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Sensitivity analysis of runoff to climate variability and land-use changes in the Haihe Basin mountainous area of north China

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ABSTRACT

Runoff has changed significantly in most regions in China over the past decades. Climate variability and land-use changes are considered to be the two main factors contributing to runoff variation. Investigating the mechanism of runoff variation is of great significance for the sustainable utilization of water resources. In this study, Mann-Kendall test, double cumulative curve method, and runoff sensitivity analysis method are adopted to separate and quantify the relative impacts of climate variability and land-use changes on runoff. Furthermore, the sensitivities of runoff were estimated with regard to these two factors in north China during the study period from 1957 to 2000. The results revealed a significant decreasing trend in annual runoff and indicated that land-use changes had a greater effect on runoff than climate variability since 1979. The runoff decline due to land-use changes was 68.33%, whereas the runoff decline due to climate variability was only 30.85%. Further analysis of the sensitivities of runoff to climate variability and land-use changes suggested that, with a 10% increase in precipitation, the runoff will increase by 35.1%; while a 10% increase in potential evapotranspiration or the aridity index will induce 25.1% or 27.5% decrease in runoff, respectively. The sensitivity coefficients of runoff to precipitation, potential evapotranspiration and aridity index (ε_P, $|\varepsilon_{Ep}|$ and $|\varepsilon_{\phi}|$), and runoff ratio (Q/P) and the aridity index exhibited a significant nonlinear negative correlation ($Y = ax^{-b}$, $R^2 > 0.85$), and a positive linear correlation ($Y = ax + b$, $R^2 < 0.50$), respectively. All these results implied that runoff is more sensitive to the regions with water scarcity and drying climate. The average sensitivity coefficients of runoff to forest, grassland, and farmland were 1.46, 1.21 and 1.18, respectively. This means that a 10% increase in forest, grassland, and farmland coverage would induce 1.46, 1.21, and 1.18 mm decrease of runoff, respectively. This demonstrates that forests have the most effective impact on runoff reduction, followed by grassland or farmland.

1. Introduction

It is widely recognized that runoff has undergone significant changes over the past decades due to the combined impacts of climate variability and land-use changes (Bronstert et al., 2002; Lei et al., 2014; Rodriguez-Iturbe et al., 2001). These changes have caused a severe challenge for water resources management and the ecological environment (Wang and Yu, 2015). In response to this challenge, quantitating the effects of climate variability and land-use changes on runoff could better understand the hydrological circulation.

Climate variability is thought to have led to climatic warming and strong precipitation variation, whereas land-use changes have modified the time and space distribution of water resources (Brutsaert and Parlange, 1998; Jiang et al., 2011; Milly et al., 2005), both factors have resulted in great variations in hydrological processes and the amount of available water (Wang and Yu, 2015). To better understand the variations in runoff, numerous studies have focused on quantifying the relative effects of climate variability and land-use changes on runoff in many regions worldwide (Buendia et al., 2016; Dong et al., 2015; Huo et al., 2008; Liu et al., 2014; Tomer and Schilling, 2009; Zhang et al., 2016). For example, Kezer and Matsuyama (2006) showed that runoff variation has been strongly influenced by climate variability over the past 50 years. Wang et al. (2010) indicated that, in the Baimasi River, the contribution of runoff variation due to climate variability was estimated to be 89%, 66% and 56% in the 1970s, 1980s, and 1990s, respectively. On the other hand, Liu et al. (2009) reported that the reduction in runoff is mainly because land-use changes increased evapotranspiration. Yin et al. (2017) pointed out that land-use changes are responsible for 70.7% of the runoff variation in the Jinghe River Basin. Wei and Zhang (2010) concluded that climate variability and

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land-use changes each contributed 50% to the runoff variation in the Willow River watershed. These studies show that the impacts of climate variability and land-use changes on runoff variation vary from place to place.

North China is the economic, political, and cultural center of China with a significant role in the sustainable socioeconomic development (Wang et al., 2013; Wang and Yu, 2015). However, water resources shortage and ecological degradation have obstructed the economic development of this region. The Haihe mountainous area of north China is the main water-producing area of the Haihe River Basin, where runoff is only 12% of the average annual precipitation. This is an important water source for domestic and industrial uses in large cities such as Beijing and Tianjin. However, runoff in this region experienced a significant decreasing trend in recent years (Lei et al., 2014; Lu et al., 2015; Ma et al., 2010). In response to this problem, most studies have only quantified the contribution rates of climate variability and land-use changes on runoff reduction, and have mostly focused on the impact of forest on runoff. However, systematically analyzing the sensitivities of runoff to specific climatic factors and different land-use coverage (e.g., forest, grassland, and farmland) in the Haihe Basin mountainous area has not been reported.

The objectives of this study therefore are to (i) investigate the tendencies and change points of annual runoff in the Haihe Basin mountainous area from 1957 to 2000; (ii) separate the relative impacts of climate variability and land-use changes on the decrease of runoff; (iii) analyze the sensitivity of runoff to climatic factors, and (iv) identify the sensitivity of runoff to the vegetation coverage in different watersheds. The findings of this study will be very helpful for future water resources planning and land-use improvement strategies with the aim to guarantee the sustainable utilization of water resources.

2. Materials and methods

2.1. Study area

The study area is the Haihe Basin mountainous area of north China (35°3'-42°43'N, 111°57'-119°35'E), which is the main runoff-producing area of the Haihe River Basin (Fig. 1). The total area is 18.64×10^4 km^2 and the elevation ranges from 6 to 2940 m. This area is distinguished by a semi-humid continental monsoon climate with the average annual precipitation is 500 mm and distributed unevenly: approximately 70–85% of precipitation occurs between June and September. Approximately 65% of this area is occupied by forest and grassland, 25% is farmland, and the remaining 10% has other uses. Vegetation is mainly coniferous forest (e.g., *Platycladus orientalis* and *Pinus tabuliform*) and broad-leaved forest (e.g., *Quercus riabilis* and *Populus pekingensis*). A total of 66 watersheds in the study area were selected, and the control areas range from dozens of square kilometers to tens of thousands of square kilometers (Fig. 1).

2.2. Data collection

Hydrological data of runoff (1957–2000) were derived from the State Hydrological Statistical Yearbook: the Haihe River Basin volume. The meteorological data pertaining to precipitation, air temperature, and evaporation from 54 meteorological stations in and around the study area during 1957–2000 were collected from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/). Data of land-use for four periods (1980, 1990, 1995 and 2000) were obtained from Data Center for Resources and Environmental Sciences of CAS (http://www.resdc.cn).

2.3. Methodology

2.3.1. Mann-Kendall test

The Mann-Kendall test is generally used to assess the linear trends in a hydro-meteorological time series (Mann, 1945; Kendall, 1975). This method is recommended by the World Meteorological Organization as the most effective tool for hydro-climate variables analysis. The method's statistic S is calculated as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{1}$$

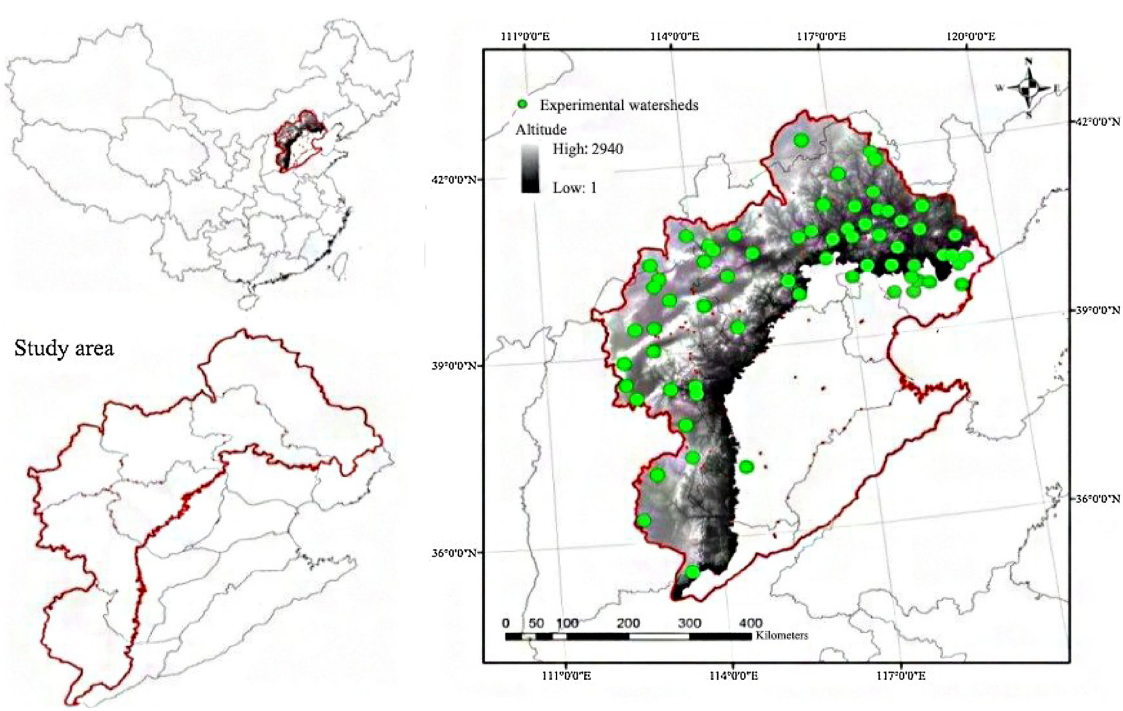

Fig. 1. Study area and the experimental watersheds.