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The role of climatic and anthropogenic stresses on long-term runoff reduction from the Loess Plateau, China

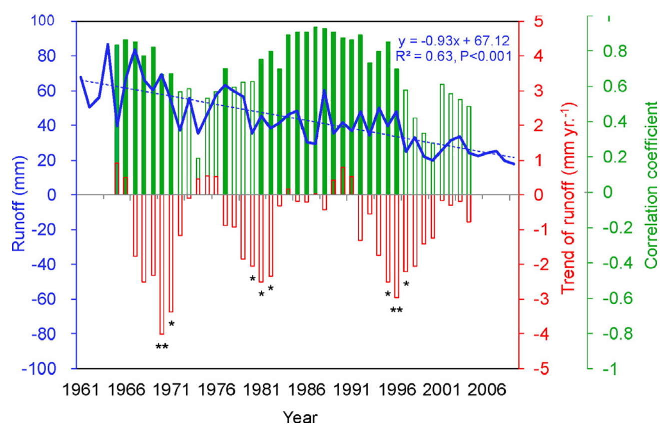
Xiaoming Feng [a], Wei Cheng [a,b], Bojie Fu [a,*], Yihe Lü [a]

[a] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
[b] School of Life Science, University of Science and Technology of China, Hefei, Anhui 230026, China

HIGHLIGHTS

- River runoff from catchments in the hilly Loess Plateau is in long-term decline.
- Precipitation was the dominant factor causing reduction in river flow.
- Human intervention created transition points in river flow.
- The ecosystem service of water provision decreased after human intervention.

GRAPHICAL ABSTRACT



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ABSTRACT

Human intervention has strongly altered patterns of river runoff. Yet, few studies have addressed the complexity and nonlinearity of the anthropogenic stresses on runoff or their interaction with climate. We study the Loess Plateau in China, whose river runoff contributes 65% of the discharge to the middle reach of the Yellow River; this landscape has been shaped by human activity and is intensively managed. Our purpose is to characterize the interactive roles of climate and human activities in defining river runoff from the Loess Plateau. Applying a transient analysis to discover the time-varying runoff trend and impact factors, we found that the average runoff in the Loess Plateau decreased continuously during the period 1961–2009 (average rate of -0.9 mm year^{-1}, $P < 0.001$). This long-term decrease in runoff mainly occurred in three stages, with transitions in 1970, 1981 and 1996. Reduced precipitation was the main reason for the decrease in runoff over the entire study period. However, human intervention played a dominant role in creating the transition points. Water yield (i.e., the ratio of runoff to precipitation) decreased following each anthropogenic transition, causing a 56% reduction in available freshwater resources during the period 1961–2009. These findings highlight the need for studies that address the dynamic and nonlinear processes controlling the availability of freshwater resources in the light of anthropogenic influences applied under a changing climate. Such studies are essential if we are to meet the human water demand in the Loess Plateau region.

* Corresponding author at: State Key Lab. of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, PO Box 2871, Beijing 100085, China.
E-mail address: bfu@rcees.ac.cn (B. Fu).

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1. Introduction

River runoff is an important component of the water resources required for human life and economic development (Farley et al., 2005; Wu et al., 2013). Importantly, river flow datasets should not be considered as stationary time series, because both climate change and human activities are driving systematic changes in runoff (Milly et al., 2005). Currently, interest is increasingly focused on analyzing how human activities may shape runoff (Entwisle and Stern, 2005; Chen et al., 2015; Milano et al., 2015); yet in most studies, human activities are simplified and represented as land-use change. The complexity and nonlinearity of runoff change is given little consideration due to a lack of knowledge on the interactive roles of climate change and human activities (Liu et al., 2007). These factors must be included in addressing the security of water supplies and avoiding unforeseen changes.

Human activity in the Loess Plateau region of northern China (see location in Fig. 1a) has a long and complicated history with >1000 years of human settlement (Shi et al., 2002; Syvitski and Kettner, 2011). Yet, particularly over the past five decades, intensive human activity with the primary purpose of alleviating severe top-soil erosion, has shaped the ecosystem services (ES, i.e., benefits people obtain from ecosystems, Millennium Ecosystem Assessment, 2005; Carpenter et al., 2006) provided by catchments in the Loess Plateau (Mu et al., 2007). Since the 1950s, a number of soil conservation measures, such as constructing terraces and sediment-trap dams, have been implemented in the Loess Plateau. These have been characterized as engineering methods related to soil conservation (Zhang et al., 2008). Furthermore, in late 1999, China implemented a massive revegetation program in the name of ecological restoration that involved returning croplands on steep slopes (>25°) back to woodland, shrub land or grassland (Xu et al., 2002).

Efforts to reduce soil erosion are critical to maintaining environmental quality. However, various studies have reported that a reduction in river runoff occurred as an outcome of the enhanced soil conservation in the Loess Plateau (Li et al., 2009; Gao et al., 2015; Wei et al., 2015; Liang et al., 2015). River runoff from the Loess Plateau contributes to the tributaries of the Yellow River; therefore, a reduction in runoff from the plateau will not only influence the provisioning of water for local residents, but will also affect the downstream flow in the Yellow River (Tang et al., 2008). Understanding the effects of soil conservation measures on river runoff from the Loess Plateau is important for guiding the implementation of future soil conservation initiatives (Xu et al., 2004). However, it is difficult to draw generally applicable conclusions based on current studies, which generalize different soil conservation measures (i.e. constructing terraces, sediment-trap dams, revegetation) as a vague concept of human intervention to river flow. For example, a change-point around 1983 was detected in the runoff from the Huangfu catchment, which has been monitored since the 1950s (Zhang et al., 2008; Zuo et al., 2016). Zhang et al. (2008) concluded that the anthropogenic factor behind the change was the construction of sediment-trapping dams and reservoirs; but in contrast, Zuo et al. (2016) concluded that it was due to revegetation. In fact, the effect of human intervention on river runoff may vary both in the details of the soil conservation measures and their efficiency, which could be partially reflected in the most recent attribution analysis on sediment reduction in the Loess Plateau (Wang et al., 2015). In current analyses of the effects of human

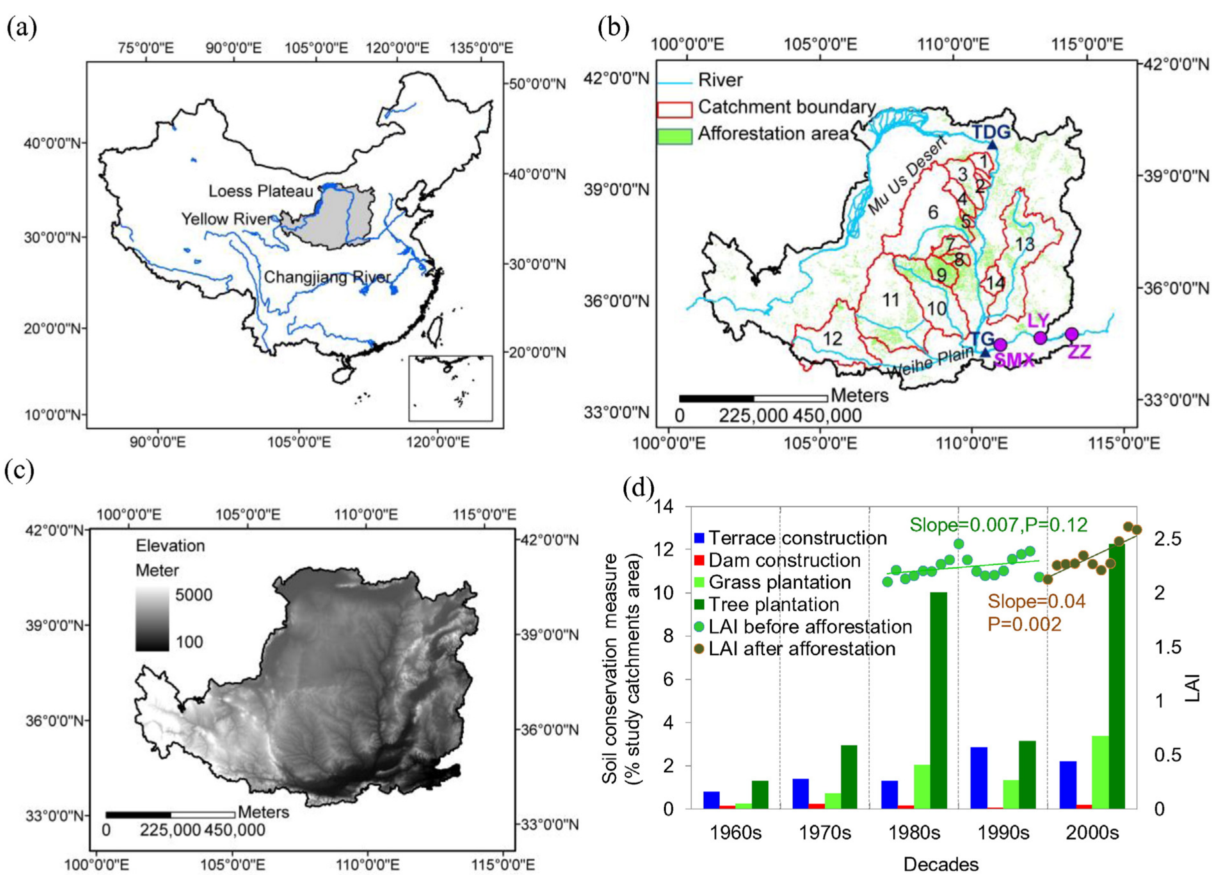

Fig. 1. The study area: (a) location of the Loess Plateau; (b) location of the 14 study catchments (abbreviated as CM in the main text); (c) elevation of the Loess Plateau and location of the Mu Us Desert and the Weihe Plain; and (d) percentage areas of soil conservation measures. Revegetation areas in (b) and LAI in (d) were based on satellite estimates. The percentage areas of soil conservation measures were obtained from the Yellow River Conservancy Commission (see details in Section 2.2). The blue triangles in (b) marked the inlet and outlet of the CM, i.e., the Toudaoguai (TDG) and Tongguan (TG) hydrological stations respectively. Three cities, Sanmenxia, Luoyang and Zhenzhou, are indicated by purple circles and marked as SMX, LY and ZZ, respectively. These three cities rely directly on the ecosystem service of water supply provided by the CM. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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