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Research article

Potential influence of climate and anthropogenic variables on water security using blue and green water scarcity, Falkenmark index, and freshwater provision indicator

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ABSTRACT

Land use change and climate variability have significantly altered the regional water cycle over the last century thereby affecting water security at a local to regional scale. Therefore, it is important to investigate how the climate, land use change, and water demand potentially influence the water security by applying the concept of water footprint. An integrated hydrological modeling framework using SWAT (Soil and Water Assessment Tool) model was developed by considering both anthropogenic (e.g. land use change, water demand) and climatic factors to quantify the spatio-temporal variability of water security indicators such as blue water scarcity, green water scarcity, Falkenmark index, and freshwater provision indicators in Savannah River Basin (SRB). The SRB witnesses a significant change in land use land cover (e.g. forest cover, urban area) as well as water demand (e.g. irrigation, livestock production). Overall our results reveal that, SRB witnessed a significant decrease in blue water due to the climate variability indicating that the precipitation has more control over the blue water resources. Whereas, green water was more sensitive to changes in land use pattern. In addition, the magnitude of various water security indicators are different within each county suggesting that water scarcity are controlled by various factors within a region. An integrated assessment of water footprint, environmental flow, anthropogenic factors, and climatic variables can provide useful information on the rising (how and where) of water related risk to human and ecological health.

1. Introduction

Land use and climate variables are likely to alter hydrologic process within a river ecosystem (Nijssen et al., 2001; Oki and Kanae, 2006; Li et al., 2009; Mishra and Singh, 2010; Chawla and Mujumdar, 2015; Mukherjee et al., 2018) and related ecosystem services, especially during the 21st century (Teshager et al., 2016; Ostberg et al., 2015; Howells et al., 2013). The unevenness in the spatio-temporal distribution of rainfall over a period of time further complicates regional water resources availability (Mishra et al., 2011). For example, a year of the uneven distribution or lack (excessive) of rainfall can create a significant effect on local crop yields, livestock and aquaculture production. Therefore, it is important to appraise the water use in the agricultural sectors to meet the compounding challenges on fresh water resources (Wu et al., 2010; Wada et al., 2012; Cao et al., 2015). Several methodologies/indices have been developed for evaluating the water security of a region (e.g. Falkenmark et al., 1989; Gleick, 1996; Ohlsson et al., 2000; Pfister et al., 2009; Rodrigues et al., 2015). The water scarcity indices based on the water footprint concept are important tools to improve water resources management (Hoekstra et al., 2011; Veettil and Mishra, 2016; Xinchun et al., 2017; Marston et al., 2018; Giri et al., 2018). This approach can inform broad aspect of policies from environmental, social and economic perspectives.

Water footprint (WF) (Hoekstra and Hung, 2002; Hoekstra et al., 2011) indicators can quantify the amount of water consumed in a specific river basin or from an aquifer at a local or regional scale (Schuol et al., 2008a; Abbaspour et al., 2009; Wu et al., 2012). Blue water footprint is the human water consumption from blue water resources (Hoekstra et al., 2011; Veettil and Mishra, 2016) and it can be quantified based on the volume of surface and groundwater consumed as a result of the production of goods or services [e.g., domestic, industrial, power production, and irrigation] (Falkenmark and Rockström, 2006, 2010; Schuol et al., 2008b; Rockström et al., 2009; Hoekstra et al., 2011; Rodrigues et al., 2014; Veettil and Mishra, 2016). Green water footprint (GWfootprint) refers to the consumption of green water resources (Hoekstra et al., 2011; Rodrigues et al., 2014; Veettil

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and Mishra, 2016), for example, evapotranspiration from agriculture and forest area. The green water footprint is relevant to agricultural, biofuel and forestry products. The applications of water footprint concept are rapidly increasing in various sectors (Hoekstra et al., 2011). The applications can be categorized into regional to global ecosystem for different sectors including food products (e.g., Chapagain and Hoekstra, 2006; Rost et al., 2008; Mekonnen and Hoekstra, 2010; Mekonnen and Hoekstra, 2010a; Jackson et al., 2015), biofuel products (e.g., Gerbens-Leenes et al., 2009; Wu et al., 2012; Dalla Marta et al., 2012; Demissie et al., 2012; Chiu and Wu, 2012; Kongboon and Sampattagul, 2012) and other commercial products (e.g., copper (Peña and Huijbregts, 2014), electricity (Mekonnen and Hoekstra, 2011), platinum mine (Haggard et al., 2013), and paper (Van Oel and Hoekstra, 2010)). Water footprint approaches are currently applied for ecosystem services (Galli et al., 2012; Karabulut et al., 2016) as well as for water security analysis (Veettil and Mishra, 2016).

Anthropogenic factors, such as increase in population and water consumption (Vorosmarty et al., 2000; Nilsson et al., 2005; Hanasaki et al., 2006; Pokhrel et al., 2012; Haddeland et al., 2014; Van Loon and Van Lanen, 2013) are likely to tremendously impact blue water resources through altering seasonal flow regime and depleting groundwater storages (Wada et al., 2013). Whereas, land use and land cover change (LULC) can upset the water balance by changing the segregation of precipitation, i.e. by altering the quantity of evapotranspiration, runoff and groundwater flow (Sahin and Hall, 1996; Costa et al., 2003). For example, agricultural sector has a consumptive use of about 85%–90% (Shiklomanov, 2000; Gleick, 2003), which often reduces the normal flow in several river networks (Rosegrant et al., 2002). It is also recognized that land use change has substantial influence over water quality by altering the concentration of nutrients (Stonestrom et al., 2009; Schlesinger et al., 2006) and sediment budget (Valentin et al., 2008). This suggests that, water scarcity is mainly driven by the anthropogenic factors (Schmitz et al., 2013). As these facts are crucial for land use planning and water resources management, the quantification of land use change and climate variability on water demands, and related water scarcity can expose current state of a river basin's ecological health.

Therefore, quantifying the sensitivity of water resources due to the fluctuations in climate variables and anthropogenic activities (e.g. land use change) is an important step for water resources planning and management in a river basin (Andréassian, 2004; Konapala and Mishra, 2016). The water security may be defined as the capability of a water resource system to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods (UN Water, 2013). In this study, we used four indicators, such as, blue water scarcity, green water scarcity, Falkenmark Index (FLK Index), and freshwater provision index (FPI) for water security analysis. Blue and green water scarcity can identify the critical hydrological regions based on the water withdrawal, environmental flow, and crop water requirements. Whereas, the FLK Index identifies the situation where there is not enough water for human water requirements (Falkenmark et al., 1989; UN-WBCSD, 2006; Karabulut et al., 2016) and FPI represents the influence of drought/low flow on environmental flow (Logsdon and Chaubey, 2013). Therefore, using the water security indicators it is possible to identify the threats on human and ecosystems. Our proposed modeling framework was applied to Savannah River Basin, which shares boundary between South Carolina, Georgia and North Carolina States of Southeastern USA. The Savannah River basin is under increased stress due to frequent drought scenarios (Knaak et al., 2011; Roehl and Conrads, 2015). The river is considered as the third most polluted river in the country, which further complicates the allocation of water resources for different stake holders of the adjacent states (Veettil and Mishra, 2016).

Although the influence of anthropogenic activities (e.g., land use change) on hydrologic cycle, water and energy budget are extensively studied (McColl and Aggett, 2007; Wijesekara et al., 2012; Choi and Deal, 2008; Van Loon, 2015), the possible influence of combined land use change and climate variability on water footprints (e.g. blue and green water) as well as water security (scarcity) are limited. This study is important in order to identify potential influence of human activities on water footprint indicators. This study also evaluates the sustainability of water provisioning services to satisfy the major agricultural sectors for the counties located in the Savannah River Basin.

The objective of this work is to quantify the individual and combined impact of land use change and climate variability on the water resources and related water security for the Savannah River Basin. The specific objectives are: (i) to investigate the sensitivity of water footprint with respect to land use change and climate variability, (ii) to quantify the impact of land use change and climate variability on water footprints (blue and green water), and (iii) to evaluate the potential influence of land use change and climate variability on the water security indicators such as, the blue water scarcity, green water scarcity, freshwater provision index, and Falkenmark index.

2. Methodology

The hydrological modeling framework applied for assessing the land use change and climate variability impact on different water security indicators is provided in Fig. 1. The following sections provide an overview of individual components incorporated in the conceptual modeling framework.

2.1. Study area description

Savannah River Basin (SRB) has a drainage area of 27,171 km^2, out of which 11,875 km^2 is located in the South Carolina and 14,965 km^2 in Georgia and the remaining portion located in the state of North Carolina of USA (SCDHEC, 2010). The major impoundments in the basin are Hartwell Lake, Richard B Russel Lake and J. Strom Thurmond Lake. The climate in the SRB is highly variable and characterized by mild winters and hot summers in the lower portions and cold winters and mild summers in the upper basin area. The annual precipitation ranges from 1000 mm to 2050 mm. The rainfall is evenly distributed throughout the year, but a dry weather typically occurs between mid-summers to fall (SCDHEC, 2010). The geographical location of SRB and the counties located within SRB are shown in Fig. 2. The irrigated agriculture land in the SRB increased by 1.8% from 1984 to 1995 and the majority of the irrigation water is used from surface water resources (Veettil and Mishra, 2016). The agriculture in the SRB includes livestock, crop production and a minor percentage of aquaculture production. Almost 75% of the farm land is hay/pasture cultivation and the remaining 25% includes cotton, peanuts, and soybean.

2.2. Overview of land use land cover (LULC) changes in the Savannah River Basin

Like much of the Southeast, the land use in the SRB changed substantially during the last century. The percentage change in land use and land cover pattern from 1992 to 2001 for the SRB is analyzed by using the classified images of National Land Cover Dataset (NLCD). The percentage change (Fig. 3) in land use/land cover (LULC) from 1992 to 2001 indicates that the total forest cover decreased by 20.5% and the built-up area which includes construction land, residential area and commercial area increased by 247%. The farm land is decreased by 21%, whereas the pastureland is increased by 53%.

Agriculture constitutes a substantial land use activity, especially in the counties located at southern portions of the SRB (Regional water plan, 2017). Urban area (or developed area) over the SRB is gradually increasing and recent trends indicate a significant increase in urban sprawl, with South Carolina being ranked among the top 10 states in urban growth (Wachob, 2010). The majority of the developed area exist in Richmond and Columbia Counties. In the year 2000, the population

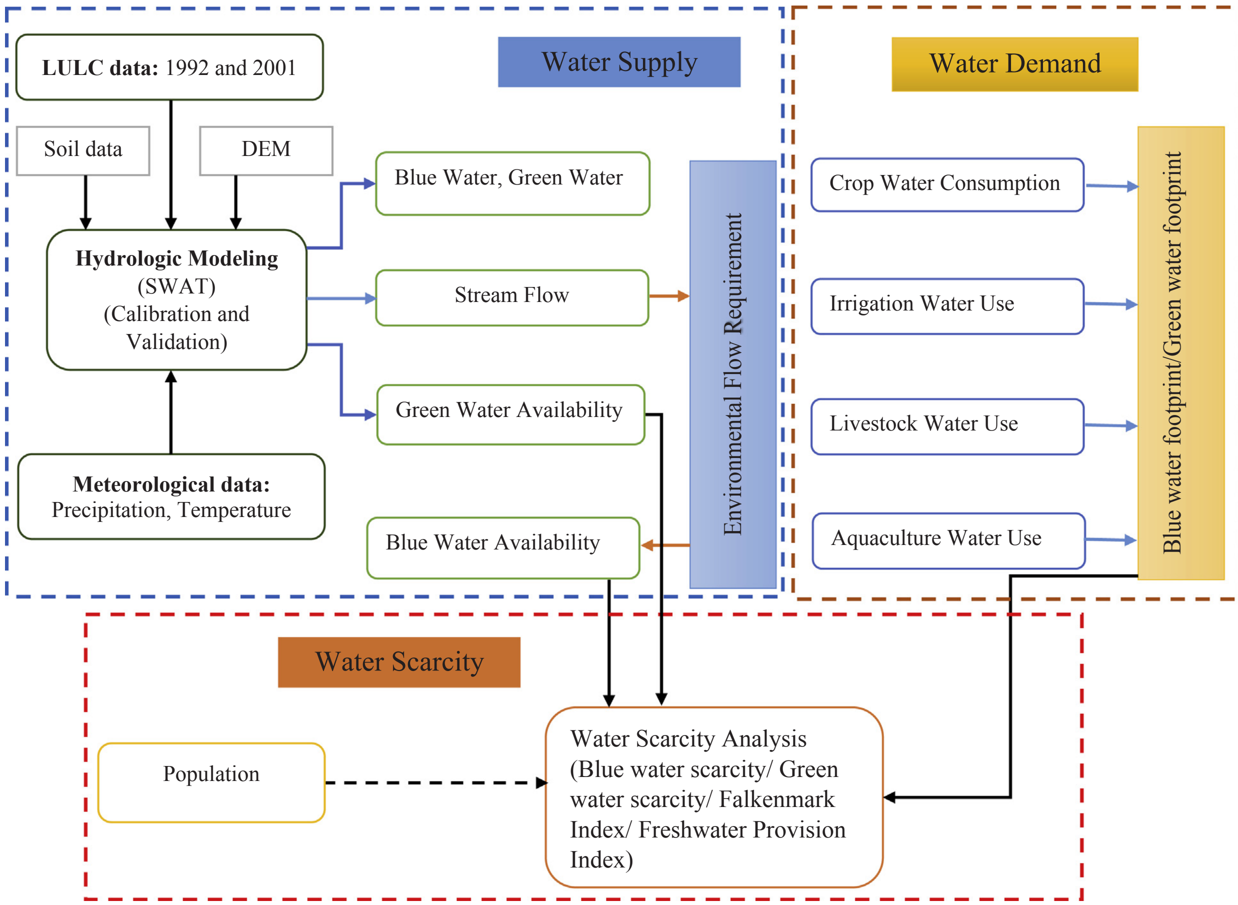


Fig. 1. The modeling framework for quantifying the impact of land use change and climate variables over the Savannah River Basin by applying the water footprint concept.

of the SRB in the state of South Carolina was 8.6% of the state's total population and it is expected to increase by 25% during 2020 (Wachob, 2010). In 2010, the SRB region's daily water withdrawals averaged over 275 million gallons per day (MGD) on an average daily basis for municipal, industrial, energy, and agricultural use, where 78% was obtained from surface water supply sources and 22% from groundwater supply sources (Regional water plan, 2017).

2.3. Data

To address our objectives, we collected datasets from multiple sources. The basic component of our hydrological modeling framework is SWAT model and the datasets used for the model development are (a) the digital elevation model (DEM), obtained from National elevation data set at a resolution of 30 m. The DEM is used to delineate the study area and to estimate the topographic features; (b) the land use data sets are obtained from national Land Cover Dataset (NLCD) for the years 1992 and 2001; (c) the soil data is downloaded from SSURGO data base of United State Department of Agriculture (USDA); (d) the daily meteorological (precipitation and temperature) data from 1990 to 2013 were collected from National Climatic Data Centre (NCDC); (e) the observed streamflow for evaluating the model performance was obtained from United States Geological Survey (USGS) gaging stations located in the SRB. (f) The reservoir outflow data collected for Hartwell reservoir, Richard B Russel reservoir, and J. Strom Thurmond reservoir from Savannah District Water Management (US Army Corps of Engineers) was also incorporated in SWAT model development. The datasets used for quantifying the water scarcity includes population data and the water use data for irrigation, livestock and aquaculture, these are collected from USGS.

2.4. Hydrologic model

The Soil and Water Assessment Tool (SWAT) developed by the United States Department of Agriculture (USDA) (Arnold et al., 1998; Neitsch et al., 2004) was used for simulating the hydrological fluxes for SRB. The SWAT model is widely used around the world for studying water quantity (stream flow), water quality (e.g., sediment load and nutrients flow) and crop growth in different landscapes and management practices (Faramarzi et al., 2009; Giri et al., 2014). SWAT is a process based, semi-distributed basin scale model (Arnold et al., 1998; Neitsch et al., 2004) and it operates at a daily time step. The SWAT model is useful for quantifying blue and green water available at a catchment scale to continental scale (Veettil and Mishra, 2016; Zang et al., 2012; Schuol et al., 2008b; Abbaspour et al., 2015).

The SRB is divided into sub-basins, which are further divided in to unique land use/soil/slope units called Hydrologic Response Units (HRUs). Five classes of slopes used for HRU delineation were 0–2.5%, 2.5–5%, 5–10%, 10–40% and above 40%. The number of HRUs were controlled by adjusting the threshold (Her et al., 2015) of land use (6%), soil (12%) and slope (20%), which resulted 1464 and 1412 HRUs under 1992 and 2001 land use scenarios. Three large reservoirs (Hartwell, Thurmond and Russel reservoirs) were included in the SWAT model for reducing the uncertainty associated with hydrological parameter estimation. Here, the surface runoff is estimated by Soil Conservation Service-Curve Number (SCS-CN) (equation (1)) using daily precipitation data and soil hydrologic group, land use and land cover characteristics and antecedent soil moisture.

$$Q = \frac{(P - Ia)^2}{(P - Ia + S)} \quad (1)$$

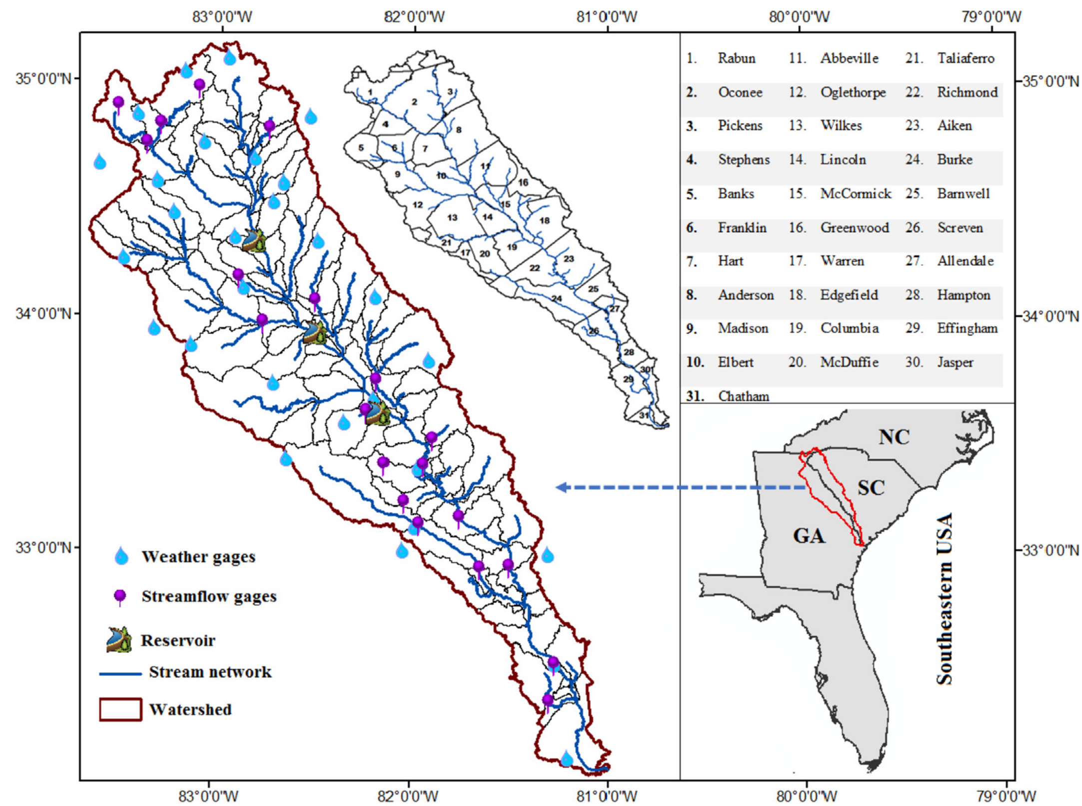
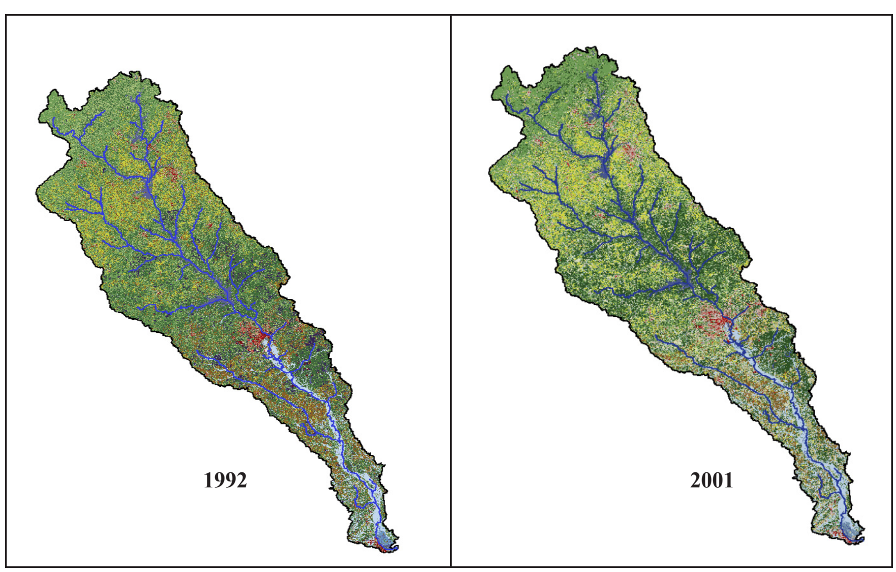


Fig. 2. The Savannah River Basin showing the weather stations, streamflow stations and stream network with their respective sub-basins. The spatial location of counties in the Savannah River Basin is also shown here.



Land use	Forest	Row crops	Pasture	Development	Water body
1992 Area (km^2)	17538	2874	2007	691	845
2001 Area (km^2)	13932	778	3071	2403	870
% Change in area	-20.5	-73.0	+53	+247.0	+3.0

Fig. 3. The percentage change in the land use land cover (LULC) in Savannah River Basin from 1992 to 2001.

where Q is the direct runoff (mm), P is the precipitation (mm), Ia is the initial abstraction (mm), and S is the potential maximum retention after beginning of the runoff (mm). This retention parameter is defined as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{2}$$

where, CN is the curve number for the day and Ia is calculated as $0.2S$. The streamflow routing was performed by applying variable storage routing (Williams and Hann, 1973) as shown in equation (3).

$$\Delta t.\left(\frac{q_{in,1} + q_{in,2}}{2}\right) - \Delta t.\left(\frac{q_{out,1} + q_{out,2}}{2}\right) = V_{stored,2} - V_{stored,1} \tag{3}$$

where, Δt is the change in storage time (t), $q_{in,1}$ is the inflow rate (m^3/s) at the beginning of the time step, $q_{in,2}$ is the inflow rate at the end of the time step. $q_{out,1}$ and $q_{out,2}$ are the outflow rate at the beginning and end time. $V_{stored,1}$ and $V_{stored,2}$ are the storage volume (m^3) at the beginning and end time step.

The SWAT model parameters were calibrated and validated by using the Sequential Uncertainty Fitting ver. 2 (Abbaspour, 2005). The model was simulated and evaluated against the USGS (observed) stream flow data located in the Savannah River Basin. Overall, SWAT model was able to capture the streamflow adequately. For example, the USGS station located at lower SRB (Savannah River near Clyo, USGS 02198500) showed a coefficient of determination (R^2) of 0.85, Nash-Sutcliffe Efficiency (NSE) of 0.76, R-factor of 0.89 and P-factor of 0.82 during the calibration period (1992–2005). During the validation period (2006–2013) R^2 was 0.64, NSE was 0.58, R-factor was 0.58 and P-factor was 0.51. The performance of the model based on SWAT simulated flow and observed flow at USGS stream gauging stations 02192000 and 021985000 are shown in Fig. 4.

2.5. Scenario design and simulation

The approach of 'one factor at a time' (i.e., changing one variable at a time while keeping the others constant) was used to quantify the effect of land use change and climate variables on the water resources of SRB. Subsequently, the effects of land use change and climate variability were quantified by analyzing the following four scenarios (cases). Among them, case 1 is simulated by utilizing 1992 land use map and climate variables from 1992 to 2000; case 2 is created by 2001 land use map and climate variables from 2001 to 2013. In case of case 3 we used 1992 land use map and climate variables from 2001 to 2013 and case 4 is generated by utilizing 2001 land use map and climate variables from 1992 to 2000. The hydrological flux simulated from SWAT model using four scenarios (cases) by considering one factor at a time, while keeping the other factor as constant. Subsequently, the analysis was extended for investigating the concomitant influence (i.e. analysis of both factors at a given time) on water security indicators.

2.6. Estimation of blue and green water

The blue water was estimated as the combination of both water yield (WYLD) and ground water storage of SWAT HRU output. Water yield is the amount of water leaving the HRU and entering the main channel. Ground water storage is the difference between total amount of water recharge to aquifers (GW_RCHG) and the amount of water from aquifer that contributes to the main channel flow (GW_W) (Rodrigues et al., 2014; Veettil and Mishra, 2016). Blue water availability ($BW_{availability}$) is the amount of water that can be used without affecting ecology of a stream. The over exploitation of blue water from a stream can potentially damage the river ecosystem. The concept of Environmental Flow Requirement (EFR) can be an appropriate indicator for maintaining a healthy ecosystem (Honrado et al., 2013). The presumptive standard method suggested by Ritcher (2010) and Ritcher et al. (2012) is used for EFR analysis in SRB. According to this method, extraction of more than 20% of water from a stream will likely cause ecological degradation and this amount can be considered as blue water available for water provisioning services (Rodrigues et al., 2014; Veettil and Mishra, 2016). The following equations (1) and (2) are used to calculate EFR and blue water availability.

$$EFR(p)_{(x,t)} = 0.8Q_{\text{mean}(x,t)} \tag{4}$$

where EFR(p)(x,t) is the EFR according to presumptive standard for county 'x' at time period 't'.

$$BW_{\text{availability(x,t)}} = Q_{(\text{x,t})} - EFR_{(\text{x,t})} \tag{5}$$

where 'x' represent a county with respect to time 't'. EFR is the environmental flow requirement (m^3/s) and Q is the corresponding monthly stream flow (m^3/s).

Green water is estimated as the sum of evapotranspiration (ET) and soil water content (SW) (Veettil and Mishra, 2016; Rodrigues et al., 2014; Abbaspour et al., 2015; Schuol et al., 2008b). The green water availability ($GW_{availability}$) is the amount of soil moisture (SW) available for sustaining crop growth. In this modeling framework, the initial soil water (SW_i) from the SWAT HRU output (Winchell et al., 2013) is considered as the available green water to the plants (Veettil and Mishra, 2016; Rodrigues et al., 2014). The SW_i is the difference between the root-zone soil moisture and wilting point, where the wilting point is defined as the minimum soil moisture available for the plant sustainability. This water content is available to the plants for consumptive use (DeLiberty and Legates, 2003; Rodrigues et al., 2014).

2.7. Sensitivity of water footprint with respect to land use change and climate variability

The concept of elasticity (Sankarasubramanian et al., 2001; Konapala and Mishra, 2016) was used to quantify the sensitivity of blue water, green water and streamflow to the changes in climate variables and different land use scenarios. This method is useful to quantify relative change in one variable may affect the other variable (Ahiablame et al., 2017; Konapala and Mishra, 2016) and this non-parametric elasticity concept is applied in many hydro-climatic studies (Fu et al., 2007; Zhao et al., 2014; Ahiablame et al., 2017). The elasticity can be expressed as,

$$\varphi = median\left(\frac{y_i - \bar{y}}{x_i - \bar{x}} \times \frac{\bar{x}}{\bar{y}}\right) \tag{6}$$

where $y \in \{Streamflow, Bluewater, Greenwater\}$, $x \in \{Climate\ variable, Landuse\ variable\}$; Whereas, $\bar{y}$ and $\bar{x}$ represents the spatial mean of x and y variables within the watersheds in the river basin. The land use variables included in the sensitivity analysis are developed area, forest, pastureland, and agricultural row crops and the precipitation is considered as climate variable. The value of φ is a non-dimensional quantity called elasticity, which represents the spatial variation of streamflow, blue water and green water across the watersheds of Savannah River Basin. The value of φ can suggest the sensitiveness of water resources to climate variables or land use variables. Furthermore, this elasticity approach distinguishes between positive and negative sensitivities. For example, a positive elasticity value suggests that a spatial increase in a particular land use class (e.g. agricultural land, forest land) may result in increase in streamflow. Whereas, a negative value of φ indicates that, a spatial increase in a particular land use class may lead to decrease in streamflow. Therefore, this approach is found to be suitable for quantifying the spatial influence of climate and land use variables on streamflow, blue water and green water over the SRB. In this study, we applied the elasticity concept for Case 1 (1992–2000 climate variables and 1992 land use) and Case 2 (2001–2013 climate variables and 2001 land use) scenarios.

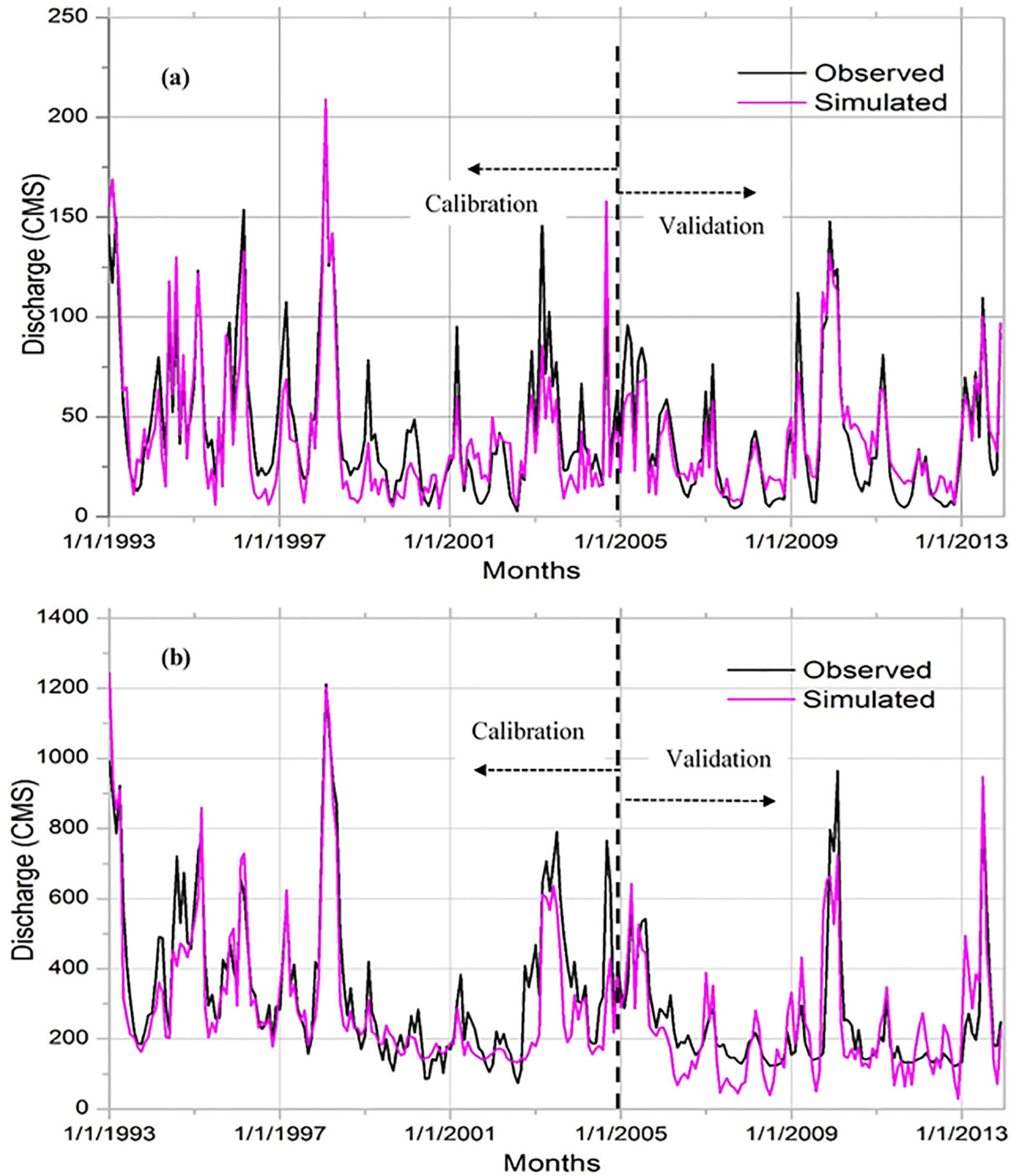


Fig. 4. Time series plot between modeled (SWAT) and observed (USGS) stream flow at gauging stations (a) 02192000 and (b) 021985000 at monthly time scale.

2.8. Water security indicators

The following section provides an overview of different indicators used for water security assessment.

2.8.1. Blue and green water scarcity

The blue and green water scarcity are quantified based on the water footprint concept (Veettil and Mishra, 2016). The blue water footprint ($BW_{footprint}$) denotes the consumptive use (i.e. the difference between water abstracted for a particular use and the remaining flow returned to the same watershed (Veettil and Mishra, 2016; Hoekstra et al., 2011; Rodrigues et al., 2014). The United State Geological Survey (USGS) provides county level sectorial water use data at an interval of 5 years period. We collected water use data separately for irrigation, livestock and aquaculture use and calculated the consumptive use (Carr et al., 1990; Fanning and Trent, 2009; Shaffer, 2008 and Solley et al., 1998; Veettil and Mishra, 2016). The consumptive water use for irrigation, livestock and aquaculture are estimated as 85%, 65% and 5% of total water abstraction (Veettil and Mishra, 2016). The blue water scarcity ($BW_{scarcity}$) is calculated as a ratio of $BW_{footprint}$ to the available blue water using equation (7).

$$BW_{\text{scarcity}} = BW_{\text{footprint(x,t)}}/BW_{\text{availability}} \quad (7)$$

where 'x' represent a county with respect to time 't'.

Green water scarcity ($GW_{scarcity}$) is estimated as the ratio between green water footprints ($GW_{footprint}$) to the green water availability ($GW_{availability}$). $GW_{footprint}$ is estimated as the evapotranspiration which is calculated by using Hargreaves method (Hargreaves et al., 1985) available in the SWAT model. In our analysis, we evaluated $GW_{scarcity}$ for the two land use change scenarios (1992 & 2001). The green water scarcity is expressed as,

$$GW_{\text{scarcity(x,t)}} = GW_{\text{footprint(x,t)}}/GW_{\text{availability}(x,t)} \quad (8)$$

where, $GW_{availability}(x,t)$ is the amount of initial soil water content (which is considered as available green water) in county 'x' during the period 't'. $GW_{footprint}(x,t)$ is the green water consumed from a county 'x'

during time '*t*'.

2.8.2. Falkenmark Index

Falkenmark (FLK) (Falkenmark et al., 1989) index is one of the most widely used indicators to measure the stress on water resources (Rijsberman, 2006), which is defined as the fraction of blue water availability to the total population. FLK index is a clear indicator of human health and water economy (Falkenmark et al., 1989; UN-WBCSD, 2006). This indicator does not consider the infrastructure operation that modifies the availability of water to users and the threshold do not reflect important variations in demand (Rijsberman, 2006). However, FLK index is a useful tool for classifying (according to the per capita demand) the water scarcity at a national (Karabulut et al., 2016) or regional scale (Schuol et al., 2008a). Based on the per capita water usage, the FLK index of a region is categorized as; no stress, stress, scarcity, and absolute scarcity regions. Where the index threshold less than 500 m^3/person/year is considered as absolute water scarcity region and threshold greater than 1700 m^3/person/year is a no stress region (Falkenmark et al., 1989).

2.8.3. Freshwater provision indicator

The fresh water provision index (FPI) is measured based on the magnitude of fresh water (stream flow) and EFR (Logsdon and Chaubey, 2013; Rodrigues et al., 2014). The FPI can provide information related to the variation in EFR due to the drought, low flow etc. The FPI in a yearly scale is calculated by using equation (9).

$$FPI_{(x,t)} = \frac{Q_{avg\,(x,t)}/EFR_{(x,t)}}{(Q_{avg\,(x,t)}/EFR_{(x,t)}) + q_t/m_t} \tag{9}$$

where $FPI_{(x,t)}$ is the freshwater provision index for a county (x) during time t; $Q_{avg(x,t)}$ and $EFR_{(x,t)}$ are the average flow and Environmental Flow Requirement for county x and during time t; q_t is the number of times the average flow is less than EFR and m_t is the total number of years considered.

3. Results

3.1. Influence of climate variability and land use change on streamflow

Streamflow simulated from each case studies (Case 1, Case 2, Case 3, and Case 4) are compared for quantifying the effect of land use change and climate variability. The boxplot of mean monthly runoff due to the individual and combined scenarios for the entire river basin is shown in Fig. 5. The difference in streamflow pattern based on case 1 (Fig. 5a) and case 4 (Fig. 5d) imply the sole effect of land use change over the SRB. The land use change from 1992 to 2001 led to a significant reduction in simulated monthly streamflow for all the months. For example, the streamflow in January is reduced from 400 cubic meter per second (cms) to less than 300 cms. Overall, the land use change resulted in a total streamflow reduction (percentage change in annual average) of 31%. The streamflow can be potentially influenced by the increase in pasture land (Zhang et al., 2016a). There is a significant increase (about 53%) in pastureland over the SRB from 1992 to 2001 (Fig. 2). The decrease in the existing farmland and forest land cover has less influence in reducing the streamflow generation due to low evapotranspiration and higher water yield (Morán-Tajeda et al., 2012). However, the pasture land increases the amount of evapotranspiration and reduce the water yield capacity of sub-basins (Zhang et al., 2016b; Sriwongsitanon and Taesombat, 2011). Therefore, significant increase in pasture land may be a possible reason for reduced streamflow in the Savannah River Basin.

The obvious distinction between Case 1 (Fig. 5a) and Case 3 (Fig. 5c) point towards the unique effect of climate variability on the streamflow. The climate variability caused a remarkable reduction in streamflow. The climate variables accounted for a streamflow reduction of 41% in the basin. Overall, the streamflow reduced during recent decade (2001–2013) compared to earlier decade (1992–2001) as seen in Fig. 5a and c. For example, the median streamflow during January is decreased by 80 cms. The above result suggests that the climate variability and land use change has a potential influence on runoff generation in the SRB. The combined effect of land use change and climate variability may not be the sum of individual impact (land use change or climate variability) (Wang et al., 2014). For example, streamflow is decreased by 31% due to the impact of land use change and 41% due to the climate variability, and as a result of joint effect the streamflow is reduced by 25%.

3.2. Influence of land use change and climate variability on blue water

The potential influence of land use change and climate variability on spatio-temporal distribution of blue and green water resources are evaluated using the hydrological fluxes (e.g., water yield, soil water, and evapotranspiration) obtained from the SWAT model (Veettil and Mishra, 2016) for different case studies (Case 1, Case 2, Case 3, and Case 4). The results showed that in most of the counties there exists a significant reduction of blue water due to the influence of land use change and climate variability. The maximum blue water was observed in Rabun County for all the scenarios, where the annual rainfall was comparatively greater than other counties from 1992 to 2013. The blue water was nearly consistent for all the four scenarios in the Rabun County. Earlier studies (Zang et al., 2012) suggested that, forest cover has potential impact on blue water. In Rabun County the forested area decreased from 96% to 88% during 1992–2001. But the average rainfall during 1992–2000 was 1800 mm/year and it increased to 1900 mm/yr during 2001–2013. This can be a possible reason for consistency of blue water resource in the Rabun County. The influence of land use change on blue water for each county is explained by analyzing two case studies (Case 1 and Case 4). The changes in spatial distribution of blue water in SRB under different scenarios are shown in Fig. 6. In Case 1 and Case 4 the minimum blue water was observed in Lincoln County, Richmond County, and Columbia County, which are located in central part of SRB. These counties also witnessed a reasonable decrease in blue water due to the individual impact of land use change (Fig. 6a). For example, the blue water at Lincoln County showed a 10% decrease, where the forest cover decreased from 67% to 53%.

The maximum reduction in blue water due to the impact of land use change was observed in McCormick County located in central SRB, where the forest cover was reduced from 78% to 70%. Whereas, most of the counties located in the lower SRB showed a minimum reduction or upsurge in blue water quantity due to the land use change (e.g. Burke County, Screven County). The influence of urban (developed) area in controlling the blue water resource also analyzed in the study. A larger proportion of precipitation leaves urban catchments as surface runoff, which reduces the water yield and groundwater recharge capacity (Paul and Meyer, 2001; Karabulut et al., 2016; Zhang et al., 2016a,b). For example, the built-up area in Richmond County almost doubled from 1992 to 2001 (from 15% to 29%), where the blue water reduced considerably. Therefore, increase in developed area can be another possible reason for decrease in the blue water in the Savannah River Basin.

The difference in spatial distribution of blue water due to the influence of climate variables is shown in Fig. 6b. Hart County, located in the upper SRB experienced maximum reduction (338 mm) in blue water flow due to the impact of climate variability. The decrease in annual rainfall led to substantial reduction of blue water in the county. Similarly, Franklin and Anderson County also witnessed a considerable reduction in blue water resources. The combined effect of climate variables and land use change (comparing Case 1 and Case 2) led to a reduction in blue water (Fig. 6c) in most of the counties of the basin. Hart County showed maximum reduction in blue water flow due to the combined effect of climate and land use change. Here, the forest cover reduced from 45% to 35% and built-up area increased from 1.7% to

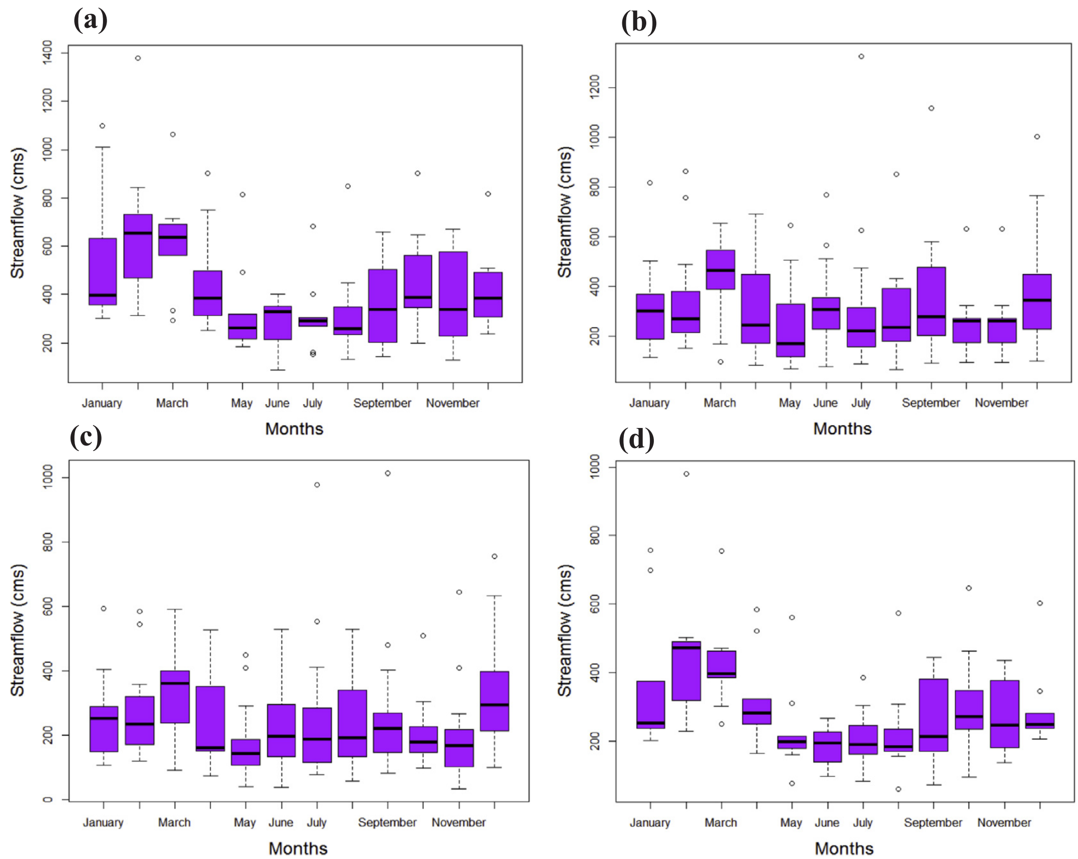


Fig. 5. Boxplots for mean monthly streamflow due to the effect of land use change and climate variability based on different case studies: (a) Case 1[1992 LULC and 1992–2000 climate variables], (b) Case 2 [2001 LULC and 2001–2013 climate variables], (c) Case 3 [1992 LULC and 2001–2013 climate variables], and (d) Case 4 [2001 LULC and 1992–2000 climate variables]. (a) (b) (c).

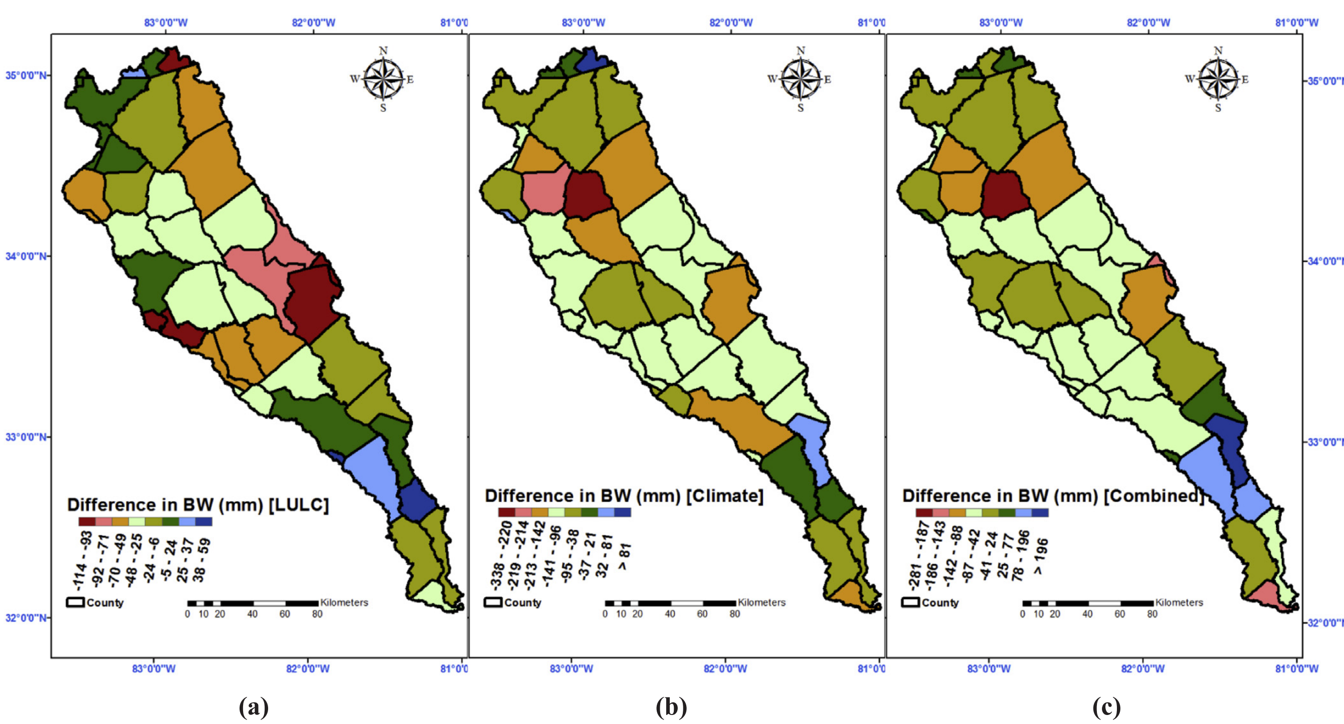
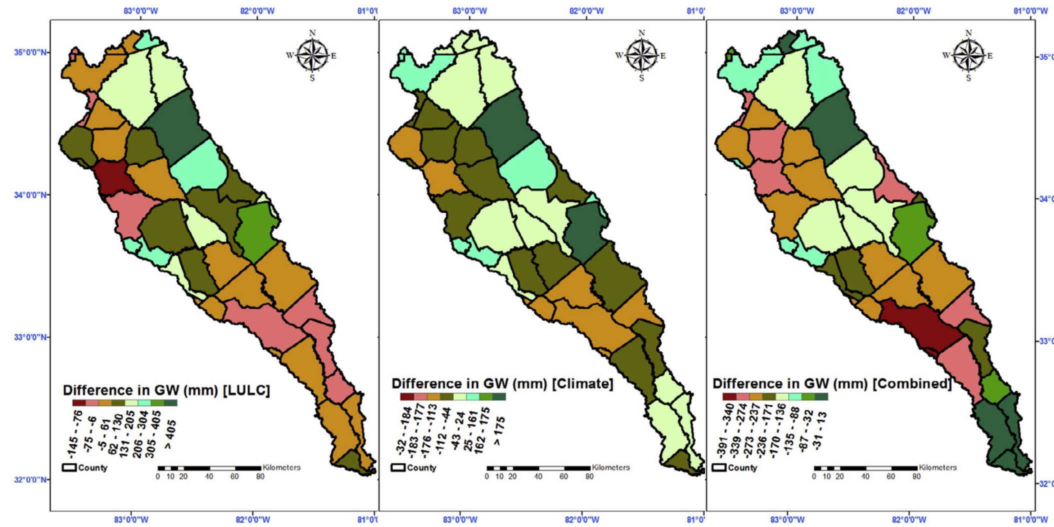


Fig. 6. Changes in the spatial distribution of blue water in Savannah River basin due to: (a) land use change during 1992 and 2001, (b) changes in climate pattern during two time periods (1992–2000 and 2001–2013), and (c) combined influence of both climate and land use change.



(a) (b) (c)

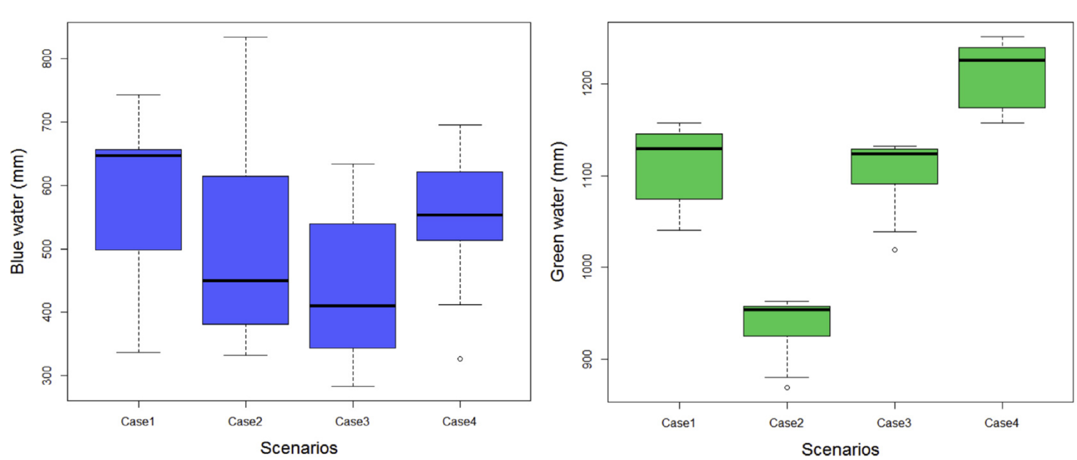
Fig. 7. Changes in the spatial distribution of green water in Savannah River basin due to: (a) land use change during 1992 and 2001, (b) changes in climate pattern during two time periods (1992–2000 and 2001–2013), and (c) combined influence of both climate and land use change.

10%.

The boxplot of mean annual blue water for entire SRB based on the four scenarios is shown in Fig. 8a. The median (50th percentile) of blue water amount is reduced by 11% due to the land use change (by comparing Case 1 and Case 4), 34% due to the climate variability (by comparing Case 1 and Case 3), and 31% due to the combined effect of climate variability and land use change (by comparing Case 1 and Case 2) during 1992–2013. Using different scenarios, our study suggests that climate variability and land use change has significant control over blue water. The decrease in forest land (20.5%) and increase in developed area (247%) can be considered as the major land use factors that has more influence on blue water resources. Similarly, the impact of climate variability has also a major influence on the blue water resources.

3.3. *Influence of land use change and climate variability on green water*

In addition to blue water, it is important to evaluate green water resources to improve water management and related policy making (Hoekstra et al., 2011). Specifically, green water plays an essential role for agricultural sector, where the majority of irrigation is applied through rain-fed system (Schuol et al., 2008a; Abbaspour et al., 2015). Typically, the green water can be characterized as the water consumed by agricultural or forest ecosystem (Karabulut et al., 2016). Since the spatio temporal distribution of green water continuously vary with respect to the land use change and climate variability, we quantified the potential influence of these two factors on green water. The changes in spatial pattern of green water due to the influence of land use change, climate variability, and combined climate and land use change are shown in Fig. 7. The spatial distribution of green water due to the influence of land use change is evaluated based on the Case 1 and Case 4 scenarios. It was observed that most of the counties witness a significant increase in green water as a result of change in land use (Fig. 7a). Anderson County located in Upper SRB showed highest increase (40%) in the green water. This may be due to the increased evapotranspiration from pastureland as well as grassland. The pastureland in the Anderson County is increased from 21% to 26% whereas, the grass land is increased from one percent to nine percent. Our analysis also indicated that green water in most of the counties located in upper SRB has a significant rise (e.g. Pickens (19%), Oconee (15%), and Hall (11%)) due to the potential influence of land use change (Fig. 7a). All these counties also witnessed a significant increase in pastureland. Burke County located in central part of SRB witnessed a significant decline in green



(a) (b)

Fig. 8. The boxplot showing the annual average of (a) blue water and (b) green water in Savannah River Basin based on the four case studies. [Note: Case studies (1–4) are similar to Fig. 5].

water due to the land use change. It was interesting to observe that the impact of climate variability on green water was conflicting with the potential influence of land use change in the SRB (Fig. 7b). The green water in most of the counties decreased as a result of changing pattern of climate variables.

Most of the counties showed a significant decrease in the magnitude of green water due to combined impacts of land use change and climate variability (Fig. 7c). The maximum reduction in green water due to the combined impact of both the factors was observed in Burke County, which is located in lower SRB. This may be due to reduction in agricultural land from 33% to 21%. Typically, agricultural land has relatively higher saturated soil water content (Karabulut et al., 2016; Hoekstra et al., 2011), which can directly influence the green water over a region. In addition to agricultural land, the annual average precipitation also decreased in this county. Overall analysis suggest that land use change has an important role in controlling green water for example, the percentage change in pasture cultivation and other agricultural crops in SRB influenced the green water distribution for most of the counties.

The boxplot of mean annual green water for entire SRB based on the four scenarios is shown in Fig. 8b. The median of the green water is reduced by 15% for the SRB due to the combined influence of land use change and climate variability. In contrast to the blue water analysis, the change in land use pattern exhibited more influence on the green water resources. The evapotranspiration found to be increasing due to the significant increase in pastureland (53%), which can be a possible reason for land use effect on green water.

3.4. Sensitivity of water footprints to LULC and precipitation

The elasticity concept was applied to investigate the sensitivity of streamflow and water footprints (i.e. blue and green water) with respect to land use change (Fig. 9). The elasticity concept can inform the spatial influence (Konapala and Mishra, 2016) of land use and climate pattern on streamflow and water footprints of a river basin. The LULC are classified in to five groups such as; developed area, forest, agricultural row crops, and pastureland for sensitivity analysis. Here the elasticity analysis is performed for the Case 1 (1992 land use and 1992–2000 climate variables) and Case 2 (2001 land use and 2001–2013 climate variables) scenarios. Since, water footprints are connected to streamflow, initially we assessed the sensitivity of streamflow to land use and precipitation. The streamflow elasticity based on different land use classes and precipitation is shown in Fig. 9. The sensitivity of streamflow with respect to the 1992 developed area has a value of 0.68, indicating that 10% increase in developed area lead to 6.8% increase in streamflow (Fig. 9a). Whereas, sensitivity of streamflow based on the 2001 developed area showed a negative value, suggesting that change in land use decreased the sensitivity of streamflow to developed area (Fig. 9b). It may be due to the increase in urbanization potentially reduces the groundwater contribution (baseflow) to the stream network and the small reduction in precipitation magnitude during 2001–2013 compared to 1990–2000 across the watersheds of SRB. There is a negative elasticity value between the forest land and streamflow for both the land use periods (1992 and 2001). It showed that a 10% increase in the forest land may results to 5.5% decrease in the streamflow during the 1992 LULC analysis (Fig. 9a) whereas, 2001 forest land exhibited 3.3% decrease in the streamflow (Fig. 9b). Overall, changes in streamflow elasticity due to land use suggest that, elasticity of streamflow at SRB may be either positive or negative, and most of the land use classes decreased the sensitivity of streamflow due to the land use change. The streamflow showed higher sensitivity to the precipitation in both the scenarios, indicating that a higher precipitation increase lead to an increase in annual streamflow across the SRB.

The sensitivity of blue water with respect to the 1992 forest cover was quantified based on a φ value of 0.144 (dark red in Fig. 9a), which indicates that a 10% increase in the forest cover results to 1.4% increase in the blue water. Whereas, sensitivity of blue water to the 2001 forest cover showed a considerable decrease in the φ value, indicating that land use change decreased the sensitivity of blue water to the forest cover. However, the sensitivity of blue water with the land use classes

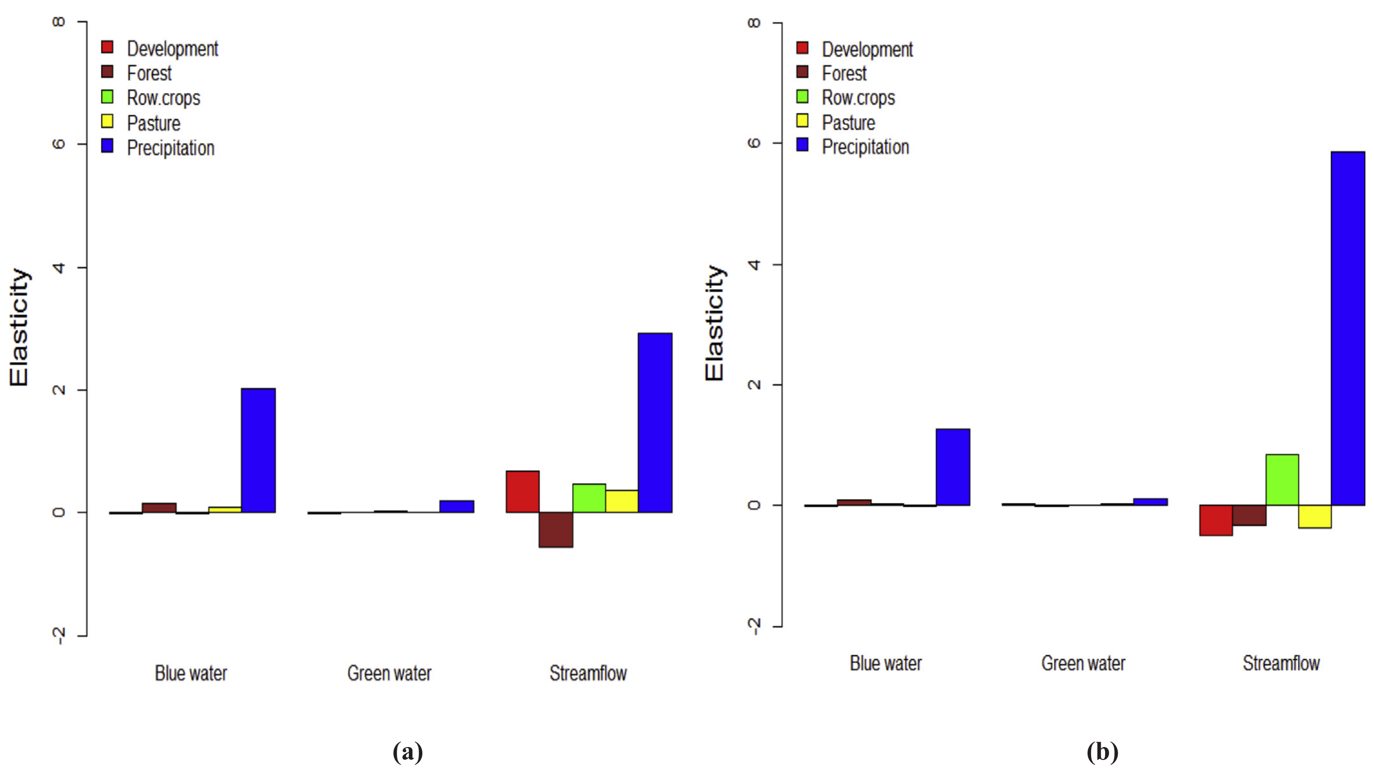


Fig. 9. Spatial sensitivity of blue water, green water, and streamflow with respect to (a) the 1992 land use and 1992–2000 precipitation (case 1); (b) 2001 land use and 2001–2013 precipitation (case 2).

including developed area, pastureland, and row crops were not significant in nature for both the land use periods (1992 and 2001). Although, the sensitivity analysis of green water to the different land use was insignificant, the 2001 pastureland showed a positive sensitivity on the green water, indicating that a 10% increase in the pastureland causes a 0.2% increase in the green water over SRB.

Impact of precipitation on the water footprints and streamflow is evaluated using the concept of elasticity. Here the elasticity concept is applied at mean annual scale of precipitation for the Case 1 (1992–2000 precipitation) and Case 2 (2001–2013 precipitation) scenarios. The sensitivity of blue water to the precipitation was comparatively higher than the land use classes. For example, sensitivity analysis of blue water to precipitation exhibited a φ value of 2.02 for the Case 1 scenario (Fig. 9a). Whereas, φ value decreased for Case 2 scenario (Fig. 9b), indicating that sensitivity of blue water to precipitation is reduced during the Case 2 scenario. Although, the sensitivity of green water to the precipitation was insignificant in nature, the φ value is further reduced during the Case 2 scenario. The green water is the amount of evapotranspiration and soil water from a basin and the precipitation plays a comparatively lesser role in influencing the evapotranspiration. Therefore, this may be a possible reason for low φ value in the analysis.

3.5. Impact of land use change and climate variability on different indicators

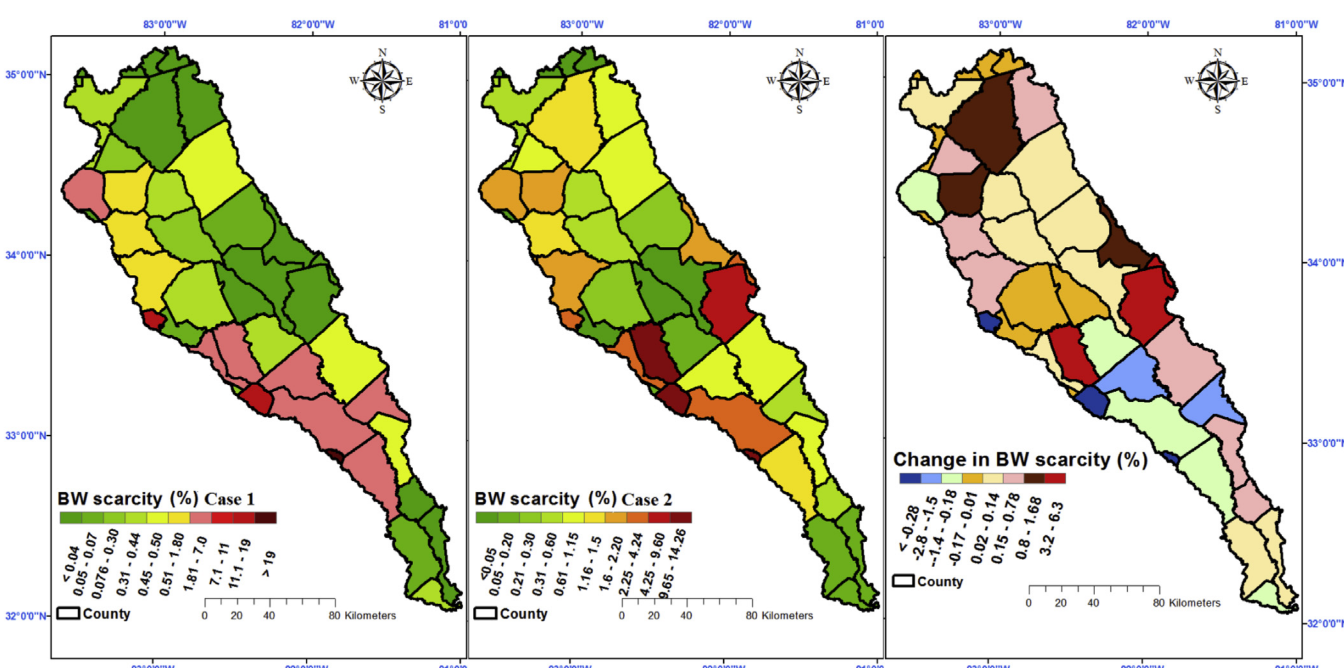
3.5.1. Impact on agricultural blue water scarcity

The agricultural water withdrawal from combined surface and ground water resources in 2013 for SRB was 38MGD and zero return flow was reported from the agricultural sector (Regional water plan, 2017). In the present study, blue water scarcity ($BW_{scarcity}$) is quantified by considering the blue water footprint and blue water availability of a county (Veettil and Mishra, 2016; Rodrigues et al., 2014). Here the water scarcity analysis is performed for the Case 1 (1992 land use and 1992–2000 climate variables) and Case 2 (2001 land use and 2001–2013 climate variables) scenarios. The blue water availability is calculated as the difference between total streamflow and EFR (Richter, 2010). The blue water footprint is calculated based on the water withdrawal data obtained from the USGS at a county scale. The water withdrawal data are available at five year interval (1995, 2000, 2005, and 2010). Therefore, the $BW_{scarcity}$ for Case 1 is calculated based on the average water consumption for the years 1995 and 2000 and $BW_{scarcity}$ for Case 2 is calculated based on the average of 2005 and 2010.

The blue water scarcity for Case 1 and Case 2 analysis are shown in Fig. 10a and Fig. 10b respectively. Whereas, Fig. 10c illustrates the difference in spatial distribution of blue water scarcity due to the combined influence of land use change and climate variability (i.e. Case 2 – Case 1). Majority of the counties showed an increase in blue water scarcity due combined influence of water withdrawal, land use, and climate variability whereas, the blue water footprint is increased (20.8%) in the SRB. Based on the county wise assessment, the $BW_{scarcity}$ increased by 6.5% and 5% in McDuffie and Edgefield County respectively (Fig. 10c). The increase in blue water footprint (178%) is identified as the major cause for the remarkable increase in $BW_{scarcity}$ in McDuffie County. Additionally, the blue water availability for this county is decreased by 49.7% during the analysis period. This may be due to the combined effect of land use change and climate variability. Counties located towards the upper SRB (e.g. Anderson County and Hart County) witnessed comparatively less variation in $BW_{scarcity}$. The irrigation water footprint is comparatively higher than livestock water and aquaculture water in SRB (Regional water plan, 2017; Wachob, 2010). Therefore, an increment in irrigation water consumption and relatively less availability of blue water due to the combined influence of land use change and climate variability may lead the counties to higher water scarcity. The majority of agricultural water demands are located in the counties located at the lower SRB of Georgia State (Regional water plan, 2017) and most of these counties witnessed a considerable change in $BW_{scarcity}$ due to the combined influence of land use change and climate variability.

3.5.2. Impact on green water scarcity

$GW_{scarcity}$ is quantified as the ratio between green water footprint to the green water availability. The Green water availability is calculated



(a) (b) (c)

Fig. 10. Blue water scarcity at Savannah River basin based on (a) Case 1 [1992 LULC and 1992–2000 climate variables], (b) Case 2 [2001 LULC and 2001–2013 climate variables], and (c) difference in blue water scarcity (i.e. Case 2 - Case 1).

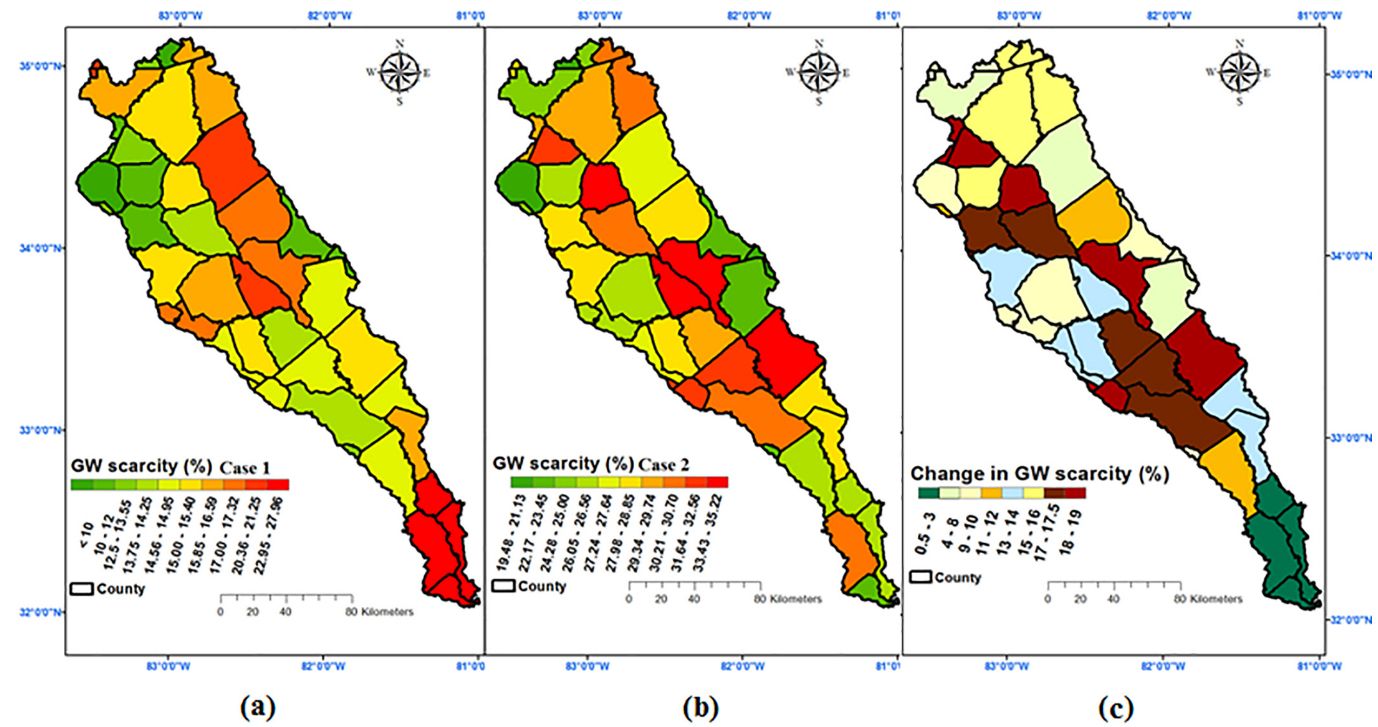


Fig. 11. Green water scarcity at Savannah River basin based on (a) Case 1 [1992 LULC and 1992–2000 climate variables], (b) Case 2 [2001 LULC and 2001–2013 climate variables], and (c) difference in green water scarcity (i.e. Case 2 – Case 1).

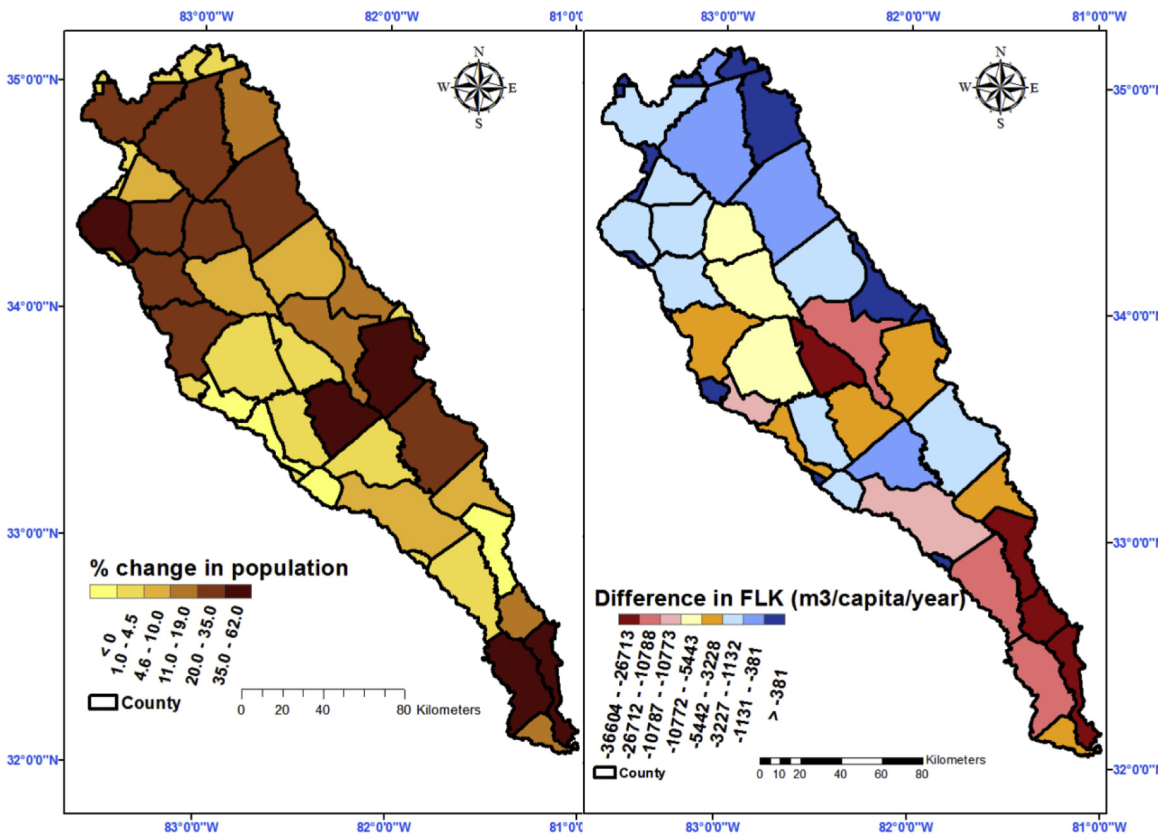
based on the initial soil water content obtained from the SWAT model HRU output (Rodrigues et al., 2014; Veettil and Mishra, 2016). The analysis of green water scarcity index for the period 1992–2000 (Case 1, Fig. 11a) and 2001–2013 (Case 2, Fig. 11b) showed that the indicator is less than 50% throughout the counties. The overall analysis suggest that the $GW_{scarcity}$ in the SRB is substantially increased (71%) due to the combined influence of land use change and climate variability. Although, the green water footprint of the SRB showed a minor decrease (5%), on the other hand, the green water availability in the basin witnessed a substantial reduction (46%) during the analysis period. Therefore, it was found that the green water availability has a significant control on $GW_{scarcity}$ of SRB.

It was observed that most of the counties located in the lower SRB witnessed a considerable increase in $GW_{scarcity}$ during the Case 2 scenario. For instance, Burke County, which has significant agricultural land witnessed 59% reduction in green water availability. Consequently, the $GW_{scarcity}$ in the Burke County increased by 16.2%. It was found that, few counties located in the upper SRB witnessed a considerable increase in the $GW_{scarcity}$ (Fig. 11c). For example, Stephens County and Hart County witnessed an increase of 19% $GW_{scarcity}$. However, Anderson County located in the upper SRB witnessed a minimum change in $GW_{scarcity}$ whereas, Anderson County showed higher values of $GW_{scarcity}$ during Case 1 and Case 2 scenarios. In addition to both climate variability and land use change the green water availability in the SRB is also influenced by the depth of the soil profile (DeLiberty and Legates, 2003). For example, the soil type in the watersheds of lower SRB are sandy or sandy over loamy, which drains completely in nature (SCDHEC, 2010). Therefore, a relatively low rainfall may lead to a high $GW_{scarcity}$ for the counties located in lower SRB. Furthermore, the reduced farmland area will also result in a reduction of green water availability in crop lands. Moreover, the assessment of change in $GW_{scarcity}$ due to land use change and climate variability can provide information on which part of the river basin is safe for practicing rain-fed agriculture (Veettil and Mishra, 2016; Abbaspour et al., 2015).

3.5.3. Impact on Falkenmark indicator

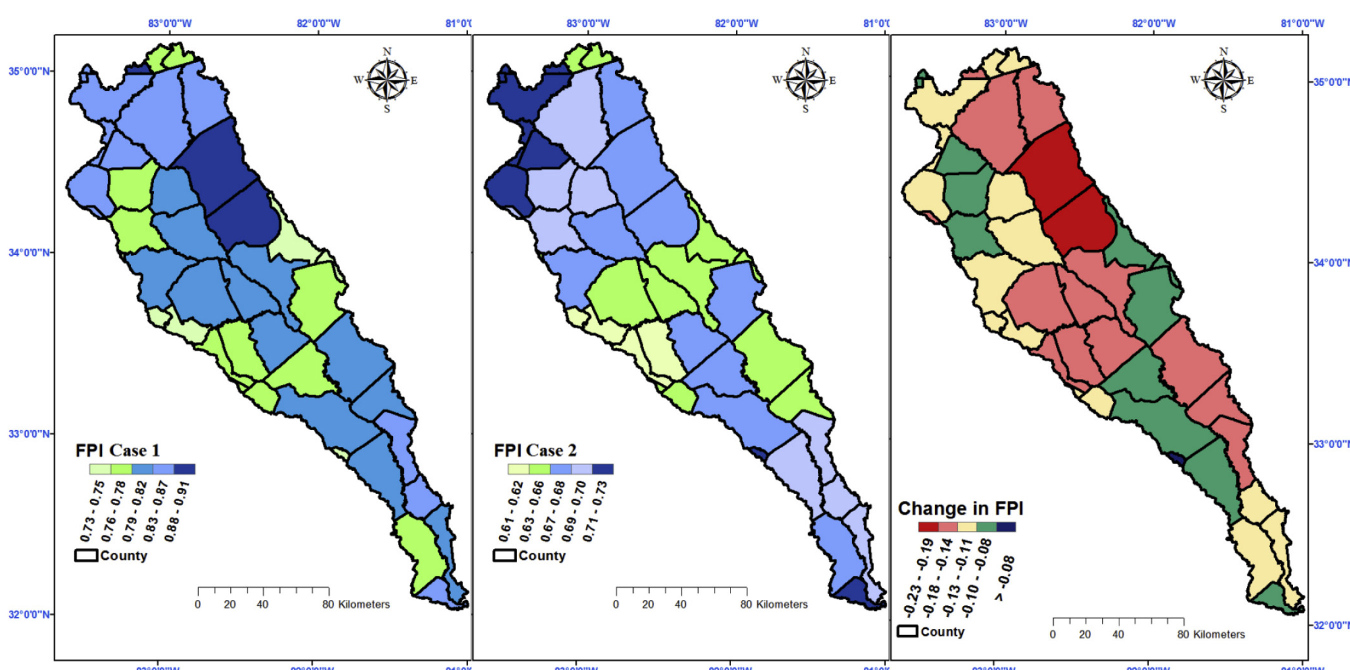
Population growth and land use change are closely related (Gleick, 2003). Communities that grow rapidly may cause increase in developed area as well as industrial sectors, thereby affecting ecological sustainability of a river basin (Palmer et al., 2008). The percentage change in population for each county located in SRB is shown in Fig. 12a. In most of the counties, human settlement significantly increased between 1995 and 2010. For example, maximum population growth was observed in Effingham County (62%) located in the central part of SRB, where the built-up area increased by 91.8% and the forest area decreased by 31%. The Columbia County, the second densely populated county in the basin (Regional water planning, 2017) also witnessed a considerable increase in population from 1995 to 2010.

The FLK indicator was calculated as a ratio between blue water availability to population for each county. However, none of the counties indicated absolute water scarcity (i.e., per capita water availability is less than 500 m^3/year) during the study period, but results indicated that fresh water availability per person is decreased in most of the counties. The total water requirement for food security is quantified as 1300m^3/capita/year (Falkenmark and Rockström, 2006; Rockström et al., 2009). Therefore, as a rule of thumb, this threshold is useful for defining the agricultural water security of a region. The minimum amount of per capita water was observed in counties located in upper SRB (e.g., Pickens and Anderson County) and the higher amount was observed in counties located in lower SRB. The result suggest that only Anderson County is likely to face chronic water stress in SRB, where the FLK index was less than the total water requirement for food security during Case 1 and Case 2 scenarios. The FLK index is further decreased (31%) in the Anderson County due to the influence of population growth, climate variability and change in land use. In Anderson County, the mean annual precipitation decreased by 13.5% and population is increased by 21%, which can be possible reason for decreasing the FLK index. Pickens and Richmond Counties also showed a comparatively higher water stress in both the scenarios. Overall, the counties that showed high values of FLK indicators during the Case 1 scenarios (e.g. Lincoln County, Effingham County, and Burke County)



(a) (b)

Fig. 12. a) The percentage change in population (from 1995 to 2010) for counties located at SRB, and b) the difference in FLK indicator (Case 2 – Case 1).



(a) (b) (c)

Fig. 13. Freshwater provision indicator at Savannah River basin based on (a) Case 1 [1992 LULC and 1992–2000 climate variables], (b) Case 2 [2001 LULC and 2001–2013 climate variables], and (c) difference in freshwater provision indicator (i.e. Case 2 – Case 1).

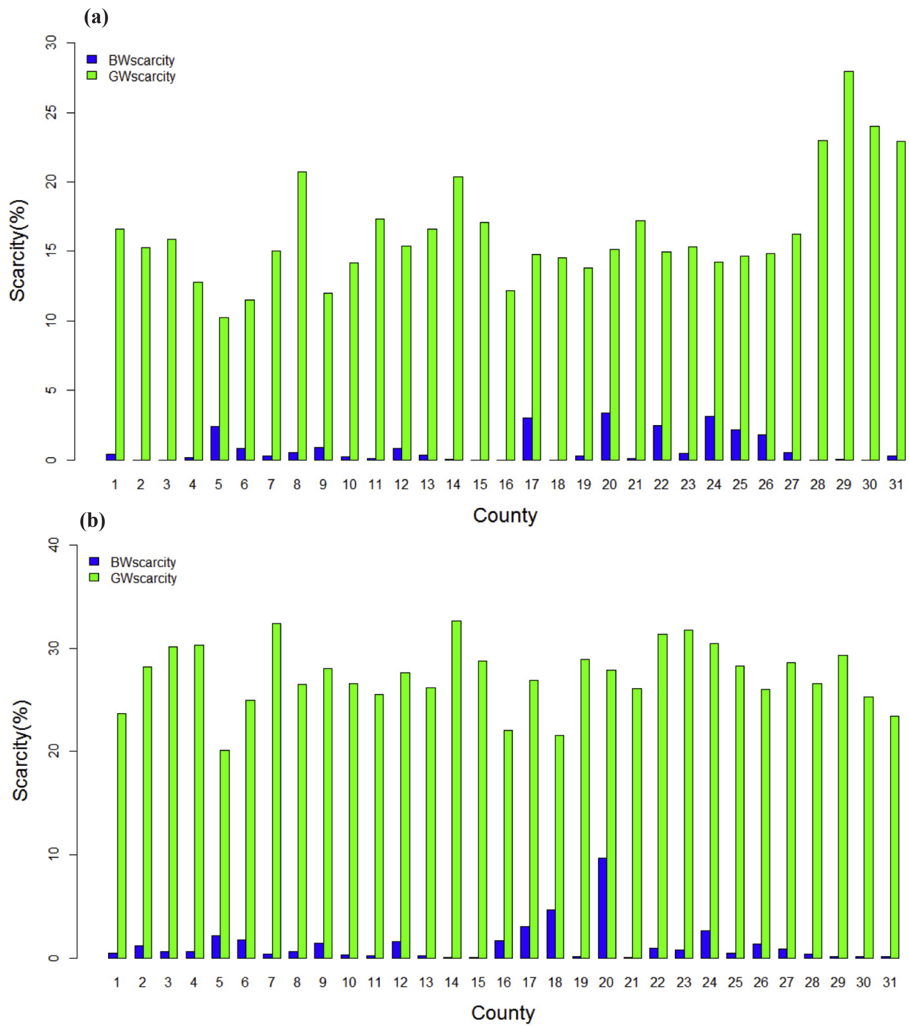


Fig. 14. Mean annual blue water scarcity and green water scarcity of the counties located at SRB for the scenarios (a) Case 1 [1992 LULC and 1992–2000 climate variables] and (b) Case 2 [2001 LULC and 2001–2013 climate variables].

witnessed comparatively higher decline in FLK indicator based on the difference between two scenarios (Fig. 12b).

3.5.4. Impact on freshwater provision indicator

The combined influence of climate variability and land use change on the environmental flow for each county is evaluated by the freshwater provision indicator (FPI). FPI will be equal to one if water provisioning service (e.g. water usage for irrigation) meets the ecosystem conditions; otherwise FPI will be less than one (Rodrigues et al., 2014). More precisely, FPI is a measure of impact of EFR on blue water availability. Our analysis showed that FPI for the SRB is less than one during the period of analysis. The FPI is further decreased during 2001–2013 due to the combined influence of land use change and climate variability. Fig. 13 illustrate the spatial distribution of FPI for these scenarios: Case 1 (Fig. 13a), Case 2 (Fig. 13b); and Fig. 13c shows the change in FPI due to the combined influence of climate variability and land use change. The counties located at upper SRB, especially in the State of South Carolina (e.g. Anderson County, Abbeville) showed considerable reduction in FPI. Whereas, the counties located in the lower SRB witnessed a comparatively lower decrease in FPI, especially for the counties located at the State of Georgia (e.g. Columbia County, Burke County). From equation (3), it is obvious that the streamflow in a catchment is the major factor in FPI estimation. Therefore, the major factors which reduces the streamflow also reduces the magnitude of FPI in a catchment. The potential influence of developed area, forest cover, and pastureland are identified as the major land use classes which control the streamflow. For instance, Anderson County witnessed the highest reduction in FPI, where the developed area and pastureland increased by 156% and 22% respectively. Whereas, average annual precipitation in Anderson County is decreased by 9% during the analysis period. Therefore, the spatio-temporal changes in these variables can be considered as the major factors that influence the FPI over the SRB.

4. Discussion and concluding remarks

In the present study, the hydrologic fluxes used for quantifying the water scarcity indices are streamflow, groundwater, evapotranspiration, and soil moisture. However, to get the best SWAT model outputs (hydrologic fluxes), it is important to estimate the robust model parameters that further depends on long-term high-quality hydrological observations. For instance, the peak flow was calibrated by adjusting the sensitive parameters including CN2.mgt (curve number), SOL_AWC.Sol (available water capacity of the soil layer) and ESCO. bsn (soil evaporation compensation factor), which indicates that a long-term hydrological observation is necessary for quantifying the range of most sensitive parameters during the calibration phase of a developed SWAT model. In addition, SWAT is a physically-based model, therefore the model is data intensive in nature (Näschen et al., 2018). The lack of data to operate the SWAT model may lead inadequate estimation of model parameters (Nyeko, 2015) and eventually it will result in inappropriate water scarcity indices. Proper monitoring of climate and surface data should be able to provide appropriate variables (model output), which is required to quantify the water scarcity indices with minimum uncertainty. Similarly, incorporating uncertainties in DEM, soil data, and land use data is a challenging task in hydrological model development (Arnold et al., 2012). Finally, the most important variable used to estimate the water scarcity (blue water scarcity) index is spatial and temporal distribution of agricultural water use data. In this study we collected county level water use data from USGS, however, this information is not available for most of the countries around the globe.

During 1992–2001, the total forest cover in the Savannah River Basin decreased by 20.5% and the settlement area, which includes construction land, residential area and commercial area has grown by 247%. The agricultural land has declined by 21% but pastureland increased by 53%. It is expected that these changes will alter regional hydrological process, thereby affecting water security within the river basin. In the past decades several indices were introduced to quantify the water security of a region (Brown and Matlock, 2011; Liu et al., 2017). Here, we used four water security indices (Blue water scarcity, Green water scarcity, Falkenmark index, and freshwater provision indicator) to investigate the water scarcity for the counties located in the Savannah River Basin. Both blue water scarcity and FLK index considers blue water availability of a county, while ignoring the green water availability. Whereas, a location may meet its crop water requirement merely from the potential green water resources. In such condition irrigation need not to be initiated in the crop field. Therefore, water shortage of river basins changes when taking green water into account. In addition to the irrigation water demand, the water requirement for livestock and aquaculture sectors, was considered, where the water is extracted only from the blue water resources. Fig. 14 illustrates the difference between blue water scarcity and green water scarcity of each county analyzed based on Case 1 (1992 land use and 1992–2000 climate variables) and Case 2 (2001 land use and 2001–2013 climate variables). It can be observed that the green water scarcity is higher than the blue water scarcity across the counties and majority of the irrigation water demand areas are located in the southern part of the region, which includes McDuffie, Burke, Jefferson, Jenkins, and Screven counties (Regional water planning, 2017). Currently, the blue water shortage in most of the counties are potentially influenced by the combined anthropogenic or climate factors, therefore the increase in green water shortage may lead to increase in the demand for irrigation water (blue water) to manage the agricultural production in the counties.

However, water scarcity is not only governed by population growth but also related to rising income and related changes in food habit (Alcamo et al., 2000; Hubacek et al., 2009; Liu et al., 2017). Based on the FLK index, value between 1700m^3/capita/year and 4000m^3/person/year is considered as satisfactory (Abbaspour et al., 2015; Schuol et al., 2008b), whereas water requirement for food security is considered as 1300 m^3/capita/year. Based on the Case 1 (1992 LULC and 1992–2000 climate variables) 7 counties witnessed a FLK index of less than 4000m^3/capita/year and number of counties increased to 11 in Case 2 (2001 LULC and 2001–2013 climate variables).

However, there are specific limitations in our study, for instance, (i) quantification of ground water to the baseflow can be improved in the hydrological modeling, specifically during the low flow period, (ii) better representation of reservoir operations and irrigation water use within the modeling framework improve the quantification of blue water and related water scarcity and (iii) the Falkenmark Index represents the per capita availability of water without considering spatial variations in water demand due to domestic, industrial, and agricultural sectors (Rijsberman, 2006; Schewe et al., 2014). Therefore, by incorporating the socio-economic aspects of water demand (e.g. SWSI (Ohlsson et al., 2000)) may improve the representation of water scarcity over the Savannah River Basin. Overall, the proposed modeling framework can provide relevant information on water stress of a region as well as potential influence of anthropogenic and climate variables. The major outcomes of the study are as follows,

(a) Savannah River Basin witnessed a decrease (11%) in blue water due to the influence of land use change. The decrease in forest land and increase in developed area can be considered as the major land use factors that has significant influence on blue water resources. Whereas, the climate variability resulted in decrease (34%) of blue water across the basin. This suggests that the precipitation has more control over the blue water resources of Savannah River Basin. In contrast to blue water analysis, land use change has dominant control over the green water of the basin. The evapotranspiration found to be increasing due to the significant increase in pastureland (53%), which can be a possible reason for increase in green water in the Savannah River Basin.
(b) The urban area has a significant influence on controlling the water resources of a river basin. A larger proportion of precipitation has leaves urban catchments as surface runoff, thereby reducing the water yield and ground water recharge capacity. For instance, Richmond County witnessed highest percentage increase in the urban area during 1992–2001, where the blue water decreased considerably. Whereas, the green water at the Richmond County showed a minor change, which suggests that the urbanization may have little influence on the green water resource of Savannah River Basin.
(c) The pastureland in the basin is significantly increased (53%) from 1992 to 2001. The pastureland increases the amount of evapotranspiration and decreases the water yield of sub-basins. Therefore, the intensification of pasture land may be a possible reason for decrease in streamflow of the Savannah River Basin.
(d) The magnitude of various water scarcity indicators was different within each county. For instance, during 2001–2013, Anderson County located in the upper Savannah exhibited a blue water scarcity of 1.15%, green water scarcity of 27%, and fresh water provision index of 68%. The observed Falkenmark index was 848m^3/capita/year. It shows that different water scarcity indices are controlled by various factors within a region. For example, blue water scarcity depends on the precipitation and water usage by different sectors, whereas in the case of green water scarcity the land use pattern play an important role.
(e) The Falkenmark Index is typically used for assessment of water scarcity (Vorosmarty et al., 2000) and applied at country level. Here, we quantified this index at a county scale using more robust hydrological and sectorial water demand information which will help to identify the water scarcity regions within a river basin. During 2001–2013 the observed Falkenmark index for the Anderson County was 848m^3/capita/year, which indicates Anderson County is experiencing water scarcity. On the other hand, the Falkenmark index for the Burke County located in the lower Savannah is more than 20,000m^3/capita/year, which indicates the county has adequate per capita water availability even though the population increased by 10%. Therefore, our study suggests that the assessment of Falkenmark index at a local to regional (e.g. watershed, county) spatial units will assist the policy makers to identify the complex pattern of water scarcity within a river basin.
(f) It was observed that most of the counties located in the lower SRB witnessed a considerable increase in the green water scarcity due to the combined influence of land use change and climate variability. For instance, Burke County, which has significant agricultural land witnessed 59% reduction in green water availability. Subsequently, the green water scarcity in the Burke County increased by 16.2%. Whereas, the counties located in the central SRB (McDuffie and Edgefield County) exhibited significant increase in the blue water scarcity. The increase in blue water footprint (178%) is identified as the major cause for the remarkable increase in blue water scarcity

at McDuffie County. Additionally, the blue water availability for this county is decreased by 49.7% during 2001–2013, due to the combined effect of land use change and climate variability.

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