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Assessing response of sediment load variation to climate change and human activities with six different approaches

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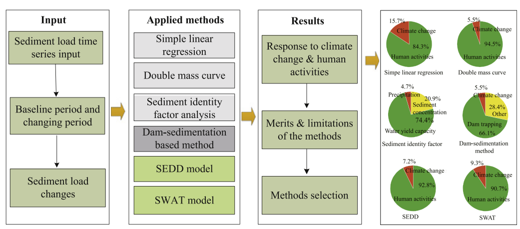
HIGHLIGHTS

- We assessed the response of sediment load to climate change and human activities with six methods.
- Five methods produced similar estimates except for the linear regression.
- Sediment load exhibited 70.5% reduction, but inconsistent with annual sediment yield.
- Human activities played a dominant role, accounting for 93.6 ± 4.1% sediment load reduction.

GRAPHICAL ABSTRACT



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ABSTRACT

Understanding the relative contributions of climate change and human activities to variations in sediment load is of great importance for regional soil, and river basin management. Considerable studies have investigated spatial-temporal variation of sediment load within the Loess Plateau; however, contradictory findings exist among methods used. This study systematically reviewed six quantitative methods: simple linear regression, double mass curve, sediment identity factor analysis, dam-sedimentation based method, the Sediment Delivery Distributed (SEDD) model, and the Soil Water Assessment Tool (SWAT) model. The calculation procedures and merits for each method were systematically explained. A case study in the Huangfuchuan watershed on the northern Loess Plateau has been undertaken. The results showed that sediment load had been reduced by 70.5% during the changing period from 1990 to 2012 compared to that of the baseline period from 1955 to 1989. Human activities accounted for an average of 93.6 ± 4.1% of the total decline in sediment load, whereas climate change contributed 6.4 ± 4.1%. Five methods produced similar estimates, but the linear regression yielded relatively different results. The results of this study provide a good reference for assessing the effects of climate change and human activities on sediment load variation by using different methods.

1. Introduction

Sediment transport plays a critical role in global biological and geochemical cycles of the terrestrial ecosystem (Keesstra et al., 2012; Syvitski et al., 2009). Recent observed evidence from many rivers indicate that sediment load have been substantially disturbed throughout

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the world owning to climate change, land use change, tillage, mining, dam construction, soil and water conservation and other human activities (Boix-Fayos et al., 2007; Fu et al., 2017; Kondolf et al., 2014; Syvitski et al., 2009). Assessment the relative role of climate change and human activities on sediment load can provide scientific insight to understand the complex hydrological response to its driving factors (Kondolf et al., 2014; Ma et al., 2014), as well to develop strategies for river basin management and sustainable agricultural production.

During the past decades, numerous studies have attempted to evaluate the relative roles of climate change and human activities in changes of riverine sediment load (Gao et al., 2017a; Shi and Wang, 2015; Wang et al., 2012). Among these studies, several types of methods were regularly employed, including the empirical regression method, sediment identity factor method, and soil erosion models. Empirical regression method (such as linear regression and double mass curve) is usually based on the relationship between sediment load and precipitation (Bhattarai and Dutta, 2008; Miao et al., 2011; Tang et al., 2013; Wang et al., 2012; Ward and Jackson, 2004). Compared with empirical methods, soil erosion models include relative complex physical mechanisms, and can assess the effects of climate change and human activities on sediment load over different temporal scales (de Vente et al., 2013). The empirical soil erosion models (i.e. RUSLE, WATEM/SEDEM and SEDD) have been widely applied with different land use scenarios at various spatial and temporal scales (Boix-Fayos et al., 2008; Fu et al., 2011; Zhao et al., 2017). The physics-based model, Soil and Water Assessment Tool (SWAT) has great applicability for predicting the impact of land management practices on sediment transport in large river basins, and has been tested in various countries (Arnold et al., 2012; Li et al., 2017; Ouyang et al., 2018; Pandey et al., 2016; Vigiak et al., 2017).

The sediment identity factor decomposition method is originally analogous to the Kaya Identity in economics (Kauppi et al., 2006; Raupach et al., 2007). Wang et al. (2017) applied this method to diagnose the contributions of precipitation, water yield capacity and sediment concentration to the relative change of sediment load in the Yellow River basin. Another method was conceptually based on the statistics in soil conservation measures, which utilized the total area of conservation measures and their trapping efficiencies to assess the effects on sediment load reduction (Ward and Jackson, 2004). Trapping efficiencies for each type of conservation measures were observed by using soil erosion plots or estimated through field survey.

The Loess Plateau has long been suffering from severe soil erosion with erosion-prone area of about 472,000 km^2. Serious soil erosion has led to unsustainable land use management, and threatened agriculture production and ecological system (Fu et al., 2011). In recent years, a series of soil and water conservation measures have been extensively implemented (Fu et al., 2017; Liu et al., 2014; Xin et al., 2015; Yao et al., 2011). These measures (e.g. terracing, afforestation and re-establishing natural vegetation cover) have considerably reduced sediment load from hillslopes to the main river channels. A significant reduction of sediment load ($p < 0.05$) in the Yellow River has been detected by a large number of studies, and the causes of sediment load changes have also been investigated with different approaches (Gao et al., 2017b; Liu et al., 2014; Xu, 2008; Yao et al., 2011). However, it is unknown that whether these methods can produce consistent results in a specific watershed; and the results might be applicable to other watersheds within the Loess Plateau or not. Because of all of the above, we selected the Huangfuchuan watershed as the case study for assessing the response of sediment load reduction to climate change and human activities with different methods. Our results not only quantify the impacts of climate change and human activities on changes in sediment load in the Huangfuchuan watershed, but provide a good reference for soil and water conservation in the Loess Plateau. The novelties and objectives of this study are: (1) to quantify the impacts of climate variability and human activities on variation of sediment load with six widely used methods. (2) to identify the applicability of the different methods, and the respective merits and limitations of the methods in detail.

2. Material and methods

2.1. Study area

This study was undertaken in the Huangfuchuan watershed in the northern Loess Plateau, China. The watershed covers an area of 3246 km^2, and is a first-order tributary of the Yellow River. The river originates from southern Inner Mongolia, drains to the Loess Plateau, and discharges into the Yellow River in northern Shaanxi Province (Fig. 1). The watershed has a typical semi-arid continental climate, with average annual rainfall of 380 mm and mean annual temperature of 7.5 °C. Rainfall is strongly seasonal, with 76% falling between June and September. Concentrated rainfall resulted in severe soil erosion, leading to large amount of sediment discharged into Yellow River. As addressed by Wei et al. (2017) and Zhao et al. (2015a), soil erosion was very serious, with average annual soil erosion rate >120 t/ha.

The catchment is characterized by three main types of soil: silt loess, sand, and deeply weathered coarse-grained sandstone (locally name Pisha stone). The dominant vegetation in the catchment is grassland, sparsely distributed on the loess soil in the gentle hill slopes. The badland Pisha sandstone has very sparse or no vegetation cover, and is the dominant sediment source, contributing >70% of coarse sediment in the watershed (Zhao et al., 2015a).

2.2. Data sets

Daily precipitation at 12 stations was obtained from the Hydrology Bureau of the Yellow River Water Resources Commission. Among these stations, seven started observations since 1950s, and the other five were established in 1976. Observed daily

sediment load data at Huangfu station is available from 1950s to 2012, which is collected from the "Hydrological Yearbook of the People's Republic of China, provided by the Yellow River Water Conservancy Committee.

The digital elevation map (DEM) with 30 m grid size was derived from topography data (1:100000), which was provided by the Geomatics Center of Shaanxi Province. The land use/cover map for the 1980s was extracted from satellite images with 30 m resolution, which originally obtained from Enhanced Thematic Mapper (ETM) sensor (http:// http://glcfapp.umiacs.umd.edu:8080/esdi/index.jsp). The images were interpreted by using the unsupervised classification method. The soil map was derived from the field survey, and provided by the Institute of Soil and Water Conservation, Chinese Academy of Sciences (Zhao et al., 2017). The data quality and results have been checked out according to field campaign before their release.

Check dam has become one of the most popular soil and water conservation measures on the Loess Plateau (Li et al., 2017; Zhao et al., 2017). The sedimentation behind the check-dam recorded detailed information of soil erosion in its upstream area. Recently, an increasing number of studies attempted to deduce sediment yield through sedimentation behind the check dams, not only on the Loess Plateau (Li et al., 2016; Wei et al., 2017), but also in other erodible regions throughout the world (Boix-Fayos et al., 2007; Romero-Díaz et al., 2007). In this study, sediment yield data behind six check dams were collected in the spring of 2014 and 2015. Fig. 1b shows their locations. An example of sediment profile and sediment yield is shown in Fig. 2. The details of sedimentation sampling procedure are available in Wei et al. (2017, 2018) and Zhao et al. (2015a).

2.3. Methodologies

2.3.1. Identification of baseline and changing periods

To assess the hydrological response to climate change and human activities, most studies divided the hydrological time series into two or more periods (Ma et al., 2014; Shi and Wang, 2015). The first period represents the baseline or referenced period, when very limited or no