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Determining the hydrological responses to climate variability and land use/cover change in the Loess Plateau with the Budyko framework

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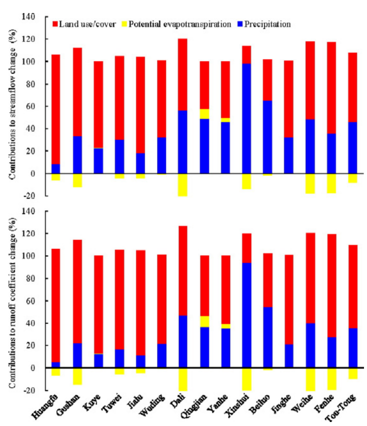
HIGHLIGHTS

- Elasticities of Q and R_c to climate variability and catchment characteristic were derived.
- Contributions of climate variability and land use/cover changes to reductions of Q and R_c were determined.
- Relationship between ecological restoration and hydrological responses was quantified.

GRAPHICAL ABSTRACT



Contributions of precipitation, potential evapotranspiration and land use/cover to the changes of streamflow and runoff coefficient in the fifteen main catchments of the Loess Plateau between 1961 and 2009.

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ABSTRACT

Understanding and quantifying the impacts of land use/cover change and climate variability on hydrological responses are important to the design of water resources and land use management strategies for adaptation to climate change, especially in water-limited areas. The elasticity method was used to detect the responses of streamflow and runoff coefficient to various driving factors in 15 main catchments of the Loess Plateau, China between 1961 and 2009. The elasticity of streamflow (Q) and runoff coefficient (R_c) to precipitation (P), potential evapotranspiration (E_0), and catchment characteristics (represented by the parameter m in Fu's equation) were derived based on the Budyko hypothesis. There were two critical values of $m=2$ and $E_0/P=1$ for the elasticity of Q and R_c. The hydrological responses were mainly affected by catchment characteristics in water-limited regions ($E_0/P>1$), and in humid areas ($E_0/P<1$), climate conditions played a more important role for cases of $m>2$ whereas catchment characteristics had a greater impact for cases of $m<2$. The annual Q and R_c in 14 of the 15 catchments significantly decreased with average reduction of 0.87 mm yr^{-1} and 0.18% yr^{-1}, respectively. The mean elasticities of Q to P, E_0 and m were 2.66, −1.66 and −3.17, respectively. The contributions of land use/cover change and P reduction to decreased Q were 64.75% and 41.55%, respectively, while those to decreased R_c were 75.68% and 32.06%, respectively. In contrast, the decreased E_0 resulted in 6.30% and 7.73% increase of Q and R_c, respectively. The contribution of land use/cover changes was significantly and positively correlated with the

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increase in the percentage of the soil and water conservation measures area ($p < 0.05$). The R_c significantly and linearly decreased with the vegetation coverage ($p < 0.01$). Moreover, the R_c linearly decreased with the percentage of measures area in all catchments (eight of them were statistically significant with $p < 0.05$).

1. Introduction

1.1. Background

The integrated consequences of climate variability and land use/cover change induced by human activities have led to considerable global alterations of catchment hydrological regimes in recent decades (Milly et al., 2005; Salmoral et al., 2015). The key climate variables influencing streamflow are precipitation and temperature, with the effect of latter manifested largely through altered evapotranspiration and snowmelt (Patterson et al., 2013; Berghuijs et al., 2014a). The hydrologic regime associated with snowmelt changed significantly in a warming climate (Berghuijs et al., 2014a; Zhang et al., 2015). Human activities can alter the spatial–temporal distribution of streamflow through land use/cover change, reservoir operation, and direct extraction from surface water and groundwater (Wang and Hejazi, 2011; Kim et al., 2013; Xu et al., 2014). With increasing scarcity of water resources, especially in arid and semi-arid areas, the hydrological impacts of climate variability and land use/cover change are drawing increasing attention from hydrological researchers, and decision and policy makers (McVicar et al., 2007; Wang et al., 2013). To manage a watershed efficiently in the face of climate change, it is necessary to understand the combined impacts of land use change and climate change, and also to distinguish the roles that land use/cover change and climate change play in the evolution of hydrological time series (Renner and Bernhofer, 2012; Wang et al., 2013).

1.2. Methods of attribution analysis on streamflow change

Various methods have been developed to isolate hydrological impacts of land use/cover change from those of climate change (Wang et al., 2013; Wang, 2014; Ahn and Merwade, 2014), which can be classified into following types: (i) paired catchment approach (Brown et al., 2005); (ii) empirically statistical methods (Wei and Zhang, 2010; Zhang et al., 2011); (iii) physically-based hydrological models (Wang et al., 2013; López-Moreno et al., 2014; Serpa et al., 2015; Buendia et al., 2015); (iv) elasticity or sensitivity based method (Schaake, 1990; Sankarasubramanian et al., 2001; Arora, 2002; Roderick and Farquhar, 2011); (v) eco-hydrological approach (Tomer and Schilling, 2009); and (vi) decomposition method (Wang and Hejazi, 2011).

The paired catchment studies have contributed significantly to our understanding of the effects of vegetation change on streamflow and its implications for water resources (Brown et al., 2005; Zhang et al., 2011). However, paired catchment studies generally involve small catchments and are expensive to conduct (Zhang et al., 2011). Empirically statistical methods such as regression modeling, time-trend analysis method (Zhang et al., 2011) and double mass curve method (Wei and Zhang, 2010) usually establish the relationships between precipitation and streamflow based on long-term historical data to detect the effects of climate change. These methods require long time series of data and generally lack physical meanings. The calibrated physically-based hydrological models such as SWAT (Shi et al., 2013; Serpa et al., 2015), MIKESHE (Wang et al., 2013), RHESSys (López-Moreno et al., 2014) and TETIS (Buendia et al., 2015) are run with one variable parameter while others remain fixed to detect the impacts of climate and land use changes on hydrological responses under various scenarios. Such hydrological models are useful for estimating the effects of climate change and site-specific changes in vegetation on streamflow over different time scales, but they are usually characterized by complicated model structures, large number of input data sets, time consuming and uncertainty in model calibration and validation. Recently, Tomer and Schilling (2009) proposed a conceptual eco-hydrological approach to study the relative effects of climate change and land use on the basis of water versus energy use efficiency indices. The eco-hydrological approach makes it easy to understand the eco-hydrological responses of watershed to changing environment, but it only provides a qualitative estimation.

The elasticity-based method initially proposed by Schaake (1990) uses elasticity coefficients to represent the sensitivity of streamflow to variations in meteorological factors. The commonly used elasticity-based methods include the nonparametric method and analytical method (Sankarasubramanian et al., 2001). The nonparametric method estimates the elasticity coefficients empirically on the basis of observed meteorological and hydrological data (Sankarasubramanian et al., 2001). Arora (2002) proposed an analytical elasticity model based on the Budyko framework to estimate the sensitivity of streamflow to long-term changes in precipitation and potential evaporation. Roderick and Farquhar (2011) derived analytical expressions of the sensitivity coefficients of streamflow to climatic variables (precipitation and evaporative demand) and catchment properties through the differentiation of the Budyko equation. In contrast to the nonparametric method, the Budyko-based approach is built on the principle of catchment water–energy balance, and it employs a simple but more physically realistic background to investigate the catchment hydrological response to environmental changes. As stated by Berghuijs et al. (2014a), the Budyko framework was a useful tool to normalize hydrological observation among a wide range of ecological and hydro-climatic conditions, and it could understand the secondary controls of climate, vegetation, landscape, soil water and groundwater on a catchment's water balance (Berghuijs et al., 2014a). Although the Budyko framework was only meant to explain the long-term or mean annual water balance in a certain catchment, it has been developed to account for temporal and spatial variability (Wang et al., 2016). According to the Budyko hypothesis, Wang and Hejazi (2011) proposed the decomposition method to isolate the relative contributions of climate change and direct human impacts on streamflow. The Budyko-based elasticity and decomposition methods usually yield similar results and have been widely used in attribution analysis of streamflow change (Wang and Hejazi, 2011; Liang et al., 2015).

Most of previous studies using the Budyko framework focused on the effects of climate variability and land use/cover change on streamflow. The runoff coefficient was also an important hydrological variable, and it signified runoff availability per unit precipitation. It indicated the streamflow production ability of precipitation, which was mainly affected by the watershed characteristic. Therefore, simultaneously considering the runoff coefficient and streamflow amount can comprehensively detect the hydrological responses among different catchments.

1.3. Previous studies in the Loess Plateau

The Loess Plateau of China is well known for the severe soil erosion and heavy sediment load because of the low vegetation cover, frequent high-rainfall storms in summer months, highly erodible loessial soil, steep topography, and long history of intensive cultivation and unsustainable land uses (Zhang et al., 2008). To control the severe soil erosion in the Loess Plateau, several soil and water conservation measures