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Streamflow response to potential land use and climate changes in the James River watershed, Upper Midwest United States

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ABSTRACT

Study region: North and South Dakotas, United States
Study focus: Changes in watershed hydrology are mainly driven by changes in land use and climate. This study evaluated the impacts of climate and land use changes on streamflow in an agricultural watershed in the Upper Midwest. Three projected climate change scenarios (A1B, A2 and B1) of three general circulation models (CGCM3.1, GFDL-CM2.1, and HADCM3) were developed for mid (2046–2065) and end (2080–2099) of the 21st century. Corresponding land use maps for years 2055 and 2090 were obtained from the FOREcasting SCEnarios of Land-Cover (FORE-SCE) model. The scenarios were designed in a way that land use was changed while climate conditions remain constant, land use was then held constant under a changing climate, and finally both land use and climate were changed simultaneously to reflect possible future land use and climate conditions.
New hydrological insights for the region: Potential land use and climate changes would result in 12–18% % and 17–41% increases in annual streamflow, respectively, by end of the century. The combined effects of land use and climate changes would intensify future streamflow responses with 13–60% increases in the region. This study provides a broad perspective on plausible hydrologic alterations in the region, prompting individual and collective opportunities to engage with this topic for sustainable planning and management of watersheds.

1. Introduction

Changes in climate and land use are dynamic factors that greatly influence water resources (Li et al., 2009; Zhao et al., 2016; Zhang et al., 2016). Effective planning and management of water resources requirebetter understanding of climate and land use change effects on watershed hydrology (Brekke et al., 2009; Hanak and Lund 2012; Nie et al., 2011; Memarian et al., 2014; Singh et al., 2014); which is critical in supporting ecosystem services and food security (Millennium Ecosystem Assessment, 2005).

Over the last century, climate observations at regional and global scales revealed more frequent extreme events characterized by changes in temperature, precipitation, and energy balance with direct impacts on local and regional water resources (IPCC, 2007a,b, 2013; NOAA, 2013). There are indications that climate change would induce intensification of the hydrologic cycle through changes in precipitation amount and intensity (e.g. Melillo et al., 2014; Johnson et al., 2015; Pervez and Henebry, 2015). In particular, observations of annual rainfall showed increasing trends in the Midwest with about double the frequency of extreme precipitation events in the latter part of the 20th Century (Easterling and Karl, 2000; Melillo et al., 2014; Kibria et al., 2016). Many recent

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hydroclimatological studies in the US indicate ongoing changes to regional hydrologic cycles, either via reduced surface water availability in summer (Hamlet et al., 2007), or shifting timing of peak streamflow due to earlier snow melt in the spring induced by increased air temperature (e.g. Christensen and Lettenmaier, 2006; Jha et al., 2004; Stewart et al., 2005; Maurer et al., 2010). In the future, mean precipitation will likely decrease in several mid-latitude and subtropical dry regions while mean precipitation will likely increase in many mid-latitude wet regions (IPCC, 2014a,b). Thus, changes in river runoff and evapotranspiration (ET) are likely to be amplified under future climate change. Analysis from multiple climate models indicated that future climate change would lead to increased heat waves (Meehl and Tebaldi, 2004), as well as surging frequency of extreme precipitation events in winters and spring while drier summers and extended length of growing seasons in the Midwest (USGCRP, 2014; Sinha and Cherkauer, 2010). Such changes in frequency and magnitude of extreme climatic events, particularly droughts, will result in significant effects on agricultural production, erosion, food security, and water supply (FAO, 2008).

In addition to climate change issues, changes in land use have also been a major driving factor of hydrologic alterations (e.g. Hurkmans et al., 2009; Im et al., 2009; USGCRP, 2014; Zhang et al., 2016). Numerous studies have investigated hydrological impacts of land use change at watershed scales (e.g. USEPA, 2013; Wijesekara et al., 2012; Im et al., 2009; Dwarakish and Ganasri, 2015). Land use change adversely affected the natural hydrologic system through increased variability in streamflow, surface runoff, ET, infiltration, subsurface flow, infiltration, and precipitation interception (e.g. Fohrer et al., 2001; Hurkmans et al., 2009; Schilling et al., 2008; Barbosa et al., 2012). For example, Schilling et al. (2008) found that average annual ET decreased with increasing corn acreage in the Raccoon River watershed in Iowa. Mishra et al. (2010) performed a sensitivity analysis at a single grid-cell (of size ~150 km^2) in Wisconsin and found that conversion of forest to cropland increased surface runoff by 20% and decreased ET by 2.5%, while replacing forests by urban area increased surface runoff by 1200% and decreased evapotranspiration by 70%, respectively. Xu et al. (2013) also assessed potential impacts of biofuel production on water resources based on streamflow analysis for 55 unregulated Midwest watersheds during 1930s to 2010 and reported that watersheds with no significant trends in climate showed statistically significant increasing trends in streamflow, possibly due to land use change in most of the studied watersheds. Given that land use change in the Midwest is mainly driven by agricultural expansion, demographic changes, climatic variability, national environmental policies, and socio-economic factors (e.g. Claassen et al., 2011; Wu et al., 2012; Wright and Wimberly, 2013), it is important to assess the effects of potential land use change on water availability and management.

Scenarios analysis with physically based, spatially distributed hydrological models have frequently been utilized to assess land use and climate change impacts on water resources. The Soil and Water Assessment Tool (SWAT) is one of such models commonly used for quantifying the impacts of land use and climate changes on hydrological processes from watershed scales to global scales (e.g. Johnson et al., 2015; Tomer and Schilling, 2009; Karlsson et al., 2016). The common traits of these studies is the use of historical climate and land use data as well as potential land use and climate change scenarios obtained from appropriate projection models. This study followed a similar approach; but nuanced it with the use of complimentary climate and land use scenarios to highlight their individual and combined roles in streamflow variations, which is not very common. This study provides a perspective of possible climate and land use change impacts on annual river flow from a large watershed in the Upper Midwest. Given that both climate and land use change can play different roles in affecting streamflow and ET under different hydroclimatic conditions (e.g. snow dominated vs rainfall-runoff dominated basins), there is a need to evaluate their relative impacts at regional scales. The specific objective of this study was to quantify the individual and combined effects of climate and land use changes on long-term annual streamflow in the James River watershed. Such local and regional studies are needed to increase understanding of economical, societal, and environment implications of land use change in the face of a changing climate.

2. Materials and methods

2.1. Study area

James River is a tributary of the Missouri River, approximately 1140 km long, with its headwaters in North Dakota (Fig. 1). James River drains parts of North Dakota (ND) and South Dakota (SD), extending over an area of approximately 53440 km^2 (USGS Hydrologic Unit Code 10160011). The watershed has a streamflow gauge station (USGS gauge number 06478500) at its outlet located near Scotland, SD. Based on the 1992 National Land Cover Dataset (NLCD) (Vogelmann et al., 2001), James River watershed is primarily dominated by agricultural land, which consists of 52% of the total watershed area (Table 1; Fig. 2). Hay, grassland, water, forest, and urban are other land uses in the watershed (Table 1; Fig. 2). The climate in the watershed is semi-humid and continental, with an average daily temperature of 7 °C with a minimum of −16 °C in January and a maximum of 30 °C in July (https://www.ncdc.noaa.gov). Annual precipitation varies between 400 and 660 mm in this watershed with an average of 457 mm (https://www.ncdc.noaa.gov). Soils in the watershed are mainly loamy and silty, moderately to well drained, with a frigid temperature regime and mixed mineralogy on 300–700 m elevation (USDA, 2009; Fig. 2).

2.2. Hydrologic model

This study used SWAT (Arnold et al., 1998) to analyze the effects of climate and land use changes on streamflow. SWAT is a process-based, distributed-parameter watershed scale model for simulation of long-term hydrologic and water quality impacts of various watershed management strategies (Arnold et al., 1998). The model is capable for routing runoff and pollutants through streams and reservoirs with readily available input data (e.g. precipitation, air temperature, land use and land cover) (Neitsch et al., 2005, 2009). It has been widely applied in many watershed scale studies and geographic locations (e.g. Gassman et al., 2007). SWAT