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Climate and Land Use Effects on Hydrologic Processes in a Primarily Rain-Fed, Agricultural Watershed

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Research Impact Statement: Seasonal changes in climate are expected to increase irrigation requirements and reduce the number of field-work days. Land use changes may mitigate or amplify these impacts on stream- and baseflow.

ABSTRACT: Anticipating changes in hydrologic variables is essential for making socioeconomic water resource decisions. This study aims to assess the potential impact of land use and climate change on the hydrologic processes of a primarily rain-fed, agriculturally based watershed in Missouri. A detailed evaluation was performed using the Soil and Water Assessment Tool for the near future (2020–2039) and mid-century (2040–2059). Land use scenarios were mapped using the Conversion of Land Use and its Effects model. Ensemble results, based on 19 climate models, indicated a temperature increase of about 1.0°C in near future and 2.0°C in mid-century. Combined climate and land use change scenarios showed distinct annual and seasonal hydrologic variations. Annual precipitation was projected to increase from 6% to 7%, which resulted in 14% more spring days with soil water content equal to or exceeding field capacity in mid-century. However, summer precipitation was projected to decrease, a critical factor for crop growth. Higher temperatures led to increased potential evapotranspiration during the growing season. Combined with changes in precipitation patterns, this resulted in an increased need for irrigation by 38 mm representing a 10% increase in total irrigation water use. Analysis from multiple land use scenarios indicated converting agriculture to forest land can potentially mitigate the effects of climate change on streamflow, thus ensuring future water availability.

(KEYWORDS: climate variability/change; land use/land cover change; precipitation; SWAT; statistical downscaling; CLUE-S; hydrologic processes.)

INTRODUCTION

Watershed hydrologic processes respond directly to climate and land use change (Neupane and Kumar 2015; Serpa et al. 2015). Seasonal variations and long-term climate change can have important impacts on water resources and water availability (López-Moreno et al. 2014; Schewe et al. 2014; Byrd et al. 2015). Therefore, anticipating and quantifying changes in the hydrologic conditions are essential for both social and economic decision making. Long-term forecasting at monthly, seasonal, or annual intervals is helpful for decision makers tasked with allocating water resources or mitigating drought.

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In the past century, the Midwestern United States (U.S.) has experienced changes in air temperature and in precipitation patterns with regard to the frequency and intensity of events (Karl et al. 2009; Pryor et al. 2014; Morton et al. 2015). Annual temperatures have increased across the region with an increase of 0.8°C between 1895 and 2012. Moreover, heat waves have increased (Kunkel et al. 2013; Pryor et al. 2014). Associated with these changes, the hydrologic processes are expected to shift, and consequently, contribute to decreasing soil moisture across much of the Midwest, negatively impacting agriculture productivity (Pryor et al. 2014).

Aside from climate change, land use change plays an important role in the hydrologic processes of evapotranspiration (ET), infiltration, surface runoff, and baseflow in a watershed. For example, changes in vegetation cover resulting from deforestation or replacement of vegetation species can alter surface roughness and the leaf area index, influencing the surface energy balance and ET (Zhu et al. 2013; Morán-Tejeda et al. 2015). Urbanization creates more impervious surface areas, which decreases the infiltration rate and time of concentration. As a consequence, surface runoff and peak discharge will be increased (Du et al. 2013; Dwarakish and Ganasri 2015). In addition, according to the latest U.S. Department of Agriculture (USDA) agriculture census report of 2012, many crop production areas in the Midwest area are rain-fed. Rain-fed crop production is very vulnerable to drought conditions; thus, water shortage during drought periods is one of the most significant stress factors on crop production (Bannayan et al. 2010; Rockström et al. 2010).

Previous studies have coupled watershed hydrologic models with climate and land use projections to estimate the potential impact of climatic and land use changes on hydrologic processes. Most of these studies have been based on a few selected general circulation models (GCMs) (El-Khoury et al. 2015; Pervez and Henebry 2015; Zhang, Nan, Yu, et al. 2016; Molina-Navarro et al. 2018). Pierce et al. (2009) found the multi-model ensemble mean is a better predictor than any individual GCM as the ensemble model mitigates errors associated with any individual model. Furthermore, trend analysis of ensemble mean values should help to better understand the robustness of the predicted future hydrologic processes (Jung and Chang 2011). Crosbie et al. (2011) found the choice of GCMs is one of the main sources of uncertainty in climate change impact studies, and suggested using the ensemble approach. In addition, there are uncertainties concerning how watersheds in different regions will respond to the combined effects of climatic and land use changes. Therefore, it is necessary to continue the integrated modeling effort to improve the understanding of the respective influences of climate and land use change on hydrologic processes (Sunde et al. 2018).

The Salt River Basin (SRB) was selected as the study area due to the combined influence of weather, soil, and land use. The basin is influenced by three air masses (Pacific, Arctic, and the Gulf of Mexico), making it very sensitive to climate change (Dean 1999). Claypan soils are predominant in all subbasins, and are classified into hydrologic groups C and D with slow infiltration rates and moderate to high runoff potential (Lerch et al. 2008). The combined climate conditions with dominant high clay content soils make this watershed sensitive to any change in the hydrologic condition. The anticipated shift in the future climate condition may result in inadequate or lack of timely precipitation to provide the necessary water for crop production (Thornton et al. 2014; Fraga et al. 2016).

The primary objective of this study was to assess the potential impact of both land use and climate change on hydrologic processes of a regional scale watershed. An ensemble modeling approach was used to estimate the impact of future climate conditions. Four land use projections were also put into the hydrologic model to bracket a large range of uncertainty, allowing for a better understanding of climate and land use change impacts on the hydrologic processes of an agricultural watershed. The Soil and Water Assessment Tool (SWAT) model (Arnold et al. 1998) was used to analyze future hydrologic conditions including water yield, surface runoff, and ET. The subobjectives of this study were to: (1) assess climate change influences on the watershed hydrology, with and without a change in land use, (2) evaluate the impact of climate change on agriculture production in this watershed, and (3) determine if land use change can mitigate climate change impacts on hydrologic processes.

MATERIALS AND METHODS

Site Description

The SRB, located in northeast Missouri, is a direct tributary to the Mississippi River. Total drainage area is 6,417 km^2 at the outlet to Mark Twain Lake (Seaber et al. 1987; Lerch et al. 2008) (Figure 1), with elevation varying from 312 m to 146 m above mean sea level. The upper basin topography ranges from 0% to 7%, becoming steeper near the major tributaries, with backslopes up to 20% (Ghidey et al. 2007; Lerch et al. 2008). It consists of eleven 10-digit hydrologic unit watersheds designated by the U.S.

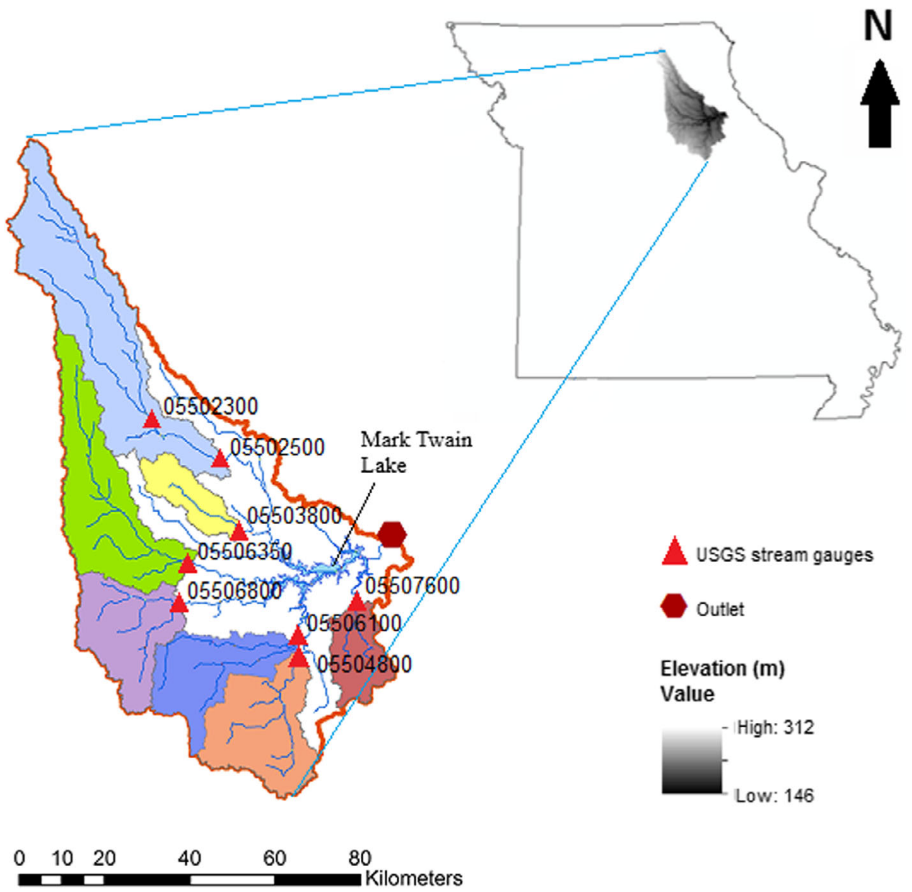

FIGURE 1. The Salt River Basin (SRB) and drainage areas of the monitored streams.

Geological Survey (USGS), monitored by eight USGS stream gauges (Figure 1). Average annual precipitation is between 889 and 940 mm.

Soils in the SRB are predominantly claypan, characterized by a subsoil horizon with an abrupt and large increase in clay content within a short vertical distance in the soil profile (Ghidey et al. 2007; Lerch et al. 2008). The argillic horizon generally has a clay content of at least 40% and is composed of smectitic (high shrink–swell) clay minerals (Jung et al. 2006). According to Lerch et al. (2008), the claypan soils in the basin include the Armstrong, Edina, Mexico, and Putnam series. Claypan soils cover 68% of the land area, with the clay depth varying from 0.1 to 0.5 m and clay content ranging from 350 to 600 g/kg. The main characteristic of claypan soil is low permeability causing a high probability and high volume of surface runoff (Udawatta et al. 2004; Jung et al. 2006). Most soils in the basin are classified into hydrologic groups C and D with slow to very slow infiltration rates and high runoff potential (Lerch et al. 2008). Blanco-Canqui et al. (2002) found that water movement through the claypan after 48 hours of saturation constitutes only 1.5% of total water flow (both lateral and vertical) and has a hydraulic conductivity of 0.002 mm/hr.

According to the USGS, the three major water uses in this region are hydroelectric power generation, domestic consumption, and agricultural usage (Maupin et al. 2014). Industrial water withdrawals are relatively small. The watershed depends heavily on surface water because deep, high yield groundwater aquifers are highly mineralized while shallower aquifers have insufficient quantities. Land use is approximately 70% agricultural, with half of these lands being cultivated for crops, predominately corn and soybeans. More than 95% of the agricultural land is rain-fed.

General Overview

Figure 2 represents the flow of data and models used to characterize future hydrology in the SRB using SWAT. Nineteen different GCM model outputs were used to simulate hydrologic watershed conditions. Weather inputs were used to force the SWAT model (Arnold et al. 1998), along with four land use scenarios. Simulated baseline (1994–2013) hydrologic variables including water yield, surface runoff, and ET were compared to those for the near future (2020–2039) and for mid-21st Century (2040–2059).

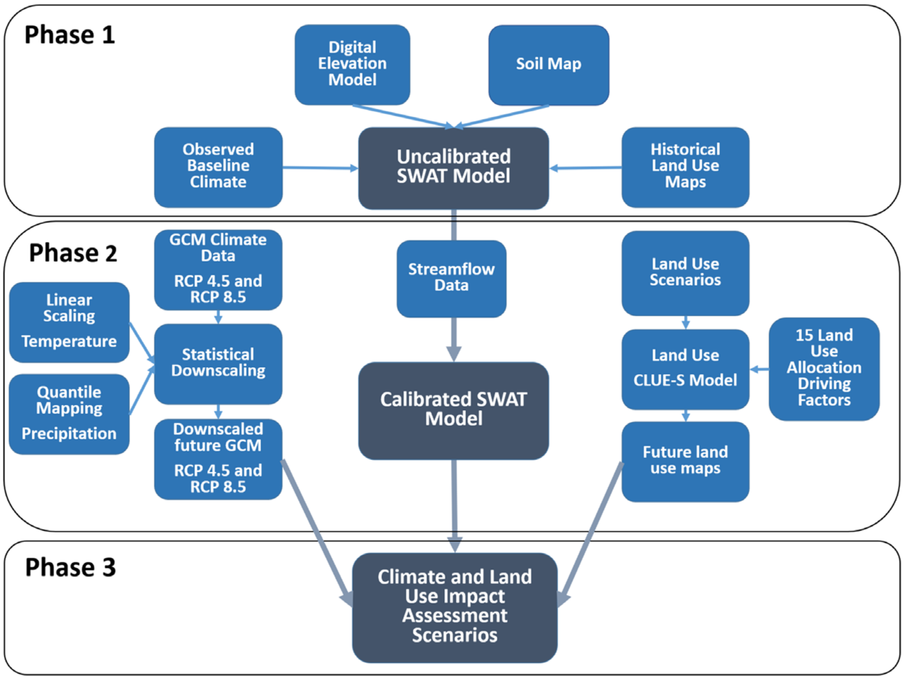

FIGURE 2. Flowchart for climate and land use change impact assessment using the Soil and Water Assessment Tool (SWAT) in the SRB, Missouri. GCM, general circulation model; RCP, representative concentration pathway.

Model Description

The SWAT model is a long-term, distributed parameter model. It is designed to simulate management impacts on water, sediment, and agricultural chemical yields in large, ungauged basins. It is capable of simulating a high level of spatial detail by dividing the watershed into a large number of subbasins that are linked through a stream network. Each subbasin is further divided into hydrologic response units (HRUs) each having unique land cover, slope, and soil characteristics. The HRU water storage is represented by four storage volumes: snow, soil profile (0–2 m), shallow aquifer (typically 2–20 m), and deep aquifer (>20 m). Weather, hydrology, soil temperature, plant growth, nutrients, pesticides, and land management are major SWAT model components. Due to the unique claypan soil properties of the SRB, a modified SWAT 2012 version 635 was used to better simulate percolation through and saturation above the claypan (Baffaut et al. 2015).

Setting Up the SWAT Model

Input Data. Data used in this study include: (1) 1 arc-second (30 m) digital elevation model from the National Elevation Dataset maintained by the USGS; (2) historical meteorological data obtained for the period of 1994–2013 from the Climate Data Online system of National Oceanic and Atmospheric Administration's National Climatic Data Center; (3) 1:12,000 scale soil map from Soil Survey Geographic (USDA-Natural Resources Conservation Service); (4) land cover maps for 2001 and 2011 with 30 × 30 m resolution from the National Land Cover Dataset (NLCD) developed by the Multi-Resolution Land Characteristics consortium. The data obtained from NLCD classified land uses/covers as cropland, pasture, forest, urban, wetland, and water. The cropland was classified into corn and soybean, based on the 2010 land use distribution data obtained from the National Agricultural Statistics Service. Agricultural management was set up with a heat unit index so that crop management dates can be adjusted as a function of temperature, which is important considering possible changes in temperature; and (5) streamflow data were taken from eight USGS streamflow stations within the SRB.

The ET was calculated in SWAT using the modified Penman–Monteith method in order to incorporate variability in radiation-use efficiency, plant growth, and transpiration induced by changes in atmospheric CO_2 concentration (Neitsch et al. 2011). In this study, ET output from the SWAT model was obtained to determine the irrigation requirement for corn and soybean in this watershed.

Calibration and Validation of SWAT. The model was calibrated and validated for daily streamflow using a manual calibration approach by adjusting one parameter at a time to fit the observed to simulated streamflow as well as the flow duration curve, with the calibration period from 2004 to 2008 and the validation period from 2009 to 2013 for all eight streamflow stations within the river basin (Figure 1). Streamflow-sensitive parameters were determined using SWAT-CUP (SUFI-2) (Abbaspour et al. 2007). The model was calibrated and validated to fit streamflow values using the respective sensitive parameters, with values adjusted within the range defined by Neitsch et al. (2002). Three widely used hydrologic model performance statistical measures were used to assess the performance of the SWAT model (Moriasi et al. 2007), the coefficient of determination (r^2), Nash–Sutcliffe efficiency (NSE), and percent bias (PBIAS). When the values for r^2 and NSE are >0.50 and PBIAS < ±25%, the model is considered satisfactory to simulate the daily streamflow of the watershed, which makes it applicable for impact analyses (Moriasi et al. 2007).

Future Climate and Land Use

Future Climate Data. In the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (Maurer and Hidalgo 2008; van Vuuren et al. 2011; Stocker et al. 2013), the climate projections are based on radiative forcing. Each representative concentration pathway (RCP) is based on the amount of radiative forcing levels anticipated by the end of the 21st Century (van Vuuren et al. 2011). Radiative forcing (W/m^2) is defined as the difference between the downward and upward radiative flux at the tropopause (top of atmosphere) caused by an increased concentration of greenhouse gas (Stocker et al. 2013). GCMs have been used to simulate the response of the global climate system to the increase in greenhouse gas concentration by representing the atmosphere, ocean, cryosphere, and land surface physical processes (Stocker et al. 2013). Future CO_2 concentrations were projected according to each RCP (Table 1) (Stocker et al. 2013).

Future climate data were obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) project (Taylor et al. 2012). The bias correction and constructed analogs (BCCA) data were downscaled from multiple GCM models under CMIP5 with the resolution of 12 × 12 km. BCCA data aim to provide consistent climate datasets for risk assessment and to strategize adaptation responses in watershed scale studies (Maurer et al. 2007; Maurer and Hidalgo 2008; Brekke et al. 2013). In line with the ensemble modeling approach, projections from 19 GCM model combinations were utilized. Details about these GCM models can be found in Table S1. The moderate emission change scenario (RCP 4.5) represents a modest change in temperature and precipitation, while the severe emission change scenario (RCP 8.5) indicates the largest shift in those climatic elements.

TABLE 1. CO_2 concentration used in SWAT simulations under different emission scenarios at midpoint for each period.

	CO_2 concentration (ppm)	
RCP	**2020–2039**	**2040–2059**
4.5	420	470
8.5	460	550

Precipitation and temperature data from CMIP5 were further downscaled using statistical downscaling techniques (Boé et al. 2007; Lenderink et al. 2007) and datasets from five weather stations from the study area during the period 1994–2013. This additional downscaling resulted in a better representation of weather in a specific area and is noted as being beneficial for impact assessment modeling (Wood et al. 2004; Feddersen and Andersen 2005; Chen et al. 2011; Gudmundsson et al. 2012). The bias in temperature was corrected using the delta change method (Lenderink et al. 2007), and the bias in precipitation datasets was corrected using modified quantile mapping (Boé et al. 2007). Both methods used a control period from 1994 to 2013 (20 years) to project future climate conditions from 2014 to 2059. The 20-year control period was used to help minimize the effect of missing weather station data. Details regarding the use of the delta change method to correct bias in temperature, and the modified quantile mapping to correct the bias in precipitation datasets can be found in Gautam et al. (2018).

Land Use Model. The Conversion of Land Use and its Effects at Small regional extent (CLUE-S) is a dynamic model used to predict land use changes that account for user-defined driving forces, including socioeconomic and biophysical factors (Verburg et al. 2004). The CLUE-S model was applied at 30-m resolution to project future land use scenarios. Land use conversions occur at locations with the highest "preference" for the specific type of land use. Preferences represent interactions between these factors and the decision-making processes resulting in a land use spatial configuration (Verburg et al. 2002). Spatial land use change was simulated based on 15 factors driving land use change: (1) elevation, (2) slope, (3) aspect, (4) distance to urban area, (5) distance to road, (6) distance to stream, (7) population density, (8) erosion factor, (9) hydrologic soil group, (10) depth to restrictive layer, (11) saturated hydraulic conductivity, (12) soil clay percentage, (13) soil sand percentage, (14) soil silt percentage, and (15) pH. Additional details about the model can be found in Verburg et al. (2002).

Probability maps for the SRB were developed for each land use based on logistic regression results. Forward stepwise logistic regression and relative operating characteristic (ROC) analyses based on 5 land use types and the 15 driving factors were conducted using the Statistical Package for the Social Sciences (IBM SPSS Statistics 23) (Nie et al. 1975). The ROC method compares predicted probabilities with observed values over the entire domain of predicted probabilities, which vary between a completely random model of 0.5 and a perfect fit model of 1.0 (Verburg et al. 2002; Park et al. 2011). In this study, the 2011 National Land Cover Database land use map (Homer et al. 2015) was used to calculate the ROC statistic.

The kappa statistic was used to compare model results with the 2011 NLCD reference map (Cohen 1960; Pontius 2000). The kappa statistic ranges between 0 (completely inaccurate) and 1 (completely accurate) (Batisani and Yarnal 2009). A kappa value > 0.75 indicates very good to excellent agreement between the observed and simulated map (Landis and Koch 1977).

Future Land Use Scenarios. Four land use change scenarios were constructed for the period from 2011 to 2060. The map was constructed for the middle year of 2030 for the near future period (2020–2039) and 2050 for the mid-21st Century period (2040–2059) scenarios. Each scenario is constructed within CLUE-S as follows:

1. Business as usual (BAU)

In this scenario, a Markov chain was used to predict land use change from 2011 to 2060, based on the transition matrix from 2001 to 2011. The land use change transition matrix was generated and analyzed by overlaying the land use maps of 2001 and 2011.

2. Reforestation (RF) scenario

This scenario assumes a high level of environmental and social consciousness with a globally coherent approach to sustainable development and a focus on resource-friendly lifestyles in accordance with a recent IPCC special report (Sleeter et al. 2012). Increases in urban area were relatively slow due to the environmental orientation of the scenario. Forest-land restoration occurred on pasture land as efforts were assumed to preserve biodiversity and water quality.

3. Best-case scenario (BCS)

Westhoek et al. (2011) estimated global livestock production accounted for around 12% of global greenhouse gas emissions. Stehfest et al. (2009) projected a global transition toward low-meat diets might reduce the costs associated with climate change mitigation by as much as 50% by 2050. For the BCS, low-meat diets were assumed to take effect, resulting in reduced demand for crop and pasture land. This scenario assumes forest area doubled at the expense of pasture land and crop land. The difference between BCS and RF scenarios is more land is converted to forest in BCS.

4. Worst-case scenario (WCS)

This scenario assumes more land will be converted into crop and pasture land to maximize potential food production. Forest area with slopes <15% were made available for conversion into crop and pasture land in CLUE-S since greater slopes would not be recommended for heavy machinery. This scenario also assumes rapid urbanization, with urban land use doubling in size. The BCS and WCS land use scenarios were conducted to evaluate the impact of larger changes in land use in this watershed compared with BAU and RF scenarios. Because it is unlikely these levels of land use change would be implemented in the near future, the BCS and WCS were simulated only for the mid-century scenario.

Analyzing Output of Hydrologic Modeling with Climate Change and Land Use Scenarios

Annual and seasonal differences were analyzed by comparing future conditions with baseline conditions. The Wilcoxon rank-sum test was used to identify statistically significant differences ($\alpha = 0.05$) between the baseline and future scenarios for the various hydrologic process components for SRB. The distribution-free Wilcoxon rank-sum test was chosen since the test variables may not be normally distributed. When compared with other tests such as Student's *t*-test, the Wilcoxon rank-sum test is considered more appropriate since the *t*-test lacks power when applied to non-normal data (Kendall and Stuart 1979; Hirsch et al. 1993). This test has been widely applied to study changes in hydrologic processes (Konrad and Derek 2005; van Vliet and Zwolsman 2008; Lupon et al. 2016; Sunde et al. 2017). The names for the combination scenarios between climate and land use are summarized in Table 2. For example, BAU 4.5 is the name for the combination of BAU land use and RCP 4.5 climate projection.

TABLE 2. Scenario names for the combination of climate and land use change.

Name of combined scenario groups		
Land use scenarios	Climate scenarios	
	RCP 4.5	RCP 8.5
No land use change	NLUC 4.5	NLUC 8.5
RF	RF 4.5	RF 8.5
BAU	BAU 4.5	BAU 8.5
Best-case	BCS 4.5	BCS 8.5
Worst-case	WCS 4.5	WCS 8.5

Notes: BAU, business as usual; RF, reforestation; BCS, best-case scenario; WCS, worst-case scenario.

RESULTS AND DISCUSSION

Calibration and Validation of the SWAT Model (Phase 1)

The model parameters controlling soil–water relationships, surface runoff, groundwater, and snowmelt were considered during calibration. Calibration parameters are listed in Table 3 and the performance values are listed in Table 4. Model performance was assessed by comparing observed and simulated daily flows during calibration and validation periods.

The calibration and validation results of the r^2 and NSE values were within 0.52–0.86 and 0.50–0.86, respectively, across all eight gauge stations. The absolute values of PBIAS were between 1.67 and 24.99, indicating satisfactory simulation (Moriasi et al. 2007). These results indicated the calibrated SWAT model provided a good basis for analyzing various scenarios for this watershed.

Downscaled GCM Result

Results indicated CMIP5 raw data were overestimated compared to historical data in the lower 40th percentile (i.e., precipitation events <5 mm depth) and underestimated above the 70th percentile (i.e., precipitation events >15 mm). The greatest precipitation event record in the observation period was 148 mm, but the greatest CMIP5 precipitation event was only 110 mm. Temperatures, particularly in summer months, were overestimated in CMIP5 compared to historical observations.

These results confirmed previous reports of overprediction of annual mean temperatures for CMIP5 GCMs (Kim et al. 2012; Miao et al. 2014). Quantile mapping was used to match the distribution function of simulated precipitation data to that of historical data, eliminating bias in the mean of daily precipitation. The delta change method resulted in improved raw GCM temperatures.

TABLE 3. Calibrated parameters in SWAT model for study watershed.

Number	Parameter	Description	Default value	Adjusted value
1	CN2.mgt[1]	Curve number	—	−0.035
2	ESCO.hru	Soil evaporation compensation factor	0.95	0.939
3	CH_N1.sub	Manning's "*n*" value for the tributary channels	0.014	0.06
4	SOL_AWC().sol[1]	Available water capacity of the soil layer	—	0.0355
5	EPCO.hru	Plant evaporation compensation factor	1	0.545
6	MSK_CO1.bsn	Calibration coefficient used to control impact of the storage time constant for normal flow	0.75	1.40
7	SMFMN.bsn	Minimum snowmelt factor for December 21 (mm H_2O/°C/day)	4.5	0.915
8	CH_N2.rte	Manning's "*n*" value for the main channel	0.014	0.0386
9	SFTMP.bsn	Snowfall temperature (°C)	1	−0.75
10	SMFMX.bsn	Maximum snowmelt factor for June 21 (mm H_2O/°C/day)	4.5	2.215
11	EVRCH.bsn	Reach evaporation adjustment factor	1	0.8
12	REVAPMN.gw	Threshold depth of water in the shallow aquifer for re-evaporation to occur (mm)	750	300
13	GW_REVAP.gw	Groundwater re-evaporation coefficient	0.02	0.0712
14	GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	1000	675
15	RCHRG_DP.gw	Deep aquifer percolation fraction	0.05	0.11
16	GW_DELAY.gw	Groundwater delay (days)	31	85
17	MSK_X.bsn	Weighting factor controlling relative importance of inflow rate and outflow rate in determining water storage in reach segment	0.2	0.229
18	ALPHA_BF.gw	Baseflow recession constant	0.048	0.605

[1]Relative change.

TABLE 4. Performance values for discharge simulation during calibration and validation periods.

USGS Gauge station	r^2		NSE		PBIAS	
	Calibration	Validation	Calibration	Validation	Calibration	Validation
5502300	0.52	0.59	0.50	0.58	−12.91	−7.24
5502500	0.59	0.61	0.59	0.61	−7.41	−0.56
5503800	0.80	0.64	0.76	0.60	−19.73	−17.31
5506350	0.70	0.57	0.70	0.57	−9.08	2.50
5506800	0.70	0.61	0.70	0.61	−1.66	−6.32
5507600	0.86	0.72	0.86	0.68	15.47	24.94
5506100	0.79	0.58	0.78	0.54	−0.53	−6.42
5504800	0.83	0.66	0.77	0.51	−24.99	−19.34

Notes: USGS, United States Geological Survey; r^2, coefficient of determination; NSE, Nash–Sutcliffe efficiency; PBIAS, percent bias.

The predicted changes in average annual precipitation and temperature in near future (2020–2039) and mid-century (2040–2059) scenarios compared with the baseline (1994–2013) are shown in Figure 3. The ensemble results for RCP 8.5 indicated an average annual temperature increase of 1.2°C and 2.3°C in near future and mid-21st Century, respectively. The increase was slightly lower under RCP 4.5 (1.0°C and 1.8°C, respectively). Annual precipitation increased 4% (42 mm) and 7% (75 mm) under RCP 8.5 for near future and mid-21st Century, respectively. Annual precipitation increased 6% (60 mm) for both periods under RCP 4.5.

Seasonal precipitation in the near future and mid-21st Century for both RCP 4.5 and RCP 8.5 scenarios are shown in Figure 4. Simulations indicated increased precipitation in spring, fall, and winter for both near future and mid-century projections, under all scenarios. Summer precipitation was projected to increase by 3% under RCP 4.5 but to remain the same under RCP 8.5 in the near future. However, both RCP scenarios indicated a 2% decrease in

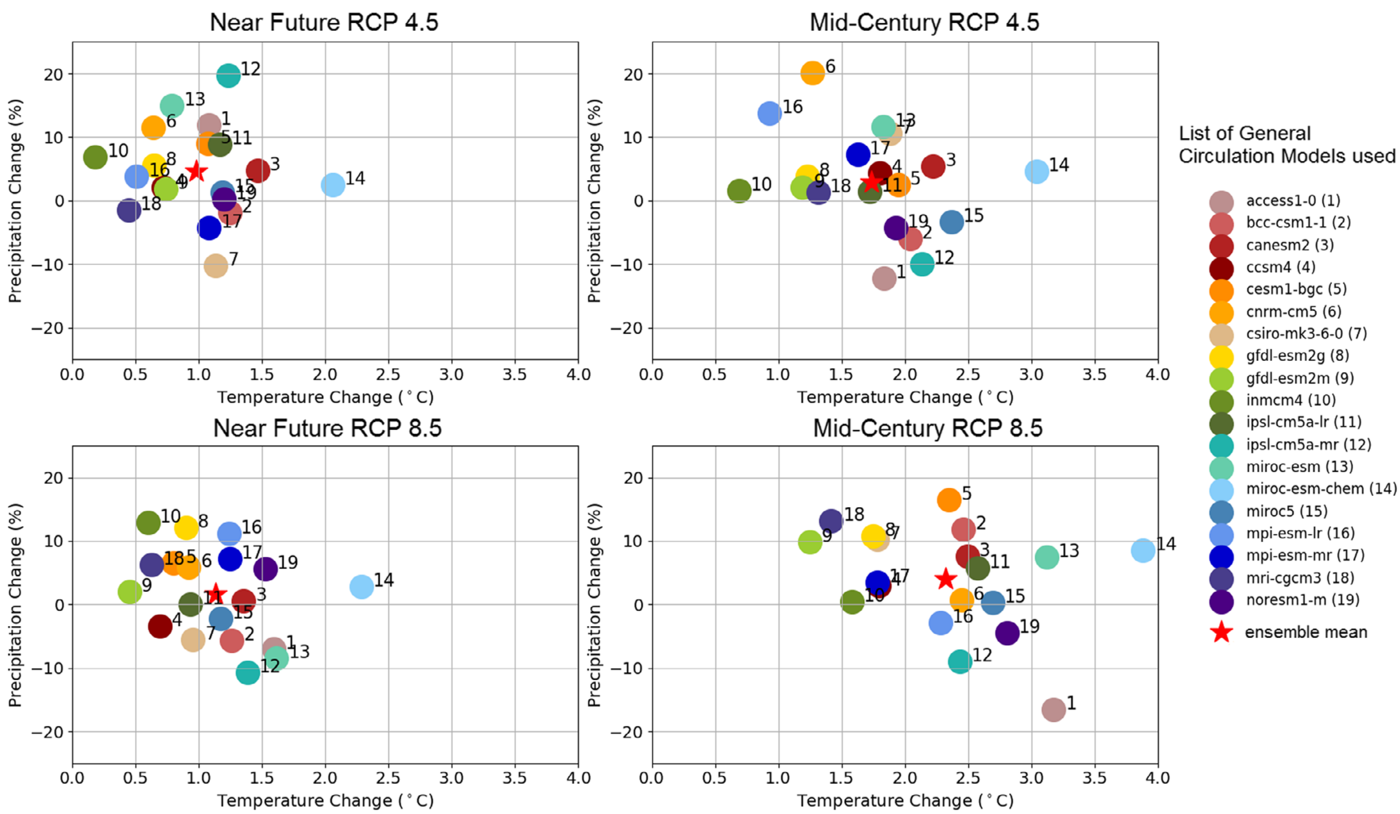

FIGURE 3. Change in average annual precipitation and temperature for near future (2020–2039) and mid-century (2040–2059) relative to the baseline (1994–2013) for RCP 4.5 and 8.5.

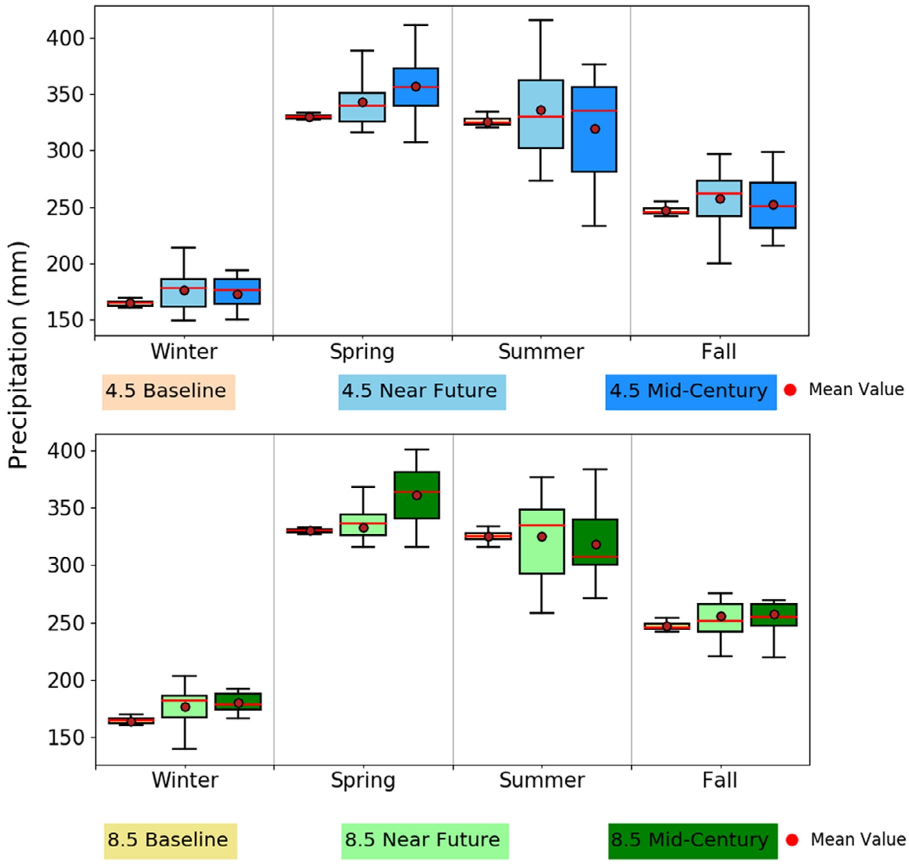

FIGURE 4. Box plot of seasonal precipitation results based on ensemble model runs based on RCP 4.5 and 8.5 for baseline (1994–2013), near future (2020–2039), and mid-century (2040–2059).

summer precipitation in the mid-21st Century. Previous studies in the Midwest region had simulated an increase in spring precipitation and a decrease in summer precipitation under RCP 4.5 and RCP 8.5 (Gautam et al. 2018). Neupane and Kumar (2015) also found precipitation during the spring months will increase, but will decrease in the summer by the end of the 21st Century in the Big Sioux River watershed, which is located in the North Central region and drains into the Missouri River.

Future Land Use Projection Data (Phase 2)

Using CLUE-S, future land use was mapped for the RF, BAU, BCS, and WCS scenarios (Figure 5). Under the RF scenario, the focus was on sustainable development and resource-friendly lifestyles where land resource is limited. Forest area was projected to expand by 28.3% (276 km^2) and pasture area to shrink by 19.4% (436 km^2) in the mid-century scenario.

For the BAU scenario, forest and wetland were projected to decrease by 20.1% (192 km^2) and 24.0% (38 km^2), respectively, in mid-century compared with the baseline period. In contrast, urban and agricultural lands were forecasted to rise by 69.2% (231 km^2) and 4.5% (115 km^2), respectively.

The BCS centered on RF efforts. From baseline to mid-century, forest area was predicted to double, from 975 to 2,188 km^2, at the expense of crop and pasture area. The opposite trend was predicted for the WCS as it required more crop and pasture land in order to meet the increased food demand of a growing population. Crop and pasture land were projected to increase by 21.6% (552 km^2) and 8% (180 km^2), respectively. Most of the forest land would be converted into agricultural food production, resulting in a reduction of 94% (917 km^2). Details about land use changes for each scenario can be found in Table S2.

Impact of Climate and Land Use Changes on Watershed Hydrology (Phase 3)

Climate Change Effects Under No Land Use Change. Scenarios No land use change (NLUC) 4.5 and NLUC 8.5 were simulated to observe the impacts of climate change with no land use change. Table 5

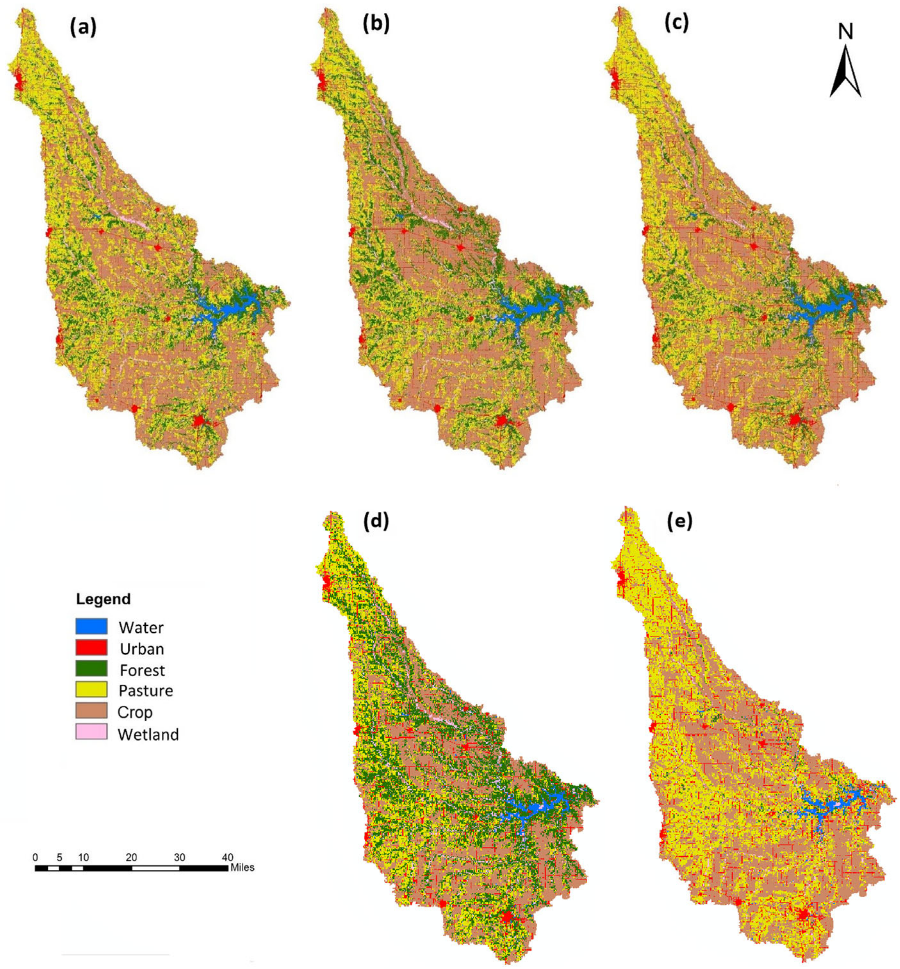

FIGURE 5. The SRB land use: (a) 2011 National Land Cover Dataset, (b) 2040–2059 RF scenario, (c) 2040–2059 BAU scenario, (d) 2040–2059 BCS, and (e) 2040–2059 WCS.

shows projected ET, runoff, baseflow, and water yield among RCP model groups in near future and mid-21st Century scenarios. Statistically significant differences ($\alpha = 0.05$) between the baseline and future scenarios for the hydrologic processes were identified using the Wilcoxon rank-sum test (Table 6).

Under both scenarios, annual ET followed an upward trend during the overall modeling period. Compared with the baseline, ET in the mid-21st Century rose by 4% (29 mm) under NLUC 4.5 and 7% (42 mm) under NLUC 8.5. These changes were due to rising temperature and precipitation. Seasonally, ET changes were statistically significant ($\alpha = 0.05$) in spring and winter, with spring experiencing the largest increase in both scenarios (Figures 6 and 7). In mid-century, precipitation would decrease during the summer, while higher temperature would lead to an increase in ET. The impacts of higher temperature and lower precipitation offset each other, leading to an insignificant change in actual summer ET.

Higher potential evapotranspiration due to increased temperature combined with lower precipitation in the summer could quickly lead to a reduction in soil moisture, which in turn could have adverse effects on plant life and groundwater supplies by restricting capillary processes (Garssen et al. 2014; Whan et al. 2015). These unfavorable conditions would mean less available water for crop production and higher crop water demand (Garssen et al. 2014). Crop water requirement was calculated based on crop ET from SWAT output, and effective precipitation was calculated based on projected precipitation. Even though the change in summer ET was minimal, a decrease in summer rainfall would reduce effective precipitation, which would increase irrigation requirement for crops in this region. On average, there would be an additional 25 and 38 mm of irrigation water needed for crops to maintain the current level of crop yield in the mid-century NLUC 4.5 and NLUC 8.5 during the growing season (April–September), respectively. The additional water equaled 9% of

TABLE 5. Seasonal ET, surface runoff, baseflow, and water yield results based on ensemble model runs that are categorized under RCP 4.5 and 8.5 for baseline (1994–2013), near future (2020–2039), and mid-century (2040–2059) under the NLUC scenario.

Scenario	Hydrologic processes	Winter	Spring	Summer	Fall	Annual
Baseline 4.5	ET (mm)	37	189	281	128	635
	Surface runoff (mm)	42	112	83	59	296
	Baseflow (mm)	17	25	24	18	84
	Water yield (mm)	64	145	113	82	403
NLUC 4.5 near future	ET (mm)	41	200	283	128	653
	Surface runoff (mm)	48	116	91	69	324
	Baseflow (mm)	17	25	21	17	81
	Water yield (mm)	70	149	117	91	429
NLUC 4.5 mid-century	ET (mm)	45	206	280	130	661
	Surface runoff (mm)	46	121	83	64	313
	Baseflow (mm)	16	23	21	16	75
	Water yield (mm)	67	152	109	84	411
Baseline 8.5	ET (mm)	37	189	280	128	634
	Surface runoff (mm)	42	111	84	58	296
	Baseflow (mm)	17	25	24	18	84
	Water yield (mm)	64	144	114	81	403
NLUC 8.5 near future	ET (mm)	43	199	282	129	654
	Surface runoff (mm)	49	108	83	64	304
	Baseflow (mm)	17	24	20	16	77
	Water yield (mm)	70	140	109	85	404
NLUC 8.5 mid-century	ET (mm)	48	212	281	135	675
	Surface runoff (mm)	50	119	81	67	317
	Baseflow (mm)	15	22	20	14	71
	Water yield (mm)	70	149	106	86	411

TABLE 6. Wilcoxon rank-sum test results for modeled seasonal estimates of hydrologic processes for SRB when near future and mid-century NLUC scenarios compared with baseline NLUC scenarios, respectively (bold denotes significance at $\alpha \leq 0.05$).

		NLUC 4.5				NLUC 8.5			
Time period	Component	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Near future	ET	**<0.001**	**<0.001**	0.242	0.374	**<0.001**	**<0.001**	0.081	0.183
	Surface runoff	**0.031**	0.419	0.300	**0.004**	**0.01**	0.300	0.488	**0.045**
	Baseflow	0.207	0.285	**0.003**	0.27	0.454	0.385	**0.002**	**0.031**
	Water yield	**0.036**	0.477	0.430	**0.007**	**0.013**	0.251	0.215	0.207
Mid-century	ET	**<0.001**	**<0.001**	0.483	0.094	**<0.001**	**<0.001**	0.215	**0.002**
	Surface runoff	0.061	**0.037**	0.500	0.147	**0.002**	**0.027**	0.270	**0.007**
	Baseflow	**0.048**	**0.045**	**0.005**	**0.003**	**0.002**	**0.006**	**<0.001**	**<0.001**
	Water yield	0.134	0.105	0.320	0.341	**0.031**	0.094	0.072	0.260

total irrigation water under NLUC 4.5 and 11% under NLUC 8.5.

During soybean growth processes, the pod setting stage must be able to achieve a full seed-filling; this is very critical to yield, and soybeans in this stage are more susceptible to water stress compared to other stages. Under adverse environmental conditions, seed-filling will be negatively impacted, and in turn, yields can be severely lowered (Doorenbos and Kassam 1979). Corn is very sensitive to heat stress and drought during the ear formation and milk stages, which can lead to decreases in dry matter weight and grain yield (Cakir 2004). Since most of this region is rain-fed, reduction in crop yield is anticipated. Even in areas with irrigation, finding additional water can be a challenge due to limited suitable groundwater resources for agricultural purposes in this region (Miller and Vandike 1997).

Ensemble mean annual surface runoff was projected to increase compared to the baseline period in all scenarios (Table 6). Seasonal increases in surface wetness and runoff during spring and fall could restrict the operation of heavy field equipment used for planting and harvesting (Torbert et al. 2001). Both NLUC 4.5 and NLUC 8.5 annual results showed an increase in the surface runoff in near future and in mid-century scenarios compared to the baseline. Seasonal analysis showed spring and fall had statistically significant changes in runoff in both mid-century NLUC 4.5 and NLUC 8.5 at a significance level

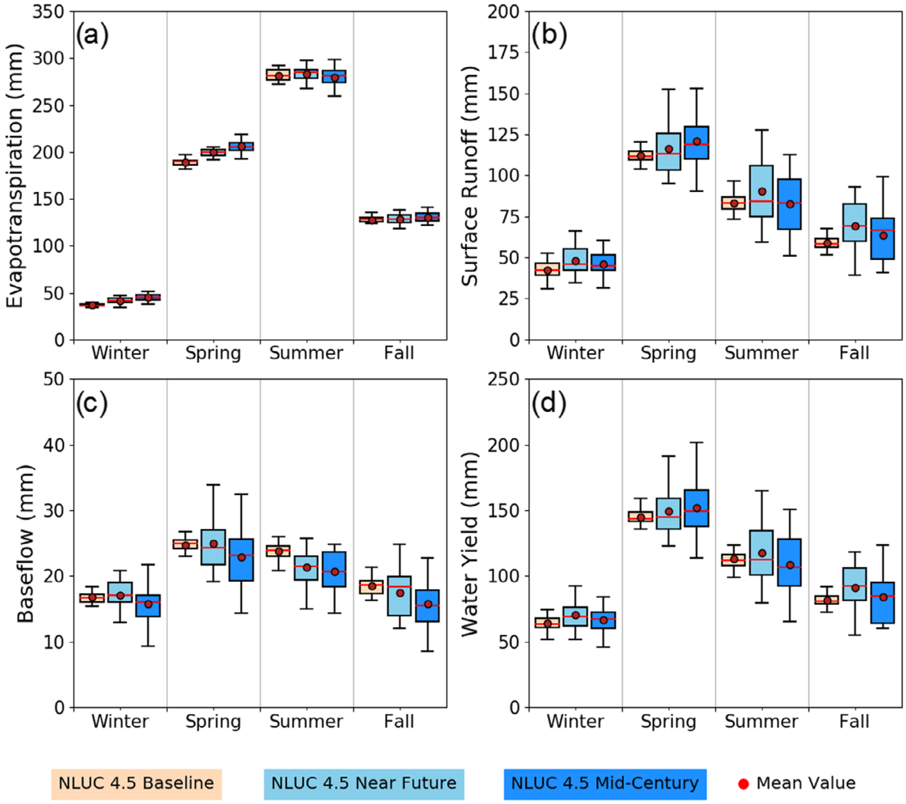

FIGURE 6. Box plot of seasonal (a) evapotranspiration; (b) surface runoff; (c) baseflow; and (d) water yield results based on ensemble model runs that represent RCP 4.5 for near future (2020–2039) and mid-century (2040–2059) given no change in land use (NLUC).

of 0.05 (Table 7) and this significant increase in surface runoff was due to increased heavy precipitation events and the claypan layer in the watershed. The very low saturated hydraulic conductivity of claypan soils contributes to this higher runoff response (Baffaut et al. 2015). The greatest incidence of flooding in this watershed occurs in the spring. Consequently, an increase in spring precipitation, combined with the characteristics of the claypan soil, could increase the likelihood of spring flooding.

Soil moisture content was evaluated using SWAT with analysis focused on the top-soil layer since soil compaction is a major concern due to the claypan soils in this region (Jung et al. 2010). The field operations of heavy equipment in wet soil conditions could lead to compacted soil with reduced rates of water infiltration and drainage, and an increased risk of root diseases. In general, the very low saturated claypan hydraulic conductivity limits downward drainage during the wet periods of winter and spring (Baffaut et al. 2015). For NLUC 4.5 near future scenarios, the number of days that soil moisture is greater than field capacity increased 7% in spring and 14% in fall when compared with the baseline period. These dropped to 2% and 4%, respectively, in mid-21st Century. As temperature increases, the plant growth cycle would be shifted to earlier in the year. The earlier emergence of biomass in the spring would result in a corresponding reduction of spring soil moisture content in mid-century compared with near future. In the fall, precipitation in mid-century was lower than near future while temperature was higher, which would lower the number of days that soil moisture is greater than field capacity. A similar trend was seen in NLUC 8.5. All these combined factors would put additional stress on the crops (Touma and Vauclin 1986; Unger and Kaspar 1994).

Annual analysis indicated ensemble mean baseflow would decrease in the future for both NLUC scenarios. For NLUC 4.5, baseflow would slightly decrease in the near future and undergo a greater decrease from 84 to 75 mm in the mid-century. A similar trend could be seen under NLUC 8.5 in the mid-century. Greater temperature is associated with greater ET, and lower future baseflow (Price 2011). Seasonally, all seasons saw a decrease in baseflow except for winter NLUC 4.5 in the near future. NLUC 8.5 had the most significant baseflow decrease of all seasons in mid-century.

Total water yield would slightly increase under both RCP 4.5 and RCP 8.5; thus, total water yield would go up in spring and down in summer during

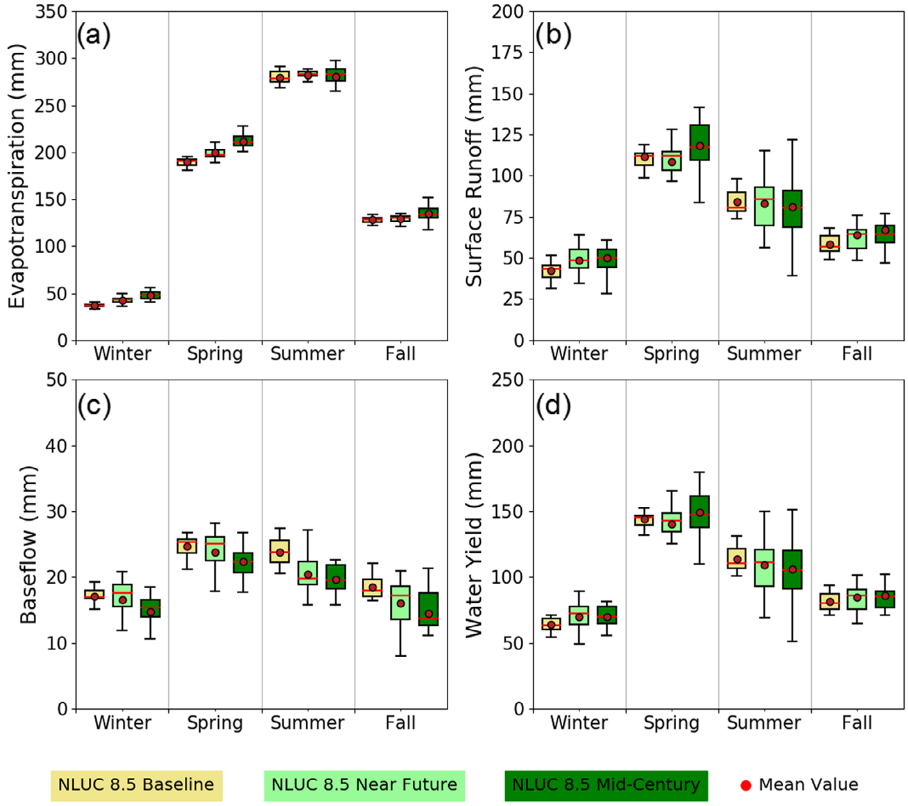

FIGURE 7. Box plot of seasonal (a) evapotranspiration; (b) surface runoff; (c) baseflow; and (d) water yield results based on ensemble model runs that represent RCP 8.5 for near future (2020–2039) and mid-century (2040–2059) given NLUC.

TABLE 7. Wilcoxon rank-sum test results for modeled seasonal estimates of hydrologic processes for the SRB for mid-century BCS and WCS scenarios compared with baseline period respectively (bold denotes significance at $\alpha \leq 0.05$).

		4.5				8.5			
Time period	**Component**	**Winter**	**Spring**	**Summer**	**Fall**	**Winter**	**Spring**	**Summer**	**Fall**
BCS	ET	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	Surface runoff	0.161	0.109	0.325	0.384	**0.032**	0.114	0.225	0.146
	Baseflow	**<0.001**	**0.004**	0.072	0.097	**0.009**	**0.018**	0.444	0.203
	Water yield	**0.025**	**0.040**	0.477	0.279	**0.014**	**0.054**	0.266	0.236
WCS	ET	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	Surface runoff	**0.002**	**0.014**	0.453	**0.050**	**<0.001**	**0.018**	0.409	**0.005**
	Baseflow	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	Water yield	0.283	0.348	**0.011**	0.330	**0.135**	0.403	**0.005**	0.408

the mid-century period in both scenarios (Figures 6 and 7). Under both RCP 4.5 and 8.5, greater projected precipitation in spring led to increased seasonal water yield, and may cause an increased risk of extreme events such as flood and drought in the watershed. Similar trends were found in other areas in the region, such as Hinkson Creek, Missouri (Sunde et al. 2017) where elevated future spring and fall total water yield under RCP 8.5 scenario in mid-century was simulated. Gautam et al. (2018) also found future spring and mean annual water yield will increase in the Goodwater Creek, Missouri due to projected changes in climate conditions.

Precipitation and total water yield were likely to decrease in the summer. Combined with higher temperatures, this would lead to an increased risk of drought conditions during critical crop growth periods, ultimately affecting yields. For example, in the initial stages, the 2012 drought was viewed favorably by row-crop producers across the Plains and Midwest, as field conditions allowed for earlier planting (Rippey 2015). However, the heat and lack of

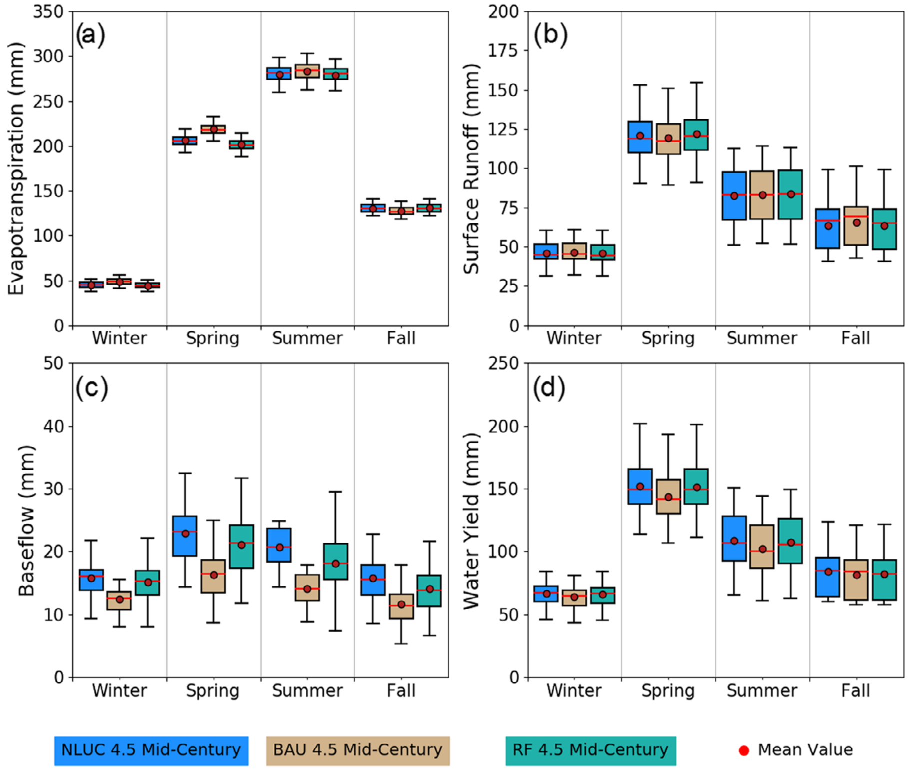

FIGURE 8. Box plot of seasonal (a) evapotranspiration; (b) surface runoff; (c) baseflow; and (d) water yield results based on ensemble model runs that are categorized under RCP 4.5 for mid-century (2040–2059) given NLUC, BAU, and RF.

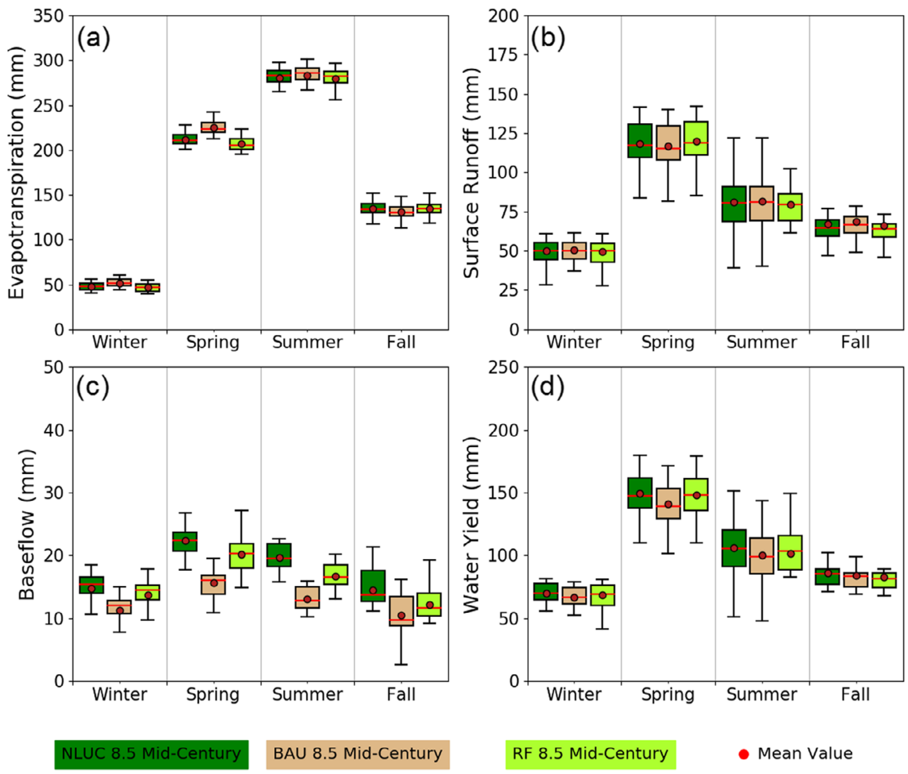

FIGURE 9. Box plot of seasonal (a) evapotranspiration; (b) surface runoff; (c) baseflow; and (d) water yield results based on ensemble model runs that are categorized under RCP 8.5 mid-century (2040–2059) given NLUC, BAU, and RF.

precipitation from June through August in 2012 caused significant stress during critical development phases of corn, reducing corn productivity by an average of 27% across the Midwest (Al-Kaisi et al. 2013; Rippey 2015). This indicates earlier planting due to favorable spring conditions (such as warmer temperature) may not be as beneficial as anticipated when the summer drought is taken into consideration.

Combined Effects of Climate and Land Use Change. Land use changes could either exacerbate or ameliorate changes to the hydrologic components as shown in BAU, RF, BCS, and WCS scenarios (Figures 8–10). Results of the annual hydrologic processes are included in Tables S3–S5.

Surface runoff and total water yield showed similar patterns under BAU and RF scenarios. For example, under both BAU 4.5 and BAU 8.5, surface runoff slightly increased (+3% for both BAU 4.5 and BAU 8.5) due to diminished forest areas. Conversely, under RF scenarios, increasing forest land while decreasing pasture land would alleviate the negative impacts of expanded agricultural land. However, most of the seasonal changes in total water yield and surface runoff were statistically insignificant when compared with NLUC scenarios (Tables S6 and S7).

Impacts of land use change on baseflow were more significant than on other hydrologic processes. In mid-century BAU 4.5 scenarios, baseflow was estimated to decrease by 36% compared with the baseline (from 84 mm to 54 mm) and 28% compared with the NLUC (from 75 mm to 54 mm). Under RF 4.5 scenarios, baseflow was also reduced but at a smaller amount (19% and 9% compared to the baseline and NLUC, respectively). Changes in seasonal baseflow

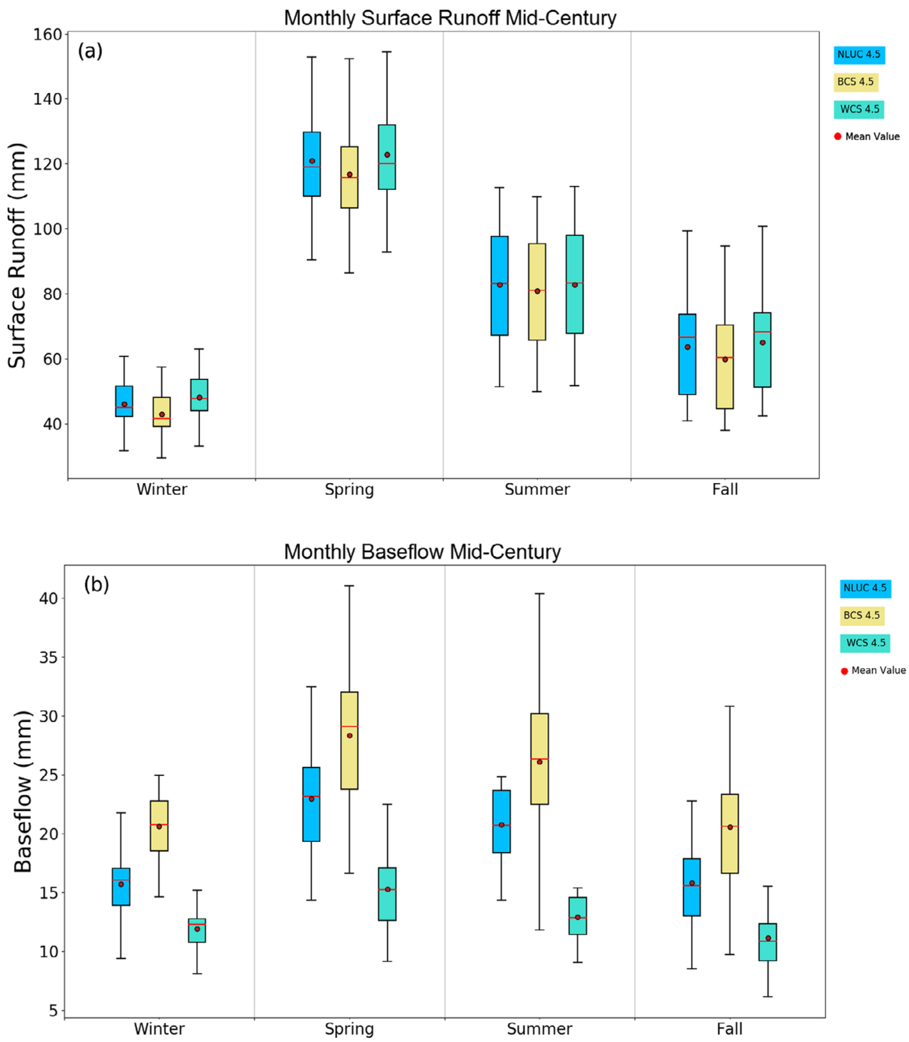

FIGURE 10. Box plot of seasonal (a) surface runoff and (b) baseflow from ensemble model runs based on RCP 4.5 for mid-century (2040–2059) given NLUC, BCS, and WCS.

for RF 4.5 were statistically significant for all seasons except winter (Table S7).

In BAU and RF scenarios, impacts of land use change on hydrologic processes were relatively minimal due to a limited change in land use. BCS and WCS were considered in order to evaluate the effect of more extended changes in land use in the SRB. The seasonal statistical analysis showed water yield under BCS would increase significantly in winter and spring. Water yield under WCS showed a notable decrease in the summer period; this decrease in water yield could lead to greater water scarcity at critical times of the growing season. Runoff and baseflow saw the most changes under these two land use scenarios (Figures 10 and S1).

Surface runoff under BCS 4.5 was 4% lower than that under NLUC 4.5 (Figure 10a). Under both NLUC scenarios, considerable increases occurred in surface runoff in the spring and summer, but BCS showed an increase in forest area would help reduce surface runoff, making it lower than the historical observation. The changes in surface runoff showed under future climate conditions, converting 1,250 km^2 of crop and pasture land to forest in this watershed would not only help mitigate the effect of climate change but also bring the quantity of surface runoff below the baseline level. This effect could be seen in the seasonal analysis (Table 7). Under the impact of climate change, the increase in surface runoff was statistically significant in spring under RCP 4.5 in mid-century. However, with the change of land use in BCS, surface runoff in mid-century from BCS 4.5 was not significantly different from the baseline period, meaning land use changes could help mitigate those climatic impacts. BCS 8.5 also simulated similar impacts of land use change. Conversely, runoff would increase by 2% under both WCS 4.5 and WCS 8.5. When compared with the baseline period, seasonally, surface runoff under WCS 4.5 and WCS 8.5 showed statistically significant changes in the spring, fall, and winter runoff results.

Baseflow in both BCS and WCS showed statistically significant changes in all seasons when compared with NLUC (Tables S8 and S9). This indicated change in land use could substantially alter the infiltration process in this watershed (Figure 10b). Brutsaert (2010) found increased baseflow in the Upper Mississippi and Ohio regions is not only the result of climate change but likely reflected changes in land use and land management. Land use change can impact the infiltration properties influencing partitioning of water between runoff and recharge (Bruijnzeel and Sampurno 1990). For example, higher infiltration rates are directly related to the increase in forest areas, leading to an increase in baseflow (Li et al. 2015). Ilstedt et al. (2007) found infiltration capacity can triple after afforestation in agricultural fields. Previous studies examining the impact of land use change on baseflow showed decreased baseflow when forest land is converted to non-forest land use (Elkaduwa and Sakthivadivel 1999; Bruijnzeel 2004), and increased baseflow due to RF efforts (Ma et al. 2009). The baseflow component is important to sustain discharge, mainly during low flow seasons when no significant amount of surface runoff exists (Price et al. 2011). Therefore, even though it contributes a smaller portion to the total water yield in this watershed, baseflow still played an important role and had influences on future water availability of the SRB.

Overall, under BAU and RF scenarios, changes in the hydrologic variations were primarily influenced by climate variability, and the role of land use changes was limited. Other studies found similar trends where land use changes had little impact on hydrologic processes compared with climate changes (Karlsson et al. 2016; Zhang, Nan, Xu, et al. 2016). However, a greater change in land use, under BCS and WCS, showed land use could have a substantial impact on the baseflow of a watershed. These results agree with Xu et al. (2013) who studied the relative importance of climate and land use changes on hydrologic processes in the U.S. Midwest from 1930 to 2010. They found climatic variability has a greater impact on streamflow compared to land use change, while land use change contributes more to changes in baseflow.

SUMMARY AND CONCLUSION

The main objective of this study was to evaluate the impacts of potential climate and land use changes on the hydrologic components of the SRB in northeast Missouri, a primarily claypan agricultural watershed. Statistical downscaling using CMIP5 climate data for RCP scenarios 4.5 and 8.5, and land use change predictions using the CLUE-S model, provided high-resolution input data for the SWAT model. By combining the ensemble results from 19 climate change models with various land use simulations, a wide range of possible outcomes of future hydrologic conditions in the SRB were studied.

Seasonally, reduced precipitation in summer months and increased ET in late spring raised the need for irrigation during the growing season (April–September). Specifically, with a decrease in precipitation in the summer months in mid-century, irrigation water requirements went up by 38 mm during the growing season, representing an increase of 11%. In addition, the possible shift of a planting date to earlier in the year due to warmer springs may benefit crop production, except in extreme years, such as the drought of 2012. Because the majority of agriculture in this region is currently rain-fed with limited groundwater resources, long-term water planning is needed should there be a surge in irrigation water use.

Soil moisture content would rise during the spring and fall months due to an increase in precipitation, which would be enhanced by the low saturated hydraulic conductivity of claypan soil. The number of days where soil moisture content was predicted to equal or exceed field capacity increased 14% in the near future and 4% in mid-century, indicating a reduction in available days of field operation due to increased field wetness.

Under the combined effects of climate and land use change, hydrologic processes of the SRB changed significantly, and each factor had different impacts on the hydrologic condition. Seasonal analysis indicated land use change could either help mitigate the impact of climate change or it could possibly amplify it. For example, under BCS 4.5 and BCS 8.5, changes in land use helped mitigate the impact of climate change on seasonal surface runoff. This result showed the important role of land use in lessening the impact of climate change in this watershed.

Hydrologic components of the regional scale watershed were well represented by hydrologic conditions simulated using high spatial resolution, along with downscaling of weather data provided by CMIP5 and multiple land use change scenarios. This approach is important in rain-fed agricultural watersheds since these regions are expected to suffer the most from climate variability. In addition, watersheds with unique claypan soil conditions like SRB amplify the negative impact of climate and land use change because crops must rely on the thin top-soil layer above a dense, compact, slowly permeable claypan for their water supply. Results from this study highlight the importance of proper land use management and availability of irrigation to mitigate impacts of climate change.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Details about GCM models, area of land use for different scenarios, additional hydrologic processes results, and statistical results.

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