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Separating the impacts of climate change and land surface alteration on runoff reduction in the Jing River catchment of China

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ABSTRACT

The Loess Plateau of China is subject to severe water shortages, and the runoff reduction observed in most watersheds exacerbates the problem. Quantifying the contributions of environmental changes to runoff reduction is thus very important for water resources management. Taking the Jing River catchment as the study area, the changes in runoff for the period of 1961–2010 at three gauge stations—the catchment outlet (Zhang Jia Shan, ZJS) and the two others from the upper reach (Yang Jia Ping, YJP, and Yu Luo Ping, YLP) were analyzed in this study. Using the Budyko framework, the spatiotemporal variations of the contributions of precipitation (P), potential evapotranspiration (ET_0), and land surface conditions (represented by the parameter n in the Choudhury–Yang equation) to runoff changes were evaluated. A significant downward trend in runoff was detected for the ZJS and YJP stations. The sensitivity of the runoff changes to the different environmental factors considered was different. The sensitivity coefficient was the greatest for P, intermediate for ET_0, and smallest for the land surface condition (n). However, the sensitivity coefficients are becoming greater over time. The decrease in P was the dominant factor in the runoff reduction at the three stations, but its effect was largely offset by the increase in n at YLP. The contribution of land surface alteration to runoff reduction has been increasing in recent years, which indicates that the improvement of vegetation coverage and the construction of terraces and check dams have strengthened their impacts on runoff. Therefore, careful attention should be paid to the hydrological effects of soil conservation measures on runoff.

1. Introduction

The Loess Plateau (6.4×10^5 km^2) is located in the upper and middle reaches of the Yellow River in northern China (Fig. 1). Because of the high erodibility of loessial soil and the intensive rainstorms and low vegetation coverage of the area, the Loess Plateau has become one of the most severely eroded areas in the world (Zhu et al. 1983). Several measures have been implemented since the 1950s in attempts to control soil loss in the area, including biological measures (replanting trees and improving pastures) and engineering measures (building terraces and sediment trapping dams). The effects of such soil conservation measures on water yield need to be assessed because the region is highly vulnerable to water shortages (Mu et al. 2007b).

Three methods have been developed to assess the hydrological effects of environmental changes: the paired catchments approach, hydrological modeling, and statistical methods (Li et al. 2009). The paired catchments approach is superior to modeling of small catchments in compensating for climate variability, but it is difficult to apply this approach to medium or large catchments because the natural conditions are rarely similar in large catchments (Huang et al. 2003; Mu et al. 1999). Hydrological models, including process-based models and conceptual models, are powerful tools for investigating the relationships between climate, human activities, and water resources (Jothityangkoon et al. 2001; Leavesley 1994). However, few process-based models can be directly used for this purpose because they lack a component for engineering measures (McVicar et al. 2007). Conceptual models and regression-based statistical models have thus been widely used to quantify the effects of environmental changes on runoff.

The climate elasticity method based on catchment-scale water and energy balance, such as the Budyko hypothesis (Budyko 1961; Budyko 1974), has been very popular in recent years because of its simple formulation but full representation of climate and land surface changes (Dooge et al. 1999; Sankarasubramanian et al. 2001). Using the water balance equation of $P = Q + ET + \Delta S$ (where P, Q, ET and ΔS respectively represents precipitation, runoff, actual evapotranspiration and changes in water storage) and the Budyko solution for ET, some analytical formulas have been developed to represent the impacts of

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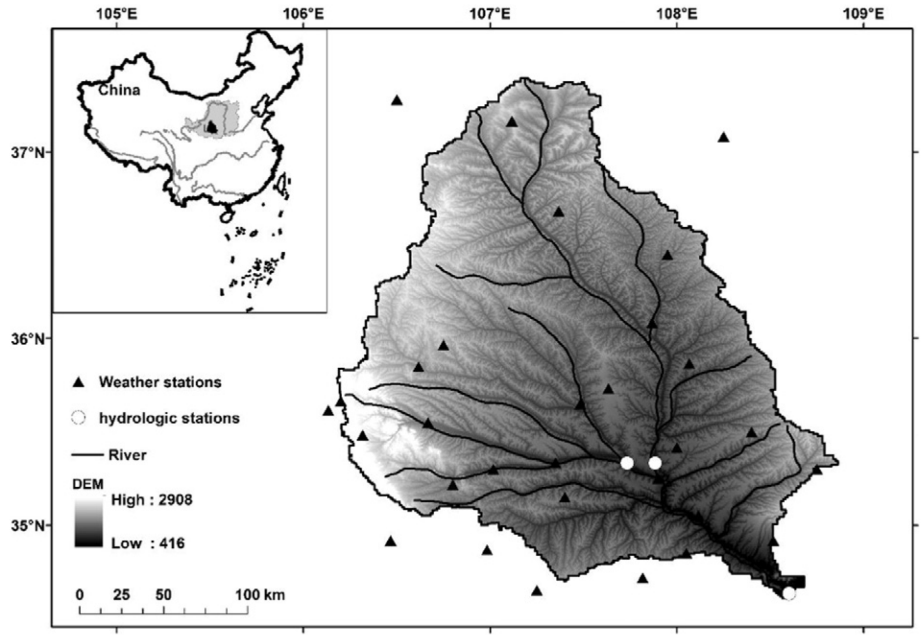

Fig. 1. Location of the Jing River catchment and the hydrologic and weather stations.

environmental factors on runoff or actual evapotranspiration. Roderick and Farquhar (2011) derived the relationship of the elasticity of runoff to three parameters, i.e., precipitation, potential evapotranspiration, and land surface conditions. Yang and Yang (2011) related the elasticity of runoff to precipitation, net radiation, air temperature, wind speed, and relative humidity and then separated the contributions of different climatic variables. Assuming ΔS as zero for long-term water balance, the elasticity method is effective to describe the sensitivity of runoff to environment factors. However, the analytical formulas have been rarely used for analysis of inter-annual variations in the elasticity coefficients though it might provide important information for water resources management.

Spatiotemporal variations exist in the hydrological effects of both human activities and climate variability on the Loess Plateau. In general, human activities account for >50% of the changes in runoff in most catchments (Zhang et al., 2008a; Zhao et al. 2014), while climate variability plays a more important role in some catchments (Hu et al. 2007; Li et al. 2009). Decade-scale variations in hydrological effects have also been observed (Mu et al. 2007a). Opinions differ on the extent of the total runoff change that has occurred in the Loess Plateau, as well as to the extent to which each factor has influenced that change. Therefore, assessing the changes and their causes at the catchment scale is important because it can provide important information for use in environmental protection and water resource management.

The objectives of this study were to (i) analyze the spatiotemporal changes in runoff in a sample catchment for the period of 1961–2010, (ii) assess the inter-annual variability of the elasticity coefficients of runoff to climatic factors and land surface conditions, and (iii) further quantify the contributions of various factors to runoff changes. A method was developed to analyze the inter-annual variability of the elasticity coefficient and the spatiotemporal variability of the runoff as well as its attribution was analyzed in detail to obtain information for use in water resource management.

2. Materials and Methods

2.1. Study area

The Jing River is a second-order tributary of the Yellow River, and its catchment is located in the south of the Loess Plateau (Fig. 1). The catchment covers an area of 45,421 km^2. The average annual precipitation is 542.5 mm, 50–60% of which falls between June and September in heavy storms. The average annual temperature for the period of 1961–2010 is 9.6 °C. The southern part of the catchment is warmer and wetter than the northern part. Farmlands and grasslands cover 88% of the whole catchment (Li et al., 2013a). The soil is predominantly silt loam, with a silt content >50%. The elevation varies from 416 to 2908 m, and the northwestern portion of the catchment is higher than the southeastern portion. The catchment is composed of five types of landform. The two main types (hilly–gully terrain and tableland–gully terrain) cover 81.2% of the catchment. These are the most eroded regions of the catchment.

Since the 1950s, a series of soil conservation practices has been implemented in the catchment. These measures have included both biological measures, such as planting of trees and improvement of pastures, and engineering measures, such as construction of terraces and sediment-trapping dams. The controlled area has increased, and accelerated after 1970s. The total controlled area reached 7562 km^2 by 1996, accounting for 23% of the water-eroded area (Ran et al. 2006).

2.2. Data collection

Three hydrologic stations, i.e., Yang Jia Ping (YJP), Yu Luo Ping (YLP), and Zhang Jia Shan (ZJS), were selected in this study because they are the most important outlets of two sub-watersheds and the whole watershed, respectively (Fig. 1). The ZJS station is the outlet of the Jing River before it feeds into the Wei River. The control areas of the YJP, YLP, and ZJS stations are 14,124 km^2, 19,019 km^2 and 43,216 km^2, respectively, which correspond to 31%, 42%, and 95%, respectively, of the total area of the Jing River catchment. The amounts of runoff of YJP and YLP and the lower reaches from the two stations to ZJS account for 54%, 32%, and 14%, respectively, of the total runoff of the catchment. Monthly runoff data for the three catchments for the period of 1961–2010 were collected from the Yellow River Conservancy Commission (YRCC). Daily meteorological data for 26 stations for the period of 1961–2010 were collected from the China Meteorological Administration. The meteorological data consisted of precipitation, daily maximum and minimum temperatures at a height of 2 m, atmospheric pressure, wind speed at a height of 10 m, mean relative humidity and sunshine duration data.