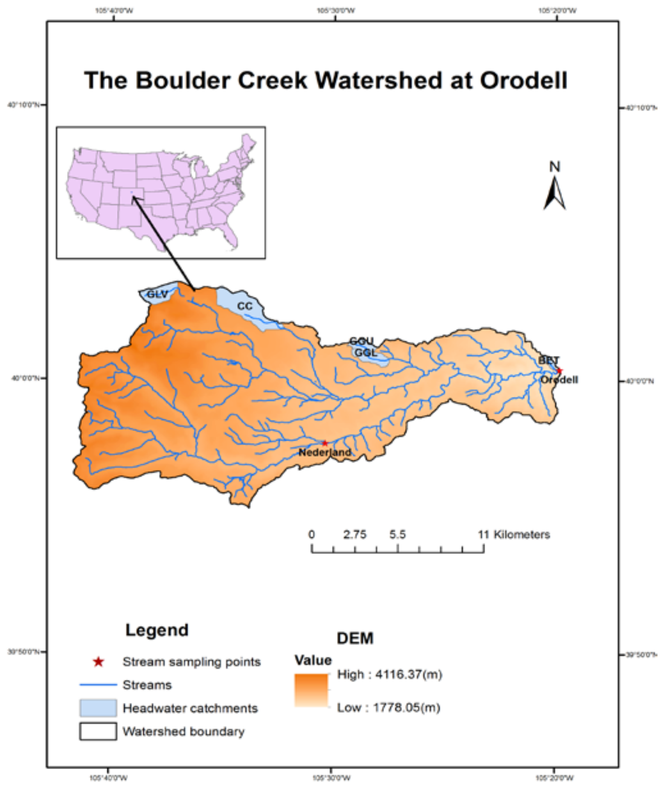

Figure 1. Locations map of the Boulder Creek Watershed at Orodell and the headwater catchments

The VIC model seeks to simulate streamflow at Orodell, using input data including climate forcing, soil parameters, and land cover types. Climate forcing data include daily precipitation, maximum and minimum temperature, and wind speed at 1/8th degree resolution (Maurer et al., 2002). Soil parameters were compiled from STATSGO dataset. Land cover types were compiled from National Gap Analysis Program, reclassified to eleven classes. Observed streamflow measurements were obtained from the Colorado Division Support System at gage BOCOROCO (Colorado's Surface Water Conditions, 2015).

Several metrics, such as Nash-Sutcliffe efficiency (NSE), root-mean-square-error (RMSE), and percent bias, were being applied to adjust the soil parameters. Once the metrics are within acceptable range, the soil parameters are considered applicable. Then climate forcing is perturbed to see the sensitivity of streamflow and snow water equivalent to climate change.

Precipitation elasticity (ε) is calculated as the fractional change in annual average runoff (Q) divided by the fractional change in precipitation (P). When using Δ = 1%, ε is calculated as

$$\varepsilon = \frac{\frac{Q_{ref+\Delta\%} - Q_{ref}}{Q_{ref}}}{\Delta\%} \quad (1)$$

Temperature sensitivity (S) is defined as the percent change in annual average Q per 1℃ temperature (T) change

$$S = \frac{\frac{Q_{ref+\Delta} - Q_{ref}}{Q_{ref}}}{\Delta} \quad (2)$$

Following Vano et al. (2012), there are two methods to change temperature: change both maximum and minimum temperature by the same magnitude, or change maximum temperature by twice the magnitude but maintain minimum temperature. The magnitude to increase temperature in this study is 0.1℃, 0.2℃, and 0.3℃.

RESULTS

Streamflow was simulated for the years 2006 to 2010, with a daily NSE of 0.77 and RMSE of 0.45. The validation period is from 1980 to 1990, with a daily NSE value of 0.67 and RMSE of 0.52. Moriasi et al. (2007) mentioned that when NSE falls between 0.65 and 0.75 indicating that the model performance is good; while NSE falls between 0.75 and 1 indicating that the model performance is very good. Thus, the adjusted soil parameters are proper for further sensitivity analysis. Figure 2 shows the simulated and observed daily streamflow for the

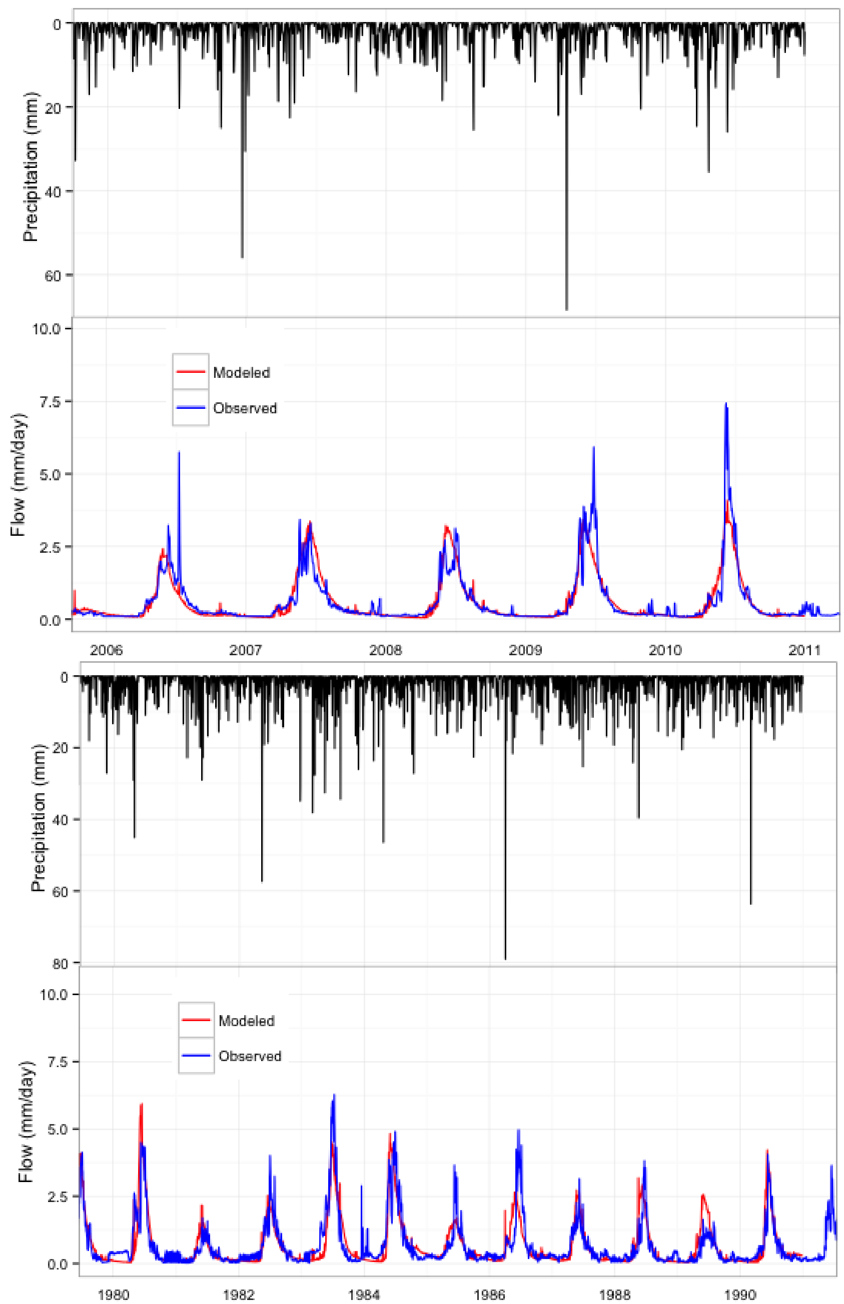

Figure 2. Daily streamflow in calibration (top) and validation (bottom) period

calibration and validation period (Figure 2). In the calibration period, the model underestimated peak streamflow. One possible reason is that climate forcing inputs, especially precipitation, is underestimated compared to observed values.

Using observed SWE data at Niwot Ridge and Lake Eldora, the simulated SWE at the grid cells with the Snotel stations give acceptable results. The simulated and observed SWE during the calibration period is shown in Figure 3. It can be seen that the model overestimated SWE at Lake Eldora station. The observed SWE is from one location, while the simulated SWE is the average condition for the whole grid cell especially at the centroid. If the Snotel station is at a lower elevation, its observed SWE will be lower than at a higher elevation. In general, the model can catch the trend and start timing of observed SWE.

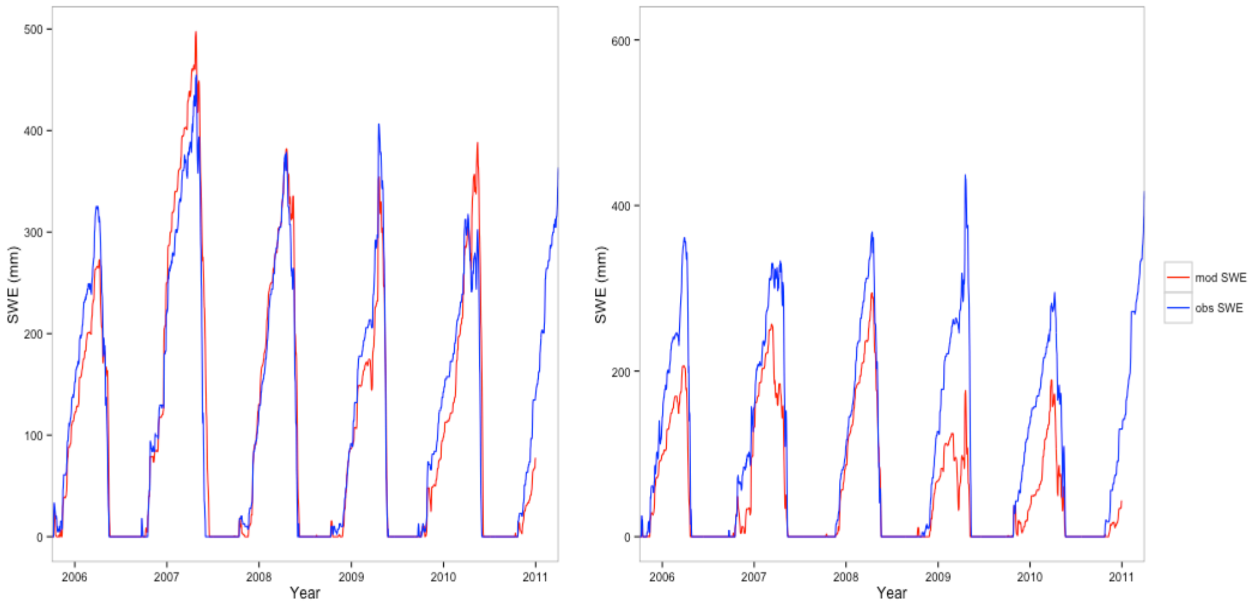

Figure 3. Simulated vs. observed SWE from Snotel sites at Niwot Ridge (left) and Lake Eldora (right)

Precipitation elasticity and temperature sensitivity is performed for calibration years during 2006 to 2010. The results show that streamflow is more sensitive to changes in temperature than precipitation. For example, 1% to 3% decreases in precipitation result to about 2% decrease in streamflow, while 1℃ to 3℃ increases in temperature results to 9% to 17% decrease in streamflow. In general, the effect of 1℃ increase in temperature is the same as 5% ~ 7% decrease in precipitation on average streamflow volume. Figure 4 shows the temperature sensitivity of streamflow at Orodell. Increasing maximum temperature by two times has a larger influence than increasing both minimum and maximum temperature. The larger temperature range of the former mechanism will influence the calculation of downward shortwave radiation, which is important for evapotranspiration. With an increased temperature, the timing of peak flow will appear early. Under the condition of decreased precipitation or increased temperature, values of daily streamflow, runoff efficiency, and SWE will decrease. This may inform water quantity condition in the future, as temperature is predicted to increase, while the magnitude and direction of changes in precipitation are uncertain (Christensen et al., 2004). Moreover, increased temperature may result to decreased soil moisture, which will influence root uptake and surface-subsurface water interactions.

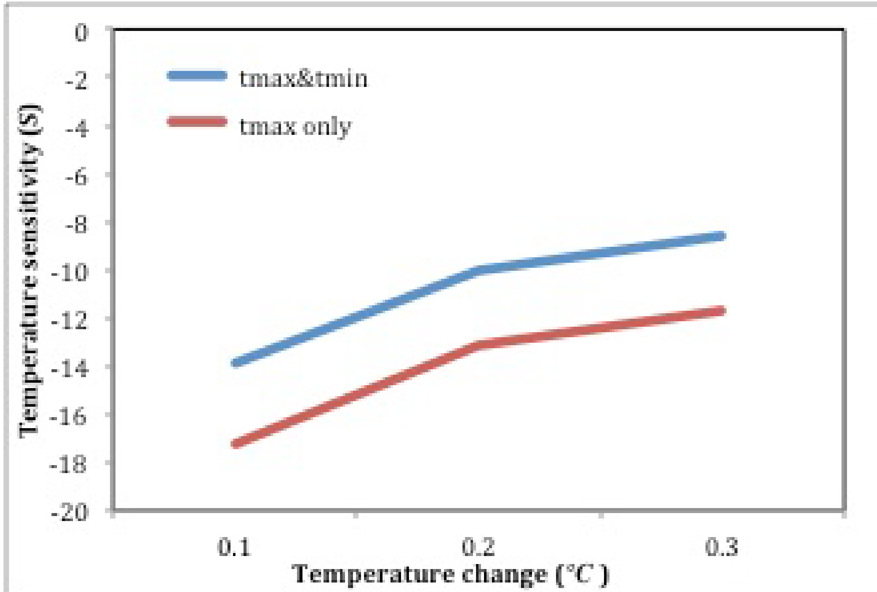

Figure 4. Temperature sensitivity at Orodell

DISCUSSION AND CONCLUSION

Hydrologic modeling has been applied to the Boulder Creek Watershed at Orodell. Daily NSE values for the calibration and validation period are within acceptable range. In general, the simulated streamflow is lower than the observed streamflow. Peak streamflow occurs after a rainfall event, denoting a rainfall-runoff response. At specific grid cells, the simulated SWE is close to the observed SWE, demonstrating that the model can represent snow pack amount. When increasing temperature, peak streamflow will appear earlier, while the timing of peak SWE is not as apparent. The results show that 1% to 3% decreases in precipitation result to about 2% decrease in streamflow, while 1℃ to 3℃ increases in temperature results to 9% to 17% decrease in streamflow. Approximately, the effect of 1℃ increase in temperature is the same as 5% ~ 7% decrease in precipitation on streamflow. According to the projected future climate from CMIP3 models, temperature will increase by 0.6-1.7℃, and mean annual precipitation will change -10~6% in low-emission scenario by 2050 in the Southwest U.S. In high-emission scenario, temperature will increase by 1.1-2.2℃, and mean annual precipitation will change -10~5% (Cayan et al., 2013). Overall, the combined impact of changes in temperature and precipitation should take into consideration when planning for water resources allocation. The precipitation elasticity is lower than that in the upper Colorado River Basin, which ranges from 2.2 to 3.1 (Vano et al., 2012), indicating that streamflow in the upper Colorado River Basin is more sensitive to precipitation perturbations. On the other hand, the higher temperature sensitivity indicates that streamflow at Orodell is more sensitive to temperature perturbations. The magnitude of sensitivity under fixed minimum temperature is higher than changing both maximum and minimum temperature. When changing maximum temperature only, the discrepancy between net radiation and vapor pressure deficit will be larger. The sensitivity analysis also indicates that streamflow may be more sensitive to temperature perturbations. Understanding the mechanism is important for water resources management under future climate scenarios, in order to promote a more sustainable environment.

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