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# Spatiotemporal variation in the attribution of streamflow changes in a catchment on China's Loess Plateau

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ABSTRACT

Identifying the controlling factors of streamflow changes across space and time is important for water resources management. This study investigated the streamflow changes and related them to climate and land use in the Jing River catchment on China's Loess Plateau. The spatiotemporal attribution was examined with the Budyko framework through splitting the whole catchment/study period into subbasins/subperiods. The annual mean streamflow significantly decreased by 0.6–1.0 mm $yr^{-1}$ ($p < 0.05$). Land surface change and climate variability decreased streamflow for most regions and periods. Over different regions, the land surface change accounted for 38–58% to the streamflow reduction; temporally, the contributions of land surface change are gradually increasing over time. The contributions of precipitation to streamflow change are much larger than those of potential evapotranspiration. The catchment characteristics parameter ($w$) in the Budyko framework is well correlated with the accumulative area fraction of forest and grassland, which provides a potential method to develop an empirical form for $w$.

## 1. Introduction

Hydrological processes in arid regions are more sensitive to environmental changes than those in humid regions (Ukkola et al. 2016; Zhou et al. 2015). Thus, it is a great challenge to effectively manage limited water resources in dry climates. Under the background of global warming and intensive land use/land cover changes, hydrological change detection and attribution are critical to provide information for water resources management (Donohue et al. 2011).

Three methods are popular in quantifying the impacts of environmental changes on hydrology − paired catchments approach, time series analysis, and hydrological modeling (Li et al. 2009). The paired catchments approach is effective to relate streamflow changes with land use changes in small catchments with a similar climate; however, it is difficult to apply it in medium to large basins because of the difficulty in pairing catchments (Brown et al. 2005). Time series analysis is mostly employed using regression relationships between streamflow and climatic factors, but it is difficult to interpret the physical mechanism behind the changes. Hydrological modeling is a useful method to understand different variables and their interactions through physically-based mechanism; however, model performances differ due to model structure, data requirements, calibration and validation (Bronstert et al. 2002). Thus, selection of a rational and efficient hydrological model is critical to understand the mechanism of hydrological changes.

The Budyko framework is a rational water and energy balance method, in that the long-term average annual evapotranspiration from a catchment is determined by rainfall and net radiation (Budyko 1974). In recent decades, it has been successfully applied to relate hydrology to climate and catchment characteristics (Choudhury 1999; Dooge et al. 1999; Fu 1981; Yang et al. 2009; Yang et al. 2007; Yang et al. 2008; Zhang et al. 2001). Based on different analytical formulas, the elasticity of streamflow can be quantified by three parameters − precipitation ($P$), potential evapotranspiration ($ET_0$), and catchment characteristics parameter ($w$) (Roderick and Farquhar 2011; Yang and Yang 2011). $w$ is a parameter related to catchment properties, such as vegetation, soil properties and slope (Donohue et al. 2007; Li et al. 2013; Xu et al. 2013; Yang et al. 2014; Zhang et al. 2001; Zhang et al. 2016), as well as climate seasonality (Chen et al. 2013; Feng et al. 2012; Li 2014; Potter et al. 2005; Shao et al. 2012; Yang et al. 2007; Yokoo et al. 2008). It is necessary to determine the main factors affecting $w$ variations, so as to better interpret hydrological changes induced by human activities.

China's Loess Plateau (CLP) is located in the middle Yellow River, North China. Due to frequent heavy rainfall storms in summer months, steep landscape, low vegetable cover, and highly erodible loess soil, the

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CLP is one of the most severely eroded areas in the world (Li et al. 2009). Since the 1950s, a series of soil conservation measures, such as planting trees, improving pastures, building terraces and sediment trapping dams, have been implemented. These measures have substantially altered the land surface by changing the land use pattern and topographical factors (Li et al. 2016). In addition, climate on the CLP tended to become drier and warmer in the past 50 years (Li et al. 2010; Yang et al. 2015). The combined effects of these changes have contributed to streamflow reduction. Considering the variations in soil, climate and land use, interpreting the spatiotemporal variations in the attributions of hydrological changes can provide useful information for water resources management. Recently, although streamflow variations and attribution have been demonstrated in some studies (Liang et al. 2015; Zhang et al. 2008; Zhao et al. 2014), the temporal variability has not been studied.

The objectives of this study are to separate the hydrological effects of land surface change from climate variability over space and time, and to investigate the potential indicator for the catchment characteristics parameter within the Budyko framework in the Jing River catchment. The results will be useful for improving soil conservation measures and water resources management.

## 2. Data and methods

### 2.1. Study area

The Jing River is a second-order tributary of the Yellow river (Fig.1). With an area of 45,421 km$^2$, the long term (1961–2010) average annual precipitation is 555.6 mm and the annual mean temperature is 9.6 °C. The soil is predominantly silt loam with silt content > 50%. Farmland and grassland are the major land use types, respectively accounting for about 45% of the whole catchment. The average erosion rate of the Jing River catchment is 5015 tons km$^{-2}$ yr$^{-1}$ due to the erodible loess from steep slopes, and the area subject to water erosion is 33,220 km$^2$, about 73% of the catchment.

### 2.2. Datasets

Four types of data were collected to analyze the relationships between hydrology and environmental factors – Normalized Difference Vegetation Index (NDVI), land use, climate, and streamflow.

The NDVI data were obtained from the Advanced Very High Resolution Radiometer (AVHRR) products in the framework of the Global Inventory Monitoring and Modeling System (GIMMS). The latest datasets NDVI3g, for the period of 1982–2010, with a spatial resolution of 8 km and a temporal resolution of 15 days, were used in this study to indicate the catchment vegetation conditions. The land use maps include five maps derived from remote sensing images in 1986, 1995, 2000, 2005 and 2010 (Li et al. 2016). The land use was classified into six classes − farmland, forest, grassland, water, built-up land and unused land. The NDVI data will be used to analyze the spatiotemporal variations in vegetation coverage, while the land use maps will be used to interpret the changes in land use pattern, i.e. the changes in each land use type.

Climate data, including daily precipitation, maximum and minimum temperature, wind speed, relative humidity and sun duration hours, were collected from 24 weather stations (Fig.1). These data are from China Meteorology Administration, and have been carried out careful data quality control. $ET_0$ was computed by the Priestley-Taylor method (Priestley and Taylor 1972). The equally weighted spatial average of $P$ and $ET_0$ were calculated for the basins of interest.

Monthly streamflow was collected from three major gauge stations − Yang Jia Ping (YJP), Yu Luo Ping (YLP) and Zhang Jia Shan (ZJS) (Fig.1). The YJP and YLP are located in the upper reaches, and the ZJS is at the outlet of the catchment. The control area of the YJP, YLP, and ZJS stations, respectively, accounts for 32%, 42% and 95% of the catchment. For the period of 1961–2010, the streamflow in the YJP, YLP and the lower reaches (LR, the region from the two stations to the ZJS) accounts for 41%, 26% and 33% of the catchment. As the streamflow in LR cannot be directly observed, it was estimated as the streamflow difference between the ZJS and two stations, YJP and YLP.

$$Q_{LR}*S_{LR} = Q_{ZJS}*S_{ZJS} - Q_{YJP}*S_{YJP} - Q_{YLP}*S_{YLP} \tag{1}$$

where $Q$ represents streamflow, mm; $S$ represents the areas of the watershed or subbasins, km$^2$.

### 2.3. Methods

To analyze the spatial variations in streamflow change, the basin (ZJS) was divided into three subbasins according to the gauging stations: YJP, YLP, and LR (Fig.1). To investigate the temporal changes in streamflow and its attribution, the period of 1961–2010 was separated into five subperiods − 1960s, 1970s, 1980s, 1990s, and 2000s. The 10-year interval was chosen because of two reasons. First, over a period longer than 5–10 years, it is reasonable to assume that changes in soil water storage are zero (Zhang et al. 2001). Second, the intervals of the five land use maps (1986, 1995, 2000, 2005 and 2010) are either 5 or 10 years, but the land use pattern does not change greatly over 5-year intervals (Fig.2). Thus, the 10-year interval is appropriate to analyze the temporal changes.

Two steps are used to attribute streamflow changes to environmental factors. The first step analyzes the changes in both environmental factors and streamflow, and qualitatively relates them. The second step quantifies the impacts of climate change on streamflow with the water balance equation via the Budyko framework.

#### 2.3.1. Analyzing trend and inter-annual variability

The monotonic trend and abrupt changes in annual $P$, $ET_0$, $Q$ and NDVI were analyzed by the Mann-Kendall test (MK) (Kendall 1948; Mann 1945). To detect the abrupt change point, for a given time series, a rank-based procedure is constructed:

$$S_k = \sum_{i=1}^{k} r_i, \quad k = 2, 3, \ldots, n$$
$$r_i = \begin{cases} 1, & \text{if } x_i > x_j \\ 0, & \text{if } x_i \le x_j \end{cases}, \quad j = 1, 2, \ldots, i \tag{2}$$

The Mann-Kendall test statistic $UF_k$ is given as follows:

$$UF_k = [S_k - E(S_k)]/\sqrt{Var(S_k)}, \quad k = 1, 2, \ldots, n \tag{3}$$

in which $UF_1 = 0$, $E(S_k)$ and $Var(S_k)$ are average and variance of $S_k$.

$$E(S_k) = n(n+1)/4$$
$$Var(S_k) = n(n-1)(2n+5)/72 \tag{4}$$

With Eq. (3), $UF_k$ and $UB_k$ are calculated from the positive and negative sequence, respectively. The intersection of $UF_k$ and $UB_k$ is the abrupt change point, and if the intersection occurs within the reliable lines of ± 1.96 (5% confidence interval), a detectable change point can be inferred.

#### 2.3.2. Attributing streamflow changes

For a given catchment, the changes in mean annual streamflow over two historical periods can be calculated as:

$$\Delta\overline{Q}_{tot} = \overline{Q}_{change} - \overline{Q}_{base} \tag{5}$$

where $\Delta\overline{Q}_{tot}$ indicates the total changes in mean annual streamflow (mm); $\overline{Q}_{base}$ and $\overline{Q}_{change}$ are the mean annual streamflow during the baseline period and changed period (mm), respectively. This study employed the 1960s as the baseline period since it is subject to the least perturbation of human activities, and the other decades were used as changed periods to calculate the changes in streamflow.