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Spatial and temporal changes in runoff and sediment loads of the Lancang River over the last 50 years

H.J. Zhai[a,*], B. Hu[b], X.Y. Luo[a], L. Qiu[a], W.J. Tang[b], M. Jiang[b]

[a] Yangtze River Water Resources Protection Bureau, Hubei Wuhan 430051, China
[b] Department of Soil and Water Conservation, Changjiang River Scientific Research Institute, Hubei Province 430010, China

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ABSTRACT

Non-parametric Mann-Kendall, double mass curve analysis and annual variation analysis were used to analyze the spatial and temporal changes in runoff and sediment loads at the Jiuzhou, Jiajiu and Yunjinghong hydropower stations in the Lancang River from 1964 to 2010. The results indicate that the inter-annual and annual distributions of sediment have significantly changed since the 1990s, and that sediment discharge has increased at the Jiuzhou station, while sediment discharge has declined at the Jiajiu and Yunjinghong stations. Overall, annual runoff distribution patterns have been consistent since the 1990s. Spatial and temporal changes in runoff and sediment loads in the Lancang River have been attributed to the construction of hydropower stations, changes in land use and precipitation patterns. The results can provide guidance for the environmental protection and ecological restoration of rivers in the Southwest of China.

1. Introduction

Runoff and sediments play major roles in river ecosystems. Increased sediment loading to rivers can lead to excessive sedimentation in lakes and reservoirs, threatening aquatic biota and hydroelectric power generation (Vanacker et al., 2003; Wilkinson et al., 2009). Variations in runoff and sediment loading have significant effects on downstream ecological landscapes and water resource utilization (Hu et al., 2006; Kummu and Varis, 2007; Prathapar and Abdulla, 2014; Tatsumi and Yamashiki, 2015; Zhong et al., 2007). Changes in flow and sediment discharges can influence sedimentation in reservoirs, which rapidly decreases their storage capacities (Bonora et al., 2002). Most previous studies have shown a relationship between runoff and sediment load (Fang et al., 2011; Syed et al., 2003; Tuset et al., 2016). Onderka et al. (2012) found, in a small (2.7 km^2) pluvio-oceanic catchment, that the mean suspended sediment concentrations are better correlated to runoff than large area. Liu et al. (2013) reported that annual runoff in all southern rivers within humid zones of China, including Lancang River, did not change much, while the annual sediment loads of all rivers showed significant declining trends.

Previous studies have shown that land use, rainfall, human activity and other factors may have effects on runoff and sediment load (Fang et al., 2011; Swank et al., 2001; Taylor and Pearce, 1982). The relationships between rainfall, land use, runoff and sediment transport have been widely investigated (Nadal-Romero et al., 2008; Maalim et al., 2013). Estrany et al. (2009) found that rainfall was the most important factor that affects the suspended sediment concentrations in a small (1 km^2) Mediterranean catchment. Rodríguez-Blanco et al. (2010) explained that a major part of the suspended sediment load during an event can be explained by the maximum discharge and the runoff. Tuset et al. (2016) analyzed the relationship between rainfall, runoff and sediment transport in a Mediterranean mountainous catchment. Studies have examined the Lancang-Mekong River and focused on the runoff and sediment variation (Cui et al., 2011; Zuo et al., 2011), the characteristics of sediment distribution throughout the year, and the hydrological effects of cross-border impacts under the influence of hydropower development (Fu et al., 2007; He et al., 2006). These studies provide extensive background information to conduct future research.

Most previous studies have focused on the assessment of single factors, such as runoff or sediment loading. Little work has been done on analyzing the variation of both runoff and sediment loading. Most studies on river ecosystems, including those conducted on the Lancang-Mekong River, have focused on how a single impact factor, such as land use or hydropower dam development, affects the runoff or sediment loads of rivers. Few studies have investigated the combined effects of rainfall, land use and dam construction on runoff and sedimentation. As international rivers, runoff and sediment changes are important to the international community. To

* Corresponding author.
E-mail address: zhaichina@hotmail.com (H.J. Zhai).

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Table 1
The completed year of the dams from upstream to downstream.

Name	Completed Year
Gongguoqiao	2012
Xiaowan	2010
Manwan	1993
Daochaoshan	2003
Nuozhadu	2012
Jinghong	2008

a certain extent, the environmental protection and restoration of Lancang River has an impact on international relations. In order to understand their complexity and dynamism, it is necessary to study the interactions between precipitations, land use, dam construction, runoff and sediment load on a spatial and temporal scale over the last 50 years.

In this study, we move beyond the analysis of a single impact factor to (1) analyze the inter-annual and annual variations in runoff and sedimentation in the Lancang-Mekong River during the past 50 years, (2) analyze the changes of runoff and sediment in the upper, middle and lower portions of the river, (3) discuss the reasons for inter-annual and annual variation in runoff and sediment loading from the three aspects of land use, climate change and dam construction, and (4) provide scientific support for the changing hydrological characteristics of the Lancang-Mekong River.

2. Materials and methods

2.1. Study area

The Lancang-Mekong River is a river that originates on the Tibetan Plateau and runs through China, Laos, Myanmar, Thailand, Vietnam and Cambodia before finally entering the South China Sea in southern Vietnam (Fig. 1). The stretch of the Lancang-Mekong River in China is known as the Lancang River. After it leaves China, the Lancang River is known as the Mekong River. The basin area of the Lancang-Mekong River is over 810,000 km^2, with a total primary river length of approximately 4880 km and an average slope of 0.103%. The Lancang River (i.e., the China section) with a basin area of 174,000 km^2, is approximately 2161 km, and the length is 1170 km in the Yunnan province. The water energy resources of the Lancang River Basin are extremely rich. Currently, 14 stage hydropower stations have been installed along the main river channel. The completion times of the dams from upstream to downstream on the mainstream of the Lancang River (Yunnan section) are showed in Table 1.

2.2. Temporal and spatial scales for predictions

The temporal scope in the study is from 1964 to 2010. The spatial scale includes the primary sections of the Lancang River in the Yunnan province. The Jiuzhou (JZ), Jiajiu (JJ) and Yunjinghong (YJH) hydrological stations were selected to represent the upstream, midstream and downstream sections of the Lancang River for the study of runoff and sediment loads (Fig. 1).

2.3. Data source

The Yunnan Weather Bureau provided meteorological data from 18 weather stations along the Lancang river region for the years 1964–2010. The monthly runoff and sediment load data for the years 1964–2010 were provided by the Mekong River Commission and the Hydrological Bureau of Yunnan Province.

2.4. Methods

2.4.1. Mann-Kendall trend test

Nonparametric rank correlation tests (hereinafter referred to as the MK method) were applied to detect the changes of sequence in runoff and sediment loading effectively in order to determine when mutations occurred. The Mann–Kendall trend test (Mann, 1945; Kendall, 1975) is based on the correlation between the ranks of a time series and their time order. For a time series $X = \{x_1, x_2, \ldots, x_n\}$, the test statistic is given by

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} a_{ij} \tag{1}$$

$$a_{ij} = sign(x_j - x_i) = sign(R_j - R_i) = \begin{cases} 1 & x_i < x_j \\ 0 & x_i = x_j \\ -1 & x_i > x_j \end{cases} \tag{2}$$

where R_i and R_j are the ranks of observations x_i and x_j of the time series, respectively. Under the assumption that all data are independent and identically distributed, the mean and variance of the S statistic in Eq. (1) above is given as (Kendall, 1975)

$$E(S) = 0 \tag{3}$$

$$V_0(S) = n(n-1)(2n+5)/18 \tag{4}$$

where n is the number of observations. The existence of tied ranks (equal observations) in the data results in a reduction of the variance of S to

$$V_0{}^*(S) = n(n-1)(2n+5)/18 - \sum_{j=1}^{m} t_j(t_j-1)(2t_j+5)/18 \tag{5}$$

where m is the number of groups of tied ranks, each having t_j tied observations.

The significance of trends can be tested by comparing the standardized variable u in Eq. (6) with the standard normal variant at the desired significance level α, where the subtraction or addition of unity in Eq. (6) is a continuity correction (Kendall, 1975). Therefore,

$$u = \begin{cases} (s-1)/\sqrt{V_0(S)}) & S > 0 \\ 0 & S = 0 \\ (s+1)/\sqrt{V_0(S)} & S < 0 \end{cases} \tag{6}$$

2.4.2. Double mass curve analysis

Double mass curve analysis is a widely used method to describe variation trend between two parameters (Liu et al., 2007; Mu et al., 2010), and it was adopted to investigate the relationship between the accumulation of sediment and discharge. Generally, the double mass curve increases linearly if the relationship between the amount of sediment loading and runoff stays the same. However, if the sediment transport capacity of the flow suddenly increases or decreases, a double cumulative curve will appear at the inflection point.

2.4.3. Annual variation analysis

Indicators of water and sediment distribution during the year were the variation coefficient C_v, the annual distribution of regulating coefficient C_r, and the concentration degree C_d. The calculation formula is given by

$$C_v = \sigma / R \tag{7}$$