Catena 154 (2017) 1–11

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Analysis of streamflow responses to climate variability and land use change in the Loess Plateau region of China

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ARTICLE INFO

Article history:
Received 7 October 2016
Received in revised form 8 February 2017
Accepted 12 February 2017
Available online 20 February 2017

Keywords:
ArcSWAT
Land use change
Climate variability
Streamflow response

ABSTRACT

Reduced streamflow is a major concern in the Haihe river basin, which supplies water for agriculture, industry and the growing population along the river. The upper Sang-kan (USK) river basin is the headwater of the Haihe river. To understand the drivers of streamflow change in this basin, effects of land use change and climate variability on temporal flow variability were studied using the Soil and Water Assessment Tool (SWAT). The calibration and validation results of the *Scenario* 0 (*S*0) model (with land use of 1986 and climate derived from 1979 to 1990) indicated that SWAT simulated monthly streamflow well. This was indicated by the Nash–Sutcliffe model efficiency (*NS*) and the Coefficient of Correlation (r^2) for monthly flow, which were 0.89 and 0.91 for the calibration period (1981–1985) and 0.79 and 0.82 for the validation period (1986–1990), respectively. After calibration and validation of the SWAT model (*S*0), three different scenarios were simulated and compared in order to study the effects: *Scenario* 1 (land use of 2000 and climate during the 1979–1990 period, abbreviated as *S*1), *Scenario* 2 (land use of 2012 and climate during the 1979–1990 period, abbreviated as *S*2), and *Scenario* 3 (land use of 2012 and climate during the 2001–2012 period, abbreviated as *S*3). By comparing the simulated hydrological results of *S*0 vs. *S*1 and *S*2, and *S*2 vs. *S*3, and the annual changes in water use, it can be concluded that the recent perennial drought in the USK river has mainly been caused by human activities; warmer temperatures and less rainfall resulted in streamflow declining by 39.1%, while land use changes and the accompanied water use change for irrigation resulted in surface runoff increasing by 37.6% and streamflow increase between 2.2% and 3.9%, during the period of 1986–2012; increasing ground water and surface water usage for urbanization, industrialization, and reservoir constructions can be attributed from 63.1% to 64.8% of the perennial drought in USK river in recent years. The hydrological simulations provided a better understanding of streamflow changes in the USK basin. The study results can be helpful to maintain ecosystem services and sustainable water use in this region and in the Haihe River basin.

1. Introduction

Climate and land use are two important factors that influence hydrological responses of a river. Climate variability can impact flow routing time, peak-flows and volume by affecting the amount and distribution of regional precipitation and temperature (Changnon and Demissie, 1996; Schulze, 2000; Wang et al., 2008b), while land use changes can cause changes in baseflow, annual mean discharge, and flood frequency and severity (Buytaert et al., 2006; Li et al., 2009; Yang et al., 2008b; Zheng et al., 2007). Since the publication of the Third Assessment Report of the Intergovernmental Panel on Climate Change (McCarthy et al., 2001), considerable efforts have been made in China to detect trends in hydrological variables and shifts in streamflow. Results have shown different trends in streamflow in different regions. Significant decline in runoff was observed in northern China (Huang and Zhang, 2004; Wang et al., 2008b; Yang and Tian, 2009; Zhao et al., 2014), frequent floods have been happening in monsoon seasons in southern areas (Piao et al., 2010; Yang et al., 2008b; Zhang et al., 2008; Zhang et al., 2006), and the Aksu and Yarkant rivers (tributaries of the Tarim river, the largest inland river), which are supplied by melting ice, snowmelt and precipitation, have shown a tendency of increasing streamflow (Chen et al., 2006; Chen et al., 2007). While reservoir regulation, water exploitation can also cause significant changes in the hydrological processes of a basin (Bieger et al., 2014; Buytaert et al., 2006; Shen et al., 2009), to some extent these hydrological trends can all be ascribed to changes in regional temperature, precipitation and/or land use.

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http://dx.doi.org/10.1016/j.catena.2017.02.012
0341-8162/

Together with uneven space-time distribution and great inter-annual changes of precipitation, the effects of water resource exploitation on the environment are becoming more and more acute in the arid and semi-arid Loess Plateau region (Zhang et al., 2015b). The ecosystem in the Loess Plateau is quite fragile; combinations of the influences of El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), long term climate change, and human activities result in widespread water resource shortage and deterioration of aquatic ecosystems (He et al., 2003; Shi and Shao, 2000). According to Xin et al. (2008), the climate in the Loess Plateau is becoming warmer and drier. This tendency will not only lead to decreases in water supply, but it will also affect the local hydrological processes and the balance between supply and demand of water resources. The temperature increase and the decrease in relative humidity have resulted in a significant increase in potential evapotranspiration over the last 50 years in the Loess Plateau, which causes decreases in runoff, groundwater levels, and streamflow, and leads to serious soil desiccation (Li et al., 2012; Wang et al., 2008a; Wang et al., 2011). With rapid economic development and urbanization, land use has been changing drastically in this region since 1985. To mitigate the impacts of these changes, a series of important ecological projects (e.g., the "Grain for Green" and "Land Reclamation Regulations" programs), which include restoration measures of revegetation and engineering, have been implemented since the beginning of the 21st century to improve the ecological environment. These measures have improved vegetation coverage, altered land use patterns, and eventually resulted in changes in surface hydrology (Zhang et al., 2015a; Zhang et al., 2015b).

Located on the Loess Plateau, the upper Sang-kan river is the headwater of the Yongding river basin and is the main water source for local and downstream residents. However, since 1997, most parts of the Sang-kan river have been in a situation of perennial drought, largely weakening its capacity as a water supply and worsening the local ecological environment. Contributing factors including low coverage of woodlands and grasslands, hilly terrain, poor soil water holding capacity, high-intensity short-duration rainfall, made regional floods in the hilly areas and the river drying up for long periods coexist in this basin (Fan et al., 2007). Study of streamflow variation of the upper Sang-kan river and hydrological responses to climate variability and land use change is important for sustainable utilization of water resources and local ecological preservation. Therefore, the main objective of this research was to measure the temporal streamflow response to changes in climatic variability and land use in the USK basin during the past 30 years. Comparative analyses of long-term hydro-meteorological data sequences, paired catchments approaches, field investigations, and hydrological simulations are most commonly used to investigate the impacts of climate variability and human activities on streamflow. However, paired catchment approaches and field investigation methods are time consuming and highly restricted to the size and characteristics of a watershed. In addition, they also cannot differentiate impacts of climate variability from those of human activities. Hydrological models, on the other hand, can conceptualize and investigate the relationships among climate, human activities, and water resources (Lahmer et al., 2001; Leavesley, 1994; Li et al., 2009). The Soil and Water Assessment Tool (SWAT) model has been successfully applied to several rivers basins in many countries to study climate and land use impacts on hydrologic processes (Mukundan et al., 2010; Oeurng et al., 2011; Tibebe and Bewket, 2011; Ullrich and Volk, 2009; Wang et al., 2008b). Hydrologic processes including surface runoff, actual evapotranspiration, recharge, and streamflow have been simulated, calibrated, and validated worldwide at a variety of spatial and temporal scales using SWAT to address different hydrological and environmental issues (Saleh et al., 2009b). Specific objectives of this study were to (i) apply SWAT to the USK basin, a semi-arid, data-scarce river basin, (ii) simulate the impacts of different climate variability and land use on hydrological process in the USK basin, and (iii) provide decision-makers with information to promote effective water resources management and sustainable development.

2. Materials and methods

2.1. Study river basin

Flowing east, the Sang-kan river is located in the Loess Plateau region of Shanxi Province, China, and it is a tributary of the Yongding river of the Haihe basin. The study area, the upper Sang-kan (USK) basin, is the headwater of the Yongding river. Construction of the Dongyulin reservoir in 1994 has altered the hydrology and natural streamflow of the river. Streamflow from the USK basin, which is the upper region controlled by the Dongyulin hydrology station, can avoid the intervention of reservoir regulation. Boundaries of the study basin

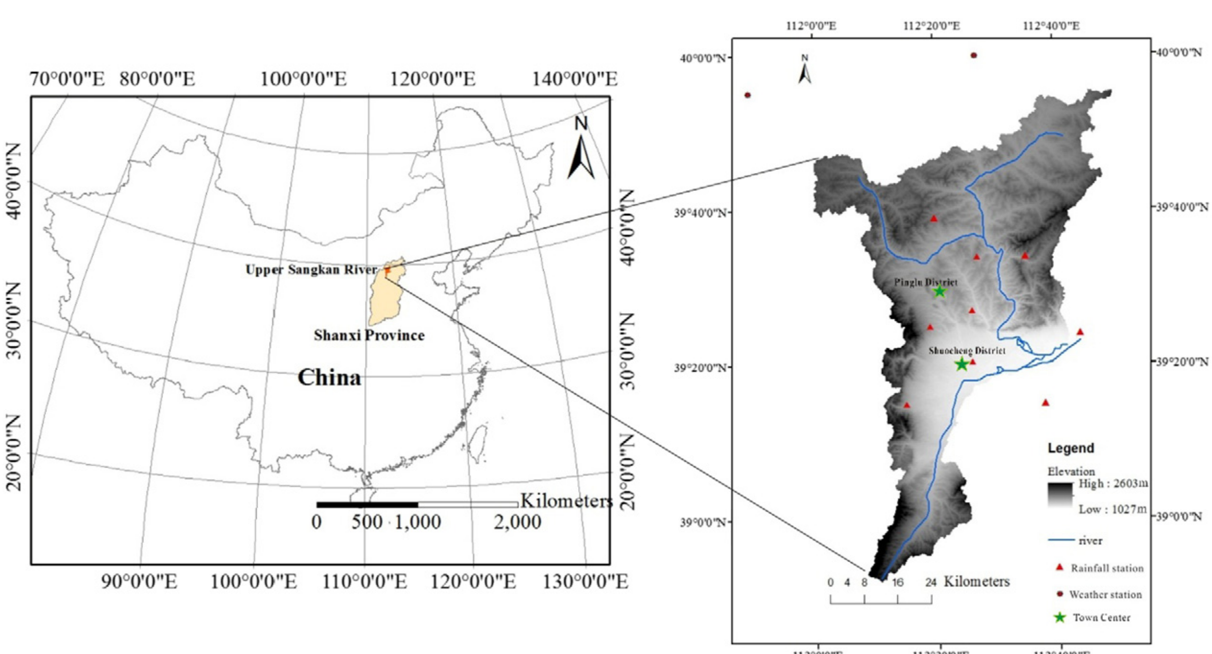

Fig. 1. The location of the upper Sang-kan (USK) river basin and its Digital Elevation Model (DEM).