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Impacts of Land Use and Climate Changes on Hydrological Processes in South Dakota Watersheds

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IMPACTS OF LAND USE AND CLIMATE CHANGES ON HYDROLOGICAL PROCESSES IN SOUTH DAKOTA WATERSHEDS

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This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science in Agricultural and Biosystems Engineering degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis doest not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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Disclaimer

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LIST OF ABBREVIATIONS

CGCM3.1	Canadian Centre for Climate Modeling and Analysis version 3.1
CI	Cyber-infrastructure
DEM	Digital Elevation Model
ET	Evapotranspiration
FORE-SCE	FOREcasting SCEnraios
GCMs	Global Circulation Models
GFDL-CM2.1	Geophysical Fluid Dynamics Laboratory version CM2.1
HadCM3	Hadley Centre for Climate Predictions and Research Coupled Model, UK
HRU	Hydrological Response Units
IPCC	Intergovernmental Panel on Climate Change
LULC	Land Use and Land Cover
NCDC	National Climatic Data Center
NED	National Elevation Dataset
NLCD	National Land Cover Dataset
NSE	Nash-Sutcliffe Efficiency
ParaSOL	Parameter Solution
SRES	Special Report on Emission Scenarios
STATSGO	State Soil Geographic Data

SUFI-2	Sequential Uncertainty Fitting-ver.2
SWAT	Soil and Water Assessment Tool
USDA	United States Department of Agriculture
USGS	United States Geological Survey

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ABSTRACT

IMPACTS OF LAND USE AND CLIMATE CHANGES ON HYDROLOGICAL PROCESSES IN SOUTH DAKOTA WATERSHEDS

MANASHI PAUL

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This study aims to evaluate the impacts of climate and land use change on the hydrology of South Dakota's watersheds using the Soil and Water Assessment Tool (SWAT). The study analyzed the hydrologic impacts of climate and land use changes in two ways. The first aspect consists of characterizing hydrological changes between two recent decades in three representative watersheds – Bad River watershed, Skunk Creek watershed and Upper Big Sioux River watershed. Two historical land use maps (NLCD 1992 and 2011) were used to represent land use change on these watersheds, and two historical climate datasets (1981-1990 and 2005-2014) were used to create SWAT models for each watershed. Results showed that due to historical land use and climate variations the annual water balance components mostly increased in the 2000s compared to 1980s. Between the 1980s and 2000s, seasonal variation in hydrology mostly increased during the wet season (i.e., May to October) in all three watersheds. Spatial analysis revealed that the hydrological components increased with a decrease in grassland in the watersheds, except in Skunk Creek watershed. The second aspect was to quantify the influence of future climate and land use changes on hydrological processes in the James River Watershed located in South and North Dakotas. A set of 42 scenarios of future projected land use and climate changes were developed under three emission scenarios (A1B, A2 and B1) to represent mid (2046-2065) and end (2080-2099) of the 21st century.

Corresponding land use maps (2055 and 2090) were derived from the FOREcasting SCEnarios (FORE-SCE) model to represent land use conditions for mid and end of the century. Projected climate data were used from three general circulation models (CGCM3.1, GFDL-CM2.1, and HADCM3) for the mid-century (2046-2065) and end of the century (2080-2099). The scenarios were designed in a way that (1) land use was changed while climate conditions remained constant, (2) land use remained constant under a changing climate, and (3) both land use and climate were changed simultaneously. Results showed that future climate change will likely have more influence on hydrology compared to future land use change. The combined effects of land use and climate changes would intensify changes in hydrological processes of the region in the near future.

CHAPTER 1: INTRODUCTION

1.1 Background

Land use and climate are determinant factors that influence the global energy and water cycle (Dale, 1997; El-Khoury et al., 2015; Mahmood et al., 2010; Mishra et al., 2010). Land use and climate influences on the water cycle are usually reflected in the long-term spatial and temporal variation of water balance components such as surface runoff, soil moisture, evapotranspiration, groundwater and streamflow (e.g., Deng et al., 2015; Fang et al., 2013; Li et al., 2009; Memarian et al., 2014). Recent studies show that intense land use changes affect local, regional, and global ecosystems and environmental processes (DeFries et al., 2004; Ellis and Pontius, 2007; Lambin and Meyfroidt, 2011; Sleeter et al., 2013; Turner et al., 2007). Over the past few decades, in the Midwestern United States, land use change intensified with high grain prices (Omega-Research, 1997; Reitsma, 2014), economic development (Rashford et al., 2011), and increasing demand for biofuel feedstocks following the Energy Independence and Security Act (EISA) of 2007 (Wu et al., 2012). In the Western Corn Belt (WCB), land use changes are mainly characterized by the conversion of rangeland, pastureland, and grassland to agricultural land uses. Claassen et al. (2011) found that almost 31,444 km^2 (7,770,000 acres) of rangeland were converted to cultivated crops between 1997 and 2007 in the northern Great Plains. From 2001 to 2009, a total of 0.24 million km^2 grassland were converted to cropland in the conterminous US (Singh, 2013). Meanwhile, climate change led to more frequent extreme events. Higher temperature induces higher amount and intensity of precipitation which affects hydrology (Huntington, 2006; Johnson et al., 2015; Melillo et al., 2014; Pervez and Henebry, 2015). Variation in precipitation was found influential in streamflow trends in various regions across the United States (Changnon and Kunkel, 1995; Chien et al., 2013; Hall et al., 2006; Jha et al., 2006; Lins and Slack, 2005; Novotny and Stefan, 2007; Small et al., 2006). Changes in precipitation pattern affected the magnitude and frequency of floods in the Upper Midwest between 1920 and 1990 (Changnon and Kunkel, 1995; Douglas et al., 2000; Groisman et al., 2001; Kunkel, 2003). Increased precipitation also led to increases in water yield, ET and surface runoff in the region (e.g., Ficklin et al., 2009; Jha et al., 2006; Lirong and Jianyun, 2012).

1.2 Problem Statement

In the past 150 years, the Great Plains underwent extensive land use and land cover changes (Sohl et al., 2012). The land conversion occurred mainly from grassland and wetlands to agricultural lands (Sohl et al., 2012). According to Wright and Wimberly (2013), 1 to 5% of grassland is converted to corn and soybean annually across the WCB region. Among the WCB states, from 2006 to 2011, the estimated net grassland loss was about 1,820 km^2 in South Dakota, which was higher compared to the neighboring states (Singh, 2013; Wright and Wimberly, 2013). Future scenario-based modeling revealed that natural land cover may be lost, while agricultural and urban areas may expand considerably (Sohl et al., 2012). Concurrently, since the early 20th century, the global average temperature increased by approximately 1.4°F (NOAA, 2010). According to the Intergovernmental Panel on Climate Change (IPCC)'s Special Report on Emission Scenarios (SRES), the air temperature will increase approximately 1 to 5°C by 2100 throughout the US (IPCC, 2013; Johnson et al., 2015).

In South Dakota, the temperature increased between 0.4 to 0.8 °F per decade and total annual precipitation increased between less than 0.6 to more than 1 inch over the last 70 years (DOI, 2015). Under these circumstances, water resources in South Dakota may be adversely affected. Although several regional studies have evaluated hydrologic responses to climate and land use change across the Midwest region (e.g. Wu et al., 2012; Wu et al., 2013; Schilling et al., 2008; Schilling et al., 2014), there is no study that exclusively focuses on South Dakota watersheds to account for local trends in land use change (i.e. loss of grassland to other uses), climate variability, and potential climate change scenarios. Therefore, a thorough understanding of hydrological processes under changing climate and land use in watersheds of various sizes is needed for developing sustainable water resources management in the state.

1.2 Objectives

The objectives of this research were to:

1. Characterize hydrological changes between two recent decades in three representative watersheds.
2. Evaluate the effects of projected land use change with existing climate conditions and projected climate change scenarios with existing land use conditions on hydrologic processes.
3. Assess the combined effects of potential land use and climate changes on hydrologic processes.

1.3 Significance of Thesis

This study provides insight into hydrologic responses to climate and land use changes in South Dakota's watersheds in recent the past and in years to come. Understanding how land use and climate changes affect hydrology in the state would help watershed managers, agricultural producers, policy makers, and the general public make informed assessments of the effects of land use and climate on hydrology. This is an important step toward development of strategies for sustainable water resources management.

1.4 Thesis Organization

This thesis is organized in four chapters. Chapter 1 provides the background, problem statement and objectives of the study. Chapter 2 provides a literature review related to the effects of land use and climate change on watershed hydrology. This chapter also provides information on hydrologic modeling and future emissions scenarios for climate and land use changes. Chapter 3 presents the methodology, results, and outcomes of objective 1 of the study, and it is titled “Spatial and Temporal Evaluation of Hydrological Response to Climate Variability and Land Use Change in Three South Dakota Watersheds”. Chapter 4 contains the methodology, results, and outcomes of objectives 2 and 3, and it is titled “Impacts of Land Use and Climate Change on Hydrological Processes in James River Watershed”.

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CHAPTER 2: LITERATURE REVIEW

2.1 Land Use Change Impacts on Hydrology

Land use and land cover (LULC) changes influence hydrological processes (Wu et al., 2013; Zhang et al., 2014) by altering interception rates, soil water, evapotranspiration (ET), infiltration, and groundwater, leading to changes in surface runoff, streamflow and flood frequency (e.g., Baker and Miller, 2013; Deng et al., 2015; Fang et al., 2013; Li et al., 2009; Memarian et al., 2014).

2.1.1 ET and Soil Moisture

LULC plays an important role in influencing the water cycle through changes in ET, soil water holding capacity, and the vegetation's ability to intercept precipitation (Chen and Li, 2004; Li et al., 2009; Mao and Cherkauer, 2009; Mishra et al., 2010; Zhang et al., 2014). ET is one of the most significant components of the hydrologic budget, which is a combination of two sub-processes - evaporation and transpiration (Hanson, 1988). Evaporation is water loss from open water bodies, wetlands, bare soil, snow cover, etc., while transpiration is water loss from living plant surfaces (Hanson, 1988). Therefore, land-surface characteristics influence the process of ET. Studies revealed that changes in land use, land cover, crop rotation and crop types mainly influence ET in a watershed. Zhang and Schilling (2006) found that land conversion from perennial vegetation to seasonal row crops led to a reduction in ET between 1940s-2003 in the Upper Mississippi River. Baker and Miller (2013) reported that a decrease in forest area also caused a reduction in ET. Forest areas promote elevated ET because of low albedo, deep roots and water interception (Lull and Sopper, 1969). Similar results were shown in the midwestern US (Roy et al., 2009), Georgia (Rose and Peters, 2001) and China (Liu et al., 2008); where ET decreased in the study watersheds due to urban expansion. ET is also affected by crop density which controls rainfall interception, leaf area index, canopy resistance and plant-available water capacity (Zhang et al., 2001). As an example, dense vegetation cover (e.g., perennial grassland) has higher crop density, leaf area index, and permeable soils compared to agricultural land (e.g., row crops) (Kim et al., 2013a). Thus, land use conversion from native vegetation (grassland) to agricultural or developed land would result in a decrease in ET and soil water content (Wu et al., 2013). However, other research efforts reported that woodland and grassland conversion to agricultural land led to increases in ET (Deng et al., 2015; Fang et al., 2013). ET is a complex process with a combination of evaporation and transpiration. These two sub-processes can be non-linear in nature (Ghaffari et al., 2010; Pai and Saraswat, 2011). As an example, with land cover conversion from plant cover to impervious areas, transpiration can be decreased while evaporation can be increased (Pai and Saraswat, 2011).

2.1.2 Surface Runoff and Groundwater

LULC changes alter vegetation cover and surface roughness that affect the timing and magnitude of surface runoff and groundwater discharge, leading to changes in streamflow, and magnitude and frequency of floods (Jones and Post, 2004; Mao and Cherkauer, 2009; Niehoff et al., 2002; Pai and Saraswat, 2011; Schilling et al., 2014). Land use changes, such as urbanization and agricultural activities cause, greater surface runoff (Pai and Saraswat, 2011; Tong et al., 2009). Urban areas have large paved areas in the landscape that increase impervious surfaces. Therefore, little rainfall can soak into the soil profile, which produces greater surface runoff (Jacobson, 2011). Similar results were shown in the Cedar River basin, in which suface runoff was predicted to increase due to projected urban expansion (Wu et al., 2013). Intensive agricultural activities can reduce surface roughness (Baker and Miller, 2013) that contribute to lower interception (Ghaffari et al., 2010) and less pore space availability in the soil to store water (Busman and Sands, 2002), leading to greater runoff generation. Deforestation may also cause greater runoff. In East Africa, Baker and Miller (2013) reported that due to land conversion from forest to agricultural land increased surface runoff. Ghaffari et al. (2010) showed that decreasing grassland and increasing agricultural land decreased groundwater recharge and baseflow in the semi-arid Zanjanrood basin in Iran. Nie et al. (2011) also reported that grassland replacement with woodland contributed to lower percolation rate and reduced baseflow in the upper San Pedro watershed in Arizona.

2.2.3 Streamflow and Flood

Increasing land use conversion (especially for urbanization, deforestation, grassland depletion) can potentially lead to an increase in streamflow and flood frequency (Brath et al., 2006; Guo et al., 2008; Mao and Cherkauer, 2009; Matheussen et al., 2000; Schilling et al., 2014; VanShaar et al., 2002; Zhang and Schilling, 2006). During storm events, greater surface runoff can exceed the flow carrying capacity of the stream within the watershed which may increase the risk of potential flooding. Mao and Cherkauer (2009) studied hydrologic response to land use changes in the Great Lakes states (Minnesota, Wisconsin, and Michigan) and showed that greater risk of flooding was caused by deforestation. A similar study in China found that increasing forest land can reduce flood potential while depletion of forests may increase flood potential the in wet season and drought severity in the dry season (Guo et al., 2008). In addition, grassland expansion can reduce flood potential due to a decrease in streamflow. Grassland has higher ET compared to agricultural land, and may promote higher infiltration, leading to a reduction of flood potential in the watershed. Schilling et al. (2014) reported that cropland conversion to grassland reduced the occurrence and frequency of flooding in the Raccoon River watershed in Iowa.

2.2 Climate Change Impacts on Hydrology

Global climate change is one major factor that directly affects hydrological processes (Khoi and Suetsugi, 2014; Kim et al., 2013b; Zhang et al., 2016), and global warming is identified as an important issue regarding climate change during the coming century (Chien et al., 2013; IPCC, 2007). Potential impacts of changes in climate (e.g., precipitation and temperature) may cause variations in hydrological processes including ET, surface runoff, timing and magnitude of streamflow, and flood events (Neupane and Kumar, 2015; Zhang et al., 2005; Zierl and Bugmann, 2005). Variation in precipitation was found influential in streamflow trends in various regions across the United States (Changnon and Kunkel, 1995; Hall et al., 2006; Novotny and Stefan, 2007; Small et al., 2006). Temperature variation and wind speed affect evaporation and transpiration sub-processes, which influence surface and subsurface water budgets (Hanson, 1988; Hu et al., 2005; Schmid et al., 2000).

2.2.1 ET

Evaporation is the sub-process of ET which varies by season of the year, time of the day and availability of soil water. Evaporation rate is influenced by solar radiation, air temperature, humidity, and wind speed (Hanson, 1988). Solar radiation and air temperature provide the energy to evaporate the water from open water bodies such as a lake, reservoir and stream, while the air humidity and wind speed controls evaporation processes. Another sub-process the transpiration depends on the water availability in the soils and plants. The plant root takes water and transfers it into the atmosphere. As a consequence, temperature and precipitation increases result in increased ET (Ficklin et al., 2013; LaFontaine et al., 2015; Zhang et al., 2016). For example, Guo et al. (2008) reported that during dry seasons, lower temperature and higher humidity resulted in decreased ET in the Poyang Lake Basin in China. Ficklin et al. (2013) noticed that in California, projected increased temperature and decreased precipitation may result in an increase in ET. The researchers noticed that seasonal trends in ET also follow seasonal trends in solar radiation and air temperature. In China, due to potential higher temperature and increased precipitation, increased trends in ET were observed in wet season (June to September) (Zhang et al., 2016). During summer, increased temperature caused a temporal shift in plant growth patterns and decreased ET in the San Joaquin watershed in California (Ficklin et al., 2009). Studies also revealed that lower annual precipitation produced lower annual ET (Ficklin et al., 2009; Kim et al., 2013a; Neupane and Kumar, 2015).

2.2.2 Surface Runoff

As previously stated, precipitation is the source of water in the watershed and the available water is calculated by precipitation minus water loss by ET. Available water contributes to surface runoff and streamflow (Oki and Kanae, 2006). Therefore, increased precipitation may lead to an increase in surface runoff, while a decrease in precipitation can result in the opposite effects (e.g., Ficklin et al., 2009; Jha et al., 2006; Lirong and Jianyun, 2012). Wang et al. (2014) showed that under future climate change scenarios (A1B, A2 and B1), the Wolf Bay watershed in coastal Alabama would experience increases in precipitation and temperature, leading to surface runoff increase. Previous studies also linked global warming to snowmelt processes, especially to shifts in surface runoff timing (e.g., Johnson and Stefan, 2006; Novotny and Stefan, 2007; Wu et al., 2012a). For example, in Minnesota's river (Red River, Mississippi River and Minnesota River) the spring surface runoff has occurred 0.3 days/year earlier during 1964-2000 and a direct correlation was found between surface runoff and air temperature changes (Novotny and Stefan, 2007).

2.2.3 Streamflow and Flood

Many studies have revealed that climate change is expected to accelerate the global hydrological cycles and affect streamflow (e.g., Driessen et al., 2010; Ficklin et al., 2013; Jha and Gassman, 2014; Novotny and Stefan, 2007; Oki and Kanae, 2006; Tu, 2009). These studies revealed that streamflow variability is closely related to climate changes. For example, Ficklin et al. (2013) noticed that for projected higher temperature and precipitation, annual streamflow may decrease in the Californian Mono Lake Basin. Wang et al. (2014) reported that increased trends in monthly streamflow were examined in the Wolf Bay watershed of coastal Alabama as a result of higher precipitation and higher temperature.

Studies showed that due to climate change, precipitation will increase on average, while globally ET may not increase as much as precipitation because elevated CO_2 concentration may induce stomata closure and reduce transpiration (Gedney et al., 2006; Oki and Kanae, 2006). At the global scale, streamflow will increase due to increased precipitation and reduced transpiration (Milly et al., 2005; Oki and Kanae, 2006). Ficklin et al. (2009) showed that in summer months increasing temperature and precipitation caused a temporal shift in plant growth patterns that decreased ET and irrigation water demand, leading to increase in streamflow in the highly agricultural San Joaquin watershed, California. Similar results were found for the Great Plains region, where the upward trend in precipitation led to a large increase in streamflow and a comparatively lower increase in ET (Garbrecht et al., 2004). Future climate change may also impact annual streamflow increase (Neupane and Kumar, 2015; Whitfield and Cannon, 2000) and earlier spring snowmelt occurrence (Regonda et al., 2005). A study in Southern Alberta of Canada revealed that higher temperature and precipitation resulted in an increase in winter and spring streamflow and a reduction of summer and fall streamflow under future climate scenarios (A1, B2, and A1T) (Forbes et al., 2011). Studies also showed that due to increased precipitation, the Upper Midwest experienced higher streamflow, especially in the warmer season (Groisman et al., 2001; Novotny and Stefan, 2007; Small et al., 2006; Villarini et al., 2015; Zhang and Schilling, 2006). Jha et al. (2006) reported that the Upper Mississippi River Basin is very sensitive to projected future climate changes.

Climate change studies by potential climate variability may increase flood risk around the world. Examples include Kay et al. (2009) and Kay et al. (2006) in England, Burn and Whitfield (2016) in Canada, Brath et al. (2006) in Italy, Mirza et al. (2003) in Bangladesh, and Zhai et al. (2005) in China. In the United States Midwest, flood events mainly occur in spring (March to May) as snow melts and in summer months due to heavy rainfall (May to July) (Villarini et al., 2011).

2.3 Future Emissions Scenarios for Climate and Land Use Changes

The Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) published projections of future greenhouse gas emissions in 2000 (IPCC, 2000). According to this report, “a set of scenarios was developed to represent the range of driving forces and emissions in the scenario literature so as to reflect current understanding and knowledge about underlying uncertainties”. Four narrative storylines represent different demographic, economic, social, environmental and technological developments. These storylines are grouped into four scenario families: A2, B1, B2 and A1 (which include A1B, A1FI, A1T) (Arnell, 2004; IPCC, 2000).

A1: The world will have very rapid growth with increasing globalization and rapid technological changes. Wealth will increase with reduced differences in regional per capita income. Based on energy sources, this family scenario includes three variants: fossil intensive (A1FI), non-fossil fuels (A1T) or a balance across all sources (A1B).

A2: This scenario describes a heterogeneous world. Economic development is primarily region-oriented and per capita economic growth. This scenario represents less growth than A1. Technological changes are slower than other storyline scenarios with continuously increasing population growth.

B1: Development will be environmentally sustainable in this scenario but with the same population growth as in A1. This scenario emphasizes global solutions to achieve economic, social and environmental sustainability.

B2: Population growth is less than in A2 but higher than A1 and B1, with a locally-oriented development and emphasis on environmental, economical, and social sustainability.

2.3.1 Future Land Use Model

The FOREcasting SCEnarios (FORE-SCE) model was developed by the United States Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center to provide spatially explicit detailed projections of plausible future land use and land cover (LULC) change for the conterminous United States (Sohl et al., 2014; Sohl et al., 2012). Four scenarios (A1B, A2, B1 and B2) of LULC were developed based on the IPCC-SRES (Sohl et al., 2014). The FORE-SCE model produced projected land use maps for each year from 1992 through 2100 using 1992 National Land Cover

Dataset (NLCD) (Sohl et al., 2014; Vogelmann et al., 2001; Wu et al., 2013). These are the first national-scale, moderate resolution and thematically detailed LULC projections that represent the IPCC storylines which are available for the conterminous United States (Sohl et al., 2014). The LULC maps are applicable to a variety of ecological applications (Sohl et al., 2014).

2.3.2 Future Climate Model

The General Circulation Models (GCMs) are published by the IPCC 4th Assessment Report (AR4) (Meehl et al., 2007) to represent future climate conditions. According to IPCC (2007), fossil fuel consumption has caused an increase in anthropogenic emissions of carbon dioxide and other greenhouse gases in the atmosphere. GCMs predict that for all IPCC scenarios, an increase in atmospheric greenhouse gas concentration will elevate surface air temperature. Moreover, GCMs are considered to be the most adopted approach to assess information on climate change. However, the spatial resolution of GCMs is often coarse and does not match with regional scales (Chu et al., 2010). Thus, bias corrected multimodel ensembles are commonly used to quantify uncertainty in climate change predictions. Appropriate downscaling is important to improve the coarse resolution and poor representation of precipitation and temperature in global climate models (Chu et al., 2010; Maraun et al., 2010; Pervez and Henebry, 2015). It is also necessary to consider realistic future hydrologic scenarios (Deidda et al., 2013; El-Khoury et al., 2015; Serpa et al., 2015). Several studies reported that different downscaled precipitation led to varying hydrologic response estimates, giving conflicting trends (Bastola et al., 2011; Chiew et al., 2010; Jha and Gassman, 2014; Xu et al., 2013). There are two approaches to meet the need for finer spatial resolution (Hewitson and Crane, 1996). 1) Process-based techniques (e.g., downscaling approach) and 2) Empirical techniques that use identified relationships derived from the observed data.

2.4 Hydrologic Modeling

To assess the environmental impacts on hydrological processes, three methods are generally used. These are paired catchments approach, time series analysis or statistical methods, and hydrological modeling (Li et al., 2009). The purpose of a model is to represent a complex system in a simplified way. There is a wide variety of models to represent the complex hydrologic dynamics of the earth system. Various hydrologic models can be classified into categories as described by Singh (1988).

- Lumped hydrologic models – Lumped models assume the complete basin as a homogenous system without considering the spatial distribution of processes (Xu, 2002). Examples include the Stanford watershed model (Crawford and Linsley, 1966), HBV model (Bergstrom, 1976), and Sacramento Soil Moisture Accounting (SAC-SMA) model (Burnash et al., 1973).
- Semi-distributed hydrologic models – These types of model calculate flow contribution from separate subbasins, considering that the subbasins are homogenous (Xu, 2002). Examples of semi-distributed hydrologic models are the TOPMODEL (Beven and Kirkby, 1979) and Soil and Water Assessment Tool (SWAT) (Arnold et al., 2012; Neitsch et al., 2011).
- Distributed hydrologic models – In distributed models, the whole basin is divided into elementary units (i.e. areas are divided as a grid net where water flows from one grid point to another when water drains through the basin) (Xu, 2002). Examples of distributed hydrologic models are the SHE (Abbott et

al., 1986) and the Institute of Hydrology Distributed Model (IHDM) (Beven et al., 1987).

The Soil and Water Assessment Tool (SWAT) is a semi-distributed, continuous-time step, process-based river basin model (Arnold et al., 2012). SWAT has been widely used to analyze hydrological processes at watershed scales.

This model was developed to evaluate the impact of climate and land management practices on water in large and complex watersheds with varying soils, land use, and management conditions over long periods of time (Arnold et al., 1998). The hydrological component of the model is based on a water balance equation with processes that include precipitation, surface runoff, water yield, ET, lateral flow, percolation and groundwater flow (Arnold et al., 1998; Neitsch et al., 2005). The water balance equation of the model (Neitsch et al., 2011) is as follows:

$$SW_t = \mathrm{SW}_o + \sum_{n=i}^{t}(P - \mathrm{Q}_{\mathrm{surf}} - \mathrm{ET} - \mathrm{W}_{\mathrm{seep}} - \mathrm{Q}_{\mathrm{gw}})$$

where, SW is the change in soil water storage, P is the daily precipitation, ET is the ET, Q_{surf} is the surface runoff flow, Q_{gw} the groundwater flow and W_{seep} is the deep aquifer recharge. Surface runoff is determined through a modified Soil Conservation Service (SCS) curve number (CN) method (Arnold et al., 1998; Neitsch et al., 2011; Wu et al., 2012b). The Penman-Monteith method (Monteith, 1965) was used to estimate the potential ET.

For water budget, SWAT differentiates the solid and liquid precipitation based on near-surface air temperature. If the air temperature is lower than snowfall temperature, then the precipitation is considered solid (i.e. snow), which will accumulate until melt (Grusson et al., 2015). In SWAT, snowmelt in the model is estimated through mass balance approach:

$$SNO = \mathrm{SNO} + \mathrm{R_{day}} - \mathrm{E_{sub}} - \mathrm{SNO_{mlt}}$$

where, SNO is the total amount of water in snowpack on a given day (mm H_2O), E_{sub} is the amount of sublimation (mm H_2O), and SNO_{mlt} is the amount of snowmelt (mm H_2O). Changes in snowpack volume depend on additional snowfall or release of meltwater in the basin. A more comprehensive description of the equations used by SWAT can be found in Neitsch et al. (2011).

2.5 SWAT Applications in Hydrologic Assessment in the Upper Midwest

SWAT model was developed to predict the impacts of land management practices on water resources, sediment, and agricultural chemical yields in large, complex watersheds (Arnold et al., 2012; Neitsch et al., 2011). SWAT has extensively been used for land use and climate change impact assessment studies in various parts of the world, including the Upper Midwest (Chien et al., 2013; Jha et al., 2006; Jha and Gassman, 2014; Johnson et al., 2015; Neupane and Kumar, 2015; Schilling et al., 2014; Schilling et al., 2008; Wu et al., 2012b; Wu et al., 2013). Researchers often applied SWAT to evaluate changes in watershed hydrology due to land use changes by increasing cultivated crop acreages, assigning different crop rotations, and creating a conversion of one land use to another (Schilling et al., 2014; Schilling et al., 2008; Wu et al., 2012b). For example, Wu et al. (2013) examined implications of projected land use for hydrological processes in the Cedar River Basin watershed in Iowa. This study showed that due to projected urban expansion, surface runoff would increase and baseflow would decrease because of reduction in infiltration. Wu et al. (2012b) studied a series of biofuel production scenarios in the James River watershed where water yield decreased for different crop rotations. Schilling et al. (2008) also reported that increased perennial vegetation increased annual ET and decreased water yield in the Racoon River watershed. Another study reported that increases in perennial vegetation reduced flood events and frequency of severe floods in this watershed (Schilling et al., 2014).

The SWAT model has also been widely applied to analyze climate change effects on hydrological processes using future climate projections. Neupane and Kumar (2015) used projected temperature and precipitation data of the Special Report on Emissions Scenarios (SRES) to estimate climate change effects on hydrologic processes for the Big Sioux River watershed, South Dakota. In this watershed, for all the emission scenarios examined (A1B, A2, and B1), higher average annual streamflow, water yield, groundwater, percolation and lower ET were estimated compared to the baseline scenario. Jha and Gassman (2014) reported that, for A1B scenario, surface runoff would decrease by 16%, baseflow by 18%, and total water yield by 17%, which overall would result in a decrease in streamflow in the Racoon River watershed. Chien et al. (2013) studied the effects of climate change under SRES scenarios (A1B, A2, and B1) in Midwestern watersheds, for which the authors reported streamflow increase in winter and decrease in summer. This study found that future annual streamflow varied from -61% to 27% in the Rock River, Illinois River, and Kaskaskia River watersheds in Illinois.

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CHAPTER 3: SPATIAL AND TEMPORAL EVALUATION OF HYDROLOGICAL RESPONSE TO CLIMATE VARIABILITY AND LAND USE CHANGE IN THREE SOUTH DAKOTA WATERSHEDS

ABSTRACT: This study analyzed changes in hydrology between two recent decades (the 1980s and 2010s) with the Soil and Water Assessment Tool (SWAT) in three representative watersheds in South Dakota: Bad River watershed (BRW), Skunk Creek watershed (SCW) and Upper Big Sioux River watershed (UBSRW). Two SWAT models were created over two discrete time periods (1981-1990 and 2005-2014) for each watershed. National Land Cover Database 1992 and 2011 were respectively used into 1981-1990 and 2005-2014 models, along with corresponding weather data, to enable comparison of annual and seasonal runoff, soil water content, evapotranspiration, water yield, and percolation between these two decades. Simulation results based on the calibrated SWAT models showed that surface runoff, soil water content, water yield, and percolation increased in all three watersheds. Elevated evapotranspiration was also apparent, except in SCW. Differences in annual water balance components appeared to follow changes in land use more closely than variation in precipitation amounts, although seasonal variation in precipitation for the two time periods was reflected in the seasonal surface runoff. Sub-basin scale spatial analyses revealed noticeable increases in water balance components mostly in downstream parts of BRW and SCW, and the western part of UBSRW. Results presented in this study provide some insight into changes in hydrological processes in South Dakota watersheds in recent past decades.

3.1 Introduction

Long-term spatial and temporal variation of water balance components such as surface runoff, soil moisture, evapotranspiration (ET), groundwater and streamflow can be influenced by many factors within a watershed, including land use and climate change (e.g., Deng et al., 2015; Fang et al., 2013; Li et al., 2009; Memarian et al., 2014). As such, evaluation of land use and climate change effects on hydrology has been a long-standing research topic in studying agricultural management, flood forecasting and inundation mapping, soil degradation, nutrient losses, and biodiversity conservation practices (e.g., Heller and Zavaleta, 2009; Morton and Olson, 2014; Principe and Blanco, 2012; Schilling et al., 2014). Variation in precipitation was found influential in streamflow trends in various regions across the United States (Changnon and Kunkel, 1995; Novotny and Stefan, 2007). In the Upper Midwest, changes in precipitation pattern resulted in increased magnitude and frequency of floods (Changnon and Kunkel, 1995). Increased precipitation may lead to increase in water yield, ET and surface runoff, while a decrease in precipitation could result in the opposite effects (e.g., Ficklin et al., 2009; Jha et al., 2006; Lirong and Jianyun, 2012). Besides precipitation, previous studies have linked global warming to snow melt processes and shift in runoff timing in five major watersheds in Minnesota (Johnson and Stefan, 2006; Novotny and Stefan, 2007). While climate, along with land use change, have been widely acknowledged as major drivers of variation in watershed hydrology, comprehensive studies on hydrologic impacts of climate and land use change at local levels with detailed characterization of land use conversions is needed to support watershed management strategies.

Land use change is usually driven by various anthropogenic activities such as urbanization, afforestation, deforestation and expansion of agricultural lands (Öztürk et al., 2013). In recent decades, land use change in the Midwest United States intensified with high grain prices (Omega-Research, 1997; Reitsma, 2014), economic development (Rashford et al., 2011), and increasing demand for biofuel feedstocks following the Energy Independence and Security Act (EISA) of 2007 (Wu et al., 2012). Land use change in this region, especially in the Western Corn Belt (WCB), is mainly characterized by conversion of rangeland, pastureland and grassland to agricultural land uses (Claassen et al., 2011; Wright and Wimberly, 2013). According to Wright and Wimberly (2013), 1 to 5% of grassland is converted to corn and soybean annually across the WCB region. In South Dakota alone, the net loss of grassland was about 1,820 km^2 between 2006 and 2011 (Wright and Wimberly, 2013). Singh (2013) also identified South Dakota as one of the states with highest grassland conversion rates in the WCB region. This increasing land use conversion can potentially lead to changes in surface runoff, flood frequency, water yield, soil moisture and evapotranspiration (ET) (Mao and Cherkauer, 2009; Schilling et al., 2014; Schilling et al., 2008; Wu et al., 2012; Wu et al., 2013). Under these circumstances, water resources in South Dakota may be adversely affected. Although several regional studies evaluated hydrologic response to climate and land use change across the Midwest region (e.g. Wu et al., 2012; Wu et al., 2013; Schilling et al., 2008; Schilling et al., 2014), there is no study that exclusively focuses on South Dakota watersheds, taking into account local trends in land use change (i.e. loss of grassland to other uses). Therefore, the objective of this study was to characterize hydrologic changes that occurred in South Dakota between two recent decades (the 1980s and 2010s) in three representative watersheds.

Evaluation of climate and land use change impacts on water balance often requires application of physically-based hydrological models. With the advancement of computational resources, computer models can discretize geospatial heterogeneity of watershed characteristics at fine resolution and generate sound simulations of the hydrologic cycle. Out of numerous watershed models with varying levels of complexity, the Soil and Water Assessment Tool (SWAT) (Arnold et al., 2012; Gassman et al., 2007; Neitsch et al., 2011) has extensively been used for land use and climate change impact assessment studies in various parts of the world (Goldstein and Tarhule, 2015; Guo et al., 2008; Li et al., 2015; Mango et al., 2011; Natkhin et al., 2013; Pervez and Henebry, 2015; Wang et al., 2014; Wang et al., 2008). However, most of these studies involve scenario testing by varying climate input data or adjusting proportions of land use classes in the model to determine watershed sensitivity and response to these changes (e.g., Gassman et al., 2007; Hernandez et al., 1998; Pervez and Henebry, 2015; Schilling et al., 2014). In the Midwest United States, researchers often applied SWAT using the same technique to evaluate changes in watershed hydrology and water quality through hypothetical climate and land use changes. Typical scenario constructions include increasing cultivated crop acreage, assigning different crop rotations, creating cases to represent land use conversion, and applying future land use and climate projections in the model (Schilling et al., 2014; Schilling et al., 2008; Wu et al., 2012). Wu et al. (2013) for example examined the implications of projected land use change for hydrology in the Cedar River watershed in Iowa. Neupane and Kumar (2015) used projected temperature and precipitation data from the Special Report on Emission Scenarios to estimate climate change effects on hydrologic processes for a watershed located in eastern South Dakota. SWAT was also used in this study to provide a quantitative assessment of changes in watershed hydrology under climate variability and land use change in South Dakota. The contribution of this study, however, is to demonstrate how SWAT can be used to document changes in watershed hydrology based on historical climate and land use data of two distinct time periods.

3.2 Study Area

Three study watersheds were selected from different hydro-climatic and geographic settings in South Dakota (Table 3.1). The Bad River watershed is the largest of the three, located in the semi-arid region of the state, where grassland is the dominant land use (more than 80% in this watershed) followed by agricultural land use. Characterized by isolated buttes and absence of large trees, this watershed receives approximately 460 mm precipitation per year, of which 80% generally falls during the growing season (i.e. April to September). Average daily temperature ranges from a minimum of -12°C in January to a maximum of 31°C in July. Average annual snowfall varies between 650 and 1500 mm in the East, and between 650 and 5000 mm in the West. The principal soils in the watershed are deep Promise-Opal association, and minor soils are dominated by poorly drained Kolls (SDDENR, 2004). The west part of the state, known as "West River," lies west of the Missouri River. It is predominantly ranching with dry land farming compared to eastern South Dakota or "East River", which is prone to intensive agricultural uses.

Largely covered by glacial till and rich loamy soils, East River is predominantly a corn- and wheat-growing region, with substantial pig and poultry production. East River is lower in elevation and receives over 550 mm precipitation per year, of which 76% generally falls during April to September, with an average daily temperature which varies from a minimum of -13°C to a maximum of 29°C in January and July, respectively (SDSU, 2003). The region is heavily glaciated, covered by glacial till and fertile loamy soil. Skunk Creek watershed is located in southeast East River, in Minnehaha County. It covers the majority of urban developments including Sioux Falls, the largest city in the state. This watershed is an agriculture-dominated watershed (64%) followed by grassland (22%; Table 1). Geologically, Skunk Creek watershed is composed of Cretaceous formations, consisting of a heterogeneous mixture of silt, clay, sand, gravel and large rocks (SDDENR, 2004).

The Upper Big Sioux River watershed is located northeast of the East River in the Coteau des Prairies region, where the presence of wetlands is a noteworthy geophysical feature. In this watershed, grassland (37%) and agriculture land (41%) are both prominent (Table 3.1). Soils in this watershed are dominated by glacial till Mollisols over Cretaceous shales (SDDENR, 2004). From semi-arid northwest to semi-humid southeast, the general climate across the state is continental with cold winters and hot summers. Each of these watersheds has United States Geological Survey's (USGS) streamflow gauge stations at their respective outlet (Table 3.1).

Table 3. 1: Major Characteristics of the Study Watersheds.

Watershed	Drainage area (km^2)	USGS streamflow gauge station ID	Dominant land use[a]	Number of weather stations used in modeling		Maximum streamflow (annual average) m^3/s	
				1981-1990	2005-2014	1981-1990	2005-2014
Bad River	8119	06441500	Grassland	7	8	363 (1560)	462 (1846)
Skunk Creek	1605	06481500	Agriculture	4	6	214 (1435)	113 (1718)
Upper Big Sioux River	3804	06479525	Agriculture and Grassland	4	5	57 (580)	57 (1274)

[a]Based on National Land Cover Database 1992 and 2011

3.3 Data and Methodology

3.3.1 SWAT Input Data

In order to analyze hydrologic changes in response to historical climate and land use, two SWAT models were created for each of the study watersheds with two discrete time periods (1981-1990 and 2005-2014). Creation of the SWAT models in ArcSWAT 2009 requires topography, soil texture, land use and climate data. These data were extracted as follows: 30 m digital elevation model (DEM) from USGS National Elevation Dataset (USGS-NED, 2013); 30 m land use data from the National Land Cover Database (NLCD) 1992 and 2011 (USGS-NLCD, 2013); and 1:250,000 scale State Soil Geographic Data (STATSGO) included in SWAT 2009 database. Climate and land cover input data were selected to represent the two periods of simulation while creating the models. In other words, NLCD 1992 land cover data were used to create the model corresponding to 1981-1990 period and NLCD 2011 land cover data were input in the model for 2005-2014 period.

Total daily precipitation, and minimum and maximum daily temperature data for the respective time periods were obtained from the National Climatic Data Center (NCDC) for the stations that fall within or are adjacent to the watershed boundary (Table 3.1). All other related climatic data (e.g. solar radiation and relative humidity) were developed with the internal weather generator within ArcSWAT. Penman-Monteith equation was selected for computing potential evapotranspiration (PET), and observed daily streamflow time series for model calibration and validation were obtained from the USGS streamflow stations located at each watershed's outlet (Figure 3.1). This study assumed that NLCD land cover and NCDC climate data were developed and archived with negligible errors.

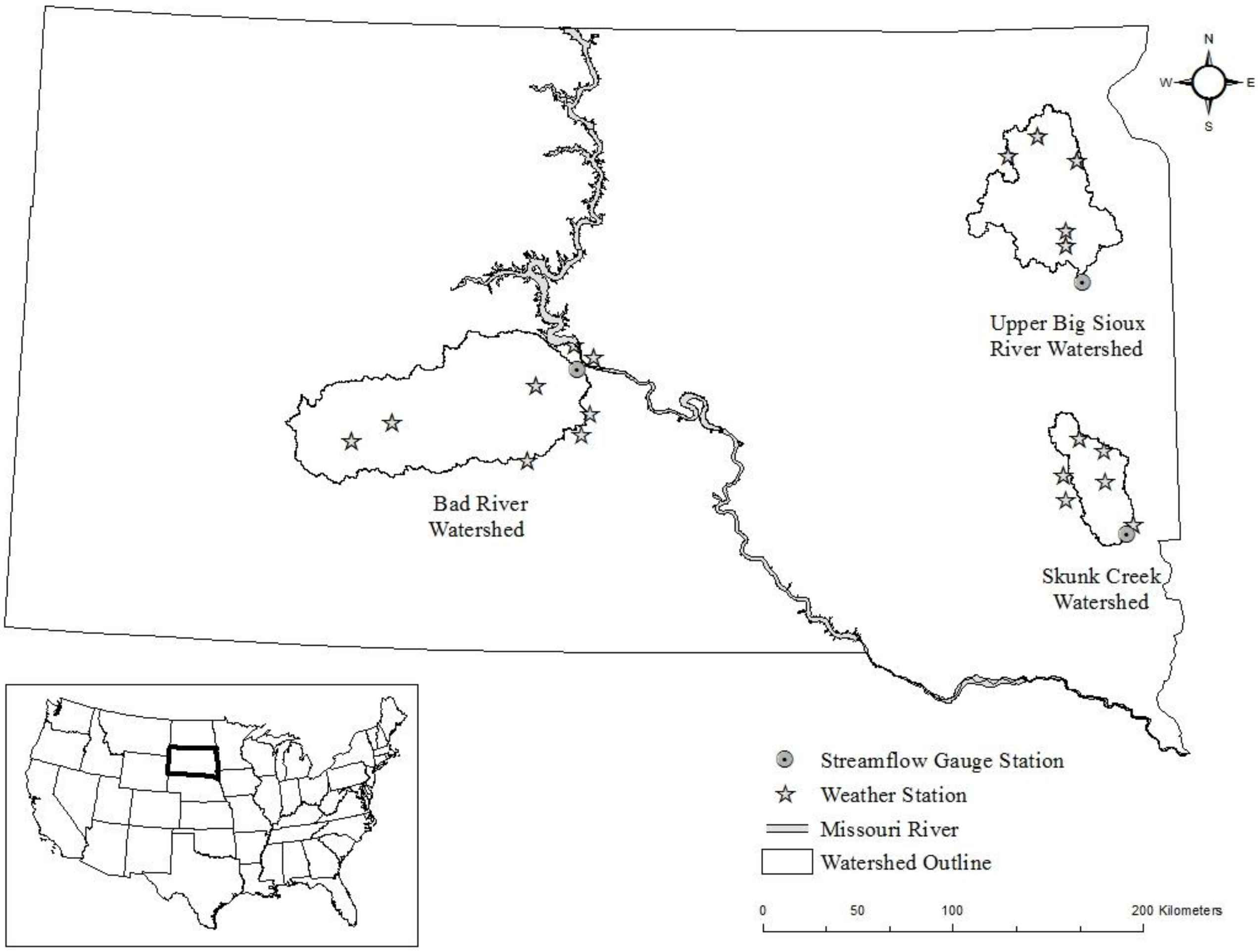


Figure 3.1: Location of Study Watersheds in South Dakota, with Selected Weather Stations and the United States Geological Survey's Streamflow Gauge Stations at Respective Watershed Outlets.

3.3.2 Watershed Spatial Discretization and Modeling

The study watersheds were first divided into sub-basins using 1% flow accumulation area threshold, and all sub-basins were further discretized into Hydrologic Response Units (HRUs) using a 10% threshold for land use, soil and slope. A 10% HRU aggregation threshold was used in this study to reduce the simulation time; a smaller (or zero) threshold value leads to higher number of HRUs, therefore, requiring excessive computational demand. Curve Number and Variable Storage methods (Neitsch et al., 2011) were selected for surface runoff generation and channel routing simulation, respectively. A common set of 19 parameters involving surface, subsurface and channel hydrologic responses were used for calibrating all six models (Table 3.2). The selection of parameters and their initial ranges were based on the review of existing literature on adjacent areas (e.g., Schilling et al., 2008; Wu et al., 2013) and suggestions from model developers presented in SWAT 2009 manual (Neitsch et al., 2011).

Calibration was performed in SWATShare (https://mygeohub.org/groups/water-hub/swatshare; Rajib et al., 2016a), which is a cyber-infrastructure (CI) for sharing, simulation, and visualization of SWAT models. SWATShare provides high-performance computational (HPC) facilities through which all the six models were calibrated in parallel, saving resources and time. The current version of SWATShare uses the Parameter Solution (ParaSol) algorithm to perform Latin Hypercube Sampling and subsequent parameter optimization. No prior parameter sensitivity analysis was performed in this study; rather a comprehensive list of 19 parameters (common to all six models; Table 3.2) representing the land surface, sub-surface, channel routing and snowmelt processes were directly included in the parameter optimization process. SWAT parameters and their initial value ranges (see Tables 3.2 and 3.3) were selected based on the review of existing literature on nearby Midwestern agricultural watersheds (e.g., Jha et al., 2007; Neupane and Kumar, 2015; Schilling et al., 2008; Wu et al., 2013) and suggestions from model developers (Neitsch et al., 2011). Nash-Sutcliffe Efficiency (NSE) was used as objective function to measure the agreement between simulated and observed streamflow hydrographs. The durations of calibration and validation were different from one watershed to another and even between the two periods for the same watershed (Table 3.3). Such uneven model evaluation periods were chosen by visual inspection of the observed streamflow hydrographs such that watershed conditions, both during the high and low flow events, can be captured while optimizing the parameters.

After evaluating the performance of the 6 models during the discrete calibration and validation time periods, the models were run with the best parameter estimates for the two study periods (i.e. 1981- 1990 and 2005- 2014), excluding the first year of each period, which was set for model warm-up in each case (Table 3.3). This post-calibration full-scale simulation provides continuous daily time-series of hydrologic fluxes. The uncalibrated SWAT models were made publicly available in the SWATShare system. Detailed information on accessing these models and model outputs are provided in SWATShare user manual (Rajib and Merwade, 2015).

3.3.3 Statistical Analysis

Nonparametric Wilcoxon test (Koch, 1972) was used to determine differences in medians of precipitation, surface runoff, water yield, evapotranspiration, soil water content, water yield, and percolation between the two study periods (i.e. 1981-1990 and 2005-2014). A significance level of α = 0.05 was used to compute statistics with the statistical computing software, R (R Development Core Team, 2008). The magnitudes of water budget components such as lateral flow and groundwater flow were relatively small so were not intensively discussed in the study.

Table 3. 2: List of Parameters Used for Model Calibration for the Study Watersheds.

No.	Parameter	Definition[a]	Scale of input	Initial range	Adjustment[b]
1	ALPHA_BF	Baseflow recession constant (days)	Watershed	0.01-1	1
2	CANMX	Maximum canopy storage (mm H_2O)	HRU	0.01-25	1
3	CH_K(2)	Main channel hydraulic conductivity (mm/hr)	Reach	5-100	1
4	CH_N(2)	Main channel Manning's *n*	Reach	0.01-0.15	1
5	CN2	Curve number for moisture condition II	HRU	-20-20	3
6	EPCO	Plant uptake compensation factor	HRU	0.75-1	1
7	ESCO	Soil evaporation compensation factor	HRU	0.75-1	1
8	GW_DELAY	Groundwater delay (days)	Watershed	-10-10	2
9	GW_REVAP	Groundwater "revap" coefficient	Watershed	0.01-0.2	1
10	GWQMN	Threshold groundwater depth for return flow (mm H_2O)	Watershed	0.01-5000	1

11	REVAPMN	Re-evaporation threshold (mm H_2O)	Watershed	0.01-500	1
12	SFTMP	Snowfall temperature (°C)	Watershed	0-5	1
13	SMFMN	Melt factor for snow on December 21 (mm H_2O/ °C-day)	Watershed	0-10	1
14	SMFMX	Melt factor for snow on June 21 (mm H_2O/ °C-day)	Watershed	0-10	1
15	SMTMP	Snow melt base temperature (°C)	Watershed	-2-5	1
16	SOL_K	Soil saturated hydraulic conductivity (mm/hr)	HRU	-15-15	3
17	SOL_AWC	Available soil water capacity (mm H_2O/mm soil)	HRU	-15-15	3
18	SURLAG	Surface runoff lag coefficient (days)	Watershed	0.05-24	1
19	TIMP	Snow pack temperature lag factor	Watershed	0-1	1

Table 3. 3: Time Periods Used for Model Calibration and Validation for 1981-1990 and 2005-2014 Study Periods.

Watershed	Calibration[a]	Validation
Bad River	(1981)1982-1986 (2009) 2010-2014	1987-1990 2005-2009
Skunk Creek	(1985) 1986-1990 (2005) 2006-2011	1981-1985 2012-2014
Upper Big Sioux River	(1985) 1986-1990 (2005) 2006-2010	1981-1985 2011-2014

[a]Values in the parentheses show model warm-up years. Simulated streamflow output for the warm-up year was not considered in calculating goodness statistics shown in Table 3.5.

3.4 Results and Discussion

3.4.1 Historical Land use Change

A GIS-based analysis of NLCD 1992 and NLCD 2011 clearly identified grassland depletion as the common feature of land use change in all three study watersheds (Table 3.4), with some differences in the conversion outcomes between the two decades. Grassland, in both Bad River and Skunk Creek watersheds (3% reduction in both cases), was directly impacted anthropogenically and was mostly converted into urban and agricultural areas (Table 3.4). With 5% increase, a trend of urbanization was noticeable in the Skunk Creek watershed. In the Upper Big Sioux River watershed, urban areas also increased along with wetlands (5% and 4%, respectively). Expansion of wetlands in this watershed has been a typical characteristic of the

Coteau des Prairies region in northeastern South Dakota for the past several years (Johnson et al., 2004; Kahara et al., 2009).

3.4.2 Climate Variation

Climate change is a much slower process which is often not precisely measurable within a short span of 10 years. Such a short-term quantitative assessment is insufficient to detect the true nature of climate change for a region, which eventually hinders correlating climate effects to changes in hydrologic processes. However, comparison between the two study periods provides an approximate indication of climate change effects. In South Dakota and the Midwest region, long-term temperature barely increased between 1941 and 2005 (0.4 - 0.8 °F) (Department of the Interior, 2015). Thus, climate analysis in this study primarily focused on changes in precipitation amounts, not how and why precipitation intensities varied between the two decades. As observed from similar average annual precipitation amounts during 1981-1990 and 2005-2014 (Table 3.4), change in precipitation is rather less pronounced in contrast to the noticeable pattern of land use alterations in the selected watersheds. While incident precipitation amounts in Bad River and Upper Big Sioux River watersheds is slightly increased by 7% and 6.5%, respectively, precipitation seemed to decrease slightly in Skunk Creek watershed (2.5%) between the two time periods (Figure 3.2).

An examination of trends in precipitation within the two study periods revealed a decreasing trend for the three watersheds, except for the Bad River watershed where precipitation seemed to increase slightly in 2005-2014 period (Figure 3.2). Other researchers also reported no significant change in historical precipitation for watersheds in the Midwest region (Xu et al., 2013). There was no trend in maximum and minimum daily temperature within and across the two study periods in Bad River and Upper Big Sioux River watersheds. In Skunk Creek watershed, both maximum and minimum temperatures showed a slightly decreasing trend in 2005-2014 period (Figure 3.2). While the difference in incident precipitation between the two study periods in all three watersheds is not statistically significant (Figure 3.4), the observed climate trends allow estimating the effects of climate variability on hydrological processes in the study watersheds.

Table 3. 4: Summary of Land Use Categories and Proportions, and Average Annual Precipitation in The Three Study Watersheds.

Land use[a]	Bad River watershed				Skunk Creek watershed				Upper Big Sioux River watershed			
	Grassland	Agriculture	Water	Urban	Grassland	Agriculture	Water	Urban	Grassland	Agriculture	Wetland	Urban
NLCD 1992 (1981-1990)	85.04	13.5	0.7	0.75	26	64.3	7.8	1.3	39.4	46.7	11.9	1.1
NLCD 2011 (2005-2014)	81.72	14.8	1.5	2.1	22.2	64.3	5.9	6.5	36.8	41.3	16.6	4.7
Difference[b]	-3.3	1.4	0.8	1.3	-3.3	0.03	-1.8	5.2	-2.6	-5.3	4.8	3.6

[a]Values indicate percentage of the total watershed area

[b]Obtained by subtracting NLCD 1992 values from NLCD 2011 values

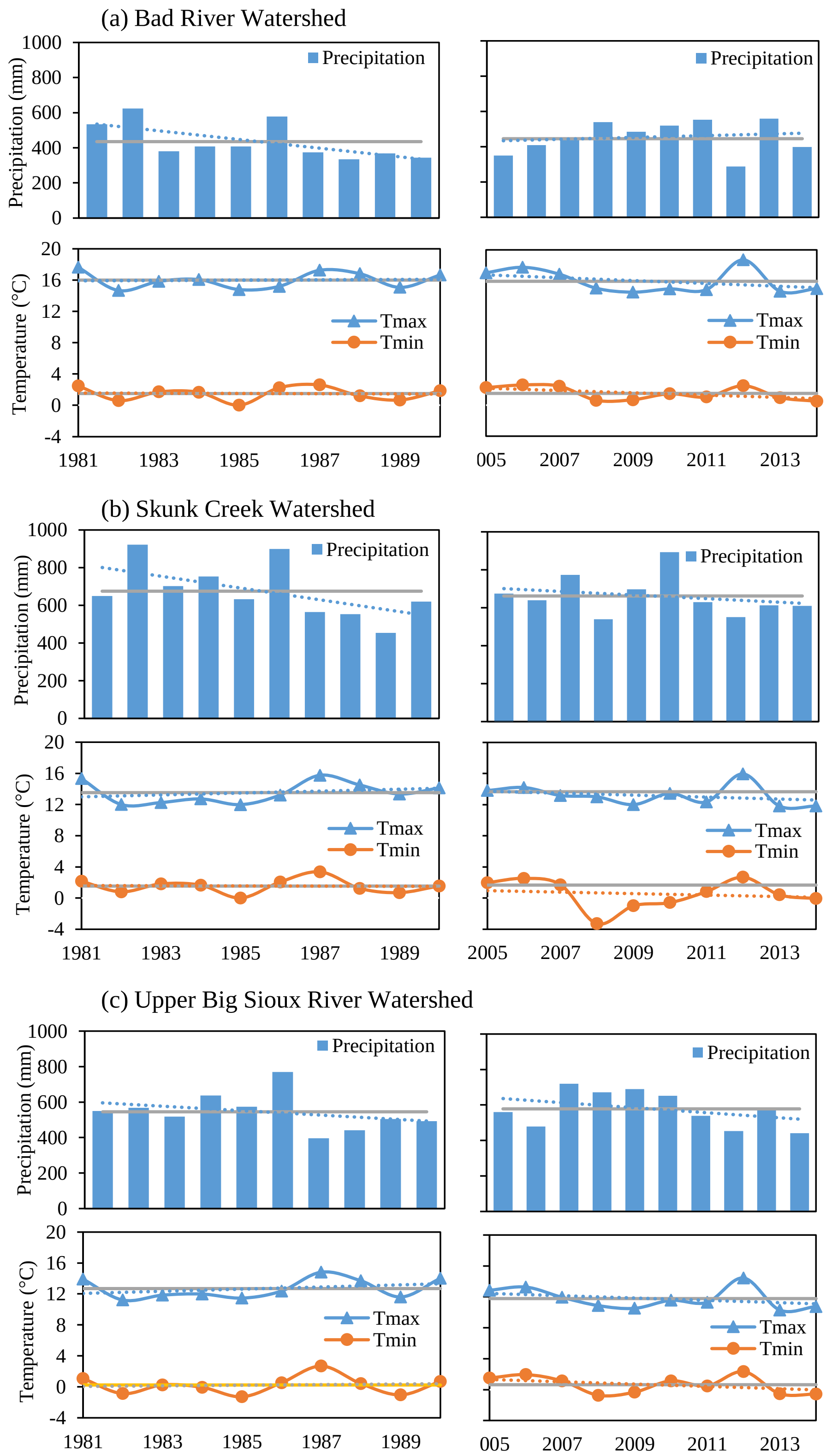


Figure 3. 2: Annual Values of Precipitation and Daily Mean Temperature (Maximum and Minimum) Along With the Trends (Dashed Line) and Average Values (Straight Line) of a) Bad River, b) Skunk Creek and c) Upper Big Sioux River Watershed.

3.4.3 Evaluation of SWAT Performance

To ascertain that the calibrated models are representative of the hydrological response in the watershed, simulated daily streamflow hydrographs were compared with observed streamflow data at respective watershed outlets (Figure 3.3). Based on model calibration criteria discussed by Moriasi et al. (2007), SWAT simulations matched well with the observed, except for few high flow events (Figure 3.3). This is comparable to findings from many past studies across different regions, reporting imprecise performance of the SWAT model in extreme flow conditions (e.g., Arabi et al., 2006; Larose et al., 2007; Oeurng et al., 2011; Qiu and Wang, 2013; Rahman et al., 2013; Rahman et al., 2014; Rajib and Merwade, 2015; Vazquez-Amábile and Engel, 2005; Wang et al., 2008). The goodness of fit scores (R^2, NSE, and PBIAS) are presented in Table 3.5, separately for calibration, validation and the entire study periods. R^2 and NSE range from 0.4 to 0.75, except the case of validation for Bad River watershed during the first study period (i.e., 1981-1990). Although the SWAT models performed reasonably well according to the evaluation guidelines from Moriasi et al. (2007) the uncertainty in precipitation input data cannot be totally disregarded while performing modeling studies on South Dakota, since the state is not well covered by a dense network of weather observatory stations with long-term data. In addition, an inspection of the data revealed frequent snow melt flash flows during spring were evident in all the three watersheds, combined with the prevalence of low flow condition throughout the rest of the year. These are the probable causes for high negative PBIAS in some of the cases reported in Table 3.5, even with reasonably high R^2 and NSE values. In those particular cases, the calibrated SWAT models are capable of capturing the time response of the watersheds, both during dry and wet conditions, but slightly deficient in simulating the total volume of flow being actually generated. Overall, considering the complexity of daily simulation in a data-scarce area, the calibration and validation results shown in Figure 3.3 and Table 3.5 can be considered satisfactory. Table 3.6 reports the optimized parameter values (best estimates) for all 6 SWAT models created in this study.

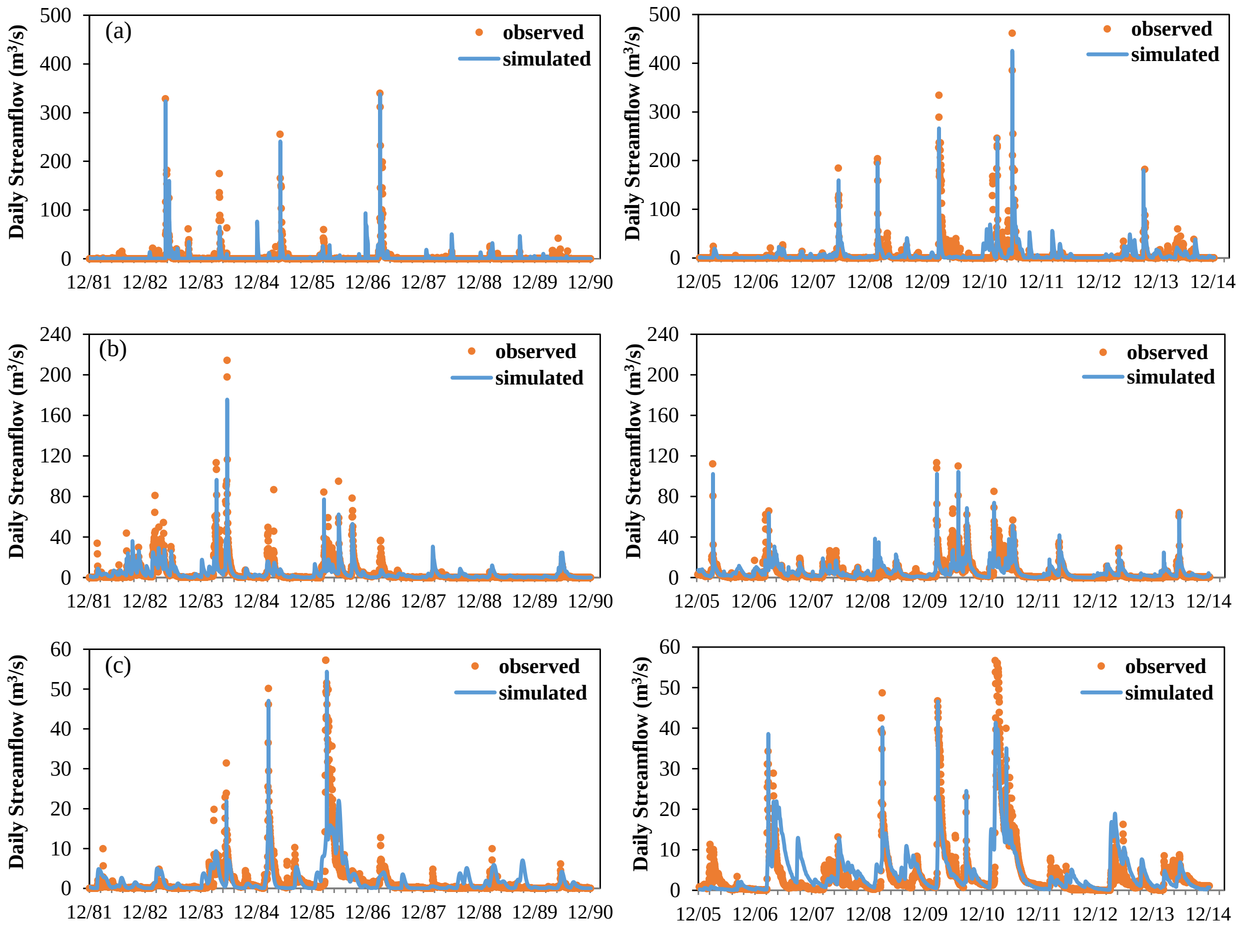


Figure 3. 3: Comparison of Observed and Simulated Streamflow Hydrographs in Daily Time Steps For The Two Study Periods (i.e. 1981-1990 and 2005-2014) for (a) Bad River Watershed, (b) Skunk Creek Watershed, and (c) Upper Big Sioux River Watershed.

Table 3. 5: Goodness-of-Fit Scores for Model Simulation with Observed Daily Streamflow at Respective Watershed Outlets.

		Statistics	Calibration	Validation	Study period
Bad River watershed	1981-1990	R^2	0.59	0.38	0.50
		NSE	0.59	0.38	0.50
		PBIAS	- 0.3	15.6	5.7
	2005-2014	R^2	0.47	0.67	0.5
		NSE	0.47	0.55	0.48
		PBIAS	- 20.4	- 46.5	- 37.9
Skunk Creek watershed	1981-1990	R^2	0.57	0.65	0.63
		NSE	0.55	0.63	0.62
		PBIAS	- 20.8	0.85	- 11.2
	2005-2014	R^2	0.56	0.75	0.52
		NSE	0.56	0.48	0.5
		PBIAS	- 7.6	- 42.6	- 21.6
Upper Big Sioux River watershed	1981-1990	R^2	0.48	0.55	0.50
		NSE	0.48	0.54	0.50
		PBIAS	- 17.2	- 6.1	- 13.2
	2005-2014	R^2	0.43	0.73	0.60
		NSE	0.40	0.72	0.59
		PBIAS	- 23.9	- 11.4	- 17.8

Table 3. 6: Best Estimates of Parameters Obtained From Model Calibration for the Three Study Watersheds.

No.	Parameter	Best parameter values					
		Bad River watershed		Skunk Creek watershed		Upper Big Sioux River watershed	
		1981-1990	2005-2014	1981-1990	2005-2014	1981-1990	2005-2014
1	ALPHA_BF	0.94	0.49	0.389	0.13	0.179	0.867
2	CANMX	24.4	8.9	13.29	14	15.24	15.09
3	CH_K(2)	80.79	36.9	22.59	32.5	80.43	42.51
4	CH_N(2)	0.04	0.145	0.016	0.13	0.023	0.097
5	CN2	-11.2	-9.4	10.72	14.3	-2.7	-11.86
6	EPCO	0.72	0.76	0.86	0.82	0.854	0.815
7	ESCO	0.68	0.91	0.84	0.98	0.774	0.995
8	GW_DELAY	-5.2	1.47	-1.65	-0.8	5.250	4.116
9	GW_REVAP	0.13	0.079	0.137	0.04	0.017	0.185
10	GWQMN	4429	2885	720	3636	3142	1689
11	REVAPMN	427	410	331	324	408	125
12	SFTMP	2.8	0.413	1.73	1.1	4.03	2.26
13	SMFMN	0.93	9.04	7.27	5.29	8.77	1.93
14	SMFMX	4.2	1.36	7.881	5.38	5.73	4.40
15	SMTMP	2.07	1.15	4.652	-1.3	0.55	3.4
16	SOL_AWC	-12.98	10.67	-13.05	-0.1	-11.01	10.7
17	SOL_K	10.9	12.39	4.02	-15	13.62	-7.16
18	SURLAG	14.9	6.26	0.20	1.2	1.19	0.057
19	TIMP	0.71	0.43	0.51	0.653	0.016	0.134

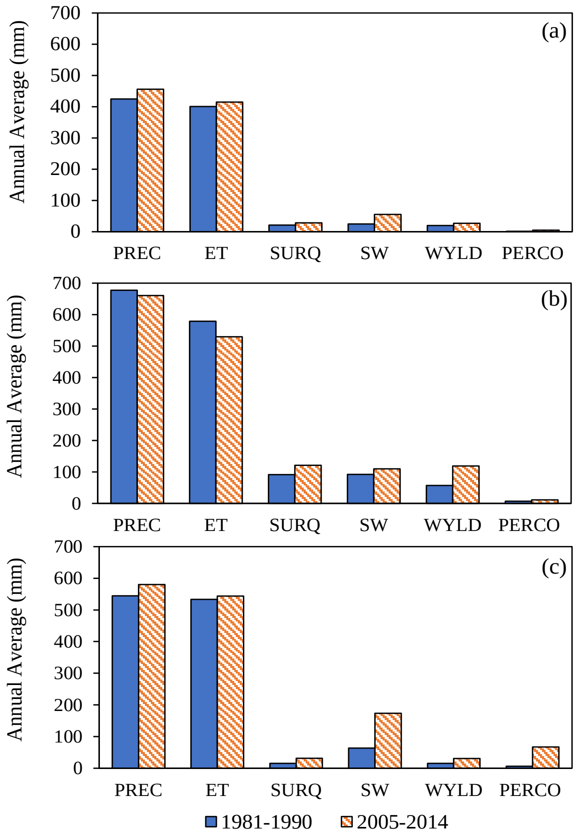
3.4.4 Assessment of Annual Water Balance

Figures 3.4 and 3.5 compare the average annual water balance components and their relative changes at the watershed outlets between the two time periods (i.e. 1981-1990 and 2005-2014). Significance (p-values) from the calculated changes in hydrology between the two periods is also shown in Figure 3.4. Average annual soil water content in the Bad River watershed shows an increase of 31 mm during 2005-2014, which is about 127% higher than that of the 1981-1990 period. This watershed is located in the semi-arid part of the state and requires irrigation to support additional water demands with the expansion of agricultural land (1.4% corresponding to 24 km^2; Table 3.4), leading to increased soil water content. Western South Dakota mostly consists of sandy soil having short-grass and weed-based rangelands (Janssen and Pflueger, 2004). With shorter roots in the sandy soil, this type of vegetation tends to deplete soil water from top soil through transpiration while sufficient water content may still exist in the deeper layers. Although precipitation slightly increased in the watershed between the two time periods, transformation of these rangelands, predominantly for wheat production (Janssen and Pflueger, 2004), could reduce moisture loss from the top soil and lead to additional water demands (i.e. irrigation) as mentioned earlier. High soil water content would lower infiltration capacity, thereby increasing surface runoff volume by 34% (Figures 3.4 and 3.5). Besides the slight increase (1.3%) in urban land cover (Table 3.4), growth in agricultural operations in a previously undisturbed grassland such as the Bad River watershed can potentially reduce soil permeability, which can be regarded as a contributing factor for runoff intensification (e.g., Pai and Saraswat, 2011). In addition, crop cultivation tends to promote additional plant transpiration from root zone. Slightly higher precipitation during the 2005-2014 study period compared to 1981-1990 and increased availability of soil water in the Bad River watershed likely contributed to increase in ET (Figures 3.4 and 3.5). Research showed that ET is correlated ($R^2 = 0.66$; $p = 0.001$) with precipitation in semi-arid rangelands (Nagler et al., 2007; Wu et al., 2012).

In Skunk Creek watershed, increased impervious land cover associated with urbanization and agricultural operations amplified surface runoff volume from 92 mm in 1981-1990 period to 122 mm (33% increase) in 2005-2014 period. This percentage increase in surface runoff is comparable to that of the Bad River watershed. While increase in average annual surface runoff is 7 mm between the two time periods in Bad River watershed, it is 30 mm in Skunk Creek watershed. The 30 mm increase in average annual runoff between the two 10-year periods is quite substantial, considering the average daily precipitation the watershed usually receives and given that total rainfall in this watershed was less in the second study period (Figure 3.4). As a result, the simulated water yield was 108% higher in 2005-2014 than in 1981-1990. Cropland in this part of the state is mostly rain-fed. With only slight increase in incident precipitation amounts between the two time periods, water content in the soil profile in Skunk Creek watershed does not show considerable increase as in the Bad River watershed (Figure 3.4). In contrast to the general cause-effect relationship of ET increasing with crop production (more plants transpiring water) and elevated soil moisture storage (e.g., Wu et al., 2012), average annual ET in Skunk Creek watershed decreased by 49 mm (8.5%) during 2005-2014 (Figure 3.4). Although urbanization in this watershed is mostly localized, significant expansion rate (Table 3.4) might have lowered average ET at the watershed scale because of the paucity of vegetation over urban impervious surfaces, reducing the amount of available water for ET (Barnes et al., 2001).

Due to the gradual expansion of wetlands in the Upper Big Sioux River watershed, the most significant hydrological changes were observed in soil water content and ground water percolation (Figure 3.4). SWAT simulations based on NLCD 2011 show an extensive increase in average annual soil water content by 174% during 2005-2014 relative to 1981-1990 ($p < 0.001$; Figure 3.4). Evaluation of HRU-scale outputs (not shown here) reveals that soil water content in the recent time period (i.e. 2005-2014) stayed nearly at field capacity all year round, except at the peak of growing season when moisture depletion is the highest. The resultant saturation excess flow from the lowest layer of the soil profile to the shallow aquifer is reflected in the Upper Big Sioux River watershed in terms of increased percolation (Figure 3.4). Higher soil water storage allows less precipitation water to infiltrate, leading to high runoff potential in the watershed during 2005-2014 period, even with the depletion of both grassland and croplands beside a 4% increase in urban areas (Table 3.4). Under these circumstances, it is unlikely that soil evaporation and plant transpiration increased in this watershed. The 2% increase in ET as shown in Figure 3.4, could be extraction from wetlands which expanded in the watershed (Johnson et al., 2004; Kahara et al., 2009).

Across watersheds and study periods, ET had the highest proportion of water budgets, followed by runoff, and percolation, except in Upper Big Sioux River watershed where percolation was higher than runoff during 2005-2014 period (Figure 3.4). Overall, surface runoff increased while ET decreased between 1981-1990 and 2005-2014 in all three watersheds under the influence of land use change and climate variability (Figure 3.4). Ghaffari et al. (2010) found that grassland replacement by other land uses caused increase in mean annual surface runoff in Northwest Iran. Similar results were also reported for the Niger River Basin and Lake Chad Basin in Africa (Li et al., 2007). The researchers explained that the increased surface runoff and water yield followed replacement of rangeland/grassland with rain-fed agriculture and bare ground (Ghaffari et al., 2010; Li et al., 2007). As mentioned earlier, agricultural activities and urbanization in Skunk Creek watershed resulted in higher magnitude of surface runoff and water yield compared to the other two watersheds. Previous studies indicated that small watersheds such as Skunk Creek watershed are sensitive to high intensity rainfall in producing surface runoff (Baker and Miller, 2013; Hernandez et al., 1998). Runoff increase might also be due to precipitation intensity but was not explicitly analyzed in this study. Results from the present study were comparable to findings from other parts of the world (Pai and Saraswat, 2011; Wu et al., 2012; Zhao et al., 2016). In the Midwestern Raccoon River watershed, modeling results showed that average annual ET decreased under increasing corn acreage, and increased under increasing grass acreage (Schilling et al., 2008). Despite the fact that there was no significant change in precipitation and temperature, soil moisture appears to increase in all three watersheds (Figures 3.4 and 3.5). An increase in precipitation will result in increased soil moisture as shown by Ballard et al. (2014) through future climate predictions for the Prairie Pothole Region of the northern Great Plains.



	Difference (mm)	% change	p- value
Precipitation	31.5	7.5	0.605
Surface Runoff	7 .0	34	0.546
Soil Water Content	31.0	127	**0.008**
ET	15.0	4	0.605
Water Yield	7.0	36	0.436
Percolation	3.5	331	**0.001**

	Difference (mm)	% change	p- value
Precipitation	-16.7	-2.5	0.730
Surface Runoff	30.0	32.5	0.222
Soil Water Content	18.0	19.5	0.436
ET	-49.0	-8.5	0.050
Water Yield	62.0	108	**0.003**
Percolation	4.5	63	0.546

	Difference (mm)	% change	p- value
Precipitation	36.0	6.5	0.436
Surface Runoff	16.0	101	0.114
Soil Water Content	110.5	174	**0.00004**
ET	11.0	2	0.258
Water Yield	15.0	97.5	0.114
Percolation	61.0	930	**0.0003**

Figure 3. 4: Average Annual Values and Percent Change of Precipitation (PREC), Evapotranspiration (ET), Surface Runoff (SURQ), Soil Water Content (SW), Water Yield (WYLD) and Percolation (PERCO) for Two Study Periods (1981-1990 and 2005-2010) in (a) Bad River Watershed, (b) Skunk Creek Watershed, and (c) Upper Big Sioux River.Watershed. Differences were Calculated by Subtracting the Values of 1981-1990 Period from Those of 2005-2014 Period. Statistically Significant Hydrological Changes were Determined by Wilcoxon Test.

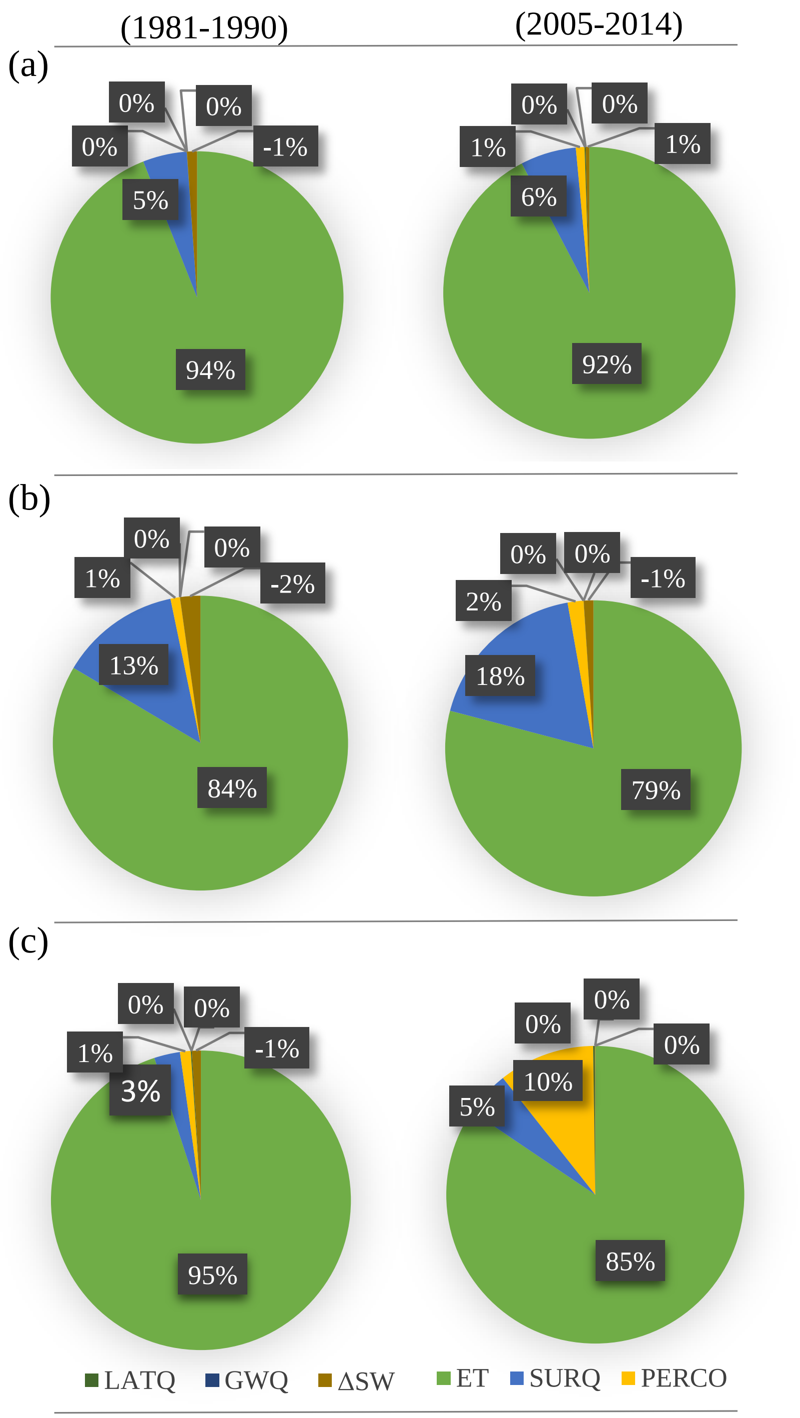


Figure 3. 5: Average Annual Water Budget for Two Study Periods (1981-1990 and 2005-2010) in (a) Bad River Watershed, (b) Skunk Creek Watershed, and (c) Upper Big Sioux River Watershed.

3.4.5 Seasonal Variation in Water Balance Components

Figure 3.6 shows seasonal variation in hydrologic components between the two time periods in terms of shifts in the temporal trends in precipitation amounts during

2005-2014 relative to 1981-1990. A comparative assessment on the relative magnitude of the changes among the three watersheds can also be deduced from Figure 3.6. The values presented here are respective monthly averages for the two time periods, calculated over the entire watershed. Seasonal variation in surface runoff, soil water and ET (especially) seems to follow variation in precipitation in all three watersheds. This is indicative that seasonal variation in the studied hydrologic processes is likely driven by variation in climate, although changes in annual hydrologic fluxes were found to correspond to land use change, specifically to grassland loss. Water budget components followed relatively the same patterns in all three watersheds for the two time periods (Figure 3.6).

Runoff generally increased from April to August (i.e. warmer months) and decreased in winter months when the ground is frozen (Figure 3.6). Occurrence of elevated surface runoff can be linked to increase in soil water level, and decline in soil water content can be associated with increased ET in summer months (May to August; Figure 3.6). Intensification of surface runoff in Skunk Creek and Upper Big Sioux River watersheds even with no increase in monthly precipitation, especially in late spring and early summer (March-May) during 2005-2014, could be the effects of spring snow melt (Kahara et al., 2009). Mao and Cherkauer (2009) also reported elevated spring runoff for the Upper Midwest states due to snow melt processes. Changes in the timing of snow melt may have caused shifts in elevated runoff events in these two watersheds. For example, high runoff events occurred in June during 1981-1990 period, while the month of April experienced the highest runoff events during 2005-2014 period in the Skunk Creek. Although the SWAT models developed in this study considered snow melt parameters, the analysis did not explicitly account for patterns in snow melt between the two time periods.

For all three watersheds, soil water content decreased during frost-free seasons, while surface runoff, ET, and precipitation increased (Figure 3.6). During the growing season, rainfall and temperature support high plant canopy activities, leading to decreased water content in the soil profile and increased ET (Figure 3.6). For example, the lowest seasonal soil water content shown in Figure 3.6 corresponds to the highest ET values at the peak of summer season (May to August). Soil water content and ET in the Bad River watershed are the lowest of all three watersheds, likely due to its location in the semi-arid region. Increase in soil water in the Upper Big Sioux River watershed from 1981-1990 to 2005-2014 can be explained by the effects of wetland expansion on soil moisture level (Table 3.4 and Figure 3.6).

Increase in ET during summer is also observable with little difference between the two time periods in all three watersheds, with the highest ET values in Skunk Creek watershed (Figure 3.6). This elevated summer ET could be linked to land use change. Research indicated that land use change (e.g. grassland depletion and agricultural land expansion) considerably influenced surface runoff and ET, mainly during summer months for watersheds in China (Deng et al., 2015; Fang et al., 2013). Monthly precipitation appears to fluctuate more noticeably between July and December than the first part of the year (i.e. January to June), especially in the Bad River and Skunk Creek watersheds during 2005-2014. However, there was little difference in the timing of the highest average monthly precipitation between the two time periods. In these two watersheds, average monthly precipitation was high in May-June, with June being the wettest month during 2005-2014 period (Figure 3.6). In the Upper Big Sioux watershed, there was a shift in high precipitation season from June for 1981-1990 period to August for 2005-2014 period (Figure 3.6). Changes in ET for all three watersheds are distinctive only during the summer growing season, while the variations throughout rest of the year and for the two study periods are quite minimal.

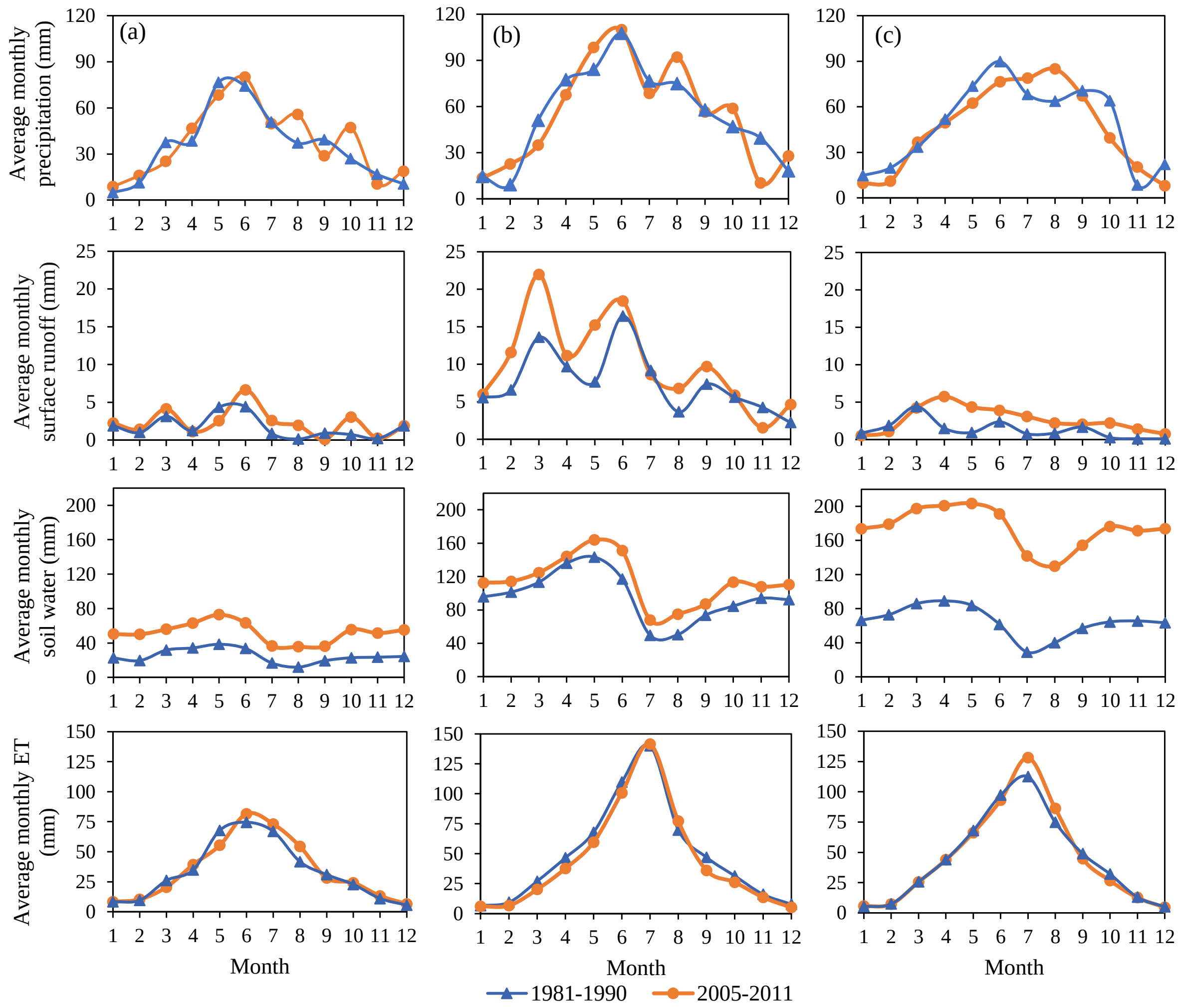


Figure 3. 6: Seasonal Variation in Surface Runoff, Soil Water Content, and ET over 1981-1990 and 2005-2014 Time Periods for (a) Bad River Watershed, (b) Skunk Creek Watershed, and (c) Upper Big Sioux River Watershed.

3.4.6 Hydrological Response at Sub-basin Scale

Sub-basin scale average annual outputs for surface runoff, soil water content and ET from the two model configurations (i.e. 1981-1990 and 2005-2014 time periods) are shown in Figures 3.7-3.9. Surface runoff in the Bad River watershed increased in the recent time period (i.e. 2005-2014) in almost all the sub-basins, especially downstream of the watershed in accordance with conversion of grassland to agricultural and urban areas (Figure 3.7). Accordingly, increase in soil water content and ET during 2005-2014 is relatively high in the downstream sub-basins and the pattern of their spatial variation is equally consistent, supporting the expected relationship of high soil moisture imparting great surface runoff potential and elevated ET demand.

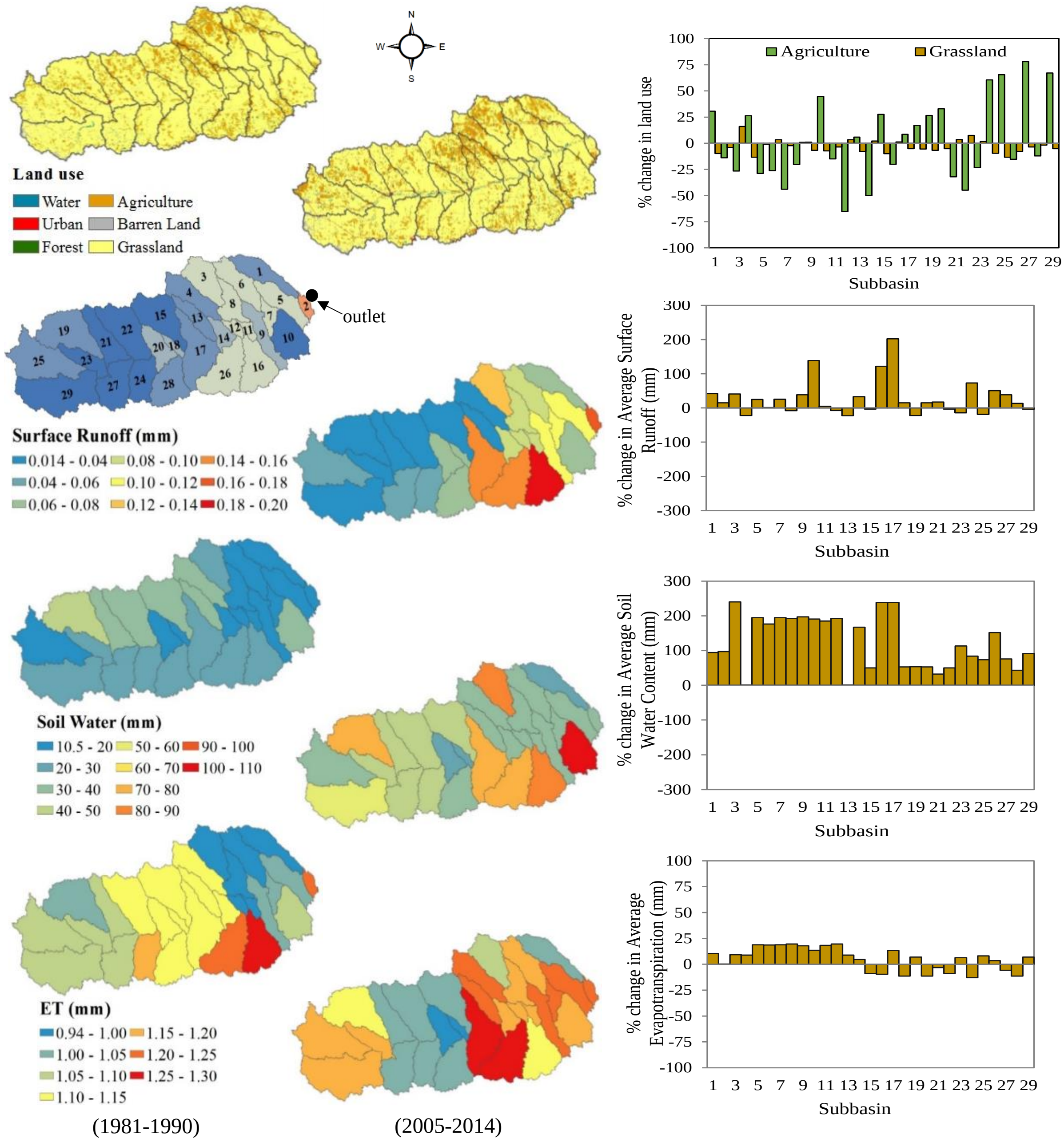


Figure 3. 7: Spatial Distribution of Land Use Classes and Water Balance Components and Their Percent Change in Individual Sub-Basins in Bad River Watershed for The Two Study Periods.

Land use conversion in Skunk Creek watershed, either from grassland to cropland or conversion of both grassland and cropland to urban land use, likely contributed to surface runoff increase in the watershed during 2005-2014, with a tendency of soil moisture increase in downstream sub-basins (Figure 3.8). The most affected part of the watershed is sub-basin 14 that houses the City of Sioux Falls. According to NLCD 2011, massive losses in grassland (-75%) and cropland (-60%) to expansion of urban developments occurred in this particular sub-basin, potentially contributing to surface runoff increase by 219% during 2005-2014 with substantial lowering of ET (Figure 3.8). A similar pattern was observed in sub-basins with reduced ET during 2005-2014 compared to 1981-1990 because of high expansion rate of urban areas that would have led to the lowering of average ET values in the watershed. Sub-basins with minimal change in land use showed the least changes in surface runoff and soil moisture.

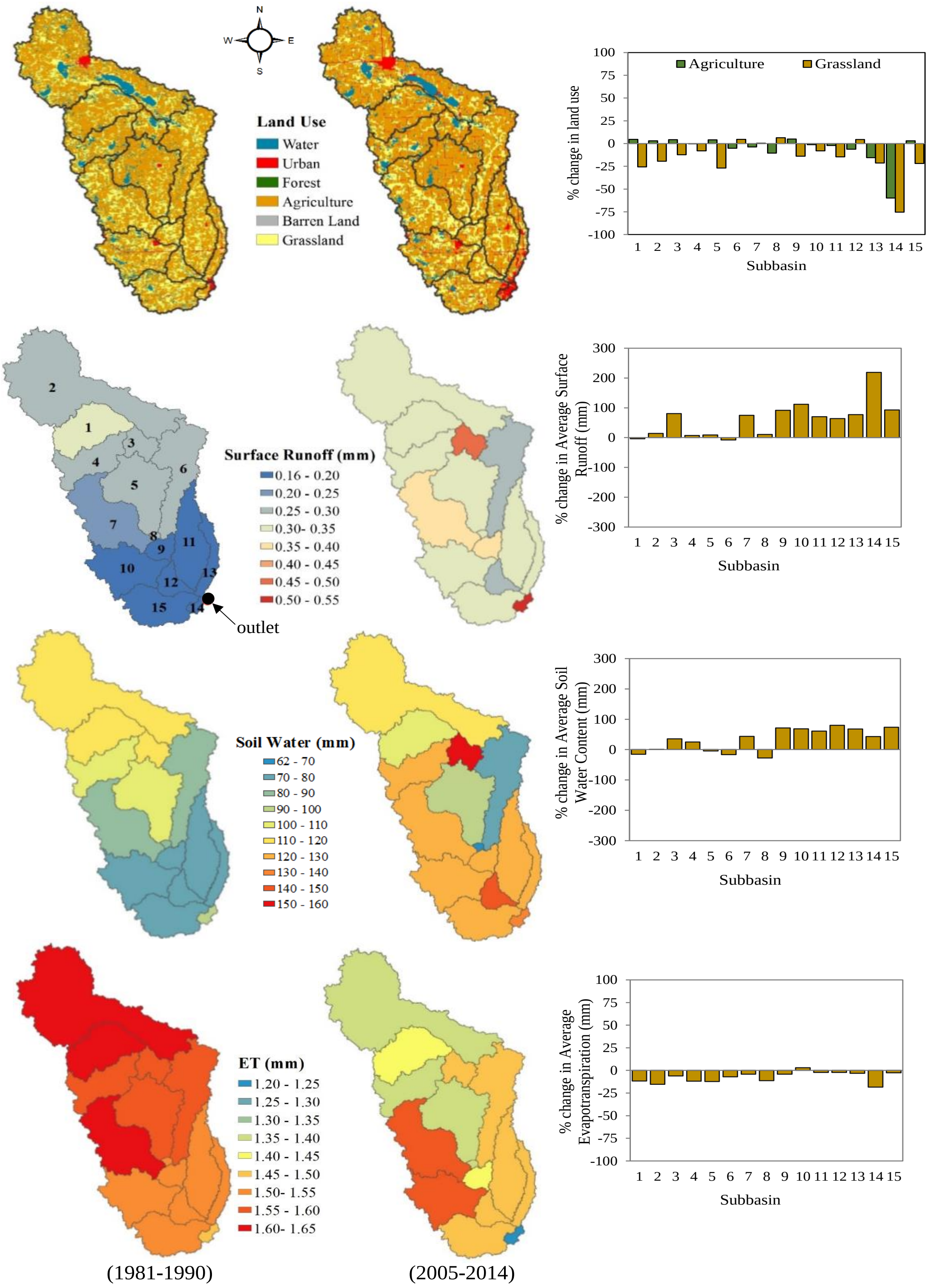


Figure 3. 8: Spatial Distribution of Land Use Classes and Water Balance Components and Their Percent Change in Individual Sub-Basins in Skunk Creek Watershed for the Two Study Periods.

Changes in the Upper Big Sioux River watershed showed a very distinctive spatial pattern, which is likely due to the expansion of wetlands all over the western part of the watershed (Figure 3.9). For example, wetlands in sub-basin 3 have expanded from 3% in 1981-1990 (NLCD 1992) to 17% of the total sub-basin area in 2005-2014 (NLCD 2011). Accordingly, surface runoff, soil water content, and ET exhibit noticeable increase in the sub-basins over the western part of the watershed.

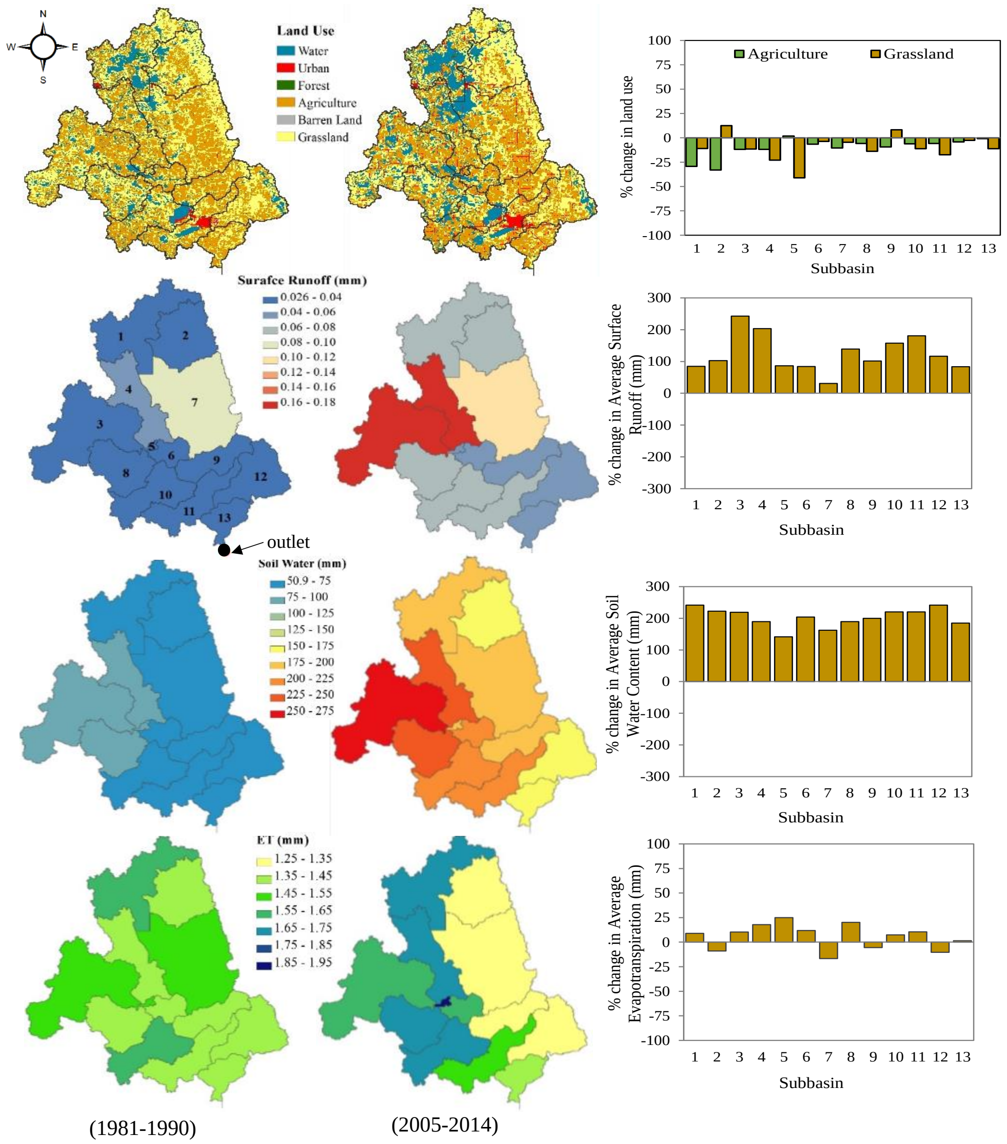


Figure 3. 9: Spatial Distribution of Land Use Classes and Water Balance Components and Their Percent Change in Individual Sub-Basins in Upper Big Sioux River Watershed for The Two Study Period.

Figure 3.7-3.9 show how the hydrology within a particular watershed changed between the two discrete time periods. To evaluate the relative magnitude of hydrologic changes in all three watersheds, sub-basin scale average annual values of the hydrologic components were mapped using the same color code to describe these variations (Figure 3.10). Having the largest percentage of expansion in urban land use from the first to the second time period, Skunk Creek watershed shows the highest surface runoff potential among the three watersheds. Changes in soil water and ET are noticeable in the Upper Big Sioux River watershed, with the distinctive spatial pattern of relatively intensive changes around the wetlands in the western part of the watershed. Changes in surface runoff in the Bad River watershed are comparable with that of the Upper Big Sioux River watershed. Even though a similar amount of grassland was converted in the Bad River watershed, soil water and ET appear to be less altered compared to the other two watersheds (Figure 3.10).

In general, the spatial pattern of increased surface runoff conformed to the spatial distribution of land use modifications in all three watersheds. In Minnesota, Wisconsin, and Michigan, Mao and Cherkauer (2009) found strong correlations between spatial and seasonal water balance variations and changes in land use type, while Nie et al. (2011) found no correlations between ET and land use in the San Pedro watershed in Mexico. In all three watersheds, there were small changes in ET at sub-basin scale (Figures 3.7-3.10). Evapotranspiration is a combination of evaporation and transpiration; these sub-processes can be non-linear in nature (Ghaffari et al., 2010). Pai and Saraswat (2011) reported that transpiration decreased while evaporation increased in the Illinois River drainage area of Arkansas between 1997 and 2008.

The spatial and temporal changes in water budget components discussed are indicative of the need to develop sustainable watershed management strategies to mitigate the effects of climate and land use changes. The sustainable water resources management plan should carefully consider competing interests of water use allocation to support local economies, protect the environment, and maintain and enhance land productivity. This can be achieved through policy empowerment of the collective efforts of producers, local decision-makers, and the general public.

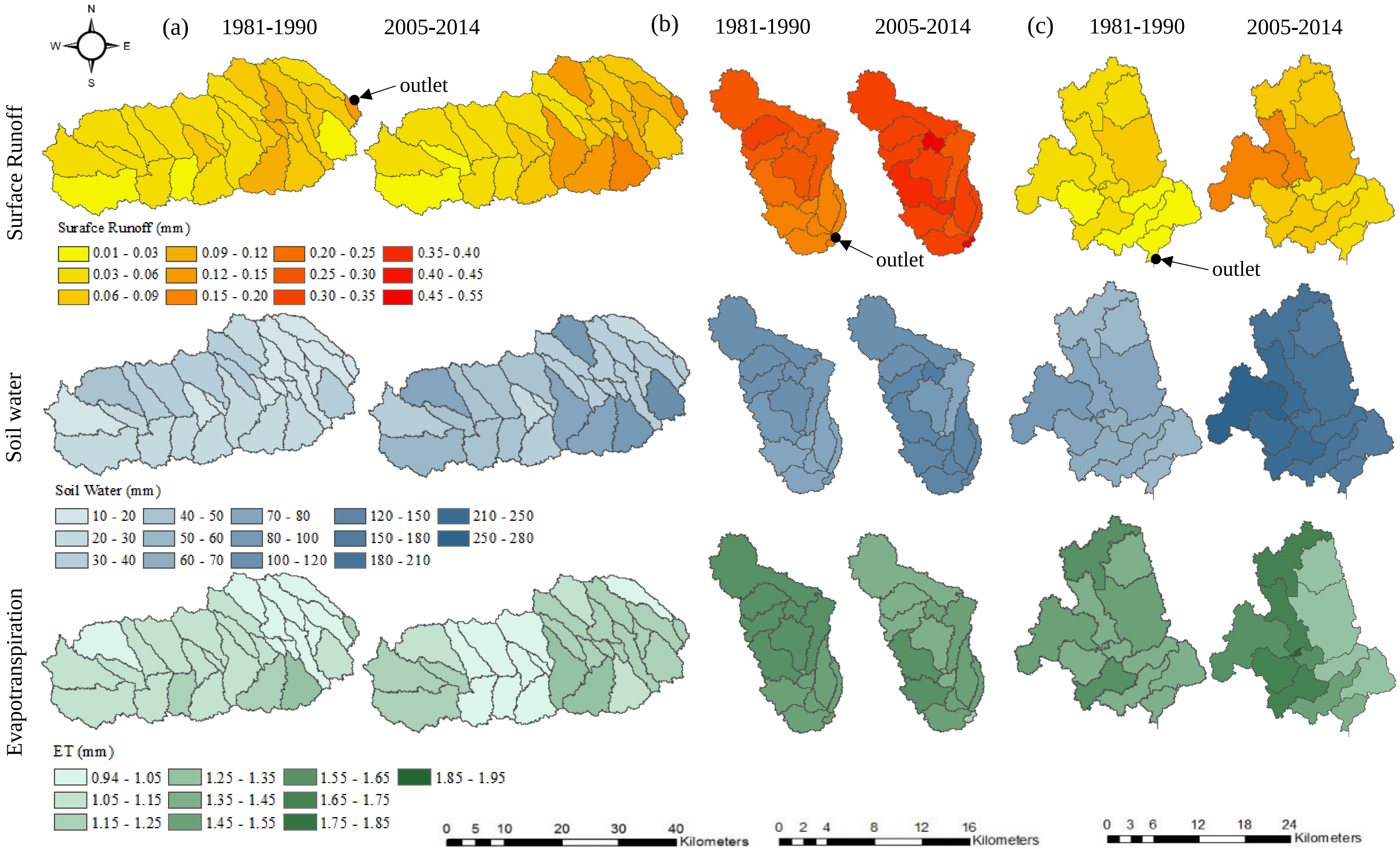


Figure 3. 10: Spatial Comparison of Watershed Balance Components between 1981-1990 and 2005-2014 Study Periods for (a) Bad River Watershed, (b) Skunk Creek Watershed, and (c) Upper Big Sioux River Watershed.

3.5 Conclusions

This study evaluated hydrologic changes under historical land use and climate observations in three watersheds (Bad River, Skunk Creek, and Upper Big Sioux River) in South Dakota. This study showed useful application of SWATShare, a cyber-enabled platform suitable for parallel execution of multiple large-scale SWAT models and intense computational tasks such as model calibration. Results obtained in this study provide some insight into hydrological response to variation in climate and land use change in South Dakota in recent decades. Based on the comparison of historical land use, climate and corresponding SWAT simulated hydrologic outputs for 1981-1990 and 2005-2014 time periods; the following conclusions can be drawn:

1. Bad River and Skunk Creek watersheds experienced grassland loss with subsequent expansion in agricultural and urban areas (1.4% and 5.2%, respectively); whereas, land use change in the Upper Big Sioux River watershed was mostly derived from expansion of wetlands (4.8%), rather than from direct land conversion as in the case of the other two watersheds. Gradual decrease in grassland is the common characteristic of land use change in all three watersheds.
2. Although climate change is not obvious from the precipitation analysis, climate variability appears with a slight precipitation increase in Bad River and Upper Big Sioux River watersheds during 2005-2014 relative to 1981-1990, while precipitation slightly decreased in the Skunk Creek watershed.
3. Comparison of watershed-scale average annual water budget components between the two decades indicates significant increase in soil water content and percolation along with slight increase in surface runoff and ET in Bad River and

Upper Big Sioux River watersheds. Higher water yield in Skunk Creek watershed during 2005-2014 compared to 1981-1990 corresponds to reduction in ET and substantial increase in surface runoff volume. Changes in water balance components shown in this study are likely driven by the combined effects of climate and land use change.

4. Analysis of seasonal variability pointed out a notable shift in elevated surface runoff in Skunk Creek and Upper Big Sioux River watersheds from June to March and from March to April, respectively, between the two time periods. Changes in ET for all three watersheds were distinctive in the summer growing season, while there was no significant variation between the two study periods (especially in Bad River and Upper Big Sioux River watersheds).
5. Based on the sub-basin scale spatial evaluation, downstream parts of both Bad River and Skunk Creek watersheds experienced increases in water balance components compared to upstream parts, while the increases were more evident in the western part of Upper Big Sioux River watershed.

Although loss of grassland and subsequent increase in agriculture area, urban development and wetland has been found as the common trend of land use change in South Dakota, this finding might be specific to the watersheds considered in this study. Similar analyses to include more watersheds or a large watershed covering the state would lead to a thorough understanding of changes in hydrologic processes in South Dakota. Considering the importance of agriculture and grassland in South Dakota’s economy, this study can be extended to examine the effects of grassland depletion and climate variability/change on water resources, including water quality, water footprint, future water security and sustainable water resources management.

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CHAPTER 4: IMPACTS OF LAND USE AND CLIMATE CHANGES ON HYDROLOGICAL PROCESSES IN JAMES RIVER WATERSHED

Abstract

This study evaluated the hydrological response to land use and climate changes in the James River watershed, using the Soil and Water Assessment Tool (SWAT) model. Calibration and validation of SWAT were performed using monthly streamflow for 1981-2000 and 2001-2014, respectively. The performance of the model was evaluated with Nash-Sutcliffe efficiency (NSE), determination of coefficient (R^2), and Percent Bias (PBIAS) which were 0.59, 0.59, and -2.64 during the calibration period, and 0.75, 0.81, and -12.1 during the validation period. Future land use and climate changes were investigated under three emission scenarios (A1B, A2, and B1) for the mid-century (2046-2065) and end of the century (2080-2099). Corresponding land use maps (2055 and 2090) were derived from the FOREcasting SCEnarios (FORE-SCE) model which showed noticeable agricultural expansion and grassland depletion compared to the baseline condition (National Land Cover Dataset 1992). Land use change projections showed an increase in streamflow (5.82% - 8.3% in 2055 and 11.9% - 18.5% in 2090) and surface runoff (6% - 8.8% in 2055 and 12.3% - 19.3% in 2090), and a decrease in evapotranspiration (about -0.16% in 2055 and from -0.5% to -0.1% in 2090), except under B1 scenario where evapotranspiration increased by 0.05% in 2055. Three emission scenarios of three general circulation models (CGCM3.1, GFDL-CM2.1, and HADCM3) were employed to generate future possible climatic conditions. Compared to the baseline condition, climate change scenarios showed an increase in precipitation (0.36% to 22.7%) and temperature (1.81°C to 4.46°C) for the three emission scenarios. Under climate

change conditions, changes in hydrology were noticeable; however, varying responses were observed across GCMs. For future possible climate changes, average annual streamflows vary from -14.5% to +96% in the mid-century and from -21.5% to +75% at the end of the century; surface runoff from -13.8% to +97% in 2046-2065, and from -20% to +75% in 2080-2099. Average annual ET can vary between 0.1% and 17.3%, and 3.6% and 17.1% in 2046-2065 and 2080-2099, respectively. The combination of potential climate and land use changes led to an increase in the streamflow (-9.9% - 104.5% in 2046-2065 and -12.9% - 96.7% in 2080-2090), surface runoff (-8.8% - 106.8% in 2046-2065 and -11.7% - 99.3% in 2080-2090), and evapotranspiration (0.2% - 17.3% in 2046-2065 and 3.4% - 16.8% in 2080-2090), where climate changes play a dominant role in impacting hydrology. The results highlight that climate and land use changes would influence hydrology in the James River watershed.

4.1 Introduction:

Land use and climate are both determinant factors that influence the global energy and water cycle (Dale, 1997; El-Khoury et al., 2015; Mahmood et al., 2010; Mishra et al., 2010). Over the years, global population, economy and energy consumption are increasing, and consequently driving changes in land use, land cover and climate (Lambin et al., 2001; Meyer and Turner, 1992). Theses changes affect the spatial and temporal distribution of water and water balance components within a watershed (Deng et al., 2015; Fang et al., 2013; Li et al., 2009; Memarian et al., 2014).

In the conterminous United States, land use changes due to government policy, economic conditions, technological innovation, and population movements (Arnell et al., 2004; Jacobson, 2011; Sohl et al., 2014; Wu et al., 2012c; Wu et al., 2013). During the last few decades, notable agricultural land use change in the Great Plains region has mainly been driven by increased global food demand, crop prices, biofuel demand and climate conditions (Babcock et al., 2007; Claassen et al., 2011; Schilling et al., 2008; Singh, 2013; Tilman et al., 2011; Wright and Wimberly, 2013). The major land use change in the Midwest states after mid-20th century consisted of grassland conversion to cultivated cropland for biofuels and biomass energy production (Schilling et al., 2008; Wu et al., 2012c). Xu et al. (2013a) assessed potential impacts of biofuel production on water resources based on long-term (1930s to 2010) streamflow analysis in 55 unregulated Midwest watersheds. The study revealed that watersheds with no significant trends in climate showed significant trends in streamflow, which indicates that land use changes may have an effect on streamflow processes.

Meanwhile, climate change has led to more frequent extreme events. Since the early 20th century, the global average temperature has increased approximately 1.4°F (NOAA, 2010). In South Dakota for example, temperature increased between 0.4 to 0.8 °F per decade and total annual precipitation increased between less than 0.6 to more than 1 inch over the last 70 years (DOI, 2015). According to future climate predictions, the air temperature will increase approximately from 1 to 5°C by 2100 throughout the US (IPCC, 2013; Johnson et al., 2015). Many studies have shown that global warming has led to an intensification of the global hydrological cycle (Huntington, 2006; Johnson et al., 2015; Melillo et al., 2014; Pervez and Henebry, 2015; Sample et al., 2015; Thodsen et al., 2016). These studies found that future climate changes may lead to alteration in both magnitude and frequency of streamflow. For example, Johnson et al. (2015) studied the effects of climate change on streamflow for 20 watersheds throughout the contiguous U.S. and Alaska; the results showed a decreasing pattern of streamflow in the central Rockies and Southwest, and an increasing pattern in the East Coast and Northern Plains.

Scenario-based simulation is commonly used by researchers to assess future land use and climate impacts on water resources (Kopytkovskiy et al., 2015; Li et al., 2015; Pervez and Henebry, 2015). A large number of studies evaluated hydrologic response to land use and climate change at global to regional scales (Chen and Yu, 2015; Driessen et al., 2010; Johnson et al., 2015; LaFontaine et al., 2015; Neupane and Kumar, 2015; Serpa et al., 2015; Wu et al., 2013; Zhang et al., 2016). These studies revealed that anticipated hydrologic changes may differ in different areas due to future shifts in precipitation and temperature. For example, surface runoff would decrease in semiarid regions and increased in wet tropical areas, while in northern and mountainous areas, an early spring and greater winter surface runoff is anticipated due to future changes in both precipitation and evapotranspiration (ET) (IPCC, 2014; Johnson et al., 2015; Melillo et al., 2014). Furthermore, surface runoff is expected to decrease as a result of lower precipitation, higher soil water deficits, and higher potential evapotranspiration under projected climate changes in the Mediterranean Basin (IPCC, 2013; IPCC, 2007; Serpa et al., 2015). In the Midwestern region, modeling studies were also conducted to investigate the impacts of land use and climate changes on hydrology (e.g., Jha and Gassman, 2014; Neupane and Kumar, 2015; Villarini et al., 2015; Wu et al., 2012b; Wu et al., 2012c). These studies used different methods, models and scenarios, including subjective land use and climate change scenarios. Recently, in climate change impact assessment studies, the General Circulation Models (GCMs) projections have been used for future climate change scenarios (Jha and Gassman, 2014; Neupane and Kumar, 2015; Zhang et al., 2016). GCMs predict climate changes based on greenhouse gas emission scenarios. These scenarios are based on different social, economic, technological and environmental development aspects which are known as -A1B, A2, B1, and B2. According to different emission scenarios, it is evident that increase in predicted temperature is consistent, but changes in predicted precipitation can vary (Jha and Gassman, 2014). For example, future projected precipitation increased in the Racoon River watershed in Iowa (Villarini et al., 2015), and Minnesota River in Minnesota (Johnson et al., 2015), while in the Big Sioux River watershed, annual precipitation decreased under all future scenarios modeled (Neupane and Kumar, 2015). This potential precipitation variability would have significant implications on water budgets and may lead to hydrological changes within the study watersheds. In the Raccoon River watershed, under A1B (medium emission), compared to the baseline condition (1996-2004), a net increase in future precipitation (0.7%) and temperature (2.78°C) resulted in decrease in baseflow (18%), surface runoff (16%), and water yield (17%), and rise in ET (8%) by the mid-21st century (Jha and Gassman, 2014). While under A2 (high emission) scenario, increased precipitation may lead to an increase in streamflow by the mid-21st century in the Northern Midwest (Minnesota River and Maumee River) (Johnson et al., 2015). A similar study in the Big Sioux River watershed found that despite decreasing trends in future precipitation, annual streamflow was estimated higher in all emission scenarios (A1B, A2, and B1). The study mentioned that potential higher groundwater may contribute to streamflow by routing a shallow aquifer storage component to the river (Neupane and Kumar, 2015).

While scenario analysis based on assumed land use and climate changes provides useful information about how these changes affect hydrology, estimation of the effects of potential land use and climate changes that are physically derived on hydrology is a superior technique for understanding the relation between regional hydrology, land use, and climate. Therefore, additional hydrologic impact studies that account for potential land use and climate changes are needed to support decision making for sustainable water management in the region. The objectives of this study were to 1) evaluate the effects of projected land use change with existing climate condition, 2) evaluate the effects of projected climate change scenarios with existing land use condition, and 3) assess the combined effects of future land use and climate projections on hydrological processes in a large watershed.

4.2 Materials and Methodology

4.2.1 Study Area

The James River is a tributary of the Missouri River that begins in North Dakota and flows into South Dakota (Figure 4.1). The James River watershed outlet (USGS gauge number 06478500) is situated near Scotland, SD. The watershed has a drainage area of approximate 53443 km^2 (USGS Hydrologic Unit Code 10160011). Based on NLCD 1992, the land use is primarily dominated by agricultural land (51.7%); the remaining area consists of hay, grassland, water, forest, and urban (Table 4.7). The James River watershed is located in the semiarid Northern Great Plains ecoregion, where average annual temperature is 6.9 °C with minimum and maximum of -16.1 and 30.8 °C during January and July months, respectively (SDSU, 2003). Annual precipitation varies from 500 to 660 mm in this watershed with an average of 457 mm (18 inches) (SDSU, 2003). Geologically, the James River watershed is composed of glacier till over Cretaceous Pierre Shale and sandstone of Niobrara formations in lowland and Fox Hills formation in drift plains. Soils in the watershed are mainly mollsoils and consists of a heterogeneous mixture of silt, clay, sand and gravel (USDA, 2009).

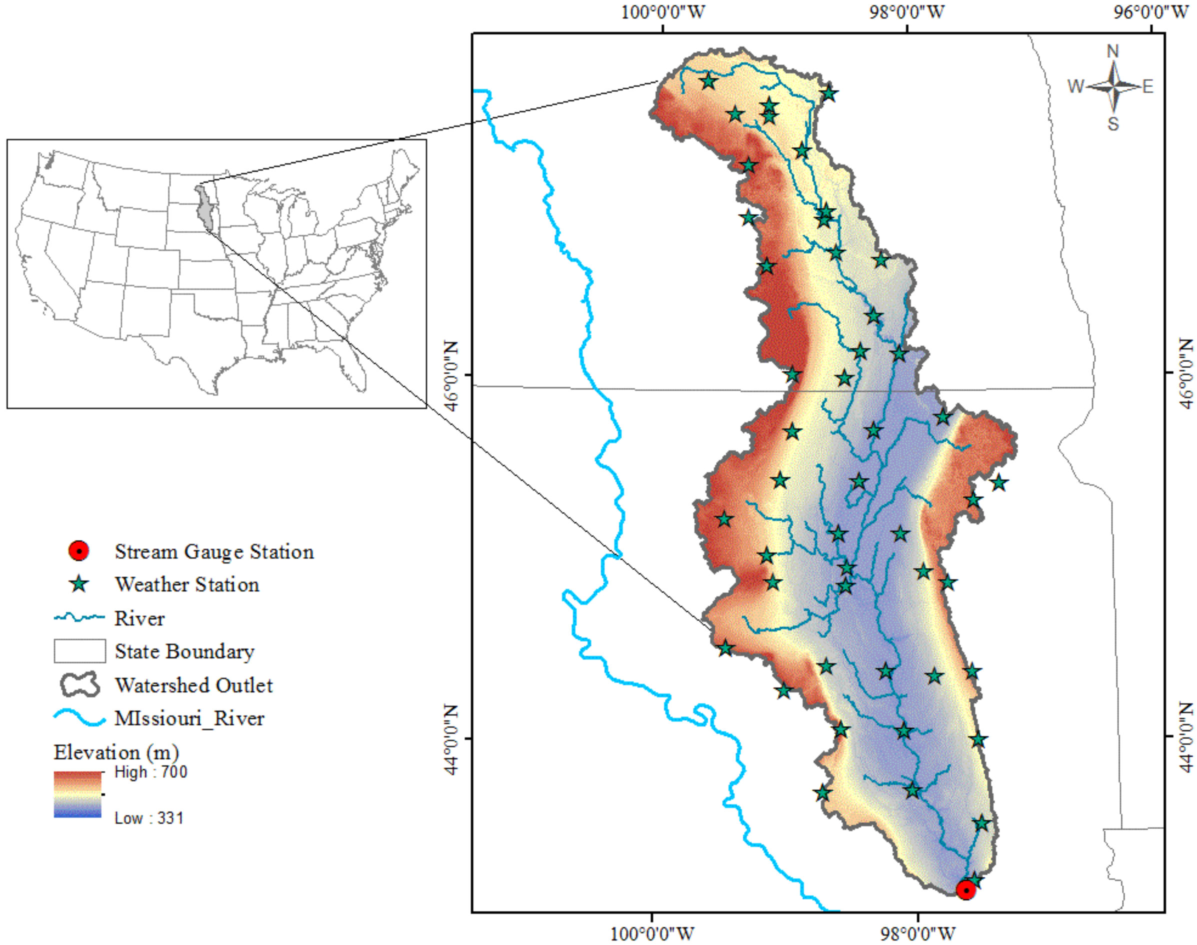

Figure 4. 1: Location of the James River watershed with selected weather stations and United States Geological Survey's Streamflow Gauge Stations.

4.2.2 Hydrologic Model

In this study, the Soil and Water Assessment Tools (SWAT; Arnold et al., 1998) model was used to assess the climate and land use change impacts on hydrology. SWAT was developed to evaluate the impact of climate and land management practices on water in large and complex watersheds with varying land use, soils and management conditions over long periods of time (Arnold et al., 1998). The hydrological parts of the model are based on the water balance equation in the soil profile with processes including precipitation, surface runoff, water yield, ET, lateral flow, percolation, and groundwater flow (Arnold et al., 1998; Neitsch et al., 2005). The water balance equation of the model (Neitsch et al., 2011) is as follows:

$$SW_t = \mathrm{SW_o} + \sum_{n=i}^{t}(\mathrm{P} - Q_{surf} - \mathrm{ET} - w_{seep} - Q_{gw})$$

where SW is the change in soil water storage, P is the precipitation, ET is the evapotranspiration, Q_{surf} is the surface runoff flow, Q_{gw} is the groundwater flow, and w_{seep} is the deep aquifer recharge. Surface runoff is determined through the modified Soil Conservation Service (SCS) Curve Number (CN) method (Arnold et al., 1998; Neitsch et al., 2011; Wu et al., 2012c). The Penman-Monteith method (Monteith, 1965) was used to estimate the potential evapotranspiration (PET).

For water budget, SWAT differentiates the solid and liquid precipitation based on near-surface air temperature. If the air temperature is lower than snowfall temperature, then the precipitation is considered solid (i.e. snow), which will accumulate until melt (Grusson et al., 2015). In SWAT, snowmelt in the model was estimated through mass balance approach:

$$SNO = SNO + R_{day} - E_{sub} - SNO_{mlt}$$

where SNO is the total amount of water in snowpack on a given day (mm H_2O), E_{sub} is the amount of sublimation (mm H_2O), and SNO_{mlt} is the amount of snowmelt (mm H_2O). Changes in snowpack volume depend on additional snowfall or release of meltwater in the basin. A more comprehensive description of the equation used by SWAT can be found in Neitsch et al. (2011).

4.2.3 Input Data

The SWAT model requires data for topography, land use, soil, weather/climate and stream discharge. In this study, a 30 m resolution digital elevation model (DEM) data derived from the USGS National Elevation Dataset (USGS-NED, 2013) was used to delineate the watershed boundary. Daily precipitation, daily maximum temperature, and daily minimum data for a period of 1978-2014 were obtained from the National Climatic Data Center (NCDC) website for 47 weather stations (Figure 4.1). A 30 m land use dataset from the National Land Cover Database (NLCD) 1992 was used. The multiple Hydrological Response Unit (HRU) option was used to represent the soil and land uses types, where a single HRU represents a unique combination of land use and soil type. This watershed was discretized into 6041 HRUs in 86 subbasins.

4.2.4 Calibration and Validation

The SWAT model was calibrated based on NLCD 1992 and observed monthly streamflow at the USGS 06478500 near Scotland, SD for 1978-2000 period, where the initial 3 years (1978-1980) were used as a warm-up period. A set of 19 parameters representing the land surface, sub-surface, channel routing and snow melt processes was used to calibrate the base model parameters; their initial value ranges (Tables 4.1) were selected based on the review of existing literature on nearby Midwestern agricultural watersheds (e.g., Folle, 2010; Jha et al., 2007; Neupane and Kumar, 2015) and suggestions from model developers (Abbaspour et al., 2015; Neitsch et al., 2011). After model calibration, an additional 14 years (2001-2014) were used for model validation. The SWAT-CUP (Abbaspour et al., 2007; Abbaspour, 2007) was used to calibrate and validate the model. Nash-Sutcliffe Efficiency (NSE), percentage of bias (PBIAS) and coefficient of determination (R^2) were used as objective function to assess the agreement between simulated and observed streamflow hydrographs.

$$\text{NSE} = 1 - \frac{\sum(Y^{obs} - Y^{sim})^2}{\sum(Y^{obs} - Y^{mean})^2}$$

$$\text{PBIAS} = \frac{\sum(Y^{obs} - Y^{sim}}{\sum Y^{obs}} \text{x}\, 100$$

$$\text{R2} = (\frac{\sum(Y^{obs} - Y^{mean})\sum(Y^{sim} - Y^{mean})}{\sqrt{(Y^{obs} - Y^{mean})^2}\sqrt{(Y^{sim} - Y^{mean})^2}})^2$$

where Y^{obs} is the observed data, Y^{sim} is the simulated output, and Y^{mean} is the mean of observed data. A NSE value that falls between 0 and 1 is considered an acceptable level of performance (Moriasi et al., 2007). The PBIAS is used to measure the average deviation of simulated outputs from observed values and 0 is considered as ideal value (Gupta et al., 1999). A positive PBIAS value shows an underestimation of the simulated variables compared to the observed variables and vice versa. Moreover, R^2 was used to analyze the goodness of fit of the calibration, with 1 as the ideal value. The mode performance is considered as satisfactory when NSE > 0.5 and PBIAS < ±15% (Moriasi et al., 2007).

Table 4. 1: List of Parameters Used for Model Calibration for the Study Watershed.

No.	Parameter	Definition[a]	Scale of input	Adjustment[b]	Initial range	Optimal Values
1	ALPHA_BF	Baseflow recession constant (days)	Watershed	1	0.01-1	0.581
2	CANMX	Maximum canopy storage (mm H_2O)	HRU	1	0.01-25	19.877
3	CH_K(2)	Main channel hydraulic conductivity (mm/hr)	Reach	1	5-100	51.266
4	CH_N(2)	Main channel Manning's *n*	Reach	1	0.01-0.15	0.114
5	CN2	Curve number for moisture condition II	HRU	3	-20-20	-0.023
6	EPCO	Plant uptake compensation factor	HRU	1	0.75-1	0.791
7	ESCO	Soil evaporation compensation factor	HRU	1	0.75-1	0.575
8	GW_DELAY	Groundwater delay (days)	Watershed	2	-10-10	-8.420
9	GW_REVAP	Groundwater "revap" coefficient	Watershed	1	0.01-0.20	0.059
10	GWQMN	Threshold groundwater depth for return flow (mm H_2O)	Watershed	1	0.01-5000	1494.6
11	REVAPMN	Re-evaporation threshold (mm H_2O)	Watershed	1	0.01-500	446.6
12	SFTMP	Snowfall temperature (^oC)	Watershed	1	0-5	2.336
13	SMFMN	Melt factor for snow on December 21 (mm H_2O/ ^oC-day)	Watershed	1	0-10	9.662
14	SMFMX	Melt factor for snow on June 21 (mm H_2O/ ^oC-day)	Watershed	1	0-10	7.602
15	SMTMP	Snow melt base temperature (^oC)	Watershed	1	-2-5	4.195
16	SOL_K	Soil saturated hydraulic conductivity (mm/hr)	HRU	3	-15-15	0.334
17	SOL_AWC	Available soil water capacity (mm H_2O/mm soil)	HRU	3	-15-15	0.202
18	SURLAG	Surface runoff lag coefficient (days)	Watershed	1	0.05-24	6.444
19	TIMP	Snow pack temperature lag factor	Watershed	1	0-1	0.240

[a] Source: Neitsch et al., 2001

[b]Type of change to be applied to the existing parameter value: '1' means the original value is to be replaced by a value from the range, '2' means a value from the range is added to the original value, '3' means the original value is multiplied by the adjustment factor (1+ given value within the range).

4.2.5 USGS Land use model

This study used the FOREcasting SCEnarios (FORE-SCE) model to generate the future land use scenarios. The FORE-SCE model was developed by the United State Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center to provide spatially explicit detailed projections of plausible future land use and land cover (LULC) change for the conterminous United States (Sohl et al., 2014; Sohl et al., 2012). Four scenarios of LULC were developed based on the Intergovernmental Panel on Climate Change (IPCC) Special Repot on Emission Scenarios (SRES) (Sohl et al., 2014). The FORE-SCE model produced the scenarios from 1992 through 2100 using 1992 National Land Cover Datasets (NLCD) (Sohl et al., 2014; Vogelmann et al., 2001; Wu et al., 2013). In this study, future LULC for A1B, A2 and B1 scenarios of 2055 and 2090 were extracted from http://landcover-modeling.cr.usgs.gov/. The LULC raster datasets were reclassified into 13 classes at 30 m spatial resolution to maintain the consistency with baseline NLCD 1992 datasets.

4.2.6 Future Climate Scenarios

It is documented that future climate impact analysis involves large uncertainties (e.g., Bastola et al., 2011; Chiew et al., 2010; Jha and Gassman, 2014; Teng et al., 2012; Xu et al., 2013b; Zhang et al., 2016). These uncertainties are due to several factors including different types of GCMs, different emission scenarios, different downscaling methods and bias correction method, hydrologic modeling setup, etc. (Forbes et al., 2011; Jha and Gassman, 2014; Jha et al., 2015; Jin and Sridhar, 2012). Therefore, three emission scenarios (A1B, A2, and B1) were selected under three GCMs (CGCM3.1, GFDL-CM2.1, and HADCM3) from different sources (Tables 4.2 and 4.3) to assess possible future climate change and its impacts on hydrological processes. The climate change projections considered in this study were obtained from the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (AR4) (Meehl et al., 2007). The GCMs selected in this study are: a) CGCM3.1 from the Canadian Centre for Climate Modeling and Analysis version 3.1 (Flato et al., 2000; Scinocca et al., 2008), b) GFDL-CM2.1 from the Geophysical Fluid Dynamics Laboratory version CM2.1 (Delworth et al., 2006; Delworth et al., 2012; Stouffer et al., 2006), and c) HadCM3 from the Hadley Centre for Climate Prediction and Research/ Met Office (Gordon et al., 2000; Mitchell et al., 1998; Pope et al., 2000) (Table 4.2). These three GCMs were selected based on their ability to represent: (1) fine and coarse spatial grid resolution, (2) realistic regional precipitation, and (3) variable sensitivity to greenhouse gases (Shamir et al., 2015; Sinha and Cherkauer, 2010). Under each GCM, three emissions scenarios were considered, which are B1, A1B, and A2 based on the Special Report on Emission Scenarios (SRES) (Table 4.3) (Nakicenovic and Swart, 2000).

The bias corrected monthly precipitation and temperature, available at 1/8th degree spatial scale (~12 km by 12 km), for the three selected GCMs were obtained from the Lawrence Livermore National Laboratory (LLNL)-Reclamation-Santa Clara University (SCU) downscaled climate projections which were originally derived from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset, stored and served at the LLNL Green Data Oasis (Maurer et al., 2007). To implement the SWAT hydrologic model, monthly precipitation and temperature time series were statistically disaggregated to daily series using the Kernel-Nearest Neighbor (KNN) algorithm (Prairie et al., 2007). The details of the disaggregation scheme are described in Sinha and Sankarasubramanian (2013), but a brief description is provided for clarity. The K-NN scheme classifies future climate monthly time series into daily time series by assigning different weights to similar monthly conditions in the historical time period based on the Lall and Sharma kernel (Lall and Sharma, 1996). Thus, higher weights were given to the daily time series of the statistically closest neighbors to obtain a single daily time series (Sinha and Sankarasubramanian, 2013).

Table 4. 2: CMIP3 model description and origins.

Model	Center	Country	Spatial Resolution		Reference
			Latitude	Longitude	
CGCM3.1	Canadian Centre for Climate Modeling and Analysis	Canada	3.75°	3.7°	Flato et al., 2000; Scinocca et al., 2008
GFDL-CM2.1	Geophysical Fluid Dynamics Laboratory	USA	~2°	2.5°	Stouffer et al., 2006; Delworth et al., 2006, 2012
HadCM3	Hadley Centre for Climate Prediction and Research/ Met Office	UK	2.5°	3.75°	Mitchell et al., 1998; Gordon et al., 2000; Pope et al., 2000

Table 4. 3: Description of the scenarios considered in the study (Nakicenovic, et al., 2000).

Emission scenarios	Data set	Description of scenario
B1	550 ppm CO_2 maximum	A convergent world with the same global population but with rapid changes in economic structures towards a service and information economy with reductions in material intensity, and the introduction of clean and resource-efficient technologies
A1B	720 ppm CO_2 maximum	A future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies with the development balanced across energy sources
A2	850 ppm CO_2 maximum	A very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines

4.2.7 Simulation Scenarios

In this study, 42 scenarios were defined and used to examine hydrological variations resulting from future climate and land use changes. All future land use and climate change scenarios were developed to represent mid (2046-2065) and end (2080-2099) of the 21st century. Three emission scenarios A1B (medium), A2 (high) and B1 (low) were selected based on the different concentration of CO_2 gas emission. In SWAT, four baselines were defined with NLCD 1992 land use data along with historical climate data for a period of 1981-2000 that covers the baseline land use map. One baseline model was constructed with historical climate data obtained from NCDC website and the other three were constructed with GCM's historical data (1981-2000). Each baseline model was used to analyze the corresponding future GCMs outputs (Table 4.4a).

To examine the land use change impact on hydrology, land use data were changed under a constant climate condition (Table 4.4b). Three emission scenarios (A1B, A2, and B1) under two FORE-SCE land use (2055 and 2090) were used to represent six future land use conditions. Each simulation was conducted independently while keeping the hydrological parameters of the baseline model unchanged, and model outputs were generated on a yearly basis.

Similarly, future climate change scenarios were developed for the mid-century (2046-2065) and end of the century (2080-2099) to represent two discrete future conditions. Projected and downscaled precipitation and temperature from each GCMs (Table 4.2) and emission scenarios (Table 4.3) were used in SWAT model under a constant land use (NLCD 1992) condition while the remaining of the model configuration (i.e., HRUs and subbasin parameters) was kept constant. Thus, 18 scenarios in total were developed for future climate change impact assessment (Table 4.4c). The results were then compared with the baseline condition of each GCM (Table 4.4a).

To assess the combined effects of future land use and climate changes, future land use data were used under corresponding climate condition and the remaining of the model configuration (i.e., HRUs and subbasin parameters) was kept constant (Table 4.4d). The scenarios were designed in a way that, land use scenarios followed the same storylines as climate change scenarios (Table 4.4d). As an example, for the mid-century, 2055 land use was used with (2046-2065) projected climate within the same emission scenarios (e.g., A1B). This approach ensured the consistency between land use and climate changes, and a total of 18 scenarios were evaluated.

Table 4. 4a: Baseline scenarios for future land use and climate change conditions.

Baseline Scenario			
Simulation Period	**Climate Data**	**Land Use Data**	**Remarks**
1981-2000	NCDC Observed data	NLCD-1992	Baseline model for future land use scenarios
	GCM-1 data		Baseline model for future climate change scenarios
	GCM-2 data		
	GCM-3 data		

Table 4. 4b: Scenarios for the future projected land use change evaluation with existing climate condition.

Land Use Scenarios (constant climate and variable land use)			
Simulation Period	**Climate Data**	**Land Use**	**IPCC-SRES**
1981-2000	NCDC Observed data	USGS-2055	A1B
			A2
			B1

		USGS-2090	A1B
			A2
			B1

Table 4. 4c: Scenarios for the future projected climate change evaluation with existing land use condition.

Climate Scenarios (constant land use and variable climate)			
Simulation Period	**Climate Data**	**Land Use**	**IPCC-SRES**
2046-2065	GCM-1 data	NLCD-1992	A1B
			A2
			B1
2080-2099			A1B
			A2
			B1
2046-2065	GCM-2 data		A1B
			A2
			B1
2080-2099			A1B
			A2
			B1
2046-2065	GCM-3 data		A1B
			A2
			B1
2080-2099			A1B
			A2
			B1

Table 4d: Scenarios for the assessment of combined effects of future projected climate and land use changes.

Future Scenarios (combined land use and climate change)			
Simulation Period	**Climate Data**	**Land Use**	**IPCC-SRES**
2046-2065	GCM-1 data	USGS-2055	A1B
			A2
			B1
2080-2099		USGS-2090	A1B
			A2
			B1
2046-2065	GCM-2 data	USGS-2055	A1B

			A2
			B1
2080-2099		USGS-2090	A1B
			A2
			B1
2046-2065	GCM-3 data	USGS-2055	A1B
			A2
			B1
2080-2099		USGS-2090	A1B
			A2
			B1

4.3 Results and Discussions

4.3.1 Hydrological Model Calibration and Validation

During model calibration, hydrologic parameters were varied within their recommended ranges to match the simulated streamflow with the observed streamflow. The optimum parameter values are listed in Table 4.1. The simulated average monthly streamflow of 29.02 m^3/s was close to the observed monthly average (32.85 m^3/s). Performance evaluation (R^2, NSE and PBAIS values) of the SWAT model for monthly and annual simulations are shown in Table 4.5. The monthly R^2 and NSE at the outlet were 0.59 and 0.59 during the calibration period; while the values were 0.52 and 0.50 for R^2 and NSE, respectively during the validation period. The hydrographs of observed and simulated streamflow for calibration and validation indicate that the SWAT model can simulate both the monthly and annual streamflow of the James River watershed very well (Figure 4.2). The SWAT model showed better performance on annual basis during the calibration period with 0.81, 0.75, and -12.1 for R^2, NSE, and PBIAS, respectively (Table 4.5). Over the calibration period (1981-2000), the simulated average annual streamflow was 33.9

m^3/s, which was close to observed values (39.3 m^3/s) at the watershed outlet. All the statistical results (Table 4.5) showed a good correlation based on model calibration criteria suggested by Moriasi et al. (2007).

Table 4. 5: Calibration and validation statistics at the outlet of James River watershed.

	Simulation period	**R^2**	**NSE**	**PBIAS**
Monthly	Calibration for (1981-2000)	0.59	0.59	-2.64
	Validation for (2001-2014)	0.52	0.5	29.1
Annual	Calibration for (1981-2000)	0.81	0.75	-12.1
	Validation for (2001-2014)	0.87	0.76	16.51

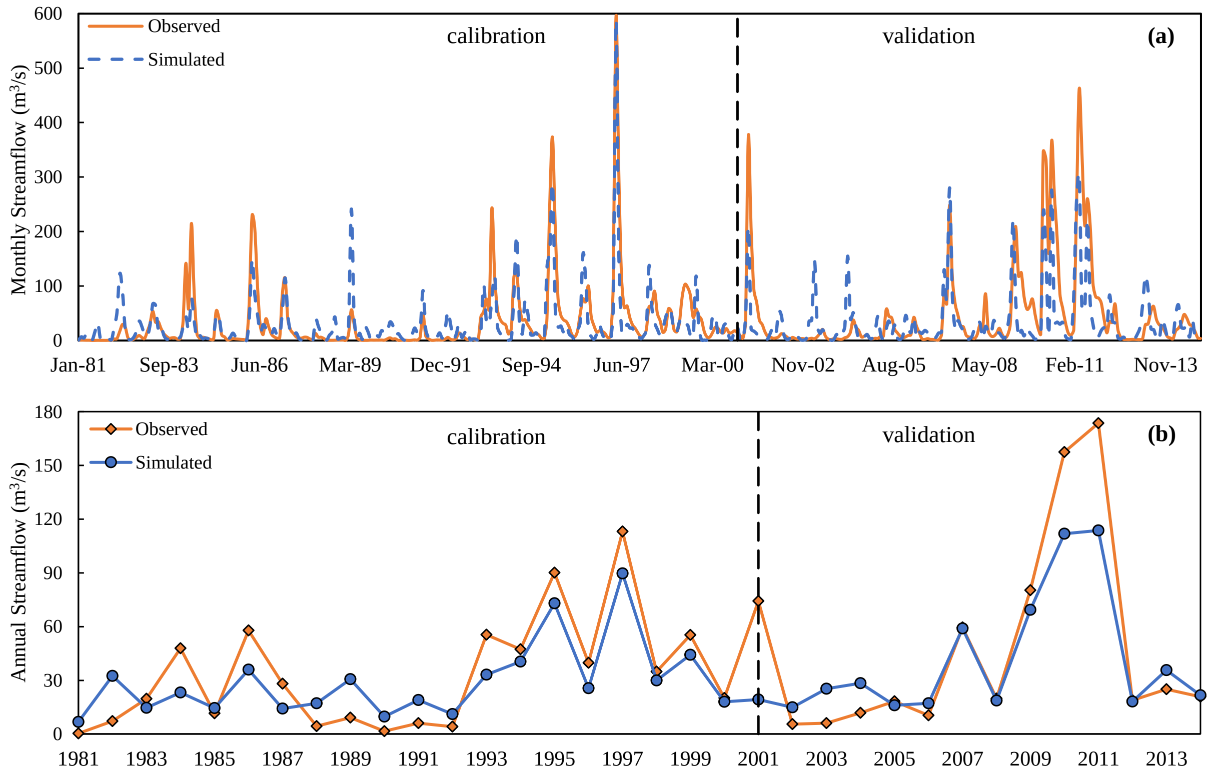

Figure 4. 2: Comparison of observed and simulated a) monthly and b) annual streamflow during the calibration and validation periods at the outlet of James River watershed.

4.3.2 Baseline Scenario

The calibrated model was used to simulate water budget components for the baseline condition (i.e. 1981-2000 period) with observed (i.e. NCDC) data (Figure 4.3 and Table 4.6). Annual precipitation varied from 400.7 mm to 707.1 mm, and annual streamflow varied between 0.4 m^3/s and 113.2 m^3/s, with an average of 32.72 m^3/s (Table 4.6). The years 1995 and 1997 had the highest streamflow (90.1 m^3/s and 113.2 m^3/s, respectively) and surface runoff (24.1 mm and 53.4 mm, respectively) due to high precipitation. From 1988 to 1992, incident precipitation was relatively lower (400.4 - 581.7 mm) than precipitation in the rest of the study period, resulting in comparatively low streamflow and surface runoff, which varied from 5.5 mm to 53.4 mm. Annual ET varied from 373.3 in 1988 mm to 664.6 mm in 1986, with a pattern that followed variation in precipitation (Figure 4.3).

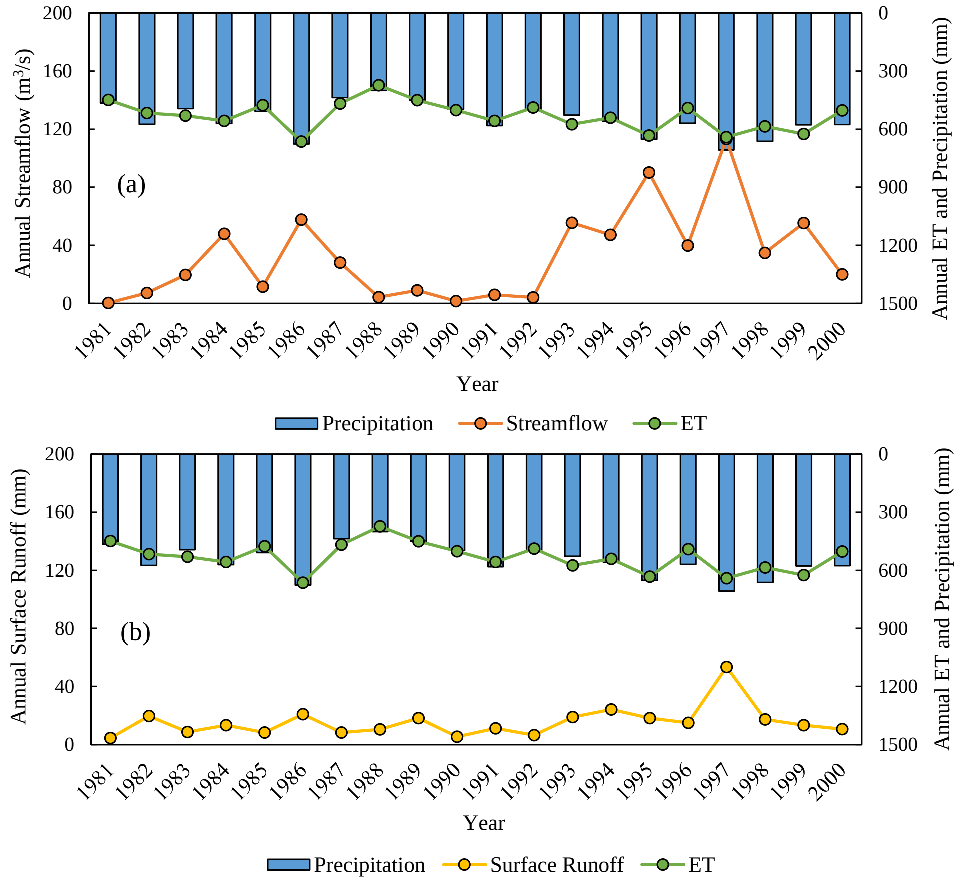

Figure 4. 3: Annual precipitation, ET, streamflow (a), and surface runoff (b) for the baseline condition (1981-2000 period). Values were computed with NCDC data.

Table 4. 6: Predicted water budget components (computed with NCDC data) of the James River watershed for the baseline condition (1981-2000 period).

Year	Precipitation (mm)	Streamflow (m^3/s)	Surface Runoff (mm)	Lateral Flow (mm)	Groundwater flow (mm)	Percolation (mm)	Soil Water (mm)	ET (mm)	Water Yield (mm)
1981	465.3	0.4	4.6	0.5	0.0	0.7	34.1	449.1	4.9
1982	575.4	7.3	19.7	0.6	0.0	1.3	80.8	517.0	19.7
1983	494.4	19.7	8.6	0.5	0.3	0.9	30.0	530.0	9.1
1984	570.3	47.9	13.4	0.7	0.5	1.8	37.0	557.6	14.1
1985	508.4	11.6	8.4	0.4	0.5	0.7	30.8	476.8	9.0
1986	676.1	57.8	20.9	0.9	0.8	3.1	57.0	664.6	21.9
1987	437.3	28.1	8.3	0.4	0.3	0.7	13.9	467.6	8.7
1988	400.7	4.4	10.4	0.4	0.4	0.7	29.5	373.3	10.8
1989	450.7	9.1	18.2	0.5	0.5	0.8	25.2	451.1	18.5
1990	498.1	1.6	5.5	0.5	0.6	0.9	13.7	501.9	6.3
1991	581.7	6.0	11.2	0.7	0.7	1.2	36.0	557.2	12.0
1992	497.3	4.1	6.5	0.4	0.4	0.7	31.8	488.8	7.0
1993	707.1	55.5	18.9	1.0	0.8	8.0	51.8	641.5	20.0
1994	558.9	47.3	24.1	0.7	0.6	2.0	71.6	541.0	24.7
1995	652.4	90.1	18.3	0.8	0.7	5.7	64.8	633.3	19.1
1996	569.0	39.8	15.0	0.5	0.5	1.2	83.7	490.9	15.5
1997	527.9	113.2	53.4	0.5	0.4	2.2	37.6	574.4	53.4
1998	662.4	34.9	17.4	0.8	0.7	1.5	94.9	585.7	18.2
1999	577.0	55.4	13.4	0.9	0.6	2.0	37.2	624.8	14.4
2000	575.7	20.1	10.7	0.5	0.6	1.0	55.7	503.2	11.4
Average	549.3	32.7	15.3	0.6	0.5	1.9	45.9	531.5	15.9

4.3.3 Future Land use Changes

Projected LULC for 2055 and 2090 from the FORE-SCE model was used to assess the potential land use change impacts on the hydrology of LULC changes by mid-century and end of the century under the IPCC-SRES A1B, A2, and B1 scenarios. The absolute (km^2) and relative (%) changes in each land use class for 2055 and 2090 for A1B, A2, and B1 scenarios are listed in Table 4.8. The future land use (2055 and 2090) projections and changes under different emission scenarios were evaluated (Figure 4.4) compared to the baseline land use condition (Table 4.7). Under the A1B scenario, which represents strong fuel demand and high technological innovation, agricultural land showed an increasing trend by 11.6% (320043.9 km^2) and 19.5 % (538617.3 km^2) in 2055 and 2090, respectively. B1 scenario also showed an agricultural land use expansion (Figure 4.4) but with lower magnitude (Table 4.8) compared to the other two scenarios due to less food demand in B1 scenario (Sohl et al., 2012). The highest agricultural land use expansion (26.1%) was projected under A2 emission scenario by 2090. A2 scenario assumptions of higher population pressure and lower biofuel demand compared to A1B scenario (Sohl et al., 2012) resulted in more agricultural land use expansion. As a result, A2 scenario showed a hay/pasture depletion by -0.3% (4,674 km^2) and -2.9% (63,901 km^2) while A1B scenario showed an expansion of hay/pasture by 7.4% (108,664.9 km^2) and 10.6% (155,368.8 km^2) in 2055 and 2090, respectively. Maximum hay/pasture depletion was found under more environmentally oriented B1 scenario by -4.4% (63,901.2 km^2) and -8.6% (125,629 km^2) in 2055 and 2090, respectively (Figure 4.4). Additionally, a substantial decrease in grassland was projected under all emission scenarios mainly due to its conversion to agricultural land use and hay/pasture (Table 4.8) (Sohl et al., 2012;

Wu et al., 2013). Maximum grassland depletion was predicted to be 48.9% (407922 km^2) and 78.6% (655194 km^2) for A1B scenario in 2055 and 2090, respectively.

Other land use classes (water, forest, and urban) cover less than 5.5% of the watershed in baseline condition and remain almost unchanged in the future (2055 and 2090). A1B and A2 scenarios showed a small decreasing trend in water and wetlands, while B1 scenario showed expansion in both 2055 and 2090 (Figure 4.4). Similar to water and wetlands, forest area slightly decreased in A1B and A2 scenarios and increased in B1 scenario in both 2055 and 2090 (Table 4.8). Forest area covered 0.9% of the watershed area in the baseline condition and remains nearly unchanged under different scenarios by mid-century and end of the century (Table 4.8 and Figure 4.4). Urban area covered only 0.4% of the watershed area in the baseline condition and expanded under all emission scenarios, but greater expansion was clearly noticeable for the highly populated A2 scenario with a maximum increase of 54.2% and 100% in 2055 and 2090, respectively. Overall, according to the FORE-SCE model predictions, all the scenarios showed similar patterns for agricultural land, urban area, and grassland although the magnitude of losses and gains differed with the scenarios.

Table 4. 7: Land use classes in the study watershed based on NLCD 1992 (Baseline scenario).

Land Use	Area (10^3 km^2)	% of Watershed Area
Agricultural land	27.65	51.7
Hay/ Pasture	14.65	27.4
Grassland	8.33	15.6
Water	2.17	4.1
Forest	0.5	0.9
Urban	0.2	0.4

Table 4. 8: Relative (%) and absolute (103 km2) changes from baseline under A1B, A2 and B1 scenarios for 2055 and 2090.

Land use	*Agricultural land*	*Hay/ Pasture*	*Grassland*	*Water*	*Forest*	*Urban*
2055 (A1B)	11.6 % (3.2)	7.4 % (1.1)	-48.9 % (-4.1)	-13.9 % (-0.3)	-1.4 % (-0.007)	31.5% (0.07)
2055 (A2)	7.6 % (2.1)	-0.3 % (-0.05)	-23 % (-1.9)	-12.6 % (-0.29)	-1.6% (-0.007)	54.2% (0.12)
2055 (B1)	6.8 % (1.9)	-4.4 % (-0.6)	-25.6 % (-2.1)	38 % (0.8)	1.6 % (0.007)	11 % (0.02)
2090 (A1B)	19.5 % (5.4)	10.6 % (1.6)	-78.6 % (-6.6)	-23.9 % (-0.5)	-3.1% (-0.01)	52.6 % (0.1)
2090 (A2)	26.1 % (7.2)	-2.9 % (-0.4)	-75.1 % (-6.3)	-36.3 % (-0.8)	-6.7 % (-0.03)	100 % (0.2)
2090 (B1)	20.5 % (5.7)	-8.6 % (-1.3)	-65.5 % (-5.5)	45 % (1)	1.2% (0.005)	17% (0.04)

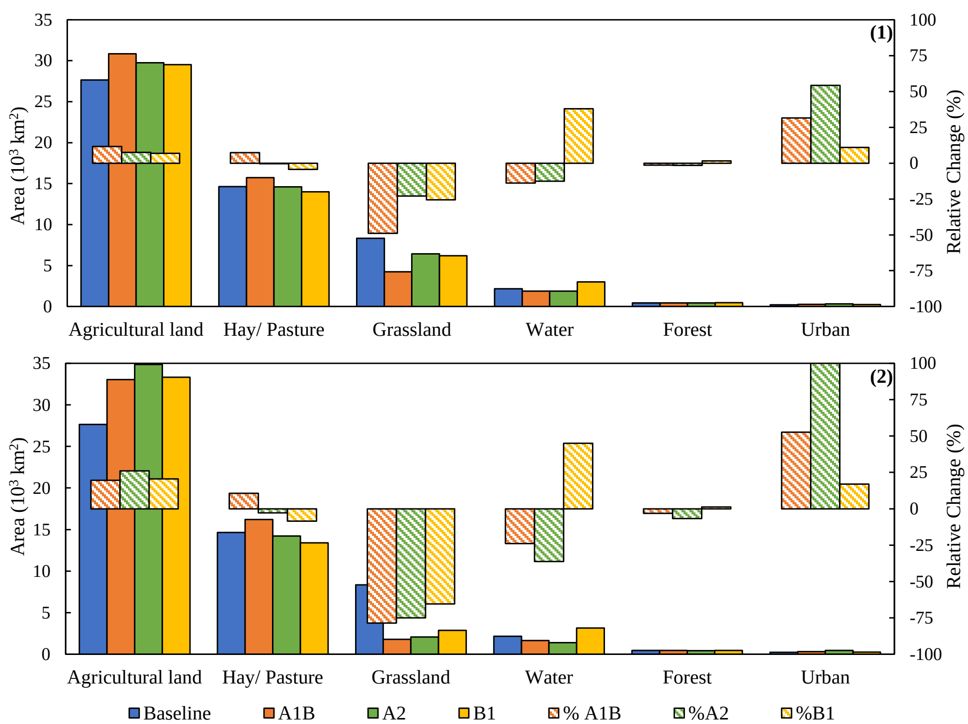

Figure 4. 4: Major land use areas for 1) 2055 and 2) 2090 and their relative changes from baseline (NLCD 1992) under the A1B, A2, and B1 scenarios.

4.3.4 Future Climate Projections

Variation of the average annual precipitation and daily maximum and minimum temperatures for baseline and future study periods (2046-2065 and 2080-2099) are illustrated through boxplots in Figure 4.5, 4.6a and 4.6b. Each boxplot was created with the median, the lower (25%) and the upper (75%) quartile, and the minimum and maximum values of the data. The absolute differences of minimum, median and maximum values between baseline and future scenarios are listed for annual precipitation and daily maximum and minimum temperature in Table 4.9, 4.10a and 4.10b. Each boxplot is based on the 20 years simulation period for each scenario.

4.3.5 Future Precipitation Projections

Variation of GCM projections clearly demonstrated that climate predictions were not uniform in the direction and magnitude of changes for both future study periods (2046-2065 and 2080-2099) (Figure 4.5). The statistical distribution of average annual precipitation of the baseline scenarios (observed and three GCMs) varied across the GCMs compared to the observed condition (Figure 4.5-i). The mean annual precipitation of the GCMs showed a deviation range from -70 mm to 11 mm from the observed condition (NCDC 1981-1990) (Figure 4.5-i). Since precipitation determines water availability in a watershed, precipitation variation may affect the average annual discharge, and thus, causes change in the water balance components compared to the baseline hydrological model prediction. Variation in precipitation was observed among the GCMs in each emission scenario (Figure 4.5-ii and 4.5-iii). Increased average annual precipitation was predicted with all GCMs under the three emission scenarios, except under B1 scenario in HADCM3 (Table 4.9). Under the A1B emission scenario, mean annual precipitation increased from 8 mm to 125 mm in the mid-century and from 41 mm to 102 mm at the end of the century compared to the baseline condition (Table 4.9). Similarly, under A2 emission scenario, mean annual precipitation may vary between 114 mm to 30 mm and 103 mm to 11 mm in the mid-century and end of the century, respectively. However, compared to the baseline condition, minimum precipitation change was demonstrated under B1 scenario with a range of -12 mm to 44 mm in 2046-2065, and 21 mm to 97 mm in 2080-2099. Although there is no clear pattern of average annual precipitation among the emission scenarios, all future projections indicate an increasing trend of different magnitude, except for the HADCM3 in B1 scenario for the 2046-2065 period (Table 4.9). Among the three GCMs, the maximum increase in precipitation (from 44 to 125 mm) was estimated by the CGCM3.1, while the minimum precipitation change (from -12 to 41 mm) was projected by the HADCM3 under all emission scenarios for both study periods (Table 4.9).

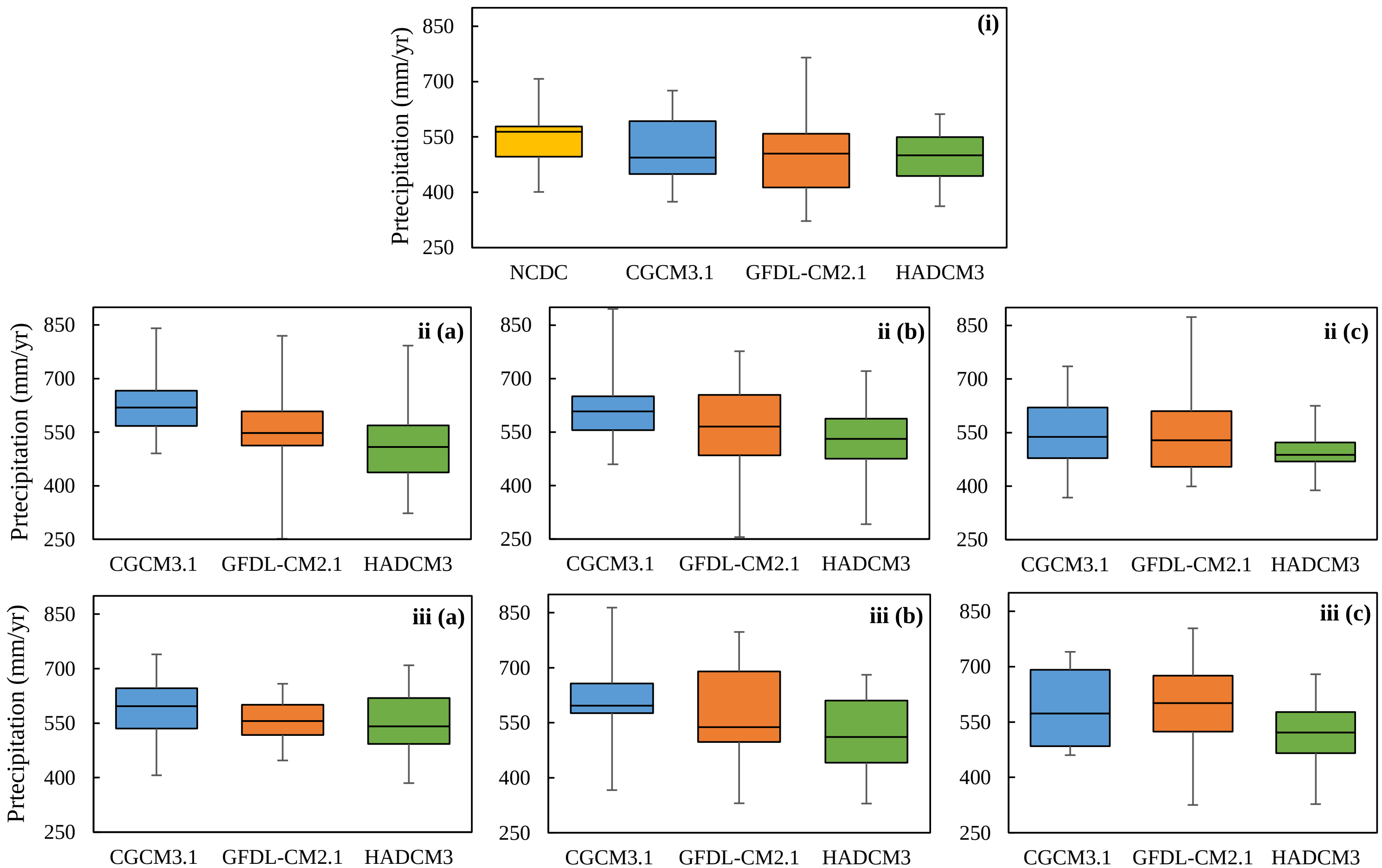

Figure 4. 5: Boxplots of projected precipitation in the study area for i) baseline (1981-2000), ii) mid-century (2046-2065) and iii) end century (2080-2099) under the a) A1B, b) A2 and c) B1 scenario.

Table 4. 9: Absolute differences of average annual precipitation from the baseline for three GCMs under the A1B, A2, and B1 scenarios.

	A1B			A2			B1		
2046-2065									
	CGCM3.1	GFDL-CM2.1	HADCM3	CGCM3.1	GFDL-CM2.1	HADCM3	CGCM3.1	GFDL-CM2.1	HADCM3
minimum	116	-73	-38	85	-66	-70	-5	77	26
median	125	39	8	114	60	30	44	24	-12
maximum	165	51	180	223	11	109	59	108	12
2080-2099									
	CGCM3.1	GFDL-CM2.1	HADCM3	CGCM3.1	GFDL-CM2.1	HADCM3	CGCM3.1	GFDL-CM2.1	HADCM3
minimum	32	125	22	-7	8	-32	86	3	-34
median	102	51	41	103	33	11	79	97	21
maximum	63	-106	96	188	32	68	64	38	67

4.3.6 Future Temperature Projections

Similar to precipitation, all three GCMs showed an increasing trend in temperature across all emission scenarios. All three GCMs predicted an increase in average maximum temperature, ranging from 1.57°C to 3.21°C in the mid-century and 1.81°C to 4.46°C at the end of the century (Table 4.10a). According to CGCM3.1, the highest "maximum temperature" was projected to increase from 4.26°C to 4.91°C in 2046-2065, and from 4.19°C to 4.45°C in 2080-2099 (Table 4.10a). Unlike the "maximum temperature", the "minimum temperature" showed slight changes under all emission scenarios (Table 4.10b). Compared to the baseline condition, a decrease in minimum temperature was shown under B1 emission scenario in the mid-century (2046-2065) for all three GCMs. All future projections indicate an increasing trend in precipitation and temperature but with different magnitudes (Figures 4.5, 4.6a, 4.6b, and Tables 4.9, 4.10a, and 4.10b).

Although air temperature is not a direct component of water balance, it affects precipitation variation and winter hydrological processes including snowfall and snowmelt (Yoshiyukiishii and Nakamura, 2004). Air temperature is an important meteorological parameter for snow melt and rainfall (Yoshiyukiishii and Nakamura, 2004). If the air temperature is lower than snowfall temperature, then the precipitation accumulates on the ground as snow (Grusson et al., 2015). The snow melting process and timing of surface runoff are influenced by air temperature (Johnson and Stefan, 2006; Novotny and Stefan, 2007) in early winter and early spring (Neupane and Kumar, 2015). In addition, air temperature is also an important driving factor for ET processes, which in turn influence surface and subsurface water budget (Hanson, 1988; Hu et al., 2005; Yoshiyukiishii and Nakamura, 2004). Therefore, temperature variations lead to variations in the hydrological components (surface runoff, ET, soil water content etc.) among the GCMs.

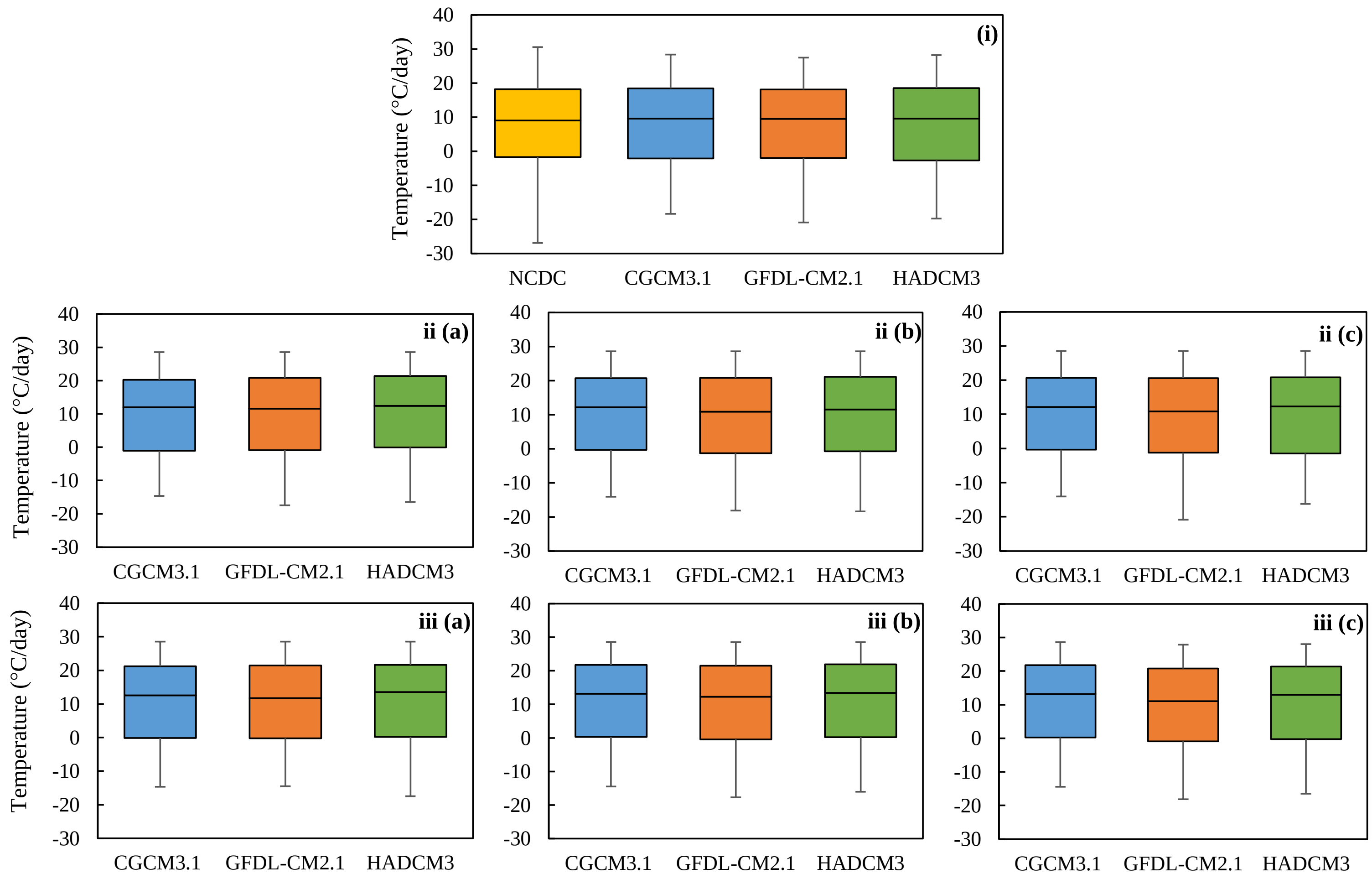

Figure 4. 6a: Projected maximum temperature for 1) baseline (1981-2000), 2) mid-century (2046-2065) and 3) end century (2080-2099) under the a) A1B, b) A2 and c) B1 scenarios.

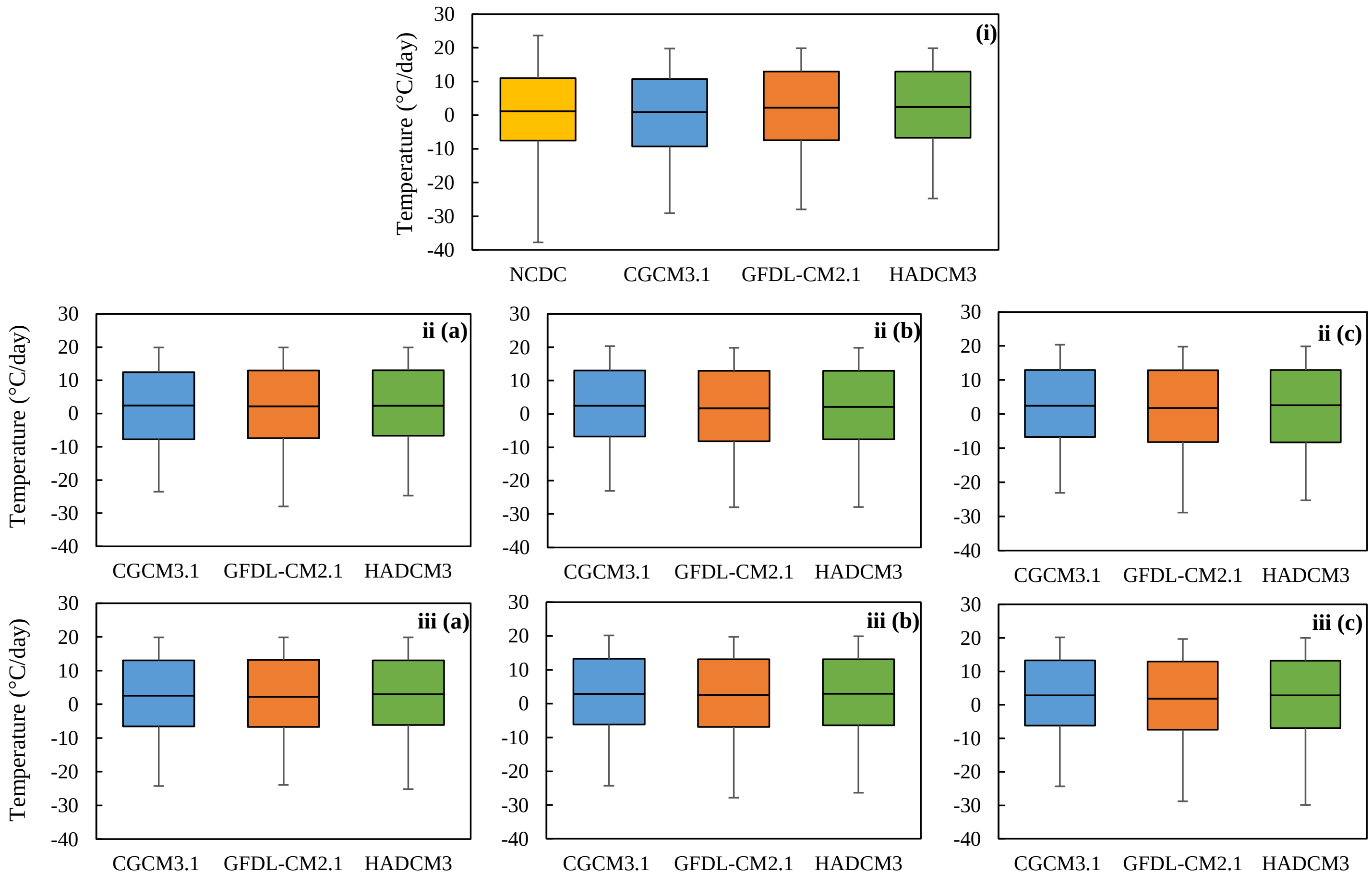

Figure 4. 6b: Differences of projected minimum temperature for 1) baseline (1981-2000), 2) mid-century (2046-2065) and 3) end century (2080-2099) under the a) A1B, b) A2 and c) B1 scenarios.

Table 4. 10a: Absolute differences of maximum temperature from the baseline for three GCMs under A1B, A2, and B1 scenarios.

	A1B			A2			B1		
2046-2065									
	CCCMA	GFDL2.1	HADCM3	CCCMA	GFDL2.1	HADCM3	CCCMA	GFDL2.1	HADCM3
minimum	4.26	3.99	3.78	4.91	3.15	1.58	4.91	0.08	4.03
median	2.75	2.35	3.21	2.87	1.56	2.17	2.87	1.58	3.05
maximum	0.21	1.23	0.36	0.21	1.23	0.36	0.21	1.23	0.36
2080-2099									
	CCCMA	GFDL2.1	HADCM3	CCCMA	GFDL2.1	HADCM3	CCCMA	GFDL2.1	HADCM3
minimum	4.19	7.34	2.62	4.45	3.69	4.25	4.45	3.12	0.21
median	3.35	2.53	4.46	4.1	3.21	4.37	4.1	1.81	3.82
maximum	0.21	1.23	0.36	0.23	1.23	0.36	0.23	1.23	0.36

Table 4. 11b: Absolute differences of minimum temperature from the baseline for three GCMs under A1B, A2, and B1 scenarios.

2046-2065

	A1B			A2			B1		
	CGCM3.1	GFDL-CM2.1	HADCM3	CGCM3.1	GFDL-CM2.1	HADCM3	CGCM3.1	GFDL-CM2.1	HADCM3
minimum	5.61	0.00	0.00	6.08	-0.03	-3.16	6.08	-0.91	-0.55
median	1.46	0.00	0.00	1.56	-0.47	-0.26	-7.70	-10.44	-10.63
maximum	0.09	0.00	0.00	0.09	0.00	0.00	-6.80	-6.96	-6.90

2080-2099

	A1B			A2			B1		
	CGCM3.1	GFDL-CM2.1	HADCM3	CGCM3.1	GFDL-CM2.1	HADCM3	CGCM3.1	GFDL-CM2.1	HADCM3
minimum	4.89	4.04	-0.41	4.83	0.15	-1.66	4.83	-0.80	-5.15
median	1.65	0.06	0.62	1.92	0.30	0.52	1.92	-0.34	0.46
maximum	0.12	0.00	0.00	0.15	0.00	0.00	0.15	0.00	0.00

4.3.7 Hydrologic Response to Land Use Change

Future land use change (2055 and 2090) impacts on long-term average annual hydrological variables including streamflow, surface runoff, and ET with NLCD 1992 land use (baseline) were evaluated under A1B, A2 and B1 emission scenarios (Figure 4.7). Simulation outputs indicated that average annual surface runoff increased due to LULC changes under all emission scenarios; the annual relative changes varied from 6% to 8.8% for 2055 and from 12.3% to 19.4% for 2090 land use. Based on the land use projections, agricultural land use will cover more than 55% (2055) and 62% (2090) of the watershed. Intensive agricultural activities can reduce surface roughness (Baker and Miller, 2013), available soil water storage (Busman and Sands, 2002), and canopy ability to intercept precipitation (Ghaffari et al., 2010). Therefore, excess water yield may produce higher surface runoff in the watershed (Busman and Sands, 2002; Ghaffari et al., 2010). In contrast, ET decreased for both 2055 and 2090 land uses under all emission scenarios, except B1 in 2055. ET is the combination of evaporation and transpiration processes (Hanson, 1988; Pai and Saraswat, 2011). Evaporation is the water loss from water bodies, wetlands, and bare soil, and transpiration is the loss from living plant surfaces (Hanson, 1988). In 2055, the B1 emission scenario showed expansion of water and wetlands (38%), and agricultural land (6.8%) which may result in an increase in ET (0.05%). The maximum decrease in annual ET may occur under A1B (-0.17%) and under A2 (-0.5%) scenario in 2055 and 2090 land use, respectively. Agricultural land has less crop density and lower leaf area index (LAI) than grassland (Kim et al., 2013), therefore, a decrease in ET can be explained by land conversion from perennial vegetation to seasonal row crops (Figure 4.4), causing a reduction in ET (Schilling et al., 2008; Zhang and Schilling, 2006). The 0.5% percent appears to be negligible, but the absolute annual reduction of 3 mm (in A2 for 2090) may not be negligible. In a semi-arid region like the James River watershed where water resources are limited (Wu et al., 2012a), ET evaluation is important for understanding of water stress (Rana et al., 1997).

For both 2055 and 2090 land uses, grassland decreased while agricultural land increased under all emission scenarios (Figure 4.4), causing an increase in streamflow (Figure 4.7). Results showed that annual ET in the watershed would decrease due to land conversion from grassland to agricultural land. As a result, a large fraction of precipitation would be delivered into nearby streams (Schilling et al., 2008). Annual streamflow increased up to 8.29% under A1B scenario, and 18.5% under A2 scenario for 2055 and 2090 land uses, respectively. Similar results were also found in the Raccoon River watershed, where agricultural land conversion from mixed perennial grassland to row crops resulted in an increase in streamflow in the watershed.

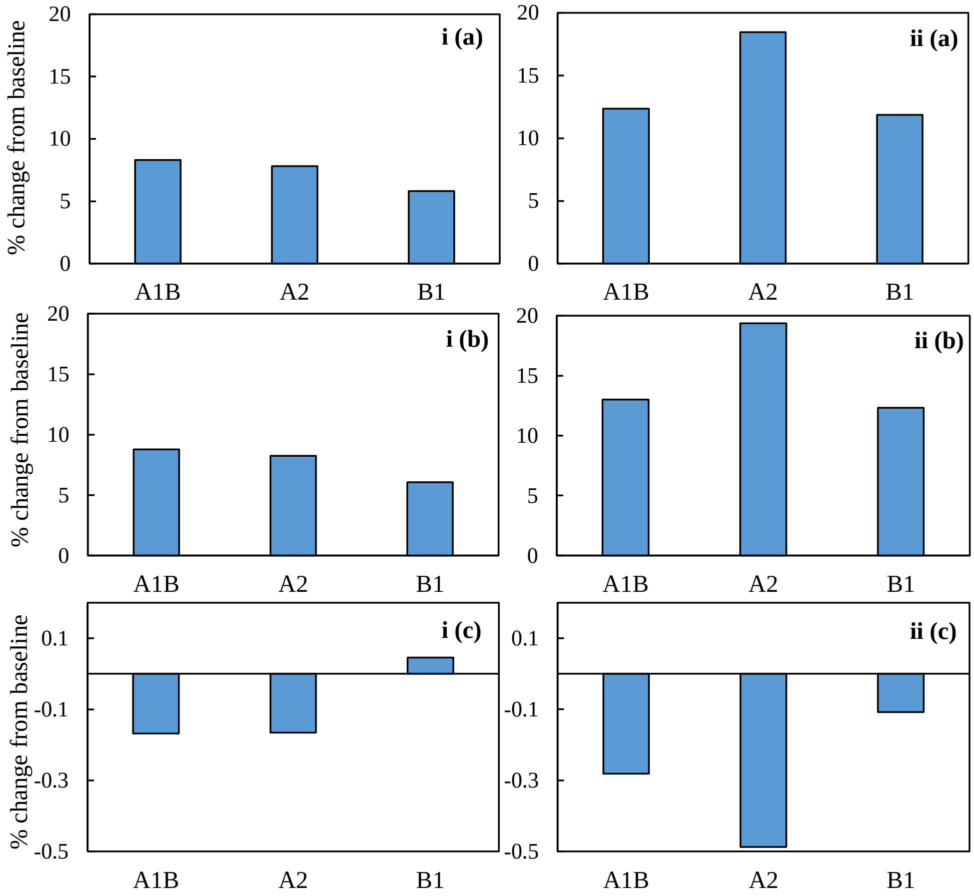

Figure 4. 7: Average annual changes in a) streamflow, b) surface runoff and c) ET from the baseline (NLCD 1992) for i) 2055 and ii) 2090 land use scenarios.

The results indicate slight increase in streamflow and surface runoff. Due to extensive agricultural land increase and grassland decrease, annual streamflow and surface runoff may increase in the future. However, the slight changes in streamflow, surface runoff, and ET indicate that land use changes would not considerably impact hydrology. These relatively small changes can occur due to the small affected areas.

4.3.8 Hydrologic Response to Climate Change

Precipitation, snowfall, and snowmelt are important water balance components of the James River watershed. It is notable that the future projected precipitation varies with the different emission scenarios among the GCMs (Figure 4.8). Across the three emission scenarios, future average annual precipitation showed an increase with a range of 0.4 to 22.7% in 2046-2065 and 4% to 20.2% in 2080-2099 compared to the baseline condition (Figure 4.8-a). Similarly, future average annual snowfall varies from -13% to 22.6% and from -10.6% to 16.9% in (2046-2065) and (2080-2099), respectively (Figure 4.8-b). As a consequence, future average annual snowmelt also showed a similar pattern and magnitude of changes (Figure 4.8-c).

Across the three emission scenarios, A1B scenario showed the maximum average annual precipitation (2.8% to 22.7%), followed by A2 (7.2% to 19.4%) and B1 (0.4% to 7.3%) scenarios in the mid-century (Figure 4.8-i-a). However, at the end of the century, A2 scenario showed the highest average annual precipitation (4.1% to 20.2%), followed by B1 (4.7% to 17.6%) and A1B (10.8% to 13.4%) scenarios (Figure 4.8-i-b). Maximum average annual precipitation increase was estimated for CGCM3 under A1B scenario (22.8%) in 2046-2065 and A2 scenario (20.2%) in 2080-2099. HADCM3 showed much less precipitation change among all the GCMs for both future periods under all emission scenarios (Figure 4.8-a).

Future annual snowfall and snowmelt showed a large variation of changes across the three emission scenarios (Figure 4.8-b and c); particularly A1B and B1 scenarios showed a large variation in average annual snowfall and snowmelt with a range of -7.2% to 22.6%, and -13.1% to 12.8% in the mid-century, and -5.2% to 12.2% and -10.6% to 14.7% at the end of the century. According to all GCMs, maximum average snowfall and snowmelt may increase in A2 scenario with a range of 5.8% to 22.4% in 2046-2065 and 17% to 22.2% in 2080-2099. Compared to the baseline condition, HADCM3 showed a decreasing trend for both snowfall and snowmelt under A1B and B1 emission scenarios (Figure 4.8-b and c). HADCM3 showed higher temperature and less precipitation increase (Figure 4.5-4.6b) compared to the other two GCMs (i.e., CGCM3 and GFDL-CM2.1). This increased temperature may lead to a decrease in snow water equivalent (water stored in snowpack) and volume of snowmelt (Neupane and Kumar, 2015). These potential climate variations will likely lead to a water stress in this watershed (Tavernia et al., 2013).

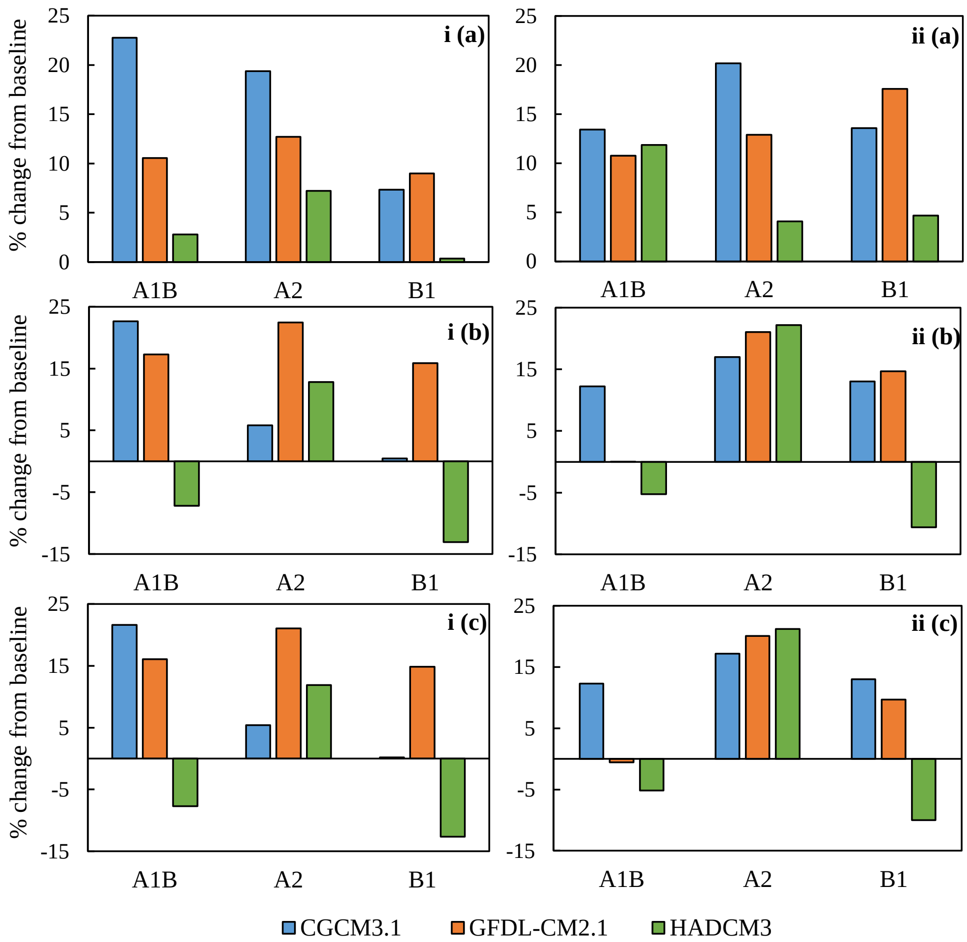

Figure 4. 8: Average annual changes in a) precipitation, b) snowfall, and c) snowmelt from baseline for i) (2046-2065) and ii) (2080-2099) in the James River watershed.

These potential changes in precipitation, snowfall and snowmelt can cause a variation in the average annual streamflow in both future periods (Figure 4.9-a). Among the three emission scenarios, average annual streamflow varied with the ranges from -14.5% to 96% in the mid-century and from -21.5% to 75% at the end of the century. Due to the potential variations in future precipitation (Figure 4.8-a), surface runoff also varied from -13.8% to 97% in 2046-2065 and from -20% to 75% in 2080-2099. Unlike land use change scenarios, future simulation output of climate changes showed an increased pattern in ET under all emission scenarios (Figure 4.9-c). The average annual ET can vary between 0.1% to 17.3% and 3.6% to 17.1% in 2046-2065 and 2080-2099, respectively.

Across the three emission scenarios, A1B scenario showed the maximum average annual streamflow (-4.5% to 96.1%), followed by A2 (14.8% to 50.8%) and B1 (-14.8% to 35.7%) scenarios in the mid-century (Figure 4.8-i-a). However, at the end of the century, A2 scenario demonstrated the maximum average annual streamflow (5.4 to 74.3%), followed by B1 (-21.5% to 75.2%) and A1B (11.4% to 24.7%) scenarios (Figure 4.8-i-b). These results indicate that streamflow increases are related to the increase in projected precipitation. Similar results were reported for the Raccoon River watershed in Iowa where future projected increases in precipitation resulted in an increase in streamflow (Villarini et al., 2015).

For all GCMs, A2 scenario showed higher surface runoff in both future periods (Figure 4.9-b). Despite higher precipitation, B1 and A1B scenarios showed smaller changes in surface runoff in the mid-century (-13.8% to 35.8%), and at the end of the century (15.3% to 25.3%). Across all emission scenarios, average annual ET may increase with a maximum change of 17% under A1B in 2046-2065 and A2 in 2080-2099 period (Figure 4.9-c). The increased ET rate could be induced by increased precipitation (Huntington, 2006), due to more water availability for transpiration (LaFontaine et al., 2015). Moreover, an increase in air temperature causes an increase in evaporation, which can also influence ET (Abbaspour et al., 2009; Chattopadhyay and Jha, 2014; LaFontaine et al., 2015; Setegn et al., 2011). A similar study in North

Carolina with CGCM3 and HADCM3 also projected higher ET, which was correlated with temperature than precipitation (Chattopadhyay and Jha, 2014).

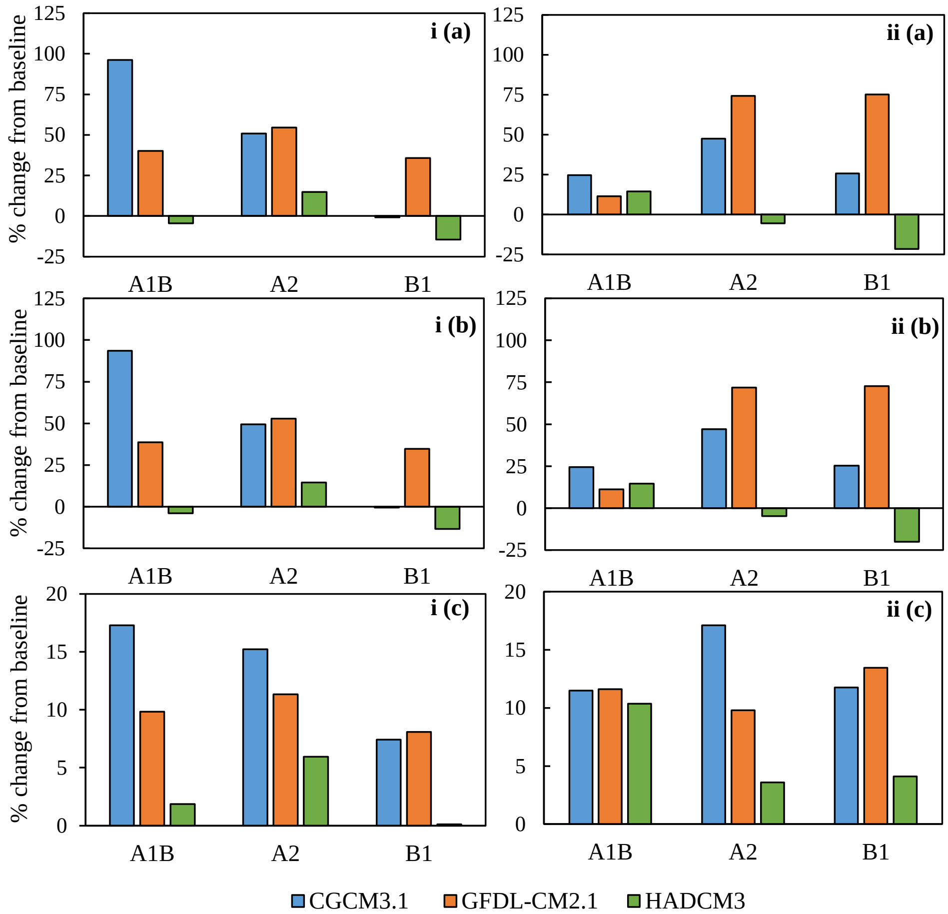

Figure 4. 9: Average annual changes in a) streamflow, b) surface runoff, and c) ET from baseline for i) (2046-2065) and ii) (2080-2099) in different climate change scenarios.

Based on three bias-corrected and downscaled GCM's climate projections for the mid-century (2046-2065) and end of the century (2080-2099), precipitation varies across the three emission scenarios. Unlike precipitation, an increasing trend was predicted in temperature under all emission scenarios. These uncertainties may be responsible for the inconsistency in streamflow estimation among the different GCMs and emission scenarios.

Overall, from this study, an increasing trend of streamflow was predicted due to potential wetter climate conditions. Based on historical data, an increasing trend in streamflow and in flood events was observed in the Midwest (Lenhart et al., 2011; Mallakpour and Villarini, 2015). These findings were consistent with the observations of wetter climate (i.e., heavy rainfall) across the United States (Groisman et al., 2001; Lins and Slack, 1999, 2005). Other global climate model analyses also confirm the increasing trend in precipitation for this region (e.g., Basche et al., 2016; Daniel, 2015; Winkler et al., 2012). Similarly, in this study a general increasing trend of projected precipitation was found for the three GCMs (CGCM3, GFDL-CM2.1, and HADCM3), but with different magnitudes (Figure 4.8-a). This precipitation variability induced a large variation in hydrological processes (Figure 4.9). Therefore, it is difficult to assess the potential hydrological changes due to uncertainties in the approach and source of these GCM data. As an example, according to HADCM3 projections, low precipitation, and high temperature can be projected a very few streamflow compared to baseline in this watershed. Thus, if the projected result of this study actually occurs, then in the future severe water stress may happen in this semi-arid region (Wu et al., 2012a). On the other hand, CGCM3.1 and GFDL-CM2.1 showed higher annual streamflow compared to HADCM3 in future annual streamflow due to higher precipitation. This higher precipitation may also have an adverse impact on agricultural activities of the James River watershed where the crop is mostly rain-fed. As an example, waterlogged soils can delay the spring planting and decrease crop productivity (Al-Kaisi et al., 2013; Basche et al., 2016).

Similar uncertainties were also found in the Northeast and Midwest region (Chien et al., 2013; Jha et al., 2006; Tavernia et al., 2013). For example, Jha et al. (2006) and Chien et al. (2013) studied the effects of climate change on streamflow with various GCM projections in the Upper Mississippi River basin, and Illinois and Indiana watersheds; the authors observed similar ranges in model outputs. Therefore, it is necessary to select multiple scenarios and GCMs to assess the impacts of climate change on hydrology (Zhang et al., 2016) to have an idea about the range of plausible future conditions.

4.3.9 Hydrologic Response to Land Use and Climate Changes

To analyze the combined effects of potential land use and climate changes, annual streamflow, surface runoff and ET under the three future scenarios (A1B, A2, and B1) for 2046-2065 and 2080-2099 were compared to the baseline (1981-2000) (Figure 4.10). Similar to climate changes, the combination of potential climate and land use changes would lead to an increase in streamflow (-9.9% - 104.5% in 2046-2065 and -12.9% - 96.7% in 2080-2090), surface runoff (-8.8% - 106.8% in 2046-2065 and -11.7% - 99.3% in 2080-2090), and ET (0.2% - 17.3% in 2046-2065 and 3.4% - 16.8% in 2080-2090).

Combined land use and climate change scenarios showed that the increase in streamflow caused by climate changes was intensified by the increase caused by land use changes. For example, the combined effects of land use and climate changes showed +2.5% to +8% more in 2046-2065, and +8.6% to +22.5% more in 2080-2090 for streamflow compared to climate change scenarios only. Average annual surface runoff also increased compared to baseline condition due to higher precipitation and agricultural activities (Figure 4.10-b). Similarly, runoff under the combined effects of land use and climate changes would be +4% to +9.6% more in 2046-2065, and +8.3% to +24.9% more in 2080-2090 compared to the climate change scenarios only (Figure 4.10-b). The slight decrease in ET caused by the land use changes did not affect ET, leading to similar results when compared to climate change scenarios (Figure 4.10-c).

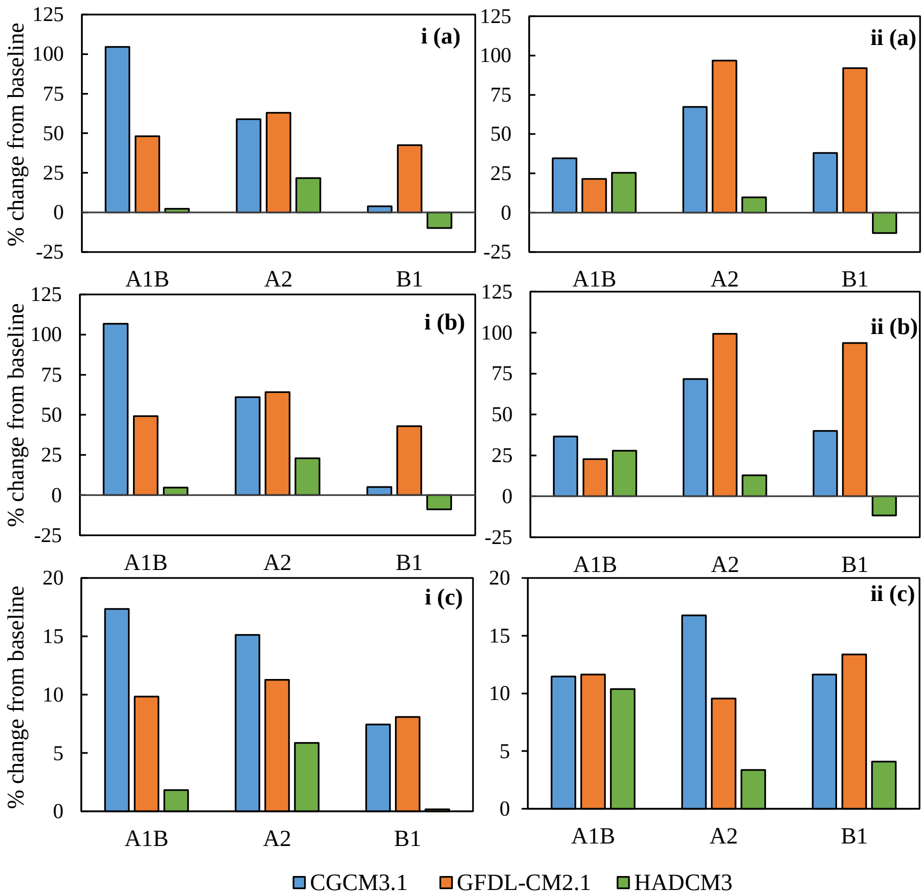

Figure 4. 10: Average annual changes in a) streamflow, b) surface runoff, and c) ET from baseline for i) (2046-2065) and ii) (2080-2099) in different land use and climate change scenarios.

The analysis of hydrological effects of land use and climate changes under three emission scenarios demonstrated how and to what extent the hydrology of the James River watershed can be altered in the future. The combined effects of land use and climate changes indicate that both land use and climate changes will intensify hydrological changes where climate changes will play a dominant role in hydrology of the James River watershed. A similar study revealed that the magnitude of projected water stress (water demand/water supply) was more sensitive due to climate changes than land use changes in Midwest (Tavernia et al., 2013). Wu et al. (2012a) also found similar results and mentioned that this watershed is relatively more sensitive to climate change when compared to the neighboring Upper Mississippi River Basin.

4.3.10 Seasonal Analysis of Future Hydrological Variables

Seasonal streamflow, surface runoff and ET were analyzed based on long-term monthly simulations. Among the three emission scenarios, A1B represents the medium emission with emphasis on balanced energy policies. GFDL-CM2.1 showed average precipitation and temperature increase compared to the other two GCMs. Thus, A1B emission scenario with GFDL-CM2.1 climate data was selected to analyze climate impacts on seasonal variation.

Land use changes showed a minor impact on average monthly streamflow (Figure 4.11-a). Due to both land use and climate changes, peaks of streamflow may occur in March-April in 2046-2065, but in 2080-2099 these peaks would shift to May-June (Figure 4.11-a). At the end of the century, fluctuations in monthly streamflow can be observed from March to July (Figure 4.11-a). Compared to 2080-2099, the largest increase (34.8 m^3/s) and decrease (-9 m^3/s) in monthly streamflow were projected for the 2046-2065 period (Figure 4.11-a). In 2080-2099, snowfall and snowmelt showed a decreasing trend under A1B emission scenario compared to 2046-2065 due to higher temperature increase (Figure 4.8-b and c). These potential decreases in snowfall can produce less monthly streamflow in spring. Moreover, a decreased streamflow may occur in dry conditions (July to September) due to a higher temperature and less precipitation availability by the end of the century (Figure 4.11-ii-a).

Fluctuations in monthly surface runoff also showed a similar pattern to streamflow (Figure 4.11). Under the combined effects of land use and climate changes, higher snowmelt and reduced surface roughness may elevate monthly surface runoff in winter months by the mid-century (Figure 4.11-i-b), while by the end of the century, peaks of surface runoff may occur in late spring (April-May). (Figure 4.11-ii-b). Similar to streamflow, monthly surface runoff showed a decreasing trend in summer (June to August) in 2080-2099. Overall, by the end of the century, monthly surface runoff may decrease in March due to less snowfall and snowmelt, and in June due to less incident precipitation in the watershed (Figure 4.11-b-ii).

Average monthly ET also showed an increasing trend for climate changes compared to land use changes, especially in growing season (April to July) in both mid and end of the century. This increasing trend can be driven by higher temperature and precipitation in A1B scenario compared to the baseline condition. The monthly variation in ET suggested that less ET can occur in fall (September to November) and in winter (December to February) due to less water use in the dormant season (Figure 4.11-c). Between the two time periods (mid and end of the century), there will be no difference in monthly precipitation based on GFDL-CM2.1 model (46.3 mm in 2046-2065 and 46.4 mm in 2080-2099), while monthly ET would be higher in 2080-2099 period compared to 2046-2065 period (Figure 4.11-c). This high monthly ET can be explained by expansion of hay/pasture land in the end of the century compared to mid-century. In this watershed, more than 90% of the precipitation contributes to ET

(Table 4.6). Thus, less monthly streamflow may be produced due to the increased trend of monthly ET (Zhang et al., 2016).

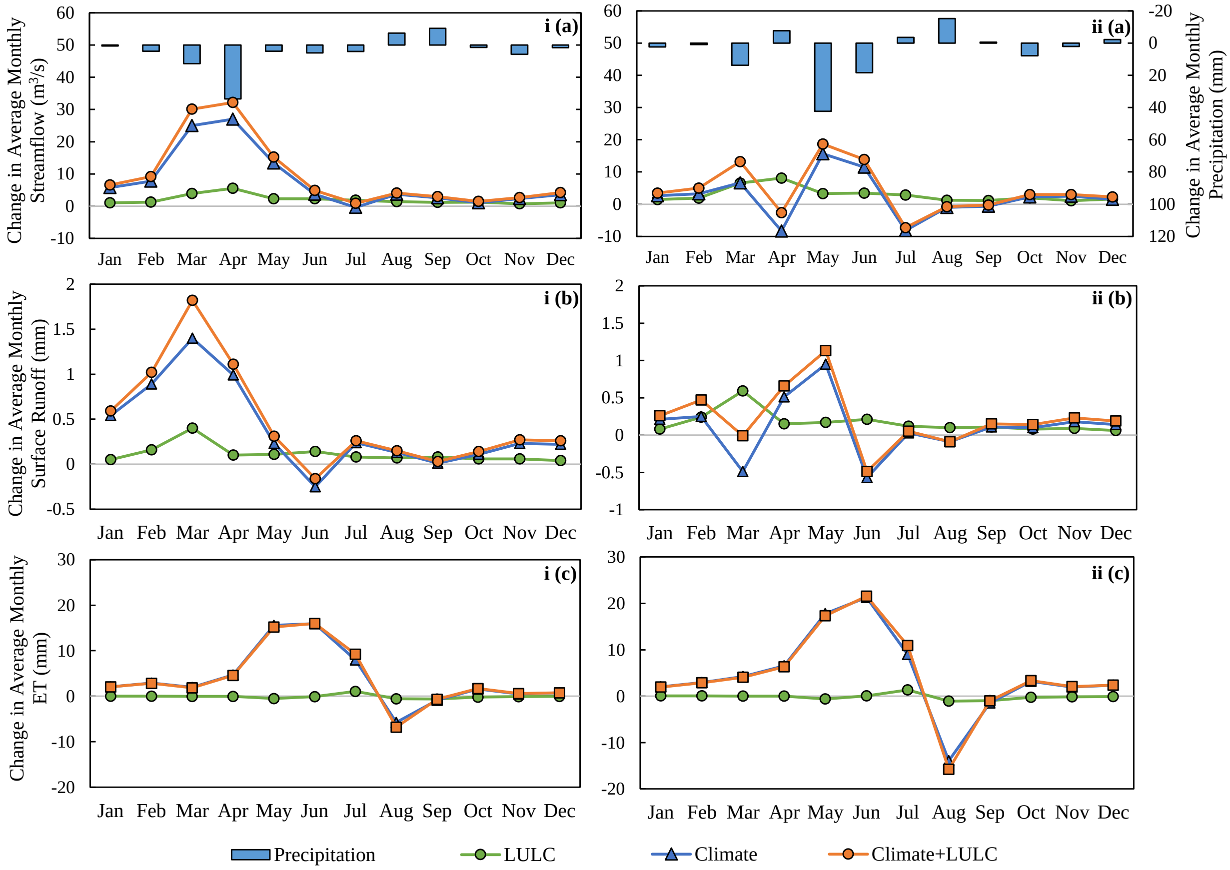

Figure 4. 11: Changes in average monthly a) streamflow, b) surface runoff and c) ET from baseline for i) (2046-2065) and ii) (2080-2099) under A1B emission scenario using GFDL-CM2.1 climate data.

4.4 Conclusions

The hydrologic responses to land use and climate changes were evaluated using SWAT in the James River watershed. Potential land use and climate change conditions were examined under A1B, A2, and B1 emission scenarios for the mid-century (2046-2065) and end of the century (2080-2099). Land use maps for the year 2055 and 2090 were derived from the FOREcasting SCEnarios (FORE-SCE) model and future projected climate data were used from three general circulation models (CGCM3.1, GFDL-CM2.1, and HADCM3). The following conclusions can be drawn from this study:

1) The SWAT model was successfully applied to assess potential land use and climate change effects on hydrologic processes in the James River watershed.
2) Future land use change scenarios showed that a large amount of agricultural land expansion (6.8% - 11.6% in 2055 and 19.5% - 26.1% in 2090 land use) and grassland depletion (from -48.9% to -23% in 2055 and from -78.6% to -65.5% in 2090 land use) are expected.
3) Due to land use change, higher streamflow (5.82% - 8.3% in 2055 and 11.9% - 18.5% in 2090) and surface runoff (6% - 8.8% in 2055 and 12.3% - 19.3% in 2090) were estimated compared to the baseline condition. A decrease in ET occurred in 2055 (about -0.16%) and 2090 (from -0.5% to -0.1%), except under B1 scenario where ET increased by 0.05% in 2055.
4) According to three GCMs, the study watershed may experience higher precipitation (0.36% - 22.7%) and temperature (1.8°C - 4.5°C) under all emission scenarios but in different magnitude compared to the baseline condition (1981-1990).
5) For future climate changes, average annual streamflows vary from -14.5% to +96% in the mid-century and from -21.5% to +75% at the end of the century; and surface runoff from -13.8% to +97% in 2046-2065 and from -20% to +75% in 2080-2099. The average annual ET vary between 0.1% and 17.3% and 3.6% and 17.1% in 2046-2065 and 2080-2099, respectively.
6) The combination of potential climate and land use changes led to an increase in the streamflow (-9.9% - 104.5% in 2046-2065 and -12.9% - 96.7% in 2080-

2090), surface runoff (-8.8% - 106.8% in 2046-2065 and -11.7% - 99.3% in 2080-2090), and ET (0.2% - 17.3% in 2046-2065 and 3.4% - 16.8% in 2080-2090), where climate changes play a dominant role in impacting hydrology.

7) The analysis of both land use and climate change impacts on hydrology showed intensification of the hydrological changes where climate changes play a dominant role in impacting streamflow and hydrological extremes.
8) Future changes in land use and climate may result in a wide range of hydrological variations.

Understanding the impacts of potential land use and climate changes is important for sustainable water resource management. The findings of this study can be useful for decision makers and planners to design adaptive measures to land use and climate changes. This study also has valuable implications for informing watershed modeling in the region.

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CHAPTER 5: CONCLUSIONS

5.1 Summary

In this study, SWAT was used to assess the impacts of land use and climate changes on hydrology in South Dakota's watersheds. Existing land use and climate data of two distinct time periods were used to characterize hydrologic changes in three watersheds (Bad River, Skunk Creek, and Upper Big Sioux River). Results indicated that changes in hydrology occurred in the study watersheds between the two time periods. Potential land use and climate change data were also used under A1B, A2, and B1 emission scenarios to evaluate land use and climate change impacts on hydrology in the James River watershed. Simulation results revealed that land use and climate changes would influence hydrology in this watershed.

The following specific conclusions can be drawn from this study:

1. Historical land use change and climate variation resulted in a noticeable increase in water balance components in the Bad River, Skunk Creek and Upper Big Sioux River watersheds.
   a. Between 1980s and 2000s, a gradual decrease in grassland is the common characteristics of land use change in all three watersheds. According to NLCD 2011, in all three watersheds, more than 3% grassland was depleted compared to grassland losses in NLCD 1992.
   b. The watersheds experienced variable climate changes between the two study periods (1981-1990 and 2005-2014). However, there was no statistically significant change in either precipitation or temperature.
   c. Based on the historical land use and climate data, annual water balance components increased in the 2000s compared to 1980s. Significant increases

in soil water content and percolation were examined in Bad River and Upper Big Sioux River watersheds, and water yield in Skunk Creek watershed.

d. Between 1980s and 2000s, seasonal variation in hydrology mostly increased during the wet season (i.e., May to October) in all three watersheds.
e. Spatial analysis revealed that the hydrological components increased with a decrease in grassland in the watersheds, except in Skunk Creek watershed.

2. Land use and climate change projections generally showed an increase in streamflow and surface runoff but a decrease in evapotranspiration in the James River watershed, suggesting that climate and land use changes will likely influence hydrological processes in the watershed.
   a. Among the three emission scenarios simulated, A1B scenario showed higher agricultural (11.6% in 2055) and hay/pasture land expansion (7.4% in 2055 and 10.6% in 2090) and higher grassland depletion (-48.9% in 2055 and -78.6% in 2090) compared to the other two scenarios (i.e. A2 and B1).
   b. Due to this land use change, an increase in streamflow (5.8% - 8.3% in 2055 and 11.9% - 18.5% in 2090) and surface runoff (6% - 8.8% in 2055 and 12.3% - 19.3% in 2090), was predicted compared to the baseline condition (1981-2000). A slight decrease in evapotranspiration was evident in 2055 (about -0.16%) and 2090 (from -0.5% to -0.1%), except under B1 scenario where evapotranspiration increased by 0.05% in 2055.
   c. Based on the three GCMs, the study watershed may experience higher precipitation (0.36% - 22.7%) and temperature (1.8°C - 4.5°C) under all emission scenarios but with different magnitude compared to the baseline condition (1981-1990).

d. The GCMs also showed that average annual streamflow may vary from -14.5% to 96% in the mid-century and from -21.5% to 75% at the end of the century; and surface runoff from -13.8% to 97% in 2046-2065, and from -20% to 75% in 2080-2099. Average annual ET can vary between 0.1% and 17.3% and 3.6% and 17.1% in 2046-2065 and 2080-2099, respectively.
e. The combination of potential climate and land use changes led to an increase in the streamflow (-9.9% - 104.5% in 2046-2065 and -12.9% - 96.7% in 2080-2090), surface runoff (-8.8% - 106.8% in 2046-2065 and -11.7% - 99.3% in 2080-2090), and evapotranspiration (0.2% - 17.3% in 2046-2065 and 3.4% - 16.8% in 2080-2090), where climate changes play a dominant role in impacting hydrology.
f. Different GCMs may result in different hydrological responses, due to differences in data development and archiving protocols.

5.2 Recommendations

Recommendations for possible future studies include:

1) In this study, NLCD land use was used to evaluate the impacts of land use change on hydrology. All row crops and cultivated cropland were assumed agricultural land without any distinction between the crop types. Various crop types and rotations should be taken into consideration for future assessment of hydrologic impacts of land use change. Incorporating crop data layer (CDL) into NLCD should also be considered for future studies.
2) National Land Cover Dataset 1992 and National Land Cover Database 2011 were used in this study. NLCD 1992 is a 21-class land cover classification scheme, while NLCD 2011 is a 16-class land cover classification scheme.

Thus, NLCD 1992 and 2011 were not developed in the same way. Future work should consider land uses that are developed with the same classification method.

3) Precipitation and snowmelt intensity were not explicitly considered in this study. Further analysis should assess rainfall intensity to identify the relative contribution of individual precipitation events in altering the distribution of surface runoff in the watershed.
4) Seasonal analysis and detailed spatial (e.g. HRU levels) should be considered in future land use and climate change impacts on hydrology to highlight potential dry and wet seasons, and sensitive areas that would experience extreme climate events.
5) This study used three GCMs with three scenarios each. Future modeling efforts should use multiple GCMs/RCMs and their combinations to assess potential climate change impacts on hydrology in South Dakota watersheds.
6) This study focused only on hydrology. Further studies are needed to evaluate climate and land use change impacts on water quality in South Dakota watersheds.