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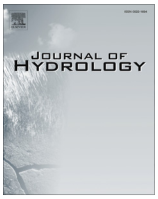

Estimating the effects of potential climate and land use changes on hydrologic processes of a large agriculture dominated watershed

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SUMMARY

Land use and climate are two major components that directly influence catchment hydrologic processes, and therefore better understanding of their effects is crucial for future land use planning and water resources management. We applied Soil and Water Assessment Tool (SWAT) to assess the effects of potential land use change and climate variability on hydrologic processes of large agriculture dominated Big Sioux River (BSR) watershed located in North Central region of USA. Future climate change scenarios were simulated using average output of temperature and precipitation data derived from Special Report on Emission Scenarios (SRES) (B1, A1B, and A2) for end-21st century. Land use change was modeled spatially based on historic long-term pattern of agricultural transformation in the basin, and included the expansion of corn (*Zea mays* L.) cultivation by 2, 5, and 10%. We estimated higher surface runoff in all land use scenarios with maximum increase of 4% while expanding 10% corn cultivation in the basin. Annual stream discharge was estimated higher with maximum increase of 72% in SRES-B1 attributed from higher groundwater contribution of 152% in the same scenario. We assessed increased precipitation during spring season but the summer precipitation decreased substantially in all climate change scenarios. Similar to decreased summer precipitation, discharge of the BSR also decreased potentially affecting agricultural production due to reduced future water availability during crop growing season in the basin. However, combined effects of potential land use change with climate variability enhanced for higher annual discharge of the BSR. Therefore, these estimations can be crucial for implications of future land use planning and water resources management of the basin.

1. Introduction

Land use and climate are two main factors that affect watershed hydrologic processes (Costa et al., 2003; Brath et al., 2006; Wang et al., 2006; Wu et al., 2012; Chien et al., 2013). Land use, a major global research issue (Foley et al., 2005; Marshall and Shortle, 2005), is considered as one of the most important components of terrestrial environment system (Lin et al., 2007, 2009) that affects surface runoff, stream discharge, and sediment transportation influenced by rainfall interception, evapotranspiration, and surface soil hydraulic conductivity (He et al., 2008; Germer et al., 2009; Scheffler et al., 2011; Munoz-Villers and McDonnell, 2013; Yan et al., 2013). Recently, land use change impacts associated with deforestation and agricultural transformation on water resources have created social and political problems at both local and national levels. Considerable stress on water supply including seasonal variations and downstream water quality issues are widely observed.

Changes in water supply and quality caused by land use change have become very critical issues (Kundzewicz et al., 2007) that affect hydrologic functions of surface water and groundwater resources (Fohrer et al., 2005; Stonestrom et al., 2009). However, these effects vary as functions of seasonality and the changing climate (Huxman et al., 2005). Knowing these responses, we can address the questions of how the on-going land use and climate changes may have influenced the annual and seasonal hydrologic components, and nutrients transportation in the system. Answers to these questions will improve the predictability of hydrologic consequences of these changes that directly influence the daily life of a large number of population downstream of the watershed. Therefore, we require the knowledge of how water resources are affected by these changes of various aspects of regional hydrologic cycle.

Global climate change and associated impacts on water resources are the most urgent challenges facing mankind today and will have enduring societal implications for generations to

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come. Potential impacts may include the changes in watershed hydrologic processes including timing and magnitude of surface runoff, stream discharge, evapotranspiration, and flood events, all of which would influence other environmental variables such as nutrient and sediment flux on water sources (Simonovic and Li, 2004; Zhang et al., 2005; Zierl and Bugmann, 2005) affecting every aspect of human life (Xu, 1999, 2000). Water resources managers are facing difficult decisions regarding current water resources and future management strategies based on dwindling freshwater supplies and human population growth. Therefore, better estimation of hydrologic responses to both land use change and climate variability is crucial, and separation of their effect is of great importance for future land use planning and water resources management, specifically for large agriculture dominated watershed.

Though a number of studies have highlighted the concerns of river water qualities, there is clear lack of assessing the impacts of potential land use and climate changes on hydrologic processes of large-scale watersheds. Therefore, this study is one of the first to estimate potential land use and climate change effects on hydrologic processes of large agriculture dominated Big Sioux River (BSR) watershed that may be crucial for better future land use planning and sustainable water resources management of the region. The major objectives of this study are: (1) to assess how the potential land use change affects surface runoff and total water yield of the BSR basin through simulation modeling, (2) to estimate the effects of climate variability on key hydrologic processes including precipitation, stream discharge, water yield, groundwater contribution to stream discharge, water percolation, evapotranspiration, snowfall, and snowmelt in the basin, and (3) to model the combined effects of potential land use change and climate variability on future water availability of the basin.

2. Materials and methods

2.1. Study site

The BSR watershed located in north-central part of the United States (Fig. 1) covers an area of 21,033 km^2 with low elevation ranges between 284 and 663 m above mean sea level. The BSR is a permanent, natural river that flows north to south along eastern edge of South Dakota and eventually drains into the Missouri River. Geologically, the watershed is composed of Precambrian Sioux Quartzite, Dakota Sandstone, Granerous Shale, Greenhorn Limestone, Carlile Shale, Niobrara Chalk, and Pierre Shale (Pirner, 2004), that form a complex geologic setting of the basin potentially influencing the interaction between groundwater and surface water reservoirs. The land use is primarily dominated by crop cultivation including corn, soybean, wheat, grassland, water, wetland, and urban with contributions of 36, 24, 1, 27, 3, 1, and 8%, respectively (Table 1). The dominant soils of the basin, derived from Soil Survey Geographic Data (SSURGO) (http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx), are silt clay loam, sandy loam, and silt loam. The average annual temperature of the region is 7.6 °C with minimum and maximum values of −7.3 and 22.7 °C during January and July months, respectively (SDSU, 2003). The average annual precipitation is 544 mm with major contribution (40%) during summer months (June–August), and the seasonal snowfall is about 1062 mm with 48% contribution during winter months (December–February). The Big Sioux River (BSR) has been subject to large fluctuation in water quantity in recent decades. These natural fluctuations, coupled with land use change and climate variability have led to deteriorate water quality of the river. About 60% of the BSR watershed is used for agricultural production with high application of chemical fertilizers, so the leading source of water pollution is fertilizer runoff leading to the river being ranked 13th most polluted in the United States (Kerth and Vinyard, 2012).

2.2. Modeling approach

For this study, we used the SWAT (version 2012) (Arnold et al., 1998), a river basin model developed for the U.S. Department of Agriculture (USDA), that incorporates the effects of weather, surface runoff, evapotranspiration, groundwater flow, crop growth, and nutrient yield as well as the long term effects of varying agricultural management practices. The water balance equation which governs the hydrologic components of the model (Neitsch et al., 2011) is as follows.

$$SW_t = SW_0 + \sum (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \tag{1}$$

where SW_t is final soil water content (mm), SW_0 is initial soil water content (mm), t is time in days, R_{day} is amount of precipitation (mm), Q_{surf} is amount of surface runoff (mm), E_a is amount of evapotranspiration (mm), W_{seep} is amount of water entering the vadose zone from the soil profile (mm), and Q_{gw} is amount of return flow (mm). The surface runoff was generated using a modified Soil Conservation Service (SCS) curve number (CN) method (USDA, 1986) based on local land use, soil type, and antecedent moisture conditions. Actual evapotranspiration was computed using an exponential function of soil depth and water content (Ritchie, 1972) whereas the potential evapotranspiration (PET) was modeled through Penman–Monteith approach (Monteith, 1965). However, Snowmelt in the model was estimated through mass balance approach as presented in the Eq. (2).

$$SNO = SNO + R_{day} - E_{sub} - SNO_{mlt} \tag{2}$$

where SNO is total amount of water in snowpack on a given day (mm H_2O), E_{sub} is amount of sublimation (mm H_2O), and SNO_{mlt} is amount of snowmelt (mm H_2O). The changes in snowpack volume depends on additional snowfall or release of meltwater in the basin.

The kinematic storage model (Sloan and Moore, 1984) that primarily accounts for soil hydraulic conductance, soil moisture, and slope was used to compute soil interflow. The baseflow components for this study were modeled as in Eq. (3) (Arnold et al., 1998), all expressed in millimeter.

$$Q_{gw,i} = Q_{gw,i-1} \exp(-\alpha_{gw}\Delta t) + w_{rchrg,sh}\left[1 - \exp(-\alpha_{gw}\Delta t)\right] \tag{3}$$

where Q_{gw} is groundwater flow into the main channel on day i, $Q_{gw,i-1}$ is groundwater flow into the main channel on day $i-1$, α_{gw} is baseflow recession constant, Δt is time step (1 day), and W_{rchrg} is amount of recharge entering the shallow aquifer on day i. Finally, the net water yield ($WYLD$ in mm) to the stream channel was computed by the following equation.

$$WYLD = SURQ + LATQ + GWQ - TLOSS \tag{4}$$

where $SURQ$ is surface runoff (mm), $LATQ$ is lateral flow contribution to stream discharge (mm), GWQ is groundwater contribution to stream discharge (mm), and $TLOSS$ is transmission losses from the system (mm).

2.3. Required input data

The SWAT model requires the data for topography, land use, soil, weather/climate, and stream discharge. For this study, we used 30 × 30 m resolution global digital elevation model (GDEM) data derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (http://gdem.ersdac.jspacesystems.or.jp/search.jsp) for delineating sub-basins and also for defining stream, area, and slope of the sub-basins. Land use data for this study was obtained from the National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (http://nassgeodata.gmu.edu/CropScape/) of the United States Department of