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Original Research

Copula-based identification of the non-stationarity of the relation between runoff and sediment load

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ABSTRACT

It is important to identify the non-stationarity in the relation between runoff and sediment load under the backdrop of the changing environment. This relation helps to further understand the mechanisms of runoff and sediment yield. A copula-based method was used to detect possible change points in the relation between runoff and sediment load in the Wei River Basin (WRB), China, where soil erosion is a very severe issue. The modified Mann-Kendall trend test method was applied to obtain the trends of runoff and sediment load spanning 1960–2010 at monthly and annual timescales. Finally, the causes of the identified non-stationarity of the relation between runoff and sediment load were roughly analyzed from the perspective of climate change and human activities. Results indicated that: (1) the runoff and sediment load in the Jinghe and Wei rivers were generally characterized by noticeably decreasing trends at both monthly and annual timescales; (2) both the Jinghe and Wei rivers had a common change point (2002), implying that the stationarity of the relation between runoff and sediment load in the Jinghe and Wei River was invalid; (3) human activities including increasing water consumption and growing application of soil conservation practices are dominant factors resulting in non-stationarity in the relation between runoff and sediment load in the WRB. This study provides a new idea for identifying the non-stationarity of multivariate relation in the hydro-meteorological field under the background of the changing environment.

1. Introduction

Runoff is an extremely important element of the global water cycle impacting earth ecology (Doll et al., 2009) and climate (Harding et al., 2011) as well as anthropogenic activities including drinking water, agriculture, recreation, etc. (Biemans et al., 2011). Sediment is defined as solid particles in natural flow and plays a key role in the evolution of rivers and the formation of terrain (Pelletier, 2012; Syvitski & Milliman, 2007). Both the runoff and sediment load delivered to the sea are dominant factors influencing the evolution of a delta (Yu et al., 2011). Therefore, the relation between runoff and sediment load is closely associated with the development, utilization and management of water resources, safe operation of water-related projects, and ecological environment (Miao et al., 2011; Peng et al., 2010). In addition, since the relation between runoff and sediment load is one of the fundamental components determining sediment dynamics (Zheng et al., 2012), understanding of their relation promises to be beneficial to the prediction of sediment yield based on runoff data, which is important due to the lack of sediment load data (Syvitski et al., 2005).

Considering the importance of the relation between runoff and sediment load,numerous scholars have investigated this topic (e.g., Alexandrov et al., 2003; Muller & Forstner, 1968; Seeger et al., 2004; Williams, 1989; Zheng et al., 2007). For instance, Muller and Forstner (1968) explored the general relation between suspended sediment concentration and water discharge in Alpenrhein and some other rivers. Alexandrov et al. (2003) studied suspended sediment concentration and its variation with water discharge in northern Negev, Israel. Zheng et al. (2007) investigated the effects of vegetation on the runoff–sediment yield relation at different spatial scales in hilly areas of the Loess Plateau in north China. These studies primarily focused on estimating the effects of

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climate change and human activities on the mechanisms of runoff and sediment yield. Because of the changing environment (human activities and climate change), the statistical characteristics of hydrological series in various watersheds might be altered, thereby resulting in so-called non-stationarity (Cong et al., 2015; Gilroy & McCuen, 2012; Vogel et al., 2011). Nevertheless, few of the previous studies took the non-stationarity of the relation between runoff and sediment load into account.

Under the backdrop of the changing environment (climate change and intensifying human activities), the stationarity of the relation between runoff and sediment load may be invalid (Cong et al., 2015; Gilroy & McCuen, 2012; Vogel et al., 2011). Climate change primarily characterized by the change in precipitation and evaporation has direct and indirect impacts on runoff change by means of natural and anthropogenically induced variations of water availability and land-use (Bates et al., 2008; Huang et al., 2015, 2016; Wang et al., 2012; Xu, 2005). Additionally, intensifying human activities, such as reservoir, dam construction, water diversion works, and soil and water conservation measures (e.g., sediment check dams, land consolidation, afforestation, contour farming, etc.), can obviously cause variations of runoff and sediment load (Gao et al., 2014a, b; Miao et al., 2010; Wang et al., 2012). Affected by the joint impacts of climate change and human activities, the relation between runoff and sediment load may be altered, even its stationarity is invalid, which has strong impacts on the accuracy of the prediction model for sediment load based on the correlation between runoff and sediment load. Hence, identifying the non-stationarity of the relation between runoff and sediment load helps to further understand the mechanisms of runoff and sediment yield under the background of the changing environment, thereby further improving the prediction accuracy of sediment load. Therefore, reasonably detecting the non-stationarity of the relation between runoff and sediment load is the major motivation of this study.

Regarding the identification of the change points in the bivariate relation, most previous studies applied the correlation coefficient method to handle this issue (Hao, 2004; Jin et al., 2006). However, the correlation coefficient method is so simple that it cannot to fully reflect the nonlinear characteristics of the bivariate relation, thereby failing to capture the real change points. Furthermore, some studies (Birkinshaw & Bathurst, 2006; Lee et al., 2005) applied conceptual models to identify the change points of the bivariate relation, which need a large amount of data, and their parameter calibration is a ticklish issue. A copulas-based method was introduced in this study to identify the non-stationarity of the relation between runoff and sediment load, which provides a new idea for the identification of the non-stationarity of the bivariate relation.

The Loess Plateau is the most serious soil erosion area in the world (Zheng et al., 2012). The Yellow River has the largest annual sediment load among the nine largest rivers in the world (Huang, 2002). The Wei River is the largest first-level tributary of the Yellow River, and its largest tributary (the Jinghe River) flows through the Loess Plateau. The Jinghe River is the primary source of sediment load in the Yellow River (Zheng et al., 2012). Its vegetation coverage is low and it yields a high river sediment concentration with a fast flow rate, resulting in serious erosion. Consequently, there is nearly 3×10^8 t of sediment load flowing into the Wei River from the Jinghe River every year (Zhu et al., 2012). For the Wei River Basin (WRB), the soil and water loss is a very serious issue. With the increasing development of the local economy and society, soil and water conservation and ecological construction have been increasing applied on the Loess Plateau with some soil and water conservation measures applied in the WRB since the 1960s. Thus, local human activities are intensifying. Additionally, previous studies (Huang et al., 2015, 2016) indicated that the runoff in the basin had a noticeably decreasing trend induced by the combined effects of climate change and human activities. The relation between runoff and sediment load in this basin may be altered under the context of the changing environment. Therefore, investigation of the evolution characteristics of the relation between runoff and sediment load under the backdrop of the changing environment has important significance for local water resources planning and management. Improved understanding of this relation will benefit the evaluation of soil conservation measures as well as ecological construction.

The primary objectives of this study are to: (1) investigate the trends of runoff and sediment load in the WRB at monthly and annual timescales; and (2) explore the non-stationarity of the relation between runoff and sediment load and the possible causes of non-stationarity.

2. Study area and data

2.1. The Wei River Basin (WRB)

The WRB, as shown in Fig. 1, was selected as the study area in this study. The Wei River is the largest first-level tributary of the Yellow River, which is located between 103.5°E–110.5°E and 33.5°N–37.5°N, covering a total area of approximately 1.35×10^5 km^2. Topographically, the elevation decreases from the highest mountainous areas in the northwest of the basin to the lowest areas in the Guanzhong Plain in its southeastern and southern parts. Situated in a continental monsoon climate zone, the WRB is characterized by rich precipitation and high temperatures in summer, and by poor precipitation and low temperatures in winter. Its annual precipitation is approximately 559 mm (Zhang et al., 2008). In addition, precipitation varies monthly and annually, such that the flood season (June to September) comprises nearly 60% of the total annual precipitation. The average annual runoff of the WRB is nearly 72.77×10^8 m^3, and its average annual sediment load is approximately 3.7×10^8 t (Zhao et al., 2015). The monthly runoff and sediment load in the WRB have a non-uniform distribution, which are concentrated in the flood season (Zhao et al., 2015).

2.2. Data

Monthly observed runoff and sediment load series covering the period of 1960–2010 at the Zhangjiashan, Huaxian, and Zhuangtou hydrological stations were utilized in this study. These data were acquired from the Yellow River Conservancy Commission (YRCC). Generally, Zhangjiashan station monitors the entire Jinghe River basin, whose catchment area is nearly 4.2×10^4 km^2. The summation of runoff and sediment load data at the Huaxian and Zhuangtou stations can be regarded as the amount of runoff and sediment load of the entire WRB. The research objectives of this study are the Jinghe and Wei River basins.

Daily precipitation; sunshine hours; wind speed; relative humidity; maximum, minimum, and mean air temperature; and absolute vapour pressure data covering 1960–2010 were collected from 21 meteorological stations in and near the WRB, whose locations are shown in Fig. 1. These meteorological data were obtained from the National Climate Center (NCC) of the China Meteorological Administration (CMA). The data quality was strictly controlled during its release. The daily potential evapotranspiration was computed based on the Penman-Monteith formulation (Monteith, 1965), then the monthly and annual potential evapotranspiration were obtained through calculating the summation of the daily potential evapotranspiration. Although many methods