MODELED HYDROLOGIC RESPONSE UNDER CLIMATE CHANGE IMPACTS OVER THE BANKHEAD NATIONAL FOREST IN NORTHERN ALABAMA

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Abstract

The impacts of climate change on water availability over the Bankhead National Forest (BNF) and Sipsey Fork Watershed (SFW) located in northern Alabama is evaluated by developing a site specific hydrologic model inside the Soil and Water Assessment Tool (SWAT). The SWAT model is utilized over Sipsey Fork (SF) subbasin of SFW to assess hydrological response under changing climatic conditions until 2100. Calibration and validation of the SWAT model is performed at daily time steps by comparing simulated and observed streamflow. Altogether 13 parameters that directly influence surface/base flow and basin response were selected and calibrated; the model simulated streamflow very well as evidenced by correlation and error statistics (“r = 0.87“, “R^2 = 0.75“, and lower “RMSE = 12 cms“). Climate forcing (e.g. precipitation, temperature) from selected regional/global climate models that represent regional climatology well over the basin were incorporated into the SWAT model to determine future water availability in the basin. The projected average change in total annual streamflow for SF varies from -10% to -18%, which ranges -7% to -16% for A1B, and -12% to -23% for A2 until 2100. This study is conducted in conjunction with other ongoing studies that looked at the impacts of forest management on BNF hydrology. Major research findings from this study will help decision makers in evaluating the combined impacts of climate change and forest management on water availability, and developing strategies to sustain available natural resources.

Keywords: Climate Change, SWAT, Streamflow, Hydrologic Modeling

Introduction

Climate change is a major concern throughout the world. The major impacts of climate change have been documented on both quantity and quality aspects in different parts of the world (e.g., Bates et al. 1994; Aizen et al. 1997; Loukas et al. 2002; Jian and Shuo 2006). The likely impacts of climate change are observed on important sectors namely water, food/agriculture, ecology, energy, and other natural and environmental sciences. This further affects the planning, strategies, polices, and decision making of resource management in each sector. The output from various global and regional climate models (GCMs/RCMs) have been utilized to evaluate the regional or local impacts of climate change on water availability. Model simulations applying a number of GCMs, RCMs, multiple scenarios and projections have shown increasing or decreasing climate pattern based on various regions and seasons. Because various GCMs simulate future climate with different emission scenarios at different level of accuracy, utilization of multiple GCMs/RCMs and scenarios could be helpful to address uncertainty in climate-change-related studies (e.g., Covey et al. 2003; Beniston et al. 2007; Maurer 2007; Vicuna et al. 2007; Fowler and Ekström 2009). The methodology, model, and data sources adopted in this study are documented by various similar climate-change-related studies in the past (e.g., Christensen and Lettenmaier 2007; Miller et al. 2010).

This paper quantitatively assesses the potential effects of climate change on hydrology and water resources of the Bankhead National Forest (BNF). BNF is a region in northern Alabama where projected climate change and land use management could impact the available water resources. The William B. BNF is considered as one of four national forests in Alabama and is a part of the Southern Cumberland Plateau. The BNF covers 182,000 acres in northwest Alabama, and located in the counties of Franklin, Lawrence, and Winston. Almost 176,000 acres out of 182,000 acres of BNF is forested, which predominantly consists of unfragmented deciduous forest (mixed forest stands of hardwood and pine). This forest helps in protecting water quality, and also serves as a visiting arena for local and regional visitors. BNF is popular among people due to its wildlife, hunting, and recreational resources, as it consists of 26000 acre Sipsey Wilderness, 96000 acre Black Warrior Wildlife Management Area, and the Sipsey Wild and Scenic Rivers (Addor and Birkhoff, 2003). The BNF is occupied by both private and public ownership and has been impacted by this ownership pattern in addition to other ongoing land management practices, land use changes and burning and thinning of the forests. The impacts of Southern pine Beetles have also been observed in the past causing thousands of acres of pine forest convert to standing dead trees. Under changing future climatic conditions and ongoing land management practices, it is expected to change the forest hydrology and water availability over the watershed, and impact various important sectors as discussed above. No detailed studies have been carried out in the past within the BNF that evaluate the combined impacts of climate change and forest management on forest hydrology and water availability over the BNF that is of so much value to the community.

Separate studies are ongoing to evaluate the effects of operational land management practices on water quantity and quality over several riparian areas within the BNF. While relating to streamflow forecasting under anthropogenic climate change conditions, this study can be utilized in future water availability assessment over the BNF. The results obtained from this study may assist water managers, decision makers, and stakeholders in understanding the alteration to forest hydrologic response under climate change, and planning and managing water resources allocation while meeting the requirements of diverse water demands. This study represents a comprehensive study of the SFW and develops streamflow projections under changing future climate conditions over the SFW by adopting a multimodel ensemble technique. Future water resources and land management alternatives could be suggested by decision makers as a proactive step in meeting the challenges of future water demands while evaluating the climate change impacts and operational land management practices within the BNF.

Methodology

Study Area

This study is carried out in the Sipsey Fork Watershed (SFW) located in northern Alabama. SFW also encloses the BNF (as indicated by green boundary in Fig 1). The SFW consists of several water quality measurement stations downstream near to the Lewis Smith Lake Reservoir that is popular amongst visitors for recreational activities. However, it possess only two streamgage stations located upstream (see Figure 1) and at the outlet of Sipsey Fork (SF) and Clear Creek (CC) subwatersheds. Regions A and B in Figure 1 represent SF and CC subwatersheds of the SFW. The SF passes through the BNF, and CC flows outside the BNF, while both drains into the Smith Lake located far downstream.

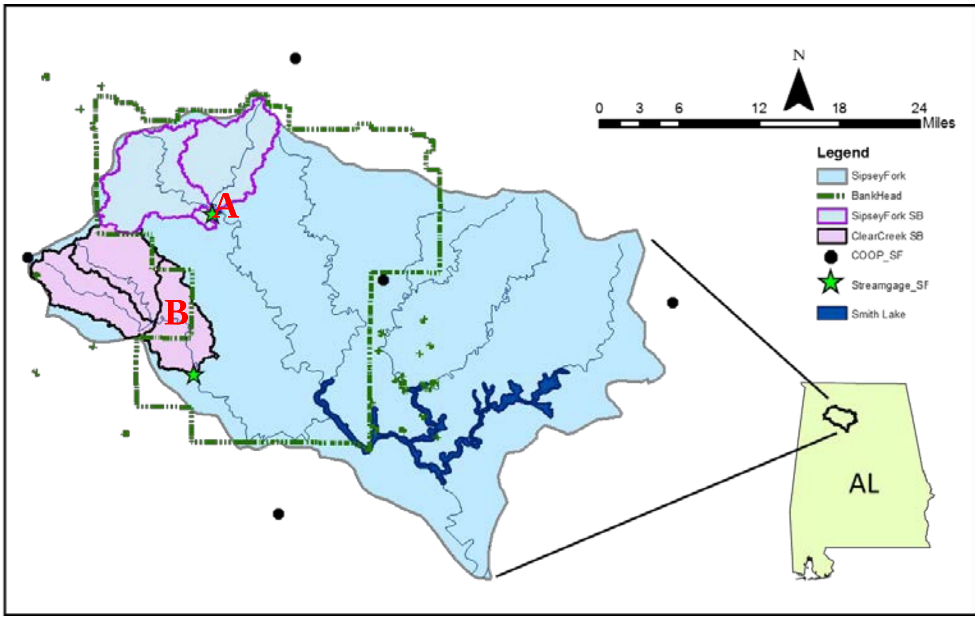

Figure 1: Location of the SFW and BNF in northern Alabama. The location of subbasins SF and CC, streamgage stations (filled star), COOP stations (filled dots), and Smith Lake are also shown.

Hydrological Model

The Soil and Water Assessment Model (SWAT) is utilized to develop a site specific hydrologic model and evaluate the impacts of climate change on water availability over the SFW and BNF. ArcSWAT (V2012.10.14) is an ArcGIS-ArcView extension and graphical user input interface for SWAT (http://swat.tamu.edu/software/arcswat/). SWAT, a physically based and distributed parameter watershed scale model, has been widely used in the past for evaluating impacts of changing climate, land use/ land cover change, and agriculture management practices on both water quantity and quality (e.g. Lin et al., 2009; Santhi et al., 2006; Van Liew et al., 2007). The SWAT model inputs are readily available and the model runs on both daily and monthly time steps. The major inputs for SWAT model are watershed boundary, climate/weather, elevation, and soil parameters. The major outputs generated by the model are runoff/flows, ET sediments, nutrients, and heavy metals.

The calibration of the SWAT model can be performed manually or automatically. SWAT-CUP (SWAT Calibration and Uncertainty Procedures) has been utilized for automatic calibration of SWAT model. SWAT-CUP is a computer program freely available from the public domain. It includes different internal procedures (e.g. GLUE, ParaSol, SUFI2, MCMC, and PSO) to link to SWAT model and perform sensitivity analysis, calibration, validation, and uncertainty analysis (http://www.eawag.ch/forschung/siam/software/swat/index Major calibration parameters for the model represent parameters that directly affect basin response (.bsn, .mgt), surface flow (.hru), base flow/ground water flow (.gw), and channel routing (.rte). A detailed description on the parameters that have been commonly utilized for calibration can be found in several references (e.g. Arnold et al., 2012; Neitsch et al., 2002; Shrestha, 2010; Van Liew et al., 2007; White and Chaubey, 2005). A number of parameters are considered during model calibration and the calibration is performed on daily or monthly time scale such that modeled streamflow resembles the historical streamflow. Various statistical parameters such as Pearson Correlation Coefficient (r), Root Mean Square Error (RMSE), and Coefficient of Determination (R^2) are calculated to examine the effectiveness of the calibrated parameters/model.

Data Description

The observed daily climate data (precipitation, max and min temperature) are obtained from the National Weather Service (NWS) Cooperative Observer Program (COOP) stations. Altogether five COOP stations are located in and near the SFW boundary (Fig 1). The wind speed and US STATSGO soil data is directly downloaded from the SWAT model. Other weather data is obtained from WGEN_US_First Order Stations. The land use land cover data is obtained from National Land Cover Data (NLCD, 2006, 2011; retrieved from http://nationalmap.gov/viewer.html). The 10m resolution digital elevation data is downloaded from the "National Map Viewer and Download Platform" (http://nationalmap.gov/viewer. html). The daily runoff data for the streamflow gages "02450250" and "02450825" located at the outlet of SF (near Grayson) and CC (new hope Church near Poplar Springs) subwatersheds are obtained from United States Geological Survey (www.usgs.gov).

A total of six future climate projections from two emission scenarios A1B and A2, and three GCMS namely CSIRO, CGCM, MIROC are adopted for this study based on a recent project "The Southern Forest Future Project" conducted in the SouthEast by USDA Forest Service. This project was conducted to "examine a variety of possible futures that could shape forests and the many ecosystem services and values forests provide" in the forests of 13 states of Southeastern United States (Wear and Greis, 2013). The county level climate projection data available from the project at monthly time steps from 2001-2100 are utilized for this study (Coulson et al. 2010). During the future forest assessment study, the county level climate data were developed based on Parameter-elevation Regressions on Independent Slopes Model (PRISM) climatology, and World Climate Research Programs (WCRP's)

Climate Model Intercomparison Project Phase 3 (CMIP3) climate projections for the United States (Maurer et al, 2007; http://gdo-dcp.ucllnl.org).

Model Simulations

A trend/time series analysis is performed on GCM output, namely precipitation and temperature, for historical (2001-2010) and future time periods (2021-2099). The daily climate data from the COOP stations are translated into future climate by applying monthly change factors calculated based on GCM's output for current and future climatic conditions. The average change factor for each month for a total of 10 years period is calculated and applied to historical climate data to perturb it to future climate conditions. Readers can refer to various past studies to further explore the weighted average method and its application (e.g. Acharya et. al., 2013; Wood et al. 2004). The projected climate change scenarios for the SFW is forced into the calibrated SWAT model to derive multiple long term streamflow projections and evaluate future changes in water availability. All projections are treated equally likely such that the results follow ensemble representation. This analysis is focused on monthly, seasonal or annual changes in streamflow. Significant changes in climate parameters, flood peak magnitude, and total runoff volume are calculated during each 10 years period until 2099. The impacts of climate change on streamflow is compared for different climate scenarios, based on simulated daily, monthly, seasonal or annual streamflow for present and future periods. The major results presented in this paper are limited to the SF, while the study for the CC subbasin will be presented in a separate paper.

Results

Climate Pattern

The climate data for the Winston County in northern Alabama is assessed since most of the study area (including BNF) is located in the Winston County. As mentioned earlier, a total of 6 projections from 3 GCMs (CSIRO, CGCM, MIROC) and 2 emission scenarios (A1B, A2) are analyzed and compared with baseline time period (2001-2010). While comparing monthly change in average temperature from all projections, a simultaneous increase in mean temperature is observed for all months from 2021 to 2100, with a maximum rise up to 6°C during summer months at the end of the century (Figure 2a). However, the minimum rise in average temperature varies from 0.2°C to 2°C for A1B, and -0.2°C to 3°C for A2; the maximum rise varies from 1.6°C to 5°C for A1B, and 2.2°C to 6.6°C for A2; the average rise varies from 1°C to 3.5°C for A1B, and 1.2°C to 5°C for A2 respectively (Figure 2b).

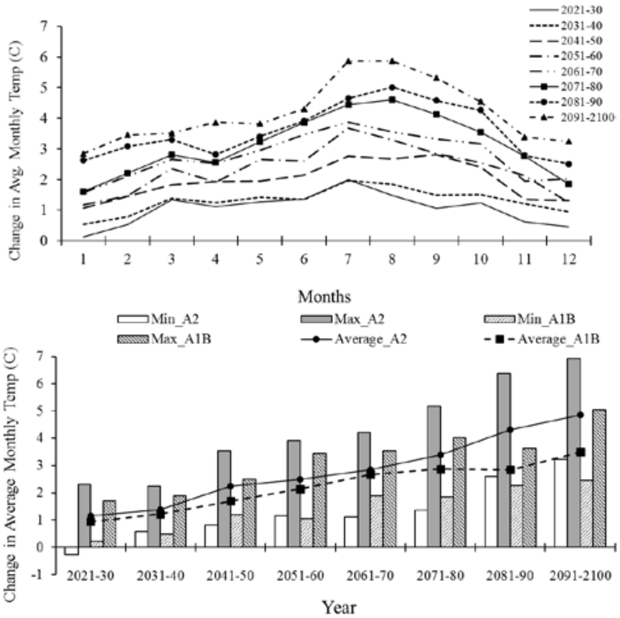

Figure 2: Change in average monthly temperature from 2021-2100 with respect to 2001-2010 for all projections. a) mean monthly change for Jan-Dec; b) minimum, maximum and average change for each scenario.

Figure 3a and 3b shows the change in average monthly precipitation for future periods with respect to 2001-2010 for all projections and for each scenario respectively. Precipitation shows both increasing and decreasing pattern for the months of Feb, Oct, Nov, and Dec. All other months show a decreasing pattern where the range varies from -1% to -30% for differing time periods and months. The range of minimum and maximum change in average monthly precipitation during 2021-2100 is higher for A2 as compared to A1. The minimum change in average precipitation varies from -15% to -30% for A1B, and -25% to -40% for A2; the maximum change varies from 6% to 25% for A1B, and 7% to 35% for A2; the average change varies from -1% to -5% for A1B, and -5% to -10% for A2 respectively. For both scenarios, the average change in mean monthly precipitation shows decreasing pattern (-ve) which signals towards decrease in total water availability for the study area in future periods.

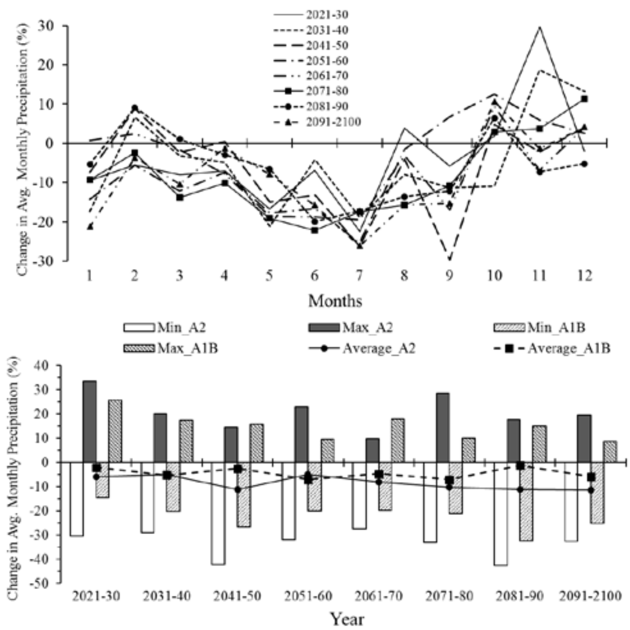

Figure 3: Change in average monthly precipitation from 2021-2100 with respect to 2001-2010 for all projections. a) mean monthly change for Jan-Dec; b) minimum, maximum and average change for each scenario.

Model Calibration and Validation

The ArcSWAT model is calibrated and validated for the SF based on daily time steps from 1980-1995, and 1996-2012 respectively. Altogether 13 model parameters are chosen for calibration purpose. The parameters used for model calibration and the calculated statistics during calibration and validation are presented in **Table 1**. During calibration and validation periods, the simulated daily streamflow represents observed daily streamflow quite well for base flows as well as most peak flows except some over/under estimation of higher peaks (**Figure 4**). This results in a very good calibration with higher ‘r=0.87’ and ‘R^2=0.75’ and lower ‘RMSE=12’**.** A slightly lower ‘r=0.79’ and ‘R^2=0.64’ during validation period is due to underestimation of some higher peaks. Among all 13 parameters used during calibration, CN2 is found as the most sensitive parameter.

Streamflow

Monthly Streamflow

Figure 5 shows the change in mean monthly streamflow with respect to baseline period for each decade starting from 2020’s. Both A1B and A2 scenarios show a decrease in mean monthly streamflow for future periods, except during Oct, Nov and Dec which shows both increasing and decreasing pattern at different time periods.

Table 1: Summary of calibrated parameters, values, and statistics

Parameters	Values	Statistics
ALPHA_BF	0.803	**Calibration**
GW_DELAY	40.587	r = 0.87
CH_N2	0.13591	R^2 = 0.75
CH_K2	469.54	RMSE = 12.04
SURLAG	18.967	
GWQMN	342.43	**Validation**
REVAPMN	314.12	r = 0.79
RCHRG_DP	0.00002	R^2 = 0.64
GW_REVAP	0.032811	RMSE = 10.94
ESCO	0.77032	
EPCO	0.94577	
CN2	-0.2	
CANMX	26.151	

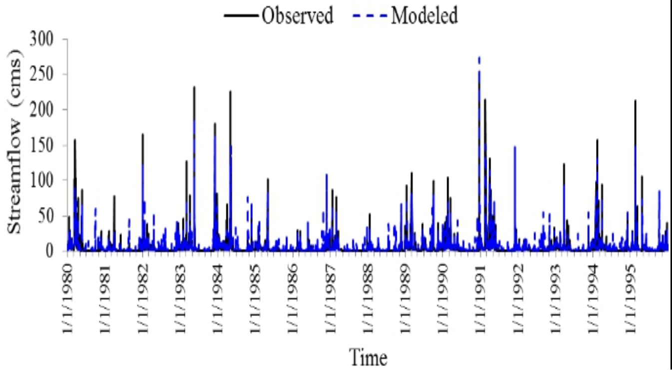

Figure 4: Observed and simulated daily streamflow (m^3/s) during calibration period (1980-1995)

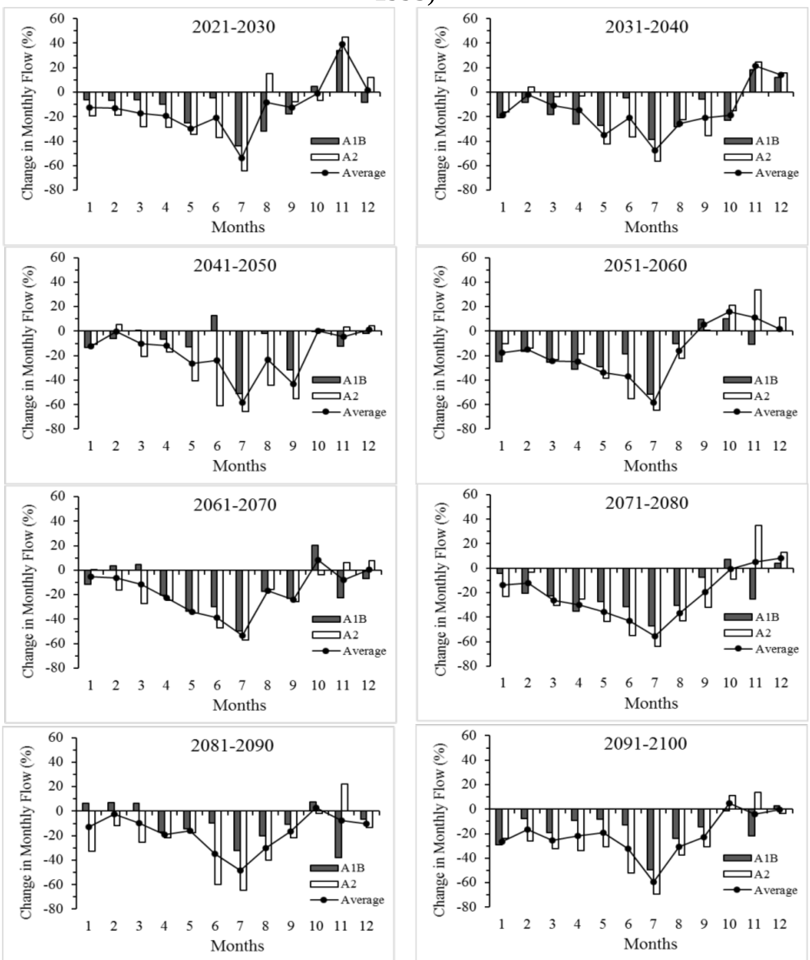

Figure 5: Change in simulated monthly streamflow (in percent) during 2021-2100 (each 10 years interval) with respect to baseline period (2001-2010) for emission scenarios A1B and A2.

An average decrease of almost 50% is calculated for some months while the maximum decrease in mean monthly streamflow is observed for A2 scenario during the months of June and July.

While comparing simulated minimum change in mean monthly streamflow as shown in **Figure 6,** a maximum decrease of -40% to -90% is calculated for the MIROC model, which is in the range of -25% to -60% for other models. While comparing simulated maximum change in mean monthly streamflow, an increase of 10% to 120% is calculated for CSIRO and CGCM; the simulated changes for MIROC varies from -30% to +30% (except 2021-30 for A2) for the same scenario. Comparatively, MIROC model simulated almost double decrease in monthly streamflow as compared to other models.

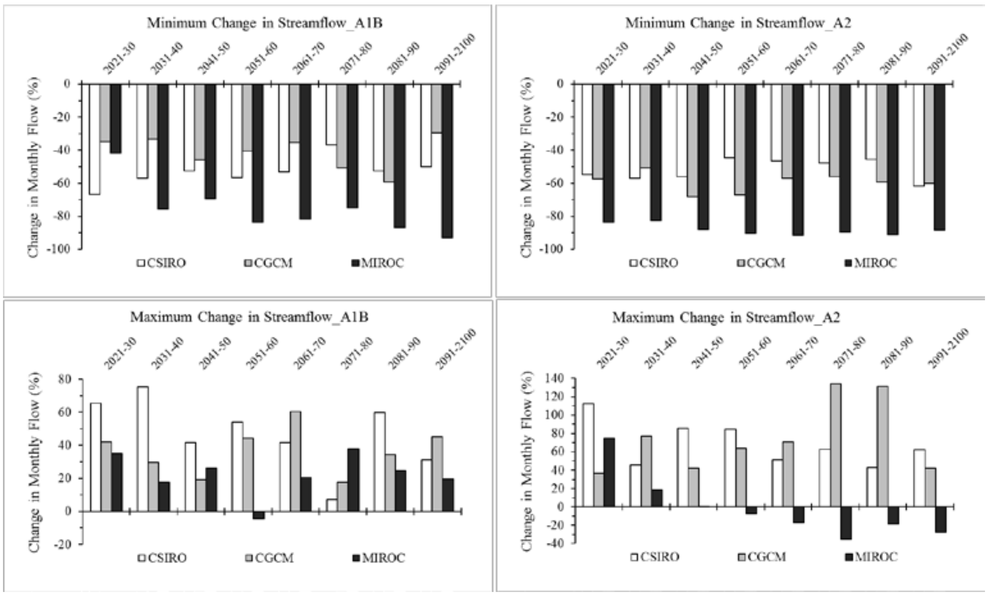

Figure 6: Comparison of simulated minimum and maximum changes in mean monthly streamflow during 2021-2100 with respect to 2001-2010 for emission scenarios A1B and A2, and GCMs CSIRO, CGCM, and MIROC.

Annual Streamflow

Figure 7 shows the simulated total annual streamflow for each GCMs and emission scenarios. The total annual streamflow shows both increasing and decreasing pattern for future time periods. The three black dotted lines show the 90th percentile, mean, and 10th percentile annual streamflow for the baseline period. During some years in the middle century, CSIRO and CGCM shows annual streamflow higher than 90th percentile flow values. For the same models, few years show annual streamflow less than 10th percentile, while during other years simulated annual streamflow lies above and below the average annual flow. A comparatively very low annual streamflow is simulated by the MIROC where the annual streamflow is less than 10th percentile for most years (except some years). The simulated annual streamflow is higher for A2 before, during and after half century, while it is higher for A1B at the end of the century (2081-2100). A very low annual streamflow is simulated by MIROC as compared to CGCM and CSIRO. While combining all projections for each scenario as shown in Figure 8a, average change in annual streamflow varies from -10% to -18%, which ranges -7% to -16% for A1B, and -12% to -23% for A2. While combining projections from CSIRO and CGCM only (Figure 8b), average change in annual streamflow varies from -3% to -9%, which ranges -3% to -11% for A1B, and 0.5% to -10% for A2. This signals towards the occurrence of drought years in future, however, the simulated streamflow clearly shows higher reduction (more than half) due to MIROC projections alone.

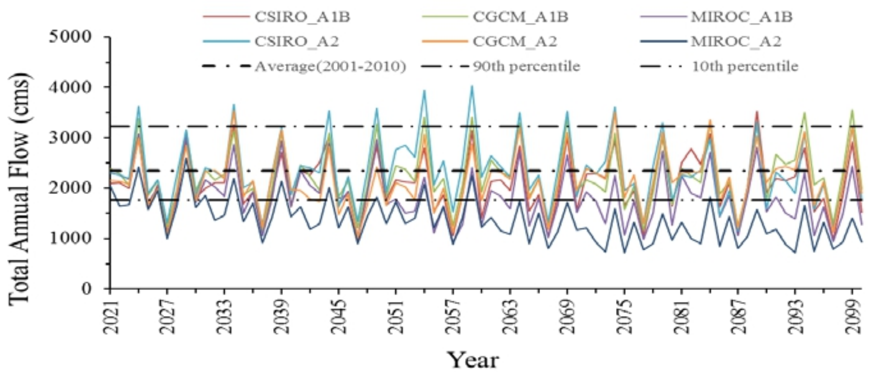

Figure 7: Simulated total annual streamflow (m^3/s) during 2021-2100 for emission scenarios A1B and A2, and GCMs CSIRO, CGCM, and MIROC.

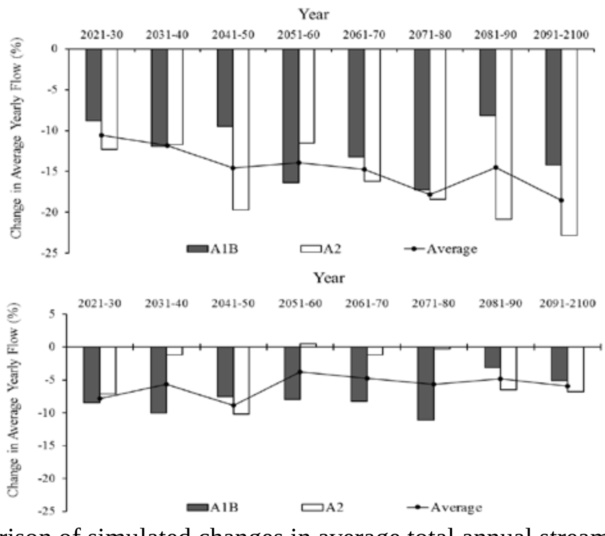

Figure 8: Comparison of simulated changes in average total annual streamflow (in percent) during 2021-2100 (each 10 years interval) with respect to 2001-2010 for emission scenarios A1B and A2: a) based on all GCMs CSIRO, CGCM, and MIROC; b) based on GCMs CSIRO and CGCM only.

Discussion

The modeled results obtained from this study clearly shows a decrease in future water availability over the sub-basins based on projected emission scenarios over the region. A higher decrease in simulated monthly and total annual streamflow for future periods is due to combined impacts of decreased precipitation and increased temperature. This study provides an indication of lower water availability in future climate which may further aggravate the water stress condition if there exists an increasing water demand over the region. This study also provides an outlook of hydrologic changes based on future climate scenarios; however the various uncertainties (e.g. station data, GCMs output, downscaling method, hydrological models) associated with this type of climate change related studies should be clearly understood before applying the results and making decisions on future management measures. All GCMs are developed for a specific purpose and with different assumptions and limitations, therefore, the practical application and simulated results for each GCM is different. As discussed earlier, this study considers only three climate models and two emission scenarios. While comparing precipitation and simulated streamflow, MIROC model is possibly under-predicting as compared to CGCM and CSIRO. Utilization of multi-model and focus on mean climate is assumed to provide a more reliable estimate of the future uncertainty. Further research with inclusion of more GCMs, scenarios, and climate projections available from WCRP CMIP3 database could be performed to look at the range of maximum/minimum change in water availability for this region. The climate data utilized in this study are at the county level. Parts of the SFW is located in the Winston and Lawrence county with similar climate pattern (not shown here separately) for both counties, the simulated result is not expected to vary. However, application of gridded finer resolution climate data and utilization of a more distributed hydrologic model might simulate significantly better results. The downscaling method used in this analysis only considers the change in rainfall intensity for a future climate, with land use, variability of extreme events and other watershed characteristics remaining constant. However, the use of other downscaling techniques may alter the simulated results more than the results from the existing approach.

Conclusion

This study has incorporated downscaled climate data into a distributed hydrological model to evaluate watershed level impacts of climate change on water quantity over the SFW. As mentioned earlier, concurrent studies are undergoing that evaluate impacts of climate change and forest management on water quantity over the CC, SF, and SFW. Utilizing results obtained from this study, one could assess the potential impacts of climate change on water resources, and design additional management measures to meet diverse future water demand more effectively while looking at the combined impacts of climate change and ongoing forest management measures over the SFW and BNF. However, various uncertainties associated with this type of climate change and hydroclimatic modeling studies should not be neglected while planning and designing additional water management measures.

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