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Impact Assessment of Hydrology and Water Quality in the Saugahatchee Creek under Projected Land Use and Climate Change Scenarios Using WARMF

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Authors' contributions

Authors collaborated for the completion of this work. Author SS designed the study, ran the model for all cases, performed the data analyses, prepared and revised the manuscript. Author XF provided valuable suggestions for the study design, supervised the data analyses, and revised the manuscript. Author RS developed the land use land cover scenarios and revised the manuscript. Author LJM supervised land use land cover study and revised the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

The hydrology and water quality of a stream or reservoir can be affected due to rapid urbanization and land use change in its watershed. Climate change, if it occurs, is likely to have additional impacts on hydrology and water quality of the watershed system. In this study, a watershed model WARMF (Watershed Analysis Risk Management Framework) was applied to the Saugahatchee Creek Watershed which includes two stream branches that were listed on State of Alabama's 303(d) list of impaired water for nutrients and organic enrichment/dissolved oxygen. WARMF model for the

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Saugahatchee Creek Watershed was developed and model calibration and validation were performed. The model was then used to investigate hydrologic and water quality response to two different land use scenarios (LU 2009 and LU 2030) and four statistically downscaled future climate scenarios derived from Canadian Global Coupled Model (CGCM3) and Hadley Centre Coupled Climate Model (HadCM3). Temperature, dissolved oxygen, total nitrogen, total phosphorus, and algal concentration were the water quality parameters simulated along with flow. Based on monthly average of daily predicted values, the effect due to land use change was not significant except for nutrient concentration. The monthly average of daily total phosphorus concentration for LU 2030 is predicted to increase up to 72% more than baseline (LU 2009) under past climate conditions (1981–2010). Based on model results, the monthly average of daily surface water temperature is predicted to rise for all future climate scenarios. The monthly average of daily flow is predicted to increase corresponding to CGCM3 (annual average increase of 88%) and decrease corresponding to HadCM3 scenarios (annual average decrease of -49%). Accordingly, nutrient concentration is expected to decrease corresponding to CGCM3 and increase corresponding to HadCM3 scenarios. DO concentration are predicted to fall up to 2.3 mg/l (monthly average), especially in summer for the four climate scenarios. Combined land use and climate change scenarios cause the increase in nutrient concentrations for future land use and climate scenarios (e.g., annual TP from 0.082 mg/l for the baseline to 0.203 mg/l for HadCM3 A2 20s scenario). Chlorophyll-a concentration during the growing season is expected to increase to 25.8 and 26.3 μg/l under HadCM3 A2 and B2 scenarios due to combined effect, respectively, in comparison to 18 μg/l for the baseline (1981–2010 and LU2009). The results of this study can be incorporated into watershed management and planning strategies.

Keywords: Hydrology; water quality; land use change; climate change; Saugahatchee; WARMF.

1. INTRODUCTION

During the recent years, rapid urbanization has led to massive land use changes, pervious forest soils have been reduced and industrial and residential areas have been increased. Similarly, the atmospheric concentration of greenhouse gases is believed to be increasing, thereby leading to climate change. Climate change, if it happens, will cause increase in temperature, evaporation, evapotranspiration, precipitation variability and extremes [1]. These alterations will change the hydrological behavior of watershed ecosystem in physical, chemical, and biological terms. The potential effects of land use and climate change are not limited to quantity; it can have serious impacts on water quality of the streams in the watershed. These changes will further affect water quality in downstream lakes and reservoirs that may alter fish habitat and have an effect on indigenous fish populations [2-5]. In this study, we utilized the Watershed Analysis Risk Management Framework (WARMF) [6,7] to develop a region-specific modeling framework to systematically assess the impact on flow and water quality in streams and reservoirs of the Saugahatchee Creek Watershed using future land use and future climate scenarios as model inputs.

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report summarized that the linear trend over the last 50 years is warming of 0.13 (0.10–0.16) ºC per decade, nearly twice temperature increase for the last 100 years, and it is projected to further increase by 0.2ºC per decade for the next two decades [8]. The IPCC [1] summarized the impact of climate change on freshwater systems are mainly due to increases in temperature and precipitation variability. Higher water temperatures, increased precipitation intensity, and longer periods of low flows exacerbate water pollution, with impacts on ecosystems (e.g., fish habitat), human health, water system reliability, and operation cost [1].

The outputs from various General Circulation Models (GCMs) like Couple Global Climate Model (CGCM3) from Canadian Climate Centre Modeling and Analysis (CCCma), and Hadley Centre Couples Climate Model (HadCM3) developed in the United Kingdom are available to generate future climate scenarios. However, the GCMs were not designed to analyze the hydrological impact at the watershed scale and therefore have coarser spatial resolution as compared to what is required for watersheds impact studies. GCMs are inherently unable to represent watershed scale features and dynamics for hydrological impact studies [9,10]. To bridge this gap, the techniques have been developed to downscale GCMs output into local meteorological variables required for hydrological modeling, usually referred to as downscaling techniques. The downscaling techniques can be statistical or dynamic. The Statistical Down Scaling Model (SDSM) was used in this study, considering its advantages over dynamic method because statistical method is computationally undemanding and provides station or local-scale climate information based on GCM-scale output [11].

Hydrological impact of land use change has been investigated in a variety of studies using modeling methods [12-15]. The water quality in a watershed is affected directly by vegetative cover and agricultural and other land management practices [16]. Bhattarai et al. [16] used BASINS-SWAT model to estimate the effect of land use change on nitrogen and phosphorus runoff and sediment deposition in a small watershed in the Alabama Wiregrass Region. Similarly, many researchers have pointed out adverse effect of increasing urban land use on water quality [17-20].

Many previous studies have assessed the impact of climate change on hydrology [21-26]. Dibike and Coulibaly [27] applied statistical downscaling techniques to generate future climate scenarios in the Saguenay watershed in Canada at a local watershed scale and simulated the corresponding flow based on the downscaled future climate data as an input to hydrological models. Rich et al. [28] applied WARMF to assess impacts of extended droughts and increased temperature due to climate change on hydrology of the San Juan Basin. Simulations showed that drought and increased temperature impact water availability and lead to increased frequency of critical storages. The assessment of impact of climate change on water quality in the southeastern United States revealed that watersheds are likely to have higher nitrogen levels and lower dissolved oxygen problems [29]. However, very few have conducted the climate change impact study for water quantity as well as quality [29-32]. Wang investigated the individual and combined impact of future land use and climate change in the Wolf Bay Watershed using SWAT. United States Environmental Protection Agency (USEPA) is evaluating the impacts of land use and climate change of hydrology and water quality in major rivers basins throughout the United States using watershed models, HSPF and SWAT [33,34]. Limited water quality parameters such as total nitrogen, total phosphorus concentration, etc. are considered in previous impact studies.

The objective of this study was to assess the impact of land use change and climate change (downscaled to local watershed scale) based on CGCM3 and HadCM3 future climate scenarios, on flow and five water quality parameters (water temperature, dissolved oxygen, total nitrogen, total phosphorus, and algal concentration) in the streams of the Saugahatchee

Creek Watershedin Alabama (Fig. 1). The physically-based WARMF model for the Saugahatchee Creek Watershed (WARMF-SCW) was set up, calibrated, and validated for observed flow and water quality, then it was run for past and future climate scenarios, and their potential impacts were evaluated. After we have a better understanding on potential changes of stream and reservoir water quality due to climate warming, we can further study its impacts on fish habitat using different oxythermal criteria [35].

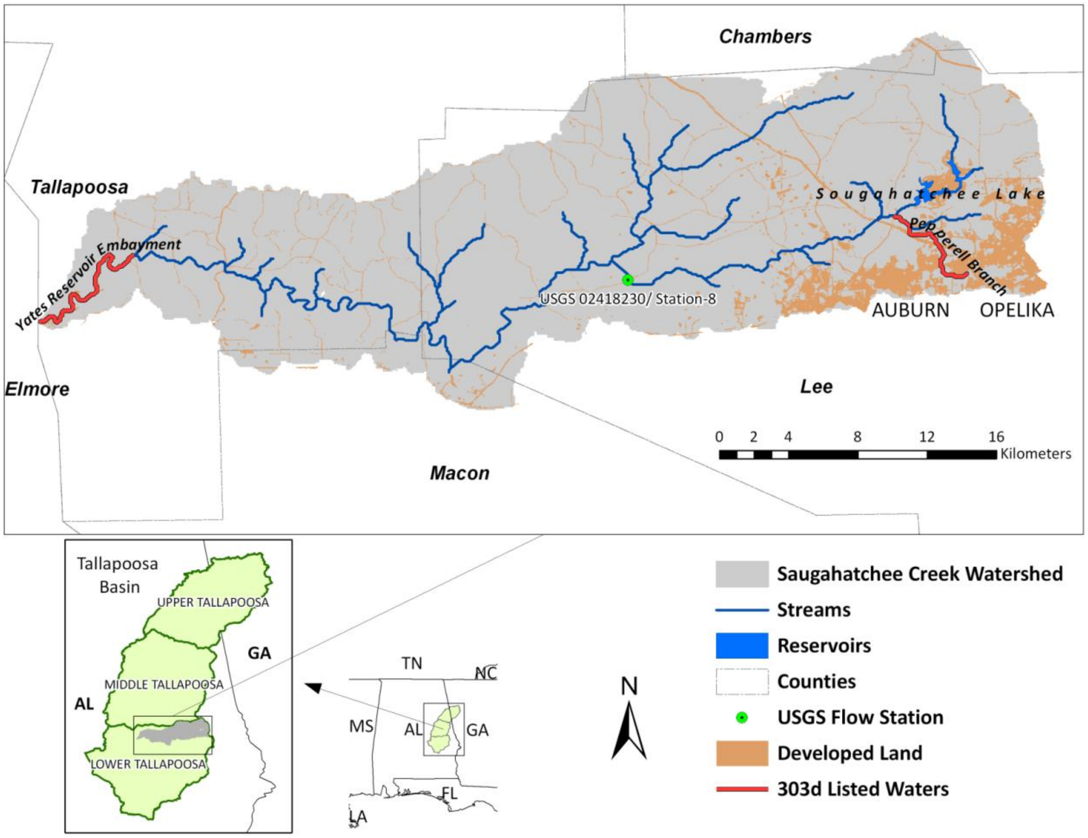


Fig. 1. Geographical location of the Saugahatchee creek watershed in the tallapoosa basin including surrounding counties in Alabama, USA. The monitoring Station-8 is at the same location as the USGS gaging station 02418230

2. MATERIALS AND METHODS

2.1 Study Area

The watershed of concern is the Saugahatchee (also referred as Sougahatchee) Creek Watershed, located mostly in Piedmont region of eastern Alabama with an area of approximately 550 km^2 (Fig. 1). Beginning with its headwaters in Chamber and Lee counties, the Saugahatchee Creek runs westward through parts of Macon and Tallapoosa counties until it enters Yates Reservoir and converges to Tallapoosa River. Two segments in the Saugahatchee Creek Watershed (Fig. 1) were listed on the Alabama Department of Environmental Management (ADEM)'s 303 (d) list of impaired waters under the federal

Clean Water Act [36]. Pepperell branch, a tributary to the Saugahatchee Creek was listed as impaired waters for nutrients and the portion of the Saugahatchee Creek entering Yates Reservoir (Yates Reservoir Embayment) was listed for nutrients and organic enrichment and dissolved oxygen. The headwater portion of the watershed is the Auburn-Opelika metropolitan area in Lee County (Fig. 1) with a 2009 population of 135,883 (140,247 in 2014). It was the 19th fastest growing metro area in the United States between 1990 and 2000<http://en.wikipedia.org/wiki/Auburn,_Alabama_metropolitan_area>. The growth of the cities has resulted in land use change and might have potential changes in stream water quality.

2.2 Models and Data

Complex hydrological models such as AGNPS (Agricultural Nonpoint Source Pollution Model [37]); BASINS (Better Assessment Science Integrating point and Nonpoint Sources [38]); HSPF (Hydrological Simulation Program – Fortran [39]); GWLF (Generalized Watershed Loading Functions [40]); SWAT (Soil and Water Assessment Tool [41]); and WARMF [6] have been frequently applied to study watershed hydrology in the United States (U.S.) and all over the world. A physically based, dynamic watershed model WARMF was applied to this study to the Saugahatchee Creek Watershed for assessing hydrology and water quality impact due to land use and climate change. Although other models, discussed above, would yield similar results, WARMF was applied here for its integration of stream and one-dimensional (1-D) reservoir water quality models, user friendly interface and ability to assess the impact of point and nonpoint sources with varying land use and meteorological scenarios.

WARMF is an integrated watershed model with simulation models and databases under one GIS-based graphical user interface (GUI). The algorithms embedded in WARMF are adapted from many well established codes such as ILWAS (Integrated Lake Watershed Acidification Study [42,43]), ANSWERS (Areal Nonpoint Source Watershed Environmental Response Simulation [44,45]), SWMM (Storm Water Management Model [46]) and WASP (Water Quality Analysis Simulation Program [47]).

WARMF represents a watershed by dividing it into a network of land catchments, river segments, and one- or two-dimensional reservoirs. Land catchment is further divided into a canopy layer, a snowpack, and up to five soil layers. Each compartment is considered as a seamlessly connected continuously stirred tank reactor (CSTR) for flow routing and mass balance calculation. WARMF simulates the process of canopy interception, snowpack accumulation and snowmelt, infiltration through soil layers, evapotranspiration, surface runoff, and groundwater exfiltration to river segments. The water from the upstream river segment is mixed with water in the river segment from previous time step and the point and nonpoint loads entering the river segment during the time step. Heat budget and mass balance are performed to calculate the temperature and concentration of various water quality constituents in each soil layer, river segment, and reservoir [6].

The flowchart of the study involving different models, data, and scenarios is given in (Fig. 2). The delineated watershed map with land catchments, stream segments and reservoirs, is required for WARMF, to which input data can be given and simulation results can be viewed. BASINS [38] provides watershed delineation tool which helps to delineate watershed based on digital elevation model (DEM) and river network. To delineate watershed, BASINS data download tool extracts nationally derived databases like boundaries for States and Cataloging Units, DEM, National Hydrography Dataset (NHD) and National Land Cover

Dataset (NLCD). A BASINS project can be set up for 8-digit hydrologic unit code (HUC) watershed by selecting the geographic area of interest from among the entire 48 contiguous United States. The watershed delineation developed from BASINS can be imported into WARMF [48]. The Saugahatchee Creek Watershed is a subset watershed of Lower Tallapoosa Watershed (Fig. 1) in Alabama (HUC 03150110). BASINS project for HUC 03150110 was built and only those catchment layers that drain into the Saugahatchee Creek were selected for the WARMF-SCW model [49].

WARMF uses readily available data from National Oceanic and Atmospheric Administration (NOAA), USEPA, and United States Geological Survey (USGS) and other online sources to predict hydrology and water quality in streams. To run the simulation, land use data, meteorological data, air quality data, and soil properties are required. Observed hydrology and water quality data are required for model calibration and validation (Fig. 2). Land use represents the characteristics of watershed. Land use data can be directly imported into WARMF as a GIS shapefile. Land use shapefile used for model calibration was obtained for the Saugahatchee Creek Watershed for 2009 (LU 2009) (Fig. 3). The meteorological data required for WARMF includes precipitation, dew point temperature, minimum and maximum air temperature, cloud cover, air pressure and wind speed. National Climatic Data Center (NCDC) Global Summary of Day, online climate dataset was used to download the necessary weather data for station in Montgomery, AL (Montgomery Dannelly Field) except cloud cover data which was calculated using recommended formula [49]. The dry and wet deposition for air quality was obtained from National Atmospheric Deposition Program (NADP) and USEPA Clean Air Status and Trends Network (CASTNET) website for GAS153 and AL10 Station, respectively [49]. There are three major point-source dischargers that contribute to the Saugahatchee Creek. The average flow discharge from these point dischargers and constituent loadings were obtained from data collected by ADEM and Auburn University [36] in previous studies.

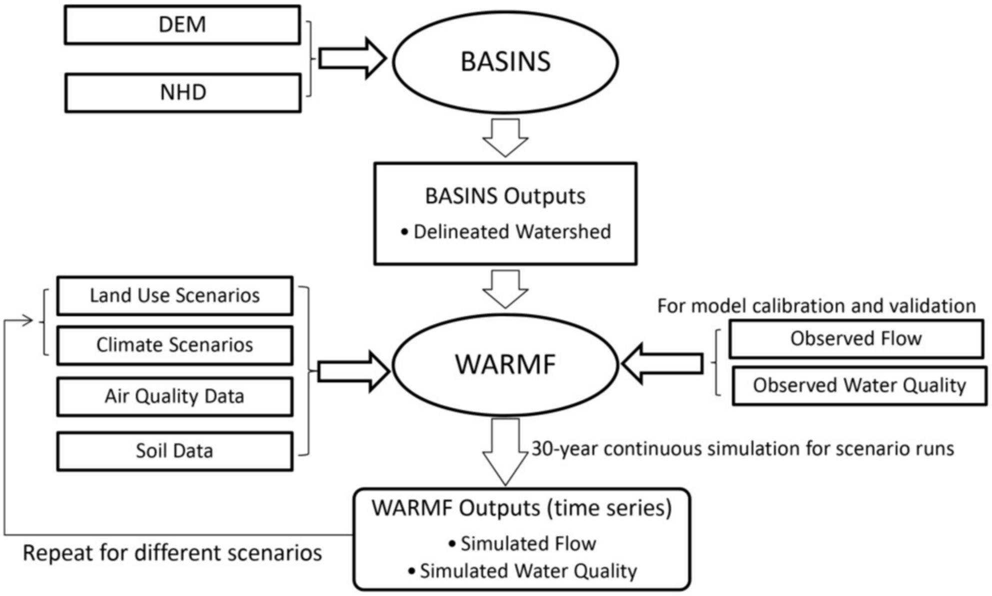


Fig. 2. Flowchart of the study involving different models, data and scenarios

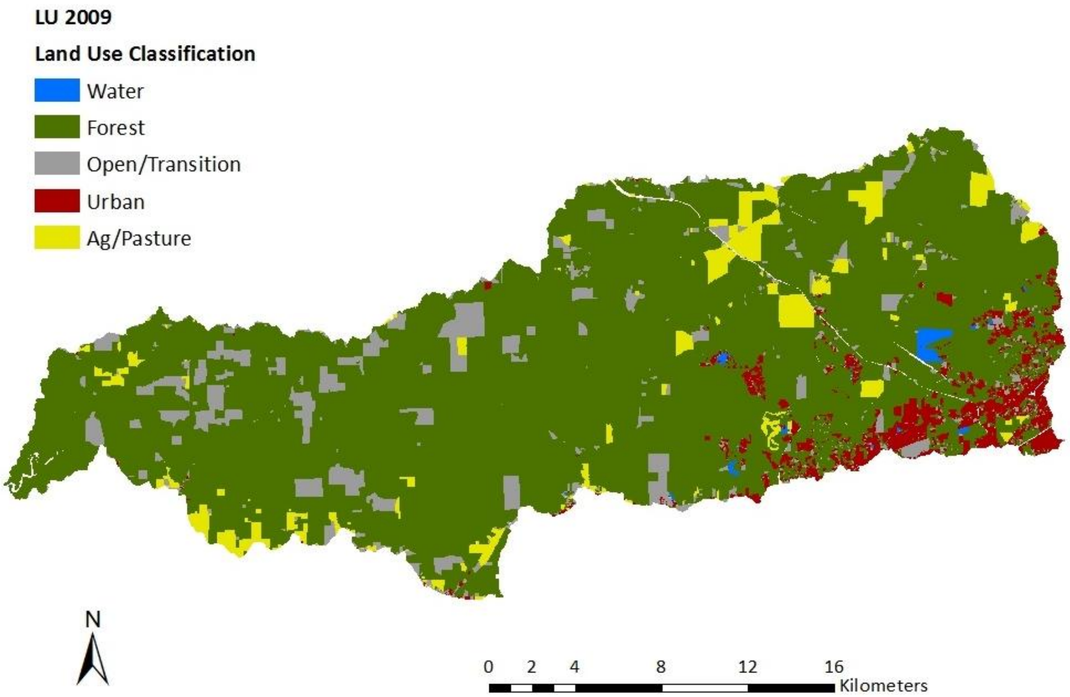


Fig. 3. 2009 land use map of the Saugahatchee creek watershed (LU 2009)

2.3 Land Use Change Scenarios

There have been significant changes in land use pattern of the Saugahatchee Creek Watershed over the last two centuries, particularly in recent years [50]. The upper watershed is undergoing rapid transition from forest to urban/developed land. Forest area has declined and urban and transitional area has increased. The changes in land use distribution are expected to bring changes in water quality, including surface flow, nutrient runoff, and sedimentation levels [16]. Multi-temporal datasets of Landsat5 Thematic Mapper imagery, aerial photographs, and other vector datasets were used to determine land use land cover (LULC) changes over the study periodfor year 1991, 2001 and 2009. Historical analyses of changes in the LULC over the study area were done to model changes in the LULC and to develop and validate logistic regression model. Landsat data was processed utilizing unsupervised classification in ERDAS Imagine with ISODATA clustering algorithm [51]. The ISODATA clustering method uses the minimum spectral distance formula to form clusters by iteration. It was followed by cluster busting method to improve accuracy of land cover classification. The classified land cover maps were produced by employing five types of land cover categories: Water, Forest, Open/Transition, Urban, and Ag/Pasture. The accuracy assessment was carried out to evaluate overall accuracy of LULC classification results. The overall accuracies for the pixel based unsupervised classification with cluster busting for year 1991, 2001, and 2009 were 90%, 90%, and 90.4%, respectively [52].

Urbanization patterns in the Saugahatchee Creek Watershed were modeled using GIS and remote sensing imagery coupled with logistic regression analysis. For modeling purposes, the spatial unit utilized was the Lee County tax parcels. Parcel data is most commonly used in city planning and unlike per pixel classification, which is limited to land cover, using parcels as spatial unit of classification it is possible to determine land use associated with it and provides better spatial configuration of land cover. The raster dataset of LULC classification for year 1991, 2001, and 2009 was then transferred from the image pixels to vector dataset of Lee County parcels using a "Majority" algorithm in ERDAS Imagine. By employing various drivers of LULC change, such as distance of a parcel from major road, school, commercial and industrial areas, provision of utility, and population density as variables, a land use model based on multiple logistic regression analysis was developed and validated over the period 1991 to 2009 [52].

The land use conversion model developed using logistic regression model in ArcGIS was then used to predict future land use of 2030 (LU 2030).For this study, LU 2009 was used as baseline scenario in logistic regression model to predict development for the year 2030. For each parcel, probability of change is computed with the fitted model for the 2030 scenario. The projected LU 2030 (Fig. 4) was then used as future land use scenario (Table 1) [52].

The change detection analysis of the study area done by Sawant [52] for the period from 1991 to 2009 shows conversion of forest to municipal land use in the Saugahatchee Creek Watershed has been the most dominant LULC change in the past two decades. Since 1991 footprint of urban area within the Saugahatchee Creek Watershed has increased by 36.5% to 7,035 acres in year 2009. Although the area of urbanization is only about 5%of the total area of the Saugahatchee Creek Watershed, the urbanization has likely played a role in impairment of the Pepperell branch of the Saugahatchee Creek. Most of the urban changes occurred within and immediate vicinity of the existing urban land use areas. The land change detection shows spread of urban land use in the surrounding areas [52].

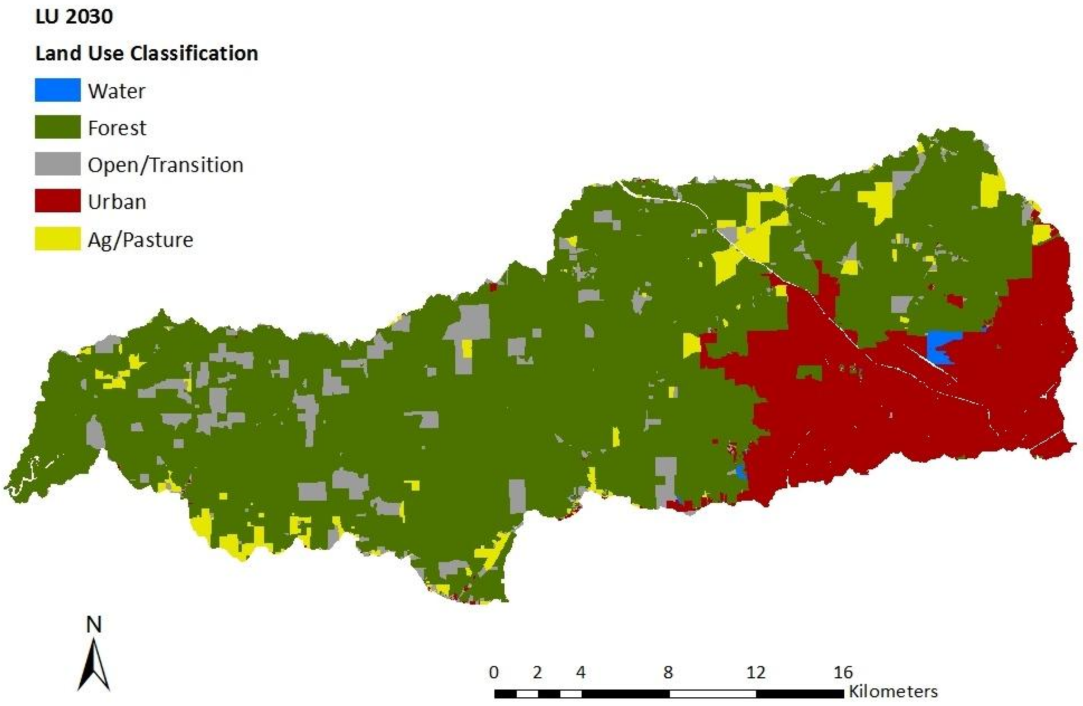


Fig. 4. Projected 2030 land use map of the Saugahatchee Creek Watershed (LU 2030)

Table 1. Land use change in the Saugahatchee creek watershed

Land use categories	**Area in km^2 (percentage of total area)**	
	LU 2009	**LU 2030**
Water	2 (0.4%)	2 (0.3%)
Forest	449 (83.3%)	385 (71.4%)
Open/Transition	43 (8.0%)	37 (6.9%)
Urban	18 (3.4%)	94 (17.5%)
Ag/Pasture	26 (4.8%)	21 (3.9%)

2.4 Climate Change Scenarios and Downscaling

Future climate projected using GCMs have coarser spatial resolutions than what is required for a watershed scale study. For hydrologic and water quality impact studies, local or station scale meteorological variables are required, which can be derived using large-scale atmospheric variables available from GCM outputs. Future climate change scenarios were downscaled for the Saugahatchee Creek Watershed at daily time scales, using four GCM outputs (CGCM3 A1B, CGCM3 A2, HadCM3 A2 and HadCM3 B2). The software used for downscaling is SDSM [11].

In statistical downscaling techniques, the quantitative relationships are established between large-scale atmospheric variables (predictors) and local or station surface variables (predictands). The National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) worked together in a reanalysis project to produce a physically consistent retroactive record of more than 50 years of global analyses of atmospheric fields to support the needs of research and climate monitoring communities [53]. Reanalysis project involved the recovery of data from many observed and measurement systems, quality controlled and assimilated with a data assimilation system kept unchanged over the reanalysis period. The main objective of reanalysis is to eliminate perceived climate jumps associated with changes in data assimilation system and provide consistent records of temperature, precipitation, winds and many other variables that describe climatic conditions from the past to the present. The daily NCEP/NCAR reanalysis data were selected to represent the large-scale predictors in the SDSM model. NCEP/NCAR data have been used in several downscaling studies in different regions over the world [27,54].

Using SDSM, the appropriate large-scale predictor variables were selected from the list of predictors obtained from NCEP/NCAR reanalysis data for the period of 1961–1990, based on regression techniques, to downscale predictands (such as station precipitation, maximum and minimum temperature). Table 2 lists the predictor variables (from NCEP/NCAR) screened for downscaling and the predictands. SDSM constructs a downscaling model with parameters of the model based on multiple regression equations, given observed daily weather data (predictand) and the selected large-scale NCEP predictors for the same time period. The observed daily weather data at Montgomery Dannely Field station from 1961 to 1990 were downloaded from NOAA's National Climatic Data Center (NCDC) web site. The climate data from 1961–1975 were used to develop the regression model and the model regression weights (as parameter file) produced were then used to validate the climate conditions for the period from 1976–1990. The detailed process of selecting predictors, calibration results (such as R^2), parameter file generation, and validation is presented elsewhere by Shrestha [49].

Table 2. List of predictands (station climate parameters) and corresponding predictors used in SDSM model to downscale GCMs outputs

Station parameters	Predictors from NCEP/NCAR and CGM[1]
Precipitation	500 hPa divergence (p5zh), Relative humidity at 500 hPa (r500), Specific humidity at 500 hPa (s500), Relative humidity at 850 hPa (r850), and Specific humidity at 850 hPa (s850)
Maximum temperature	Mean temperature (temp), and 500 hPa geopotential height (p500)
Minimum temperature	Mean temperature (temp), and Near surface specific humidity (shum)

[1] *variable name used in SDSM is given inside parenthesis*

The parameter file was then used to downscale future climate to local watershed scale based on predictor derived from GCMs. SDSM future climate predictors may be obtained for any global land area through data portal maintained by the Canadian Climate Impacts Scenarios Group (CCIS) <http://www.cics.uvic.ca/scenarios/index.cgi?Scenarios>. The predictors are available for CGCM3A1B, CGCM3 A2, HadCM3 A2, and HadCM3 B2scenarios.

Given the latitude and longitude of the Saugahatchee Creek Watershed, CGCM3 A1B, CGCM3 A2, HadCM3 A2, and HadCM3 B2 predictors were extracted for the nearest grid along with NCEP/NCAR predictors interpolated to the same grid as GCMs. The future climate projection scenarios were separated into three time frames and termed as 20s (2011–2040), 50s (2041–2170), and 80s (2071–2100). Figs. 5 and 6 show the patterns of downscaled monthly average precipitation, maximum (T_{max}) and minimum (T_{min}) temperatures compared to baseline (1961-1990) for the study watershed along with standard deviation corresponding to CGCM3 A1B, CGCM3 A2, HadCM3 A2, and HadCM3 B2 scenarios, respectively. The mean monthly maximum and minimum temperatures are projected to increase over time up to 5.98ºC in July from CGCM3 A2 80s (Fig. 5), especially similar increases in summer months for all four scenarios, e.g., 4.82ºC average increase from the baseline in July–September for CGCM3 A2 80s (Fig. 5). The standard deviations of T_{max} and T_{min} over 30 year periods are higher in the winter months (up to 7.3ºC) and lower in summer (~2ºC). The CGCM3 downscaled results projected slight changes in precipitation during early 21st century (20s), but precipitation is projected to increase during the later century (Fig. 5) whereas for HadCM3 scenarios, precipitation decreased from the baseline, especially during summer (Fig. 6). For CGCM3 A2 80s, monthly average precipitations in summer months (June–August) are projected to increase 21.4% to 68.1% (Fig. 5); while those are projected to decrease -16.7% to -76.1% for HadCM3 A2 80s (Fig. 6). Two scenarios (A1B and A2) of CGCM3 (Fig. 5) projected more increases in the winter months (November and December) and early spring (February).

The possible uncertainties that statistical model can carry is due to its assumption that the statistical relationships between the past predictors and predictands will remain valid in the future climate scenarios [11].

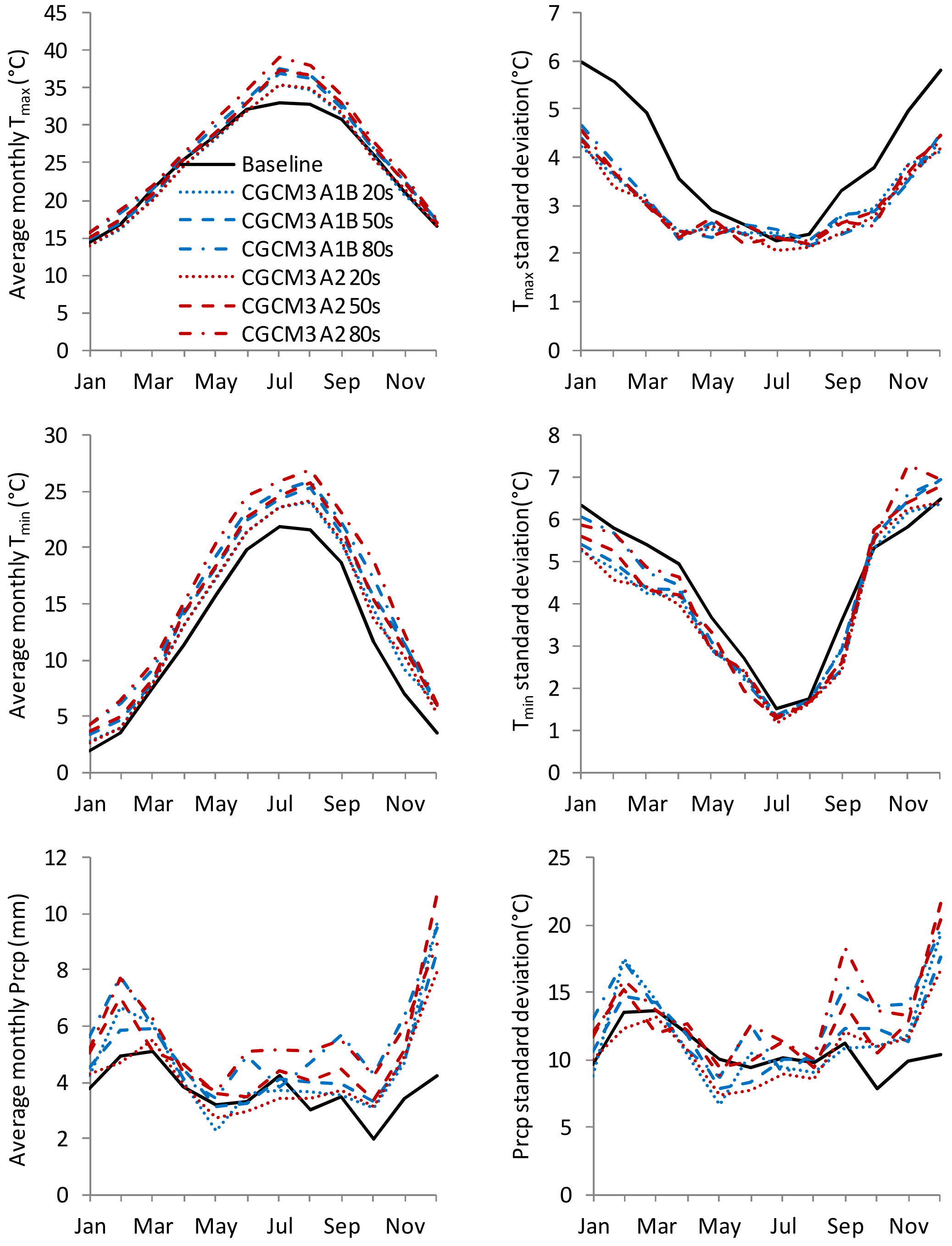


Fig. 5. General trends in average monthly maximum temperature (T_{max}), minimum temperature (T_{min}), and precipitation (*Prcp*) corresponding to downscaled climate change scenarios based on CGCM3 A1B and CGCM3 A2 for three 30-year time periods (20s for 2011-2040, 50s for 2041-2070, and 80s for 2071-2100)

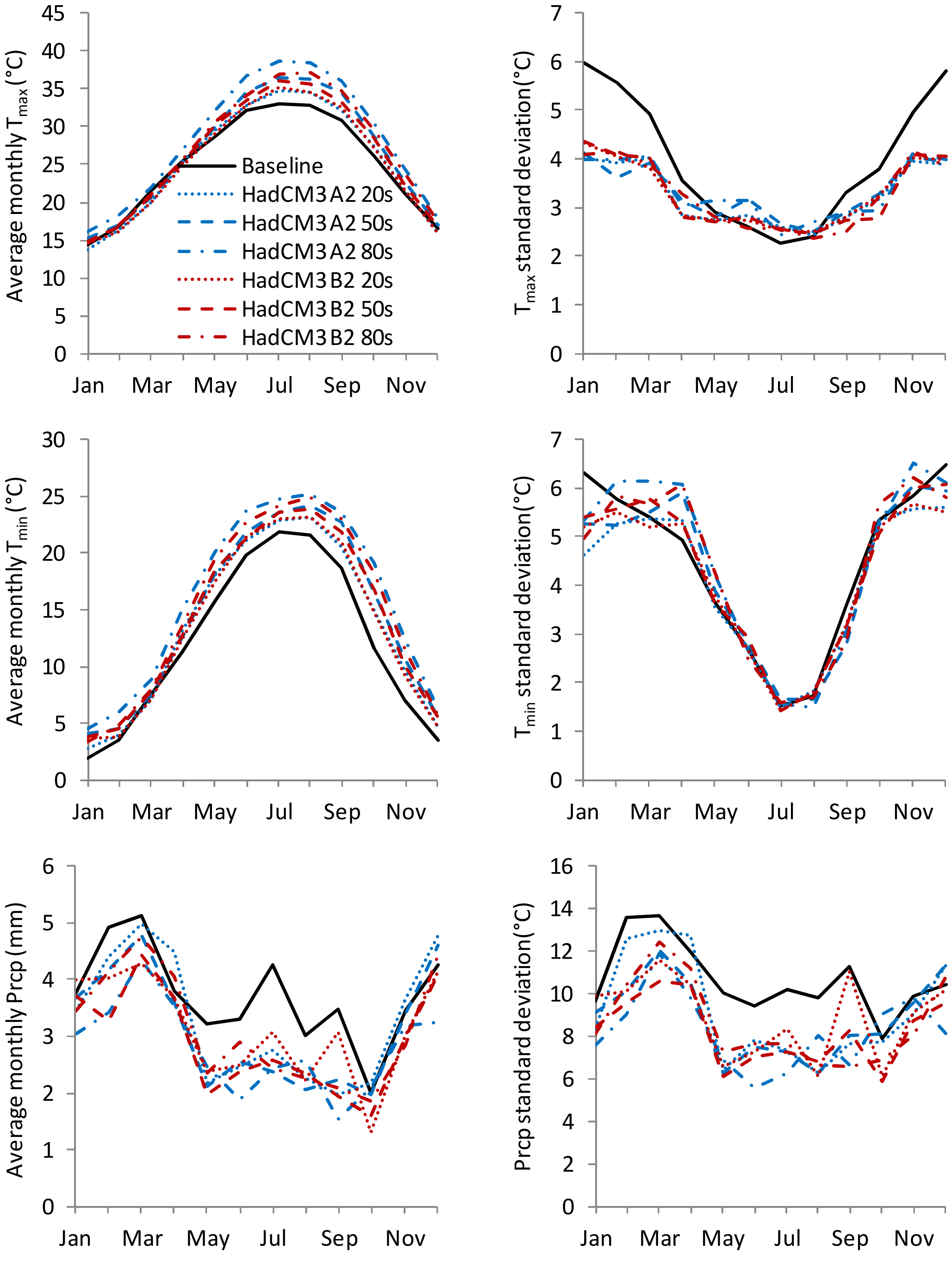


Fig. 6. General trends in average monthly maximum temperature (T_{max}), minimum temperature (T_{min}), and precipitation (*Prcp*) corresponding to downscaled climate change scenarios based on HadCM3 A2 and HadCM3 B2 for three 30-year time periods (20s for 2011-2040, 50s for 2041-2070, and 80s for 2071-2100)

3. RESULTS AND DISCUSSION

3.1 Model Calibration and Validation

The Saugahatchee Creek Watershed was divided into 44 subcatchments, 40 stream segments, and 2reservoirs (Fig. 1) [49]. The hydrologic and water quality parameters can be assigned to these segments individually, referred as catchment coefficients, river coefficients, and reservoir coefficients in WARMF manual [7]. There are another set of parameters known as system coefficients that apply to all catchments in the watershed [7]. During the calibration, some of catchment, river, reservoir, and system coefficients were manually adjusted to obtain a best fit (Table 3) based on guidance from the model parameter study [55].

Table 3. Keyparameter values after WARMF calibration

Parameters	Units	Literature range	Calibrated value
Precipitation weighting factor	-	0.5 - 1.5	0.74
Evaporation magnitude	-	0.6 - 1.4	0.91
Evaporation skewness	-	0.6 - 1.4	0.9
Number of soil layers	-	1 - 5	3
Thickness of soil layers	cm	> 0	8 – 79
Saturation moisture	-	0.2 - 0.6	0.35 – 0.45
Field capacity	-	0 - 0.4	0.18 – 0.31
Initial moisture	-	0 - 0.6	0.25
Horizontal conductivity	cm/day	> 0	3600 – 5600
Vertical conductivity	cm/day	> 0	1800 – 2800
Aeration factor	/day	0.2 - 1	0.5
Sediment oxygen demand	$g/m^2/day$	0.1 – 2	0.8

The simulation of watershed model can be judged satisfactory if Nash-Sutcliffe efficiency [56] (NSE)>0.5, if the ratio of the root mean square error to the standard deviation of measured data (RSR) ≤0.7, and if the percent bias (PBIAS) is within ±25% for flow [57].

Nash-Sutcliffe model efficiency coefficient is defined as:

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2}\right] \tag{1}$$

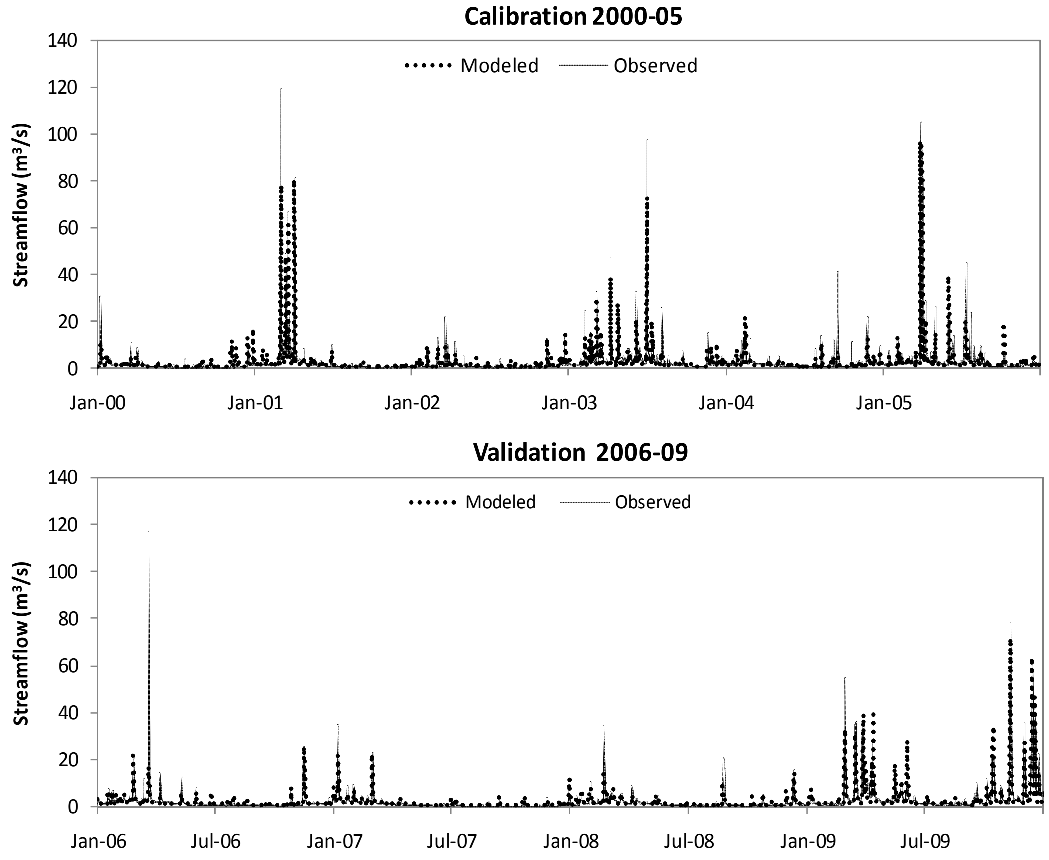
Where Y_i^{obs} stands for the i^{th} observed data, Y_i^{sim} stands for the corresponding simulated value, and Y^{mean} is mean value of all observed data. The ratio RSR is calculated as:

$$\mathrm{RSR} = \frac{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}}{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2}} \tag{2}$$

Percent bias is calculated using Eq. (3):

$$\mathrm{PBIAS} = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) * 100}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)}\right] \tag{3}$$

The observed flow daily data is available at USGS Gage Station 02418230 (Fig. 1) in the Saugahatchee Creek near Loachapoka since 2000. The flow was calibrated for the period 2000–05 and validated for the period 2006–09 (Fig. 7). The model simulation was run three years (model spin-up period) prior to the calibration period starting from 1997 to minimize the effect of initial conditions used in the model. The simulation of average daily flow resulted in NSE, RSR and PBIAS values for calibration (validation) as 0.64, 0.60 and -5.72% (0.56, 0.66 and -9.48%), respectively. These parameter values indicate overall satisfactory model calibration and validation of the WARMF-SCW.


Calibration 2000-05

Validation 2006-09

Fig. 7. Flow calibration (2000–2005) and validation (2006–2009) using WARMF-SCW at the USGS 02418230 Station in the Saugahatchee creek near Loachapoka, Alabama

ADEM and Auburn University collected water quality data in the Saugahatchee Creek Watershed in 2000–2002 [36]. The observed water quality data such as temperature, dissolved oxygen (DO), total phosphorus (TP), and nutrients were available for Station-8 (Fig. **1**) at the same location as USGS Gage Station 02418230 but not in daily basis[35].Therefore, water quality calibration was performed based on visual comparison of simulated and observed data. Time series plots shown on (Fig. 8) indicate the WARMF-SCW model simulates these water quality parameters reasonably well.

3.2 Impact of Land Use and Climate Change on Hydrology and Water Quality

The impact study was performed on the Saugahatchee Creek Watershed to evaluate the effects on hydrology and water quality due to future land use and future climate scenarios. The impact was analyzed under three categories: Impact due to land use change only, impact due to climate change only, and impact due to combined land use and climate change. Flow and water quality parameters were reported at the watershed outlet (Yates Reservoir Embayment) and their monthly average of daily values for baseline and various land use and climate change scenarios were calculated and compared for impact analysis.

3.2.1 Impact due to land use change only

The baseline scenario corresponding to land use of 2009 and future land use scenario corresponding to projected land use of 2030 were analyzed using 30 years (1981-2010) simulation results to investigate the effects of land use change only. (Fig. 9) shows monthly average of daily values for flow and water quality parameters under the baseline (LU 2009) and future land use (LU 2030) scenarios simulated using same 30-year (1981-2010) meteorological data.

The monthly averages of daily flow for LU 2009 ranged from4.14 (September) to 14.22 (March) m^3/s and are projected to rangefrom4.62 to 14.29 m^3/s for LU 2030. The increase or decrease in the monthly average flow from LU 2009to LU 2030is projected to be not more than 12.6% (Fig. 9). Similarly, for surface water temperature, there is very little or no change projected between two land use scenarios. The increase or decrease in the monthly average surface water temperature corresponding to LU 2030is less than 0.5% (Fig. 9). Therefore, land use change from 2009 to 2030 will not have significant impact on flow and surface water temperature in the Yates Reservoir Embayment for the simulation period.

Surface dissolved oxygen concentration in the Yates Reservoir Embayment, in terms of monthly average of daily values, will not experience much change due to land use change, partly because the simulation was performed on daily time step. The water body with predominance of algae shows a larger fluctuations in dissolved oxygen than less productive water with low algal concentration [58]. The water bodies with algal concentration higher than 15 µg/l are categorized as eutrophic and higher than 40 µg/l as hypereutrophic water bodies [59]. Higher eutrophic level implies algal abundance and hence exhibit higher rate of photosynthesis, respiration, and decomposition. For eutrophic and hypereutrophic systems, the dissolved oxygen concentration tends to increase during day time due to algal photosynthesis dominating over respiration and decomposition; whereas the system will have less dissolved oxygen concentration during night as there is no sunlight for photosynthesis [60,61]. Due to limited data availability, the simulation was run on daily time steps in the model, which doesn't model diurnal phenomenon [49]. Fig. 9 shows the relative change in monthly average of daily DO concentration to the baseline corresponding to LU 2030 is 2.0% at most.

In the Saugahatchee Creek Watershed, forest land has been transformed into urban land (Table 1). Pesticides, industrial waste, urban stormwater and sewage are the major source of nutrients. Therefore, the major impact that land use change has on the watershed is to the nutrient concentration in the streams and reservoirs. LU 2030 projects to produce monthly average TP concentration to be from 55.8 to 71.7% greater than baseline scenario (Fig. 9). The relative change in monthly average of daily TN concentration to the baseline corresponding to LU 2009is projected to range from1.0 to 7.7% (Fig. 9).

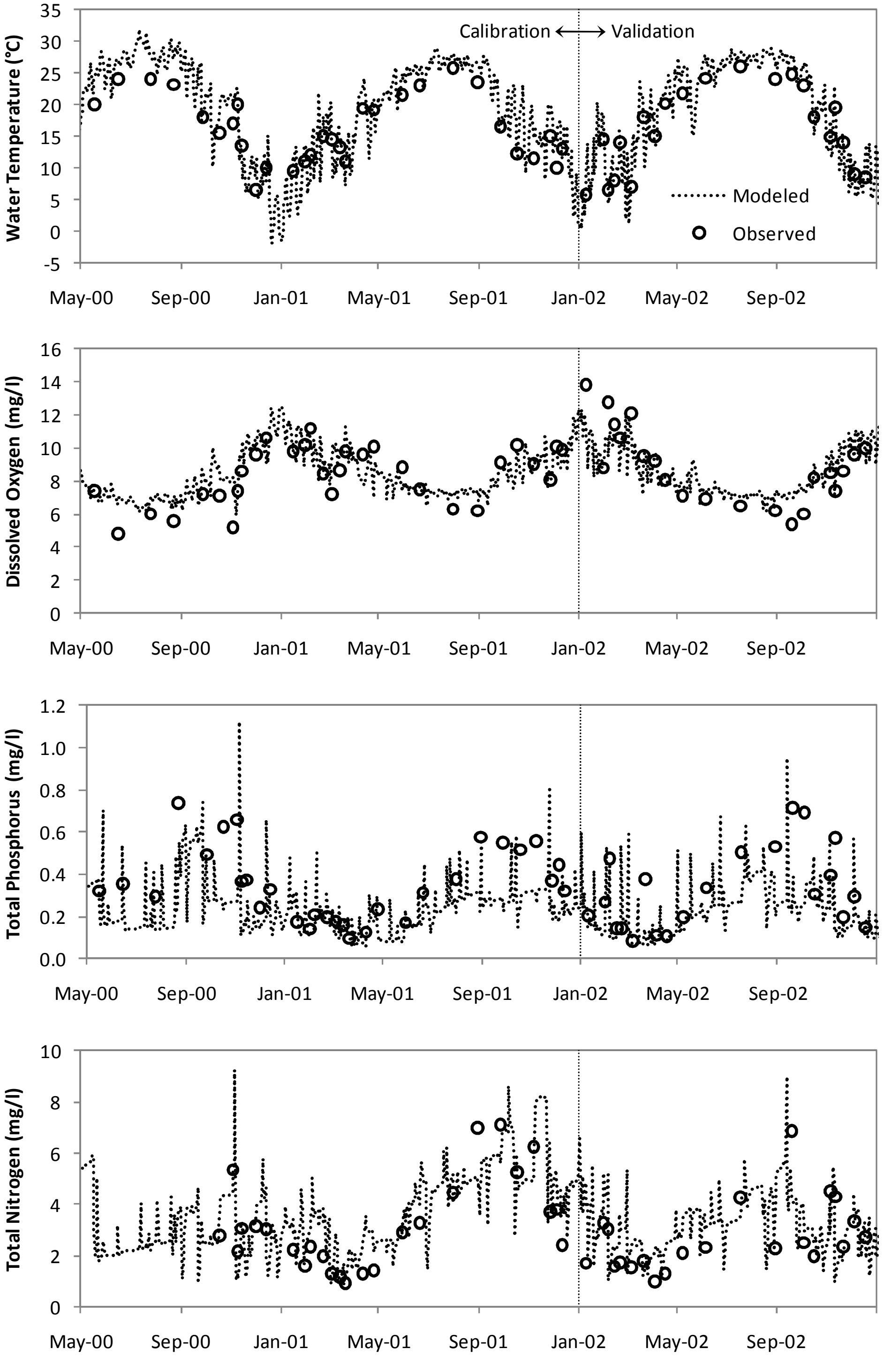


Fig. 8. Water quality calibration (2000–2001) and validation (2002) using WARMF-SCW at the Station-8 near Loachapoka, Alabama

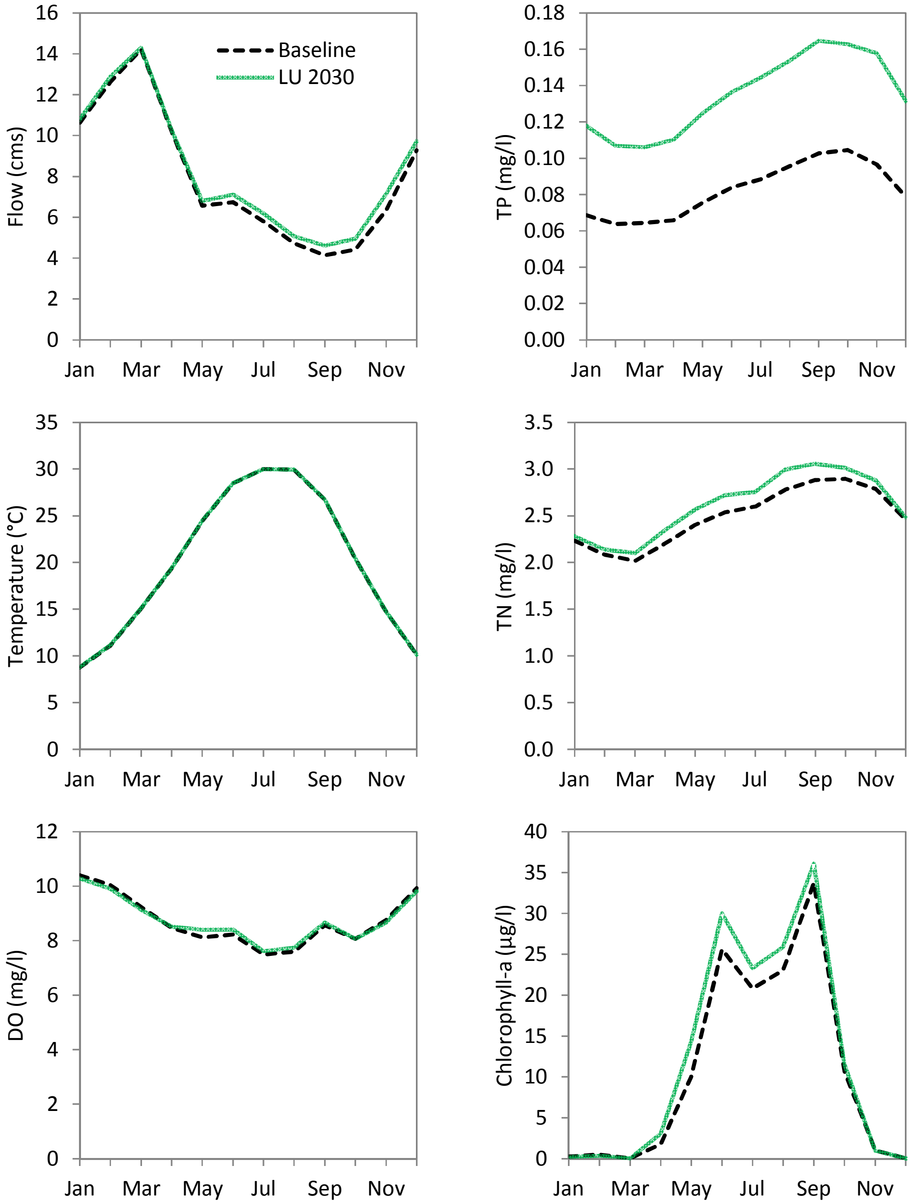


Fig. 9. Simulated monthly average flow and water quality parameters under the baseline (LU 2009) and future land use scenario (LU 2030)

The algal growth in streams and reservoirs are seasonal. The growing season for the Saugahatchee Creek Watershed has been identified as April through October [36]. Monthly average chlorophyll-a concentration under 2009 land use varied from 1.8 to 33.7 µg/L during growing season at Yates Reservoir Embayment, which is a highly eutrophic reservoir. Fig. 9 shows the relative change in the monthly average of daily algal concentration to the baseline corresponding to LU 2009 rangesfrom-32.8 to 72.1% or -0.2 to 4.4 µg/L (Fig. 9).

3.2.2 Impact due to climate change only

The impact on flow and other water quality parameters due to future climate scenarios was analyzed under four different GCMs output scenarios, namely CGCM3 A1B, CGCM3 A2, HadCM3 A2, HadCM3 B2 scenarios. Each GCMs output was further separated into three 30-year time frames: 20s (2011-2040), 50s (2041-2070), and 80s (2071-2100). For comparing results of climate change scenarios to the baseline, the monthly average of daily projected values over the period of 30-year time frame of 20s, 50s, and 80s were calculated and compared with the monthly average of daily simulated values over the baseline period (1981-2010). Land use (LU 2009) was kept constant for the baseline and climate change scenarios to analyze the effect of climate change only. Figs.10 to 13 show the monthly average of daily values of projected flow and water quality parameters under different future climate scenarios.

The monthly average of daily flow is projected to increase corresponding to CGCM3 A1B and B2 scenarios, whereas projection corresponding to HadCM3 A2 and B2 scenarios produces lower flows (
Fig. **10**–13), especially towards the end of 21st century (2080s). These projections are reflective of input precipitation pattern for the future climate scenarios (Fig. 5 and 6). For example, under CGCM3 A280s scenario (Fig. 11), projected flow is increased by 17% (July) to 256% (December) with average increase of 88%, while under HadCM3 A2 80s scenario (Fig. 12), projected flow is decreased by -31% (May) to -62% (December) with average decrease of -49%.

The surface water temperature is projected to increase, especially in summer. The increase in monthly average of daily surface water temperature reaches as high as 2.8ºC and3.6ºC for CGCM3 A1B and A2 scenarios (Figs. 10 and 11); and 5.4ºC and 4.6ºC for HadCM3 A2 and B2 scenarios, respectively (Figs. 12 and 13). The monthly average of daily surface DO will decrease by 1.8 mg/l and2.3 mg/l at most for CGCM3 A1B and A2 scenarios (Figs. 10 and 11); and 2.0 mg/l and 1.4 mg/l at most for HadCM3 A2 and B2 scenarios (Figs. 12 and 13), respectively. The decrease in DO concentration is partly because of projected increases in water temperature as dissolved oxygen solubility is inversely proportional to water temperature [62].

For CGCM3 A1B and A2 scenarios, nutrients are projected to decrease in the stream, whereas for HadCM3 A2 and B2 scenarios, nutrient concentrations are projected to increase. It corresponds to the flow decrease in HadCM3 A2 and B2 scenarios (Fig. 6) as low flow tends to have higher concentration of nutrients. The monthly average TP is projected to decrease by 41.7% and 38.4% at most for CGCM3 A1B and A2 scenarios (Figs. 10 and 11); and increase as high as 112% and 96% for HadCM3 A2 and B2 (Figs. 12 and 13), respectively. The monthly average TN will decrease by 40.6% and 36.8% at most for CGCM3 A1B and A2 scenarios (Figs. 10 and 11); and increase as high as 84.5% and 59.7% for HadCM3 A2 and B2 (Figs. 12 and 13), respectively. Precipitation variability projected by GCMs may result in higher nutrient runoff during heavy storms and nutrient concentration tends to increase during low flow condition as well [63].

The algal concentration is significant only during the growing season (April through October). For CGCM3 A1B and A2 scenarios, algal concentrations are projected to decrease in the whole summer because of projected decrease in nutrients (Figs. 10 and 11). Under the baseline scenario, algal concentration during the growing season is 18 µg/l (eutrophic) ranging from 1.8 (April) to 33.7 µg/l (September), and under CGCM3 A2 80s scenario

(Fig. 11), algal concentration during the growing season is projected to be 2.8 µg/l (oligotrophic) ranging from 0.2 to 5.5 µg/l. For HadCM3 A2 and B2 scenarios, algal concentrations are projected to increase most of the time except during late-summer of 2080s when it decreases (Figs. 12 and 13). Under HadCM3 A2 20s, 50s, and 80s scenarios, algal concentrations during the growing season are projected to be 24.1, 20.5, and 16.1 µg/l (Fig. 12), respectively. The algal growth rate increases with the increase in temperature up to the optimum level and then decreases with further increase in temperature [6].

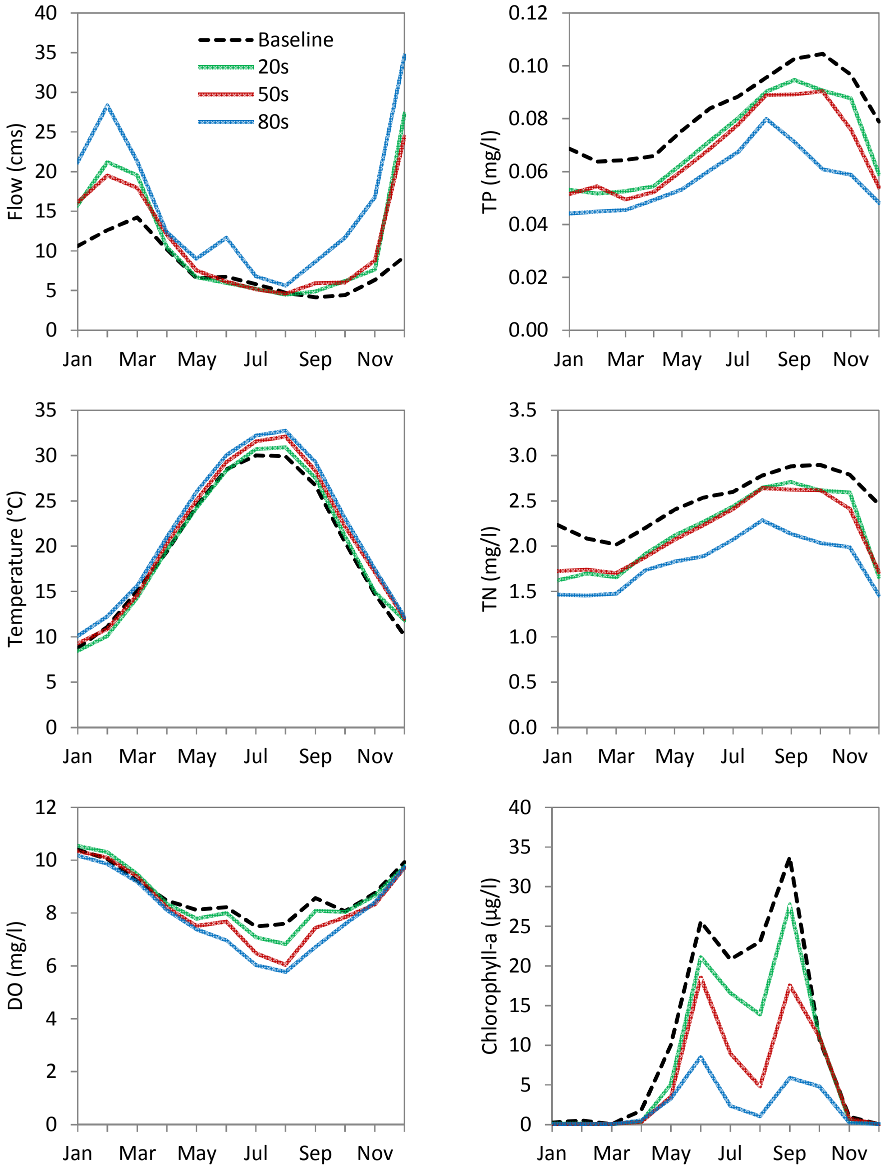


Fig. 10. Projected monthly average flow and water quality parameters under the baseline (1981–2010) and three climate change scenarios (20s, 50s, and 80s) downscaled with CGCM3 A1B

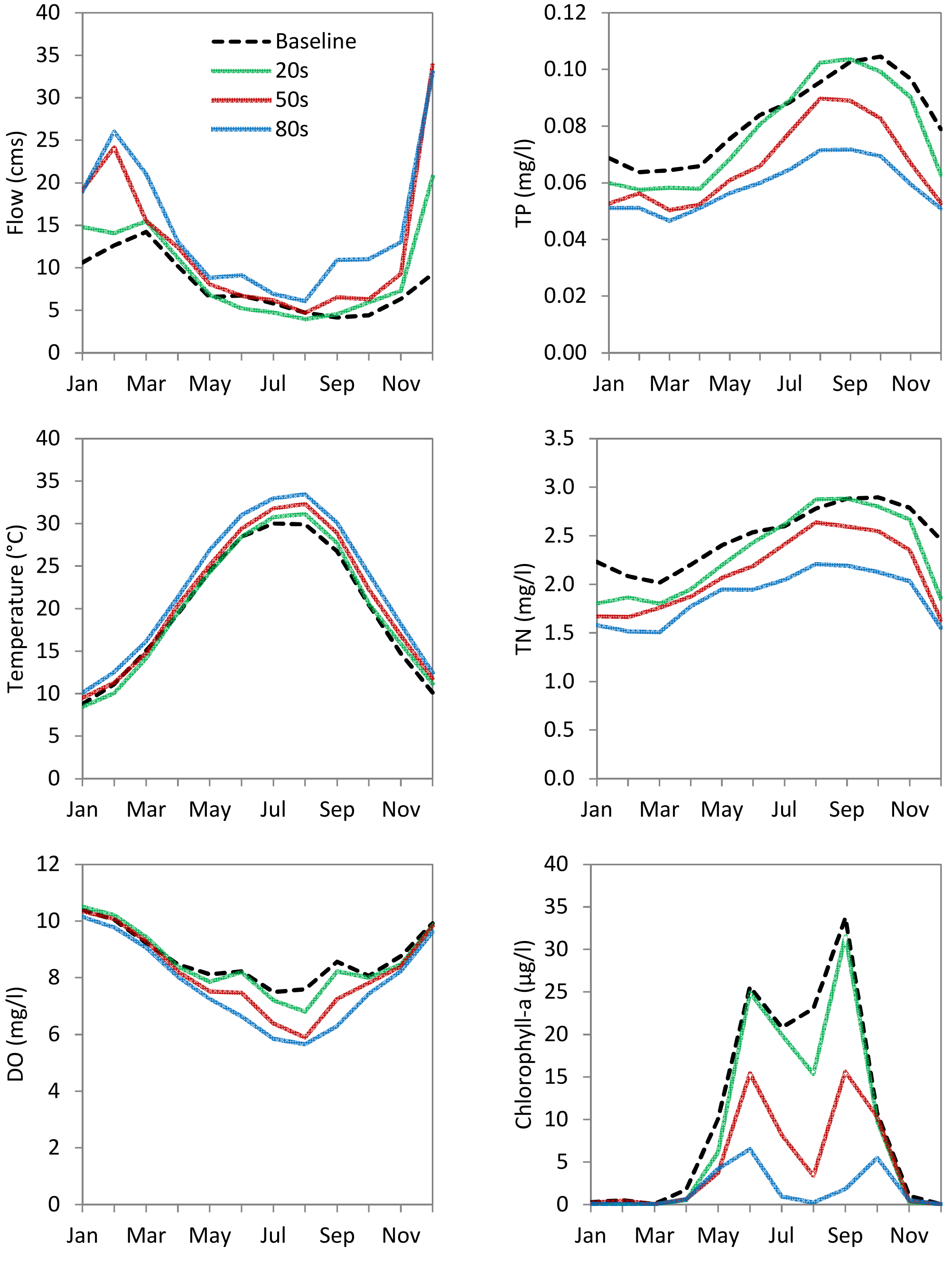


Fig. 11. Projected monthly average flow and water quality parameters under the baseline (1981–2010) and three climate change scenarios (20s, 50s, and 80s) downscaled with CGCM3 A2

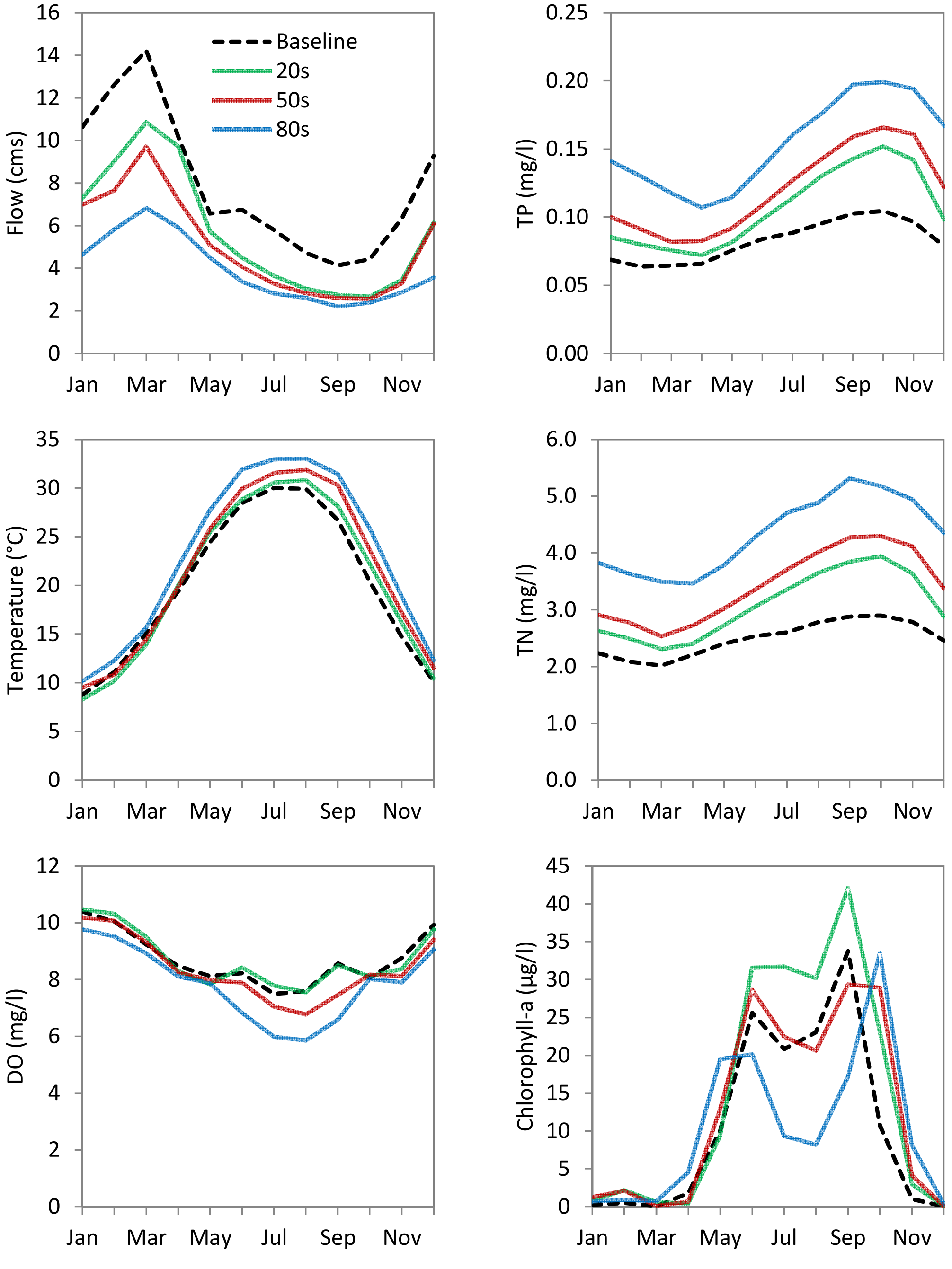


Fig. 12. Projected monthly average flow and water quality parameter under the baseline (1981–2010) and three climate change scenarios (20s, 50s, and 80s) downscaled with HadCM3 A2

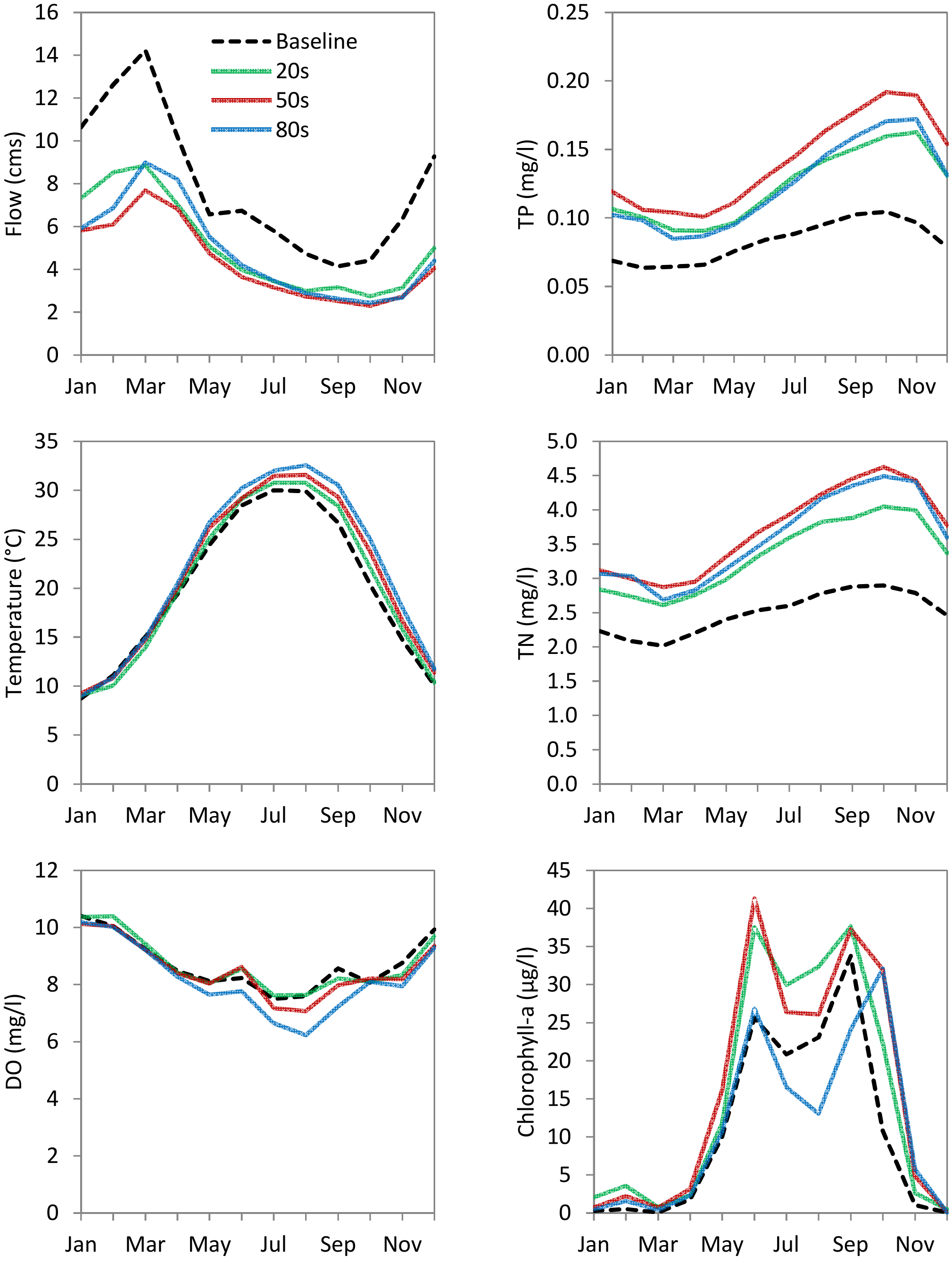


Fig. 13. Projected monthly average flow and water quality parameters under the baseline (1981–2010) and three climate change scenarios (20s, 50s, and 80s) downscaled with HadCM3 B2

3.2.3 Impact due to combined land use and climate change

For combined effect, the monthly average of daily projected values under the combined land use and climate change scenario (LU 2030 and 20s) were computed and compared with the monthly average of daily simulated values under the baseline scenario (LU 2009 and 1981-2010). Four different GCM output scenarios (CGCM3 A1B and A2; HadCM3 A2 and B2) were used for the analysis (Fig. 14).

The monthly average of daily flow is projected to increase by as high as 194.2% and 125.7% under CGCM3 A1B and A2 scenarios; and decrease by 35% and 40% at most under HadCM3 A2 and B2 scenarios, respectively (Fig. 14). The surface water temperature, in terms of monthly average of daily values, is expected to increase by as high as 17.5% and 11.4% under CGCM3 A1B and A2 scenarios; and increase as high as 9.8% and 8.5% under HadCM3 A2 and B2 scenarios; respectively (Fig. 14). The combined effect deteriorates oxygen levels in the streams and reservoirs. The average monthly DO is projected to decrease slightly under all four scenarios, with 9.6% or 0.7 mg/l at most for CGCM3 A2 scenario (Fig. 14).

The monthly average TP and TN concentration is projected to increase due to combined effect. The annual average TP for the baseline and four scenarios (CGCM3 A1B, CGCM3 A2, HadCM3 A2, and HadCM3 B2) are 0.082, 0.108, 0.123, 0.177, and 0.203 mg/l, respectively. The increase in TP and TN concentration is higher under HadCM3 compared to CGCM3 scenarios. Chlorophyll-a concentration during the growing season is expected to increase to 25.8 and 26.3 µg/l under HadCM3 A2 and B2 scenarios due to combined effect, respectively (Fig. 14).

4. SUMMARY AND CONCLUSION

In this paper, a physically-based dynamic watershed model, WARMF, was applied to assess the impact on hydrology and water quality in streams and reservoirs of the Saugahatchee Creek Watershed in Alabama, USA, due to land use change and climate change. The model was calibrated for flow using six years (2000–2005) of stream flow data from USGS gage station and the flow validation was conducted for the period 2006–2009. Water quality calibration and validation was performed for the period 2000–2002 based on available data. By employing various drivers of LULC change, future land use scenario of 2030 is projected using multiple logistic regression analysis after the land use model was validated over the period 1991 to 2009. Future climate scenarios derived from CGCM3 and HadCM3 for 30-year future period of 20s (2010–2040), 50s (2040–2070), and 80s (2070–2100), were downscaled to local scale using SDSM downscaling technique and compared to baseline scenarios of 1981-2010. The response of watershed model to these different land use and climate change scenarios was analyzed by comparing the monthly average of daily projected values of flow and water quality for 30-year period.

Land use change scenario for 2030projects forest areas will be reduced to 71.4% from 83.3% in 2009 and urban areas will be increased to 17.5% from 3.4% in 2009 in the watershed (Table 1). For the effects of land use change only, the simulation over the period of 30 years (1981–2010) predicts increases in flow to be 12.6% or less whereas increase in TP concentration to be up to 71.7% for LU 2030 in comparison to the baseline scenario LU 2009. These results demonstrate that land use change has major impact on nutrient concentration but less significant impact on flow. The algal increase up to 4.4 µg/lis expected during the growing seasons in the streams and reservoirs due to increased level of nutrients.

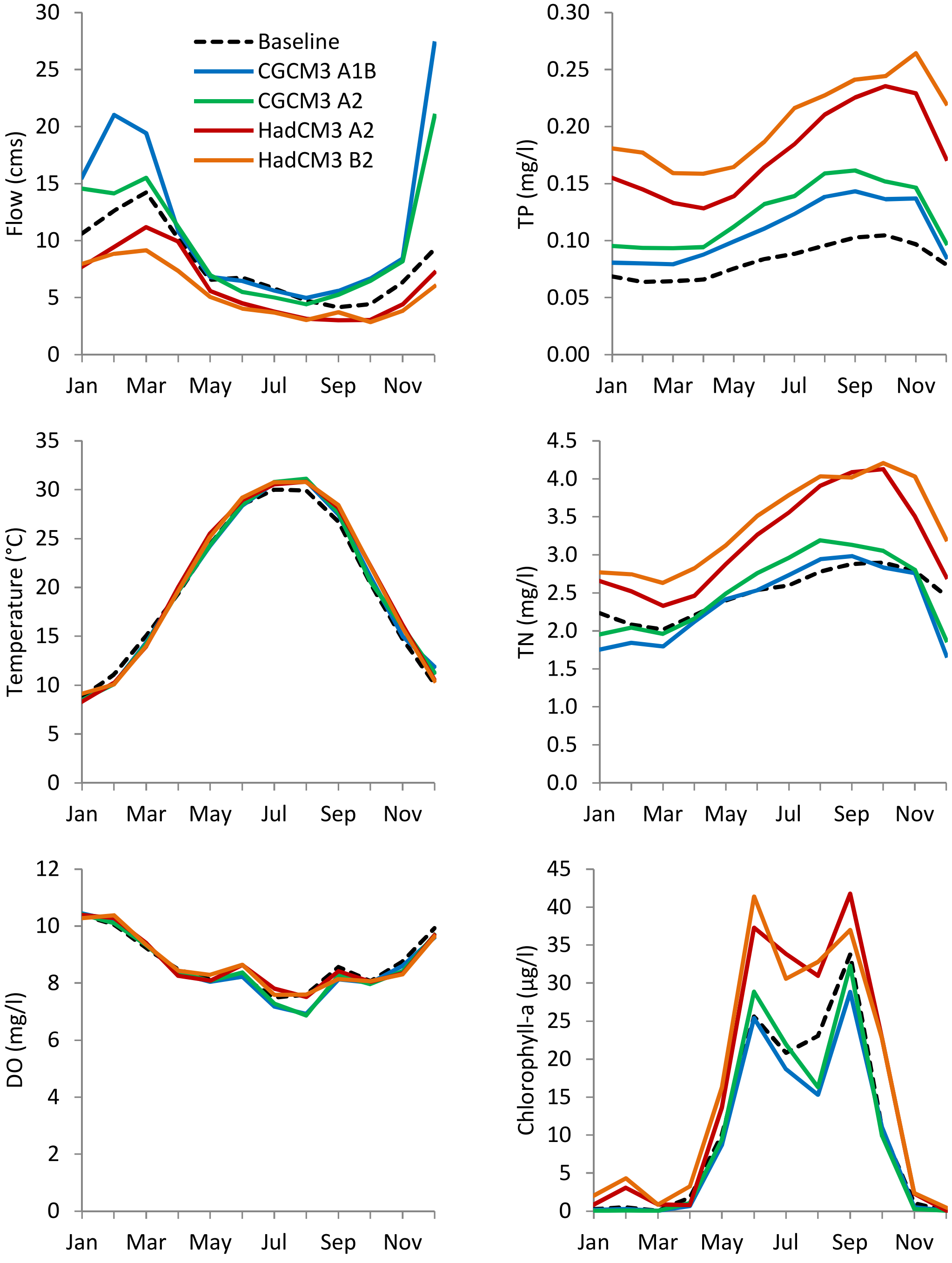


Fig. 14. Projected monthly average flow and water quality parameters under the baseline (1981–2010 and LU 2009) and combined land use change and climate change scenario (20s and LU 2030) downscaled with CGCM3 A1B and A2, and HadCM3 A2 and B2

Future climate scenarios were obtained by statistically down scaling the derived outputs from CGCM3 and HadCM3 models. Climate change scenarios CGCM3 A1B, CGCM3 A2, HadCM3 A2, and HadCM3 B2 show increasing pattern of maximum and minimum temperatures in 20s, 50s, and 80s. The anomalies of air temperature rise in these future climate scenarios to the baseline scenario (1981–2010) are higher especially in summer (up to 6.0ºC in July from CGCM3 A2 80s). The watershed response to these changes without considering land use change, based on monthly average of daily values, will result rise in water temperature ranging from 2.8 to 5.4ºC, especially during summer which is obvious corresponding to the rise in air temperatures. The monthly average of daily flow is predicted to increase corresponding to CGCM3 (annual average increase of 88%) and decrease corresponding to HadCM3 scenarios (annual average decrease of -49%). Accordingly, nutrient concentration (TP and TN) is expected to decrease corresponding to CGCM3 (Figs. 10 and 11) and increase corresponding to HadCM3 (Figs. 12 and 13) scenarios. The results show contrasting watershed response on flow and nutrient concentration based on which GCM is selected for future climate scenarios. DO concentration are predicted to fall up to 2.3 mg/l (monthly average), especially in summer for the four climate scenarios.

Combined effect due to land use change and climate change adds more to increases in nutrient concentrations underHadCM3 A2 and B2scenarios as both land use change and climate change cause nutrient concentration to increase. For CGCM3 A1B and A2 scenarios, nutrient concentrations are shifted from relatively decreasing under climate change only effect to increasing under combined effect. The annual average TP for four scenarios (CGCM3 A1B, CGCM3 A2, HadCM3 A2, and HadCM3 B2) are projected to be 0.108, 0.123, 0.177, and 0.203 mg/l, respectively, comparing 0.082 mg/l for the baseline. The average monthly DO is projected to decrease slightly under all four scenarios (up to 9.6% or 0.7 mg/l decrease for CGCM3 A2 scenario, Fig. 14).

Flow, temperature, nutrients concentration, algae, and dissolved oxygen concentration, all interact with each other in a complex watershed system. The impact study under different scenarios of land use and climate change using advanced watershed model gives us better understanding about how management alternatives can be launched during watershed planning.

CONSENT

Not applicable.

ETHICAL APPROVAL

Not applicable.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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