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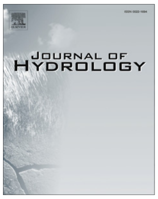

Exploring the spatial variability of contributions from climate variation and change in catchment properties to streamflow decrease in a mesoscale basin by three different methods

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SUMMARY

The hydrological response to environmental changes has attracted a lot of attention and a couple of methods have been used to quantify the relative contributions of climate variability and change in catchment properties to streamflow change at basin scale. However, few studies have been carried out to explore the spatial variability of the results at sub-basin scale. The aim of this study is to explore the spatial variability of relative contributions from climate variability and change in catchment properties to streamflow change within a mesoscale basin using three methods, namely elasticity and decomposition methods based on the Budyko framework, and the dynamic hydrological modeling method. The Upper Hanjiang River Basin (UHRB) is chosen as the study area, which presents a significantly decreasing trend of annual streamflow since 1990. We partitioned change in catchment properties into vegetation-induced change and non-vegetation-induced change in the hydrological modeling method, and climate conditions into precipitation and potential evaporation in the elasticity method. The results of the three methods suggest that climate variability is a greater contributor to streamflow decrease than change in catchment properties for the UHRB, whereas the relative contribution from change in catchment properties increases from 17% in the upper parts to 54% in the lower parts, which is likely linked to the population growth. The relative climate contribution estimated from the hydrological model is greater than these from the two Budyko framework based methods, and the estimated relative climate contribution from the decomposition method is the smallest in the three methods.

1. Introduction

Substantial climate change and intensive anthropogenic activities have induced a non-stationary hydrological system which no longer fluctuates within an unchanging envelope of variability (Intergovernmental Panel on Climate Change, 2007; Milly et al., 2008; Vaze et al., 2010). As a consequence, significant trend of streamflow has been detected in many rivers around the world (Arrigoni et al., 2010; Ma et al., 2008; Ren et al., 2002; Rossi et al., 2009; Schilling et al., 2010; Tang et al., 2007, 2008; Vaze et al., 2011; Wang et al., 2009; Yang et al., 2004). The research interests of understanding the streamflow trend and its driving forces have increased due to the large impacts of streamflow change on social development, ecosystem, local climate, and entertainment. For example, Zhang et al. (2008) investigated the responses of streamflow to the land use/cover changes in the Loess Plateau of China which accounted for more than 50% of the reduction in mean annual streamflow. Tomer and Schilling (2009) suggested that climate change had increased the discharge in Midwest watersheds of US since the 1970s. Zheng et al. (2009) assessed the impacts of climate and land surface change on the streamflow in the headwater catchments of the Yellow River Basin in China, and they found that land use change was responsible for more than 70% of the streamflow reduction in the 1990s. Roderick and Farquhar (2011) related variations in runoff to variations of climatic conditions and catchment properties in Murray–Darling basin, Australia. Tao et al. (2011) attributed the negative runoff trend of the main stream of the Tarim River in China to human water use activities (such as irrigation and domestic water use) and climate changes.

The streamflow change is considered to be induced by climate variability and change in catchment properties (including land cover and land use change) besides direct human activities such as water withdrawal and groundwater abstraction. Several methods have been proposed to separate the effects of climate variability and change in catchment properties on streamflow change. The first type of these methods is elasticity-based method initially proposed by Schaake (1990). The elasticity-based method uses elasticity coefficients to represent the sensitivity of streamflow to

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variations of meteorological factors. After Schaake (1990) several other elasticity-based methods were proposed such as nonparametric method and Budyko based method. Sankarasubramanian et al. (2001) suggested the nonparametric elasticity method by statistically using long-existing meteorological and hydrological data. Zheng et al. (2009) found this method would be weak for the small sample size of time series data and then improved it by using the least square estimator. More recently, Ma et al. (2010) improved the nonparametric method by adding a temperature elasticity coefficient. Concurrently with the nonparametric method, Dooge et al. (1999) proposed an analytical elasticity model based on Budyko framework (Budyko, 1958, 1974), in which the humidity index (annual precipitation over potential evaporation) is adopted to estimate the sensitivity of streamflow to long-term changes in precipitation. Arora (2002) developed a very similar formula by using aridity index (annual potential evaporation over precipitation) instead. Roderick and Farquhar (2011) expanded the previous work by Dooge et al. (1999) and Arora (2002) to evaluating the sensitivity of streamflow to both precipitation and potential evaporation by deriving an integral elasticity formula through the differentiation of the Budyko equation (detailed in Section 3.2.2). Compared to the nonparametric method which estimates the elasticity coefficients empirically based on the observed streamflow and meteorological data, the Budyko based method derives the formula of elasticity coefficients based on different functions of Budyko curve and has more physical background. The second type of these methods is decomposition method proposed recently by Wang and Hejazi (2011), which is also based on the Budyko framework (detailed in Section 3.2.3). This method was applied to the Model Parameter Estimation Experiment (MOPEX) basins in the United States. The third type of these methods is the dynamic hydrological modeling method, which is also called "fixing-changing" method (e.g., Cong et al., 2009; Ma et al., 2010; Li et al., 2012a; Yan et al., 2013). In this method, the calibrated hydrologic model was run with one variable or parameter changed while others fixed to detect the impact of one specific factor on hydrological responses.

To the best of our knowledge, few studies were devoted to make a comparison among these different methods. An exceptional work was recently done by Li et al. (2012a), in which the authors compared the sensitivity-based methods (including nonparametric model proposed by Sankarasubramanian and Budyko framework based elasticity method proposed by Arora mentioned above) and two lumped hydrologic models in three medium sized catchments in Australia. They found that the reduction in streamflow due to increase in vegetation estimated from the Budyko framework based methods was larger than these from hydrological models.

In addition, most of existing studies in this field considered the study area as a whole, and just a few studies made comparisons among different basins with distinct climate or land use/cover conditions. For example, Wang and Hejazi (2011) quantified the climate and direct human impact on mean annual streamflow for 413 watersheds in the contiguous United States. Brown et al. (2013) assessed the impact of forest cover change in afforestation and deforestation experiments on annual streamflow and flow duration curves at 16 paired catchments in Australia and Africa. The spatial variability of the results is seldom investigated at a sub-basin scale.

The aims of this study are: (1) to explore the spatial variability of relative contributions from climate and catchment within a mesoscale basin, (2) to make a comparison study among three different methods, namely the elasticity method (Roderick and Farquhar, 2011) and decomposition method (Wang and Hejazi, 2011) (both based on the Budyko framework), and the dynamic hydrological modeling method. The Upper Hanjiang River Basin (UHRB) is chosen as the study area, which presents a significantly decreasing trend of annual streamflow since 1990. We delineated the UHRB into four sub-basins to explore the spatial variability of the streamflow trend and the contributions. Change in catchment properties are further partitioned into vegetation-induced change and non-vegetation-induced change in the hydrological modeling method, and climate conditions are partitioned into precipitation and potential evaporation in the elasticity method.

The paper is organized as follows. In Section 2, an introduction to the study area and data is provided. The methodology including the three methods is presented in Section 3. Section 4 present the results of relative contribution assessments and spatial variability study. The paper would be closed by summary and conclusion in Section 5.

2. Study area and data

2.1. Study area

The Hanjiang River is the largest tributary of the Yangtze River. The study area is the Upper Hanjiang River Basin (UHRB) draining to the Danjiangkou reservoir (see Fig. 1). It is the water source area of the central route of the South to North Water Diversion Project (SNWDP) in China. This largest water transfer infrastructure is projected to divert 13 billion $m^3\ yr^{-1}$ of water to the North China Plain from 2014. The Hanjiang River flows through Shaanxi, Henan, Hubei provinces of China to the Danjiangkou reservoir with the length of approximate 925 km. The altitude of the basin decreases from 3500 m in the northwest to 88 m at the Danjiangkou reservoir in the southeast. This mountainous basin has a drainage area of 95,200 km^2. The dominant vegetation is shrubs (42.2%) and forest (34.7%). The rest of the land use is covered by croplands (19.8%) and others (including urban, barren and water) according to the land cover data obtained from the U.S. Geological Survey (USGS) Global Land Cover Characteristics Database (Moody and Strahler, 1994; Loveland et al., 2000). The study area lies in a subtropical monsoon region featured with semi-humid climate and distinguished seasons. The mean annual temperature is about 14 °C during the study period (1970–2000). The mean annual precipitation is about 877 mm, of which 40–60% falls in rainy season (from July to September). The mean annual potential evaporation is as high as 1180 mm, and the mean annual streamflow at the Danjiangkou reservoir is about 1123 $m^3\ s^{-1}$.

2.2. Data

Daily precipitation data at 49 rain gauge stations were provided by the Bureau of Hydrology, Ministry of Water Resources of PR China. Daily pan evaporation data at 19 stations were obtained from the China Meteorological Administration. The potential evaporation is calculated based on pan evaporation and conversion coefficients (Stanhill, 2002; Fu et al., 2004). Daily streamflow data at Yangxian, Ankang, and Baihe hydrological stations were also collected from the Bureau of Hydrology, Ministry of Water Resources of PR China. The monthly inflow data of Danjiangkou reservoir was provided by the Management Bureau of the Danjiangkou reservoir, which was calculated according to the reservoir operational records and the downstream runoff measurement at Danjiangkou hydrological station. All the stations are shown in Fig. 1, and all the data cover the period of 1970–2000. The 90-m resolution digital elevation data was extracted from the Shuttle Radar Topography Mission (SRTM) (http://srtm.csi.cgiar.org/). The semi-monthly normalized difference vegetation index (NDVI) data from 1982 to 2000 of the Global Inventory Modeling and Mapping Studies-Advanced Very High Resolution Radiometer