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Hydrological variation and hydro-sediment interrelation of the Luozha River in the Lancang River Basin

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ABSTRACT

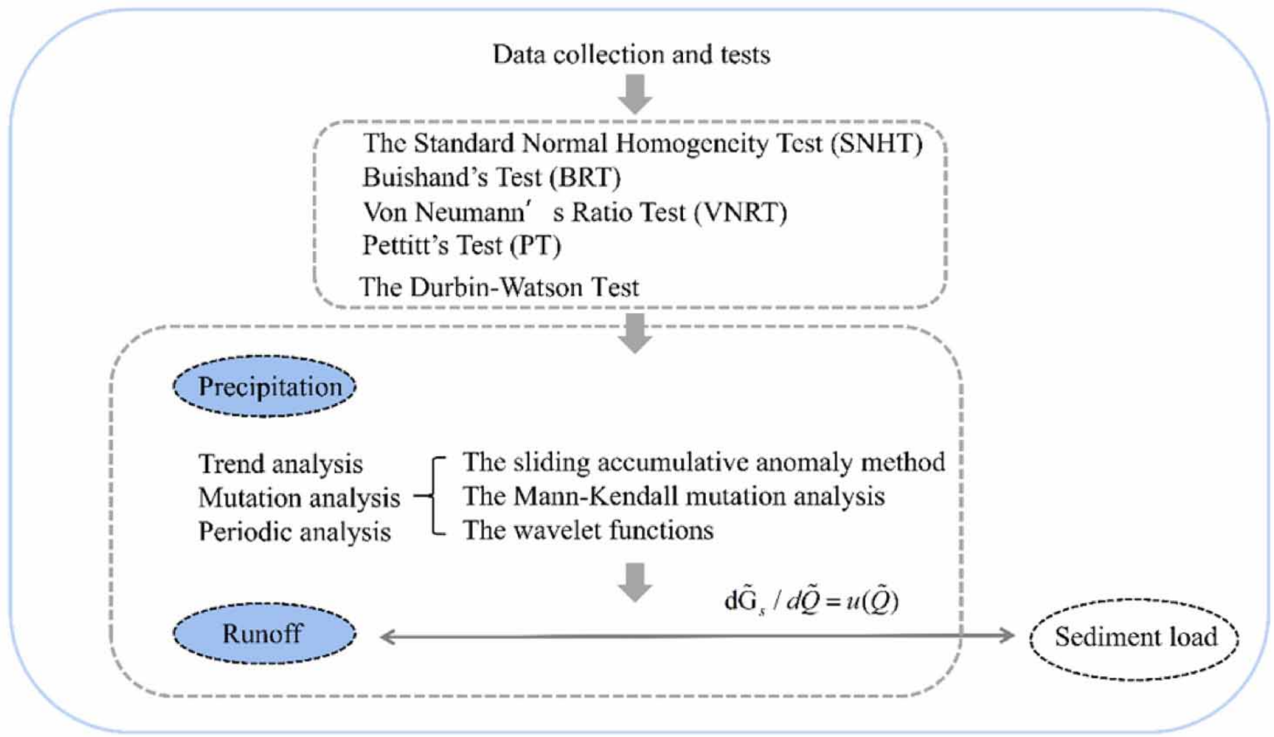
The research on water and sediment variations is of great importance for regional resource and watershed management. Studying the relationship between precipitation, runoff and sediment load, traditional methods are based on observational data fitted or artificial intelligence predictions, whose accuracy is directly dependent on the quality and quantity of the data. This paper developed a new approach for researching the relationship between precipitation, runoff and sediment load. Based on the sliding accumulative anomaly method, the M-K mutation analysis and the wavelet functions, variation of precipitation and runoff annually were discussed. The results indicated the annual variation trend of the precipitation and runoff have been consistent since 1969, both with a 28-year main cycle, and runoff variations were less subject to human influence in the Luozha River. Therefore, the formula of the relationship between annual runoff and sediment load can be obtained by integrating discrepancy in the magnitude of its variation in the natural state, which was verified by the observational data and was applicable to acquisition of annual sediment load. The current work broadens the current knowledge of recent changes in the Lancang River Basin and improves the recognition of the water-sediment interrelation in the river.

Key words: hydrological variation, Luozha River, precipitation and runoff, sediment load

HIGHLIGHTS

- The sliding average accumulation method is proposed to describe hydrological trends.
- The correlation between sediment load and runoff was obtained by integrating.
- This paper firstly details description of the hydrological variations and the relationship with sediment in the Luozha River of Lancang River Basin.

GRAPHICAL ABSTRACT



1. INTRODUCTION

In the past few decades, due to changes in runoff and sediment load, drought and flood have regularly occurred (Zhang *et al.* 2013) resulting in economic and ecological damage, even affecting human security on the river sides. The variation of runoff and sediment load are subject to climate change and human activities in the river system. Among the common climate variables, the precipitation variable is the dominant factor, with the most temporal and spatial changes (Guo *et al.* 2008; Chen *et al.* 2020). Therefore, studying the relationship of variation between precipitation, runoff, and sediment load is significant for river evolution, water resources management and riverine safety.

The Lancang-Mekong river, with a length of 4909 km and an average annual discharge of 14,500 m^3/s, originates in the northeast of Tanggula Mountain in Qinghai Province, China, and is the largest international river in Southeast Asia. The Lancang River Basin contains abundant resources and has played a significant role in flood control and water supply conditions in downstream countries. Over the past 10 years, the Lancang River Basin has been a paramount research topic, especially in the fields of hydrology and sediment issues. Scientific research on the Lancang-Mekong River included the effects on runoff and sediment load from climate and power plant construction. Liu *et al.* (2020a) have studied the impact on downstream runoff conditions and interception about sediment since the successive completion of the eight planned cascade hydropower station in the 1980s. Furthermore, many researchers investigated runoff and sediment variation in the world's major rivers finding that the runoff of the world's major rivers, such as the Yangtze River, Yellow River and Amazon River, showed a decreasing trend due to excessive water utilization and inter-basin water transfer, as well as the decrease of sediment transport under the influence of runoff, whereas the annual sediment load of the Lancang river and the Songhua River were on the rise (Walling & Fang 2003). Han *et al.* (2019) demonstrated that the aforementioned phenomenon can be related to the impact of human activities such as the construction of water conservancy and hydropower facilities. However, compared with previous vast studies regarding the Lancang River Basin, studies on the Luozha River in Lancang River Basin are rare. Therefore, the aforementioned situation motivated the current study to analyze the latest measured data in the Luozha River to expand the current knowledge of the Lancang River Basin.

Hydrology and sediment are the two most essential elements in river systems. Most researchers currently work on statistical methods and artificial intelligence to deepen the research on hydrology and sediment load problems. Regarding the correlation between hydrology and sediment load in the watershed, the complete ensemble empirical mode decomposition with adaptive noise (CEEMDAN) method was used by Zhang *et al.* (2021b) to analyze the effects of precipitation and human activities on runoff and sediment transport. Through observed data with the Mann-Kendall trend test (MK) and Theil-Sen method (TSA), the relationship of sediment and runoff was established by Adib *et al.* (2021). Based on the thought of combination with wavelet function and artificial intelligence, Li *et al.* (2022) extracts and decomposes precipitation and runoff data cycles into effective information using wavelet function, before using neural network for sediment prediction, thereby effectively improving prediction accuracy and efficiency. Traditional sediment load predictions for rivers are based on empirical runoff formulas, which depend on the timescale considered (Gao 2008), and the applicability of this method is reduced due to the equipment and expertise of the collectors. Additionally, the artificial intelligence expressions for the relationship between runoff and sediment load usually require large amounts of data to be fitted and lack physical meaning (Asselman 2000). These characteristics of the hydrology and sediment load are not comprehensive enough. Hence, this article analyzed the relationship of variation between precipitation and runoff, as well as the interrelation of runoff and sediment load in the Luozha river of Lancang River Basin. The data measured about hydrology and sediment at the Luozha River of the Lancang River Basin were checked by homogeneity and correlation tests. Then, trends and periods of precipitation and runoff associated with sediment load were analyzed, providing the variation pattern of both in the long-term series. Finally, based on the properties of the studied rivers, the formula for the relationship between runoff and sediment load in the natural state was derived and verified.

2. STUDY AREA AND DATA

The Luozha River is located in the Lancang River Basin, extending from the headwaters in the Dadaoba township to Lancang River in the Huai village (100.4° E, 24.5° N), and belongs to the first level river on the right bank of Lancang River. This region has abundant water resources, owning water resources of 2,108,180,000 m^3 and average self-produced water resources of 172,623,000 m^3, with a source elevation of 2712.3 m, a total drop of 1828.3 m, and an average specific drop of 4.7‰. The Luozha River of Lancang River Basin contributes about 4,000,000 m^3 of sand transport of annually, which is traditionally one of the main input sources of sediment content in the Lancang River. The Taipinggua hydrological station is located in Yun County, Lincang City (100.3° E, 24.5° N), and belongs to the national hydrological station, of which the catchment area is 2910 km^2, and the control area accounts for about 90.23% of Luozha River. The Taipinggua hydrological station designed around the flood standard is presented in Table 1.

The hydrological observation data and sediment information in this paper was provided by Lincang Hydrological Bureau, in order to study the relationship between precipitation, runoff and sediment. The precipitation data were measured by a 20 cm JQR01 instrument. The runoff data were collected by hydrographic cable flow meter measurement at medium and high flow, and wading flow meter measurement for low (dry) flow. In accordance with the Chinese river suspended sediment specification, the measured sediment data are sampled at 0.6 relative water depths from the water surface by using the one-point method to measure the suspended sediment concentration. All data were collected with professional instrumentation and were quality checked prior to availability. The homogeneity and reliability of the data were checked and homogenization and correlation tests were performed on the data before trend and mutation analysis, so as to select the data that can be used for the study.

3. RESEARCH METHODS

3.1. Homogeneity and correlation tests

The homogeneity test is essential in hydrological studies to reflect the authenticity of data. Inhomogeneity of hydrological datasets is mostly due to several factors including the relocation of the measuring stations, replacement of instruments,

Table 1 | The results of design standard flood at the Taipingguan hydrological station

Warning flood		Guaranteed flood		Design flood	
Warning level (m)	**Warning flow (m^3/s)**	**Guaranteed level (m)**	**Guaranteed flow (m^3/s)**	**Design level (m)**	**Design flow (m^3/s)**
1016.90	577	1017.80	813	1018.35	956

and human error. In this study, the Standard Normal Homogeneity Test (SNHT) (Alexandersson 1986), Buishand's Test (BRT) (Buishand 1982), Pettitt's Test (PT) (Pettitt 1979) and Von Neumann's Ratio Test (VNRT) (von Neumann 1941) were used to assess the homogeneity of the precipitation, runoff and sediment load in annual time series. Additionally, homogeneity tests were performed by using the pyHomogeneity package and the Anclim software package at the 1% significance level. The details of the homogeneity test are described as follows.

The SNHT belongs to the maximum likelihood estimate and is based on the assumption of normality. The statistics test is:

$$T(k) = k\bar{z}_1^2 + (n-k)\bar{z}_2^2 \; 1 \le k \le n \tag{1}$$

$$\bar{z}_1 = \frac{1}{k}\sum_{i=1}^{k}\frac{(W_i - \bar{W})}{S} \tag{2}$$

$$\bar{z}_2 = \frac{1}{n-k}\sum_{i=k+1}^{n}\frac{(W_i - \bar{W})}{S} \tag{3}$$

where W_i is the ith value of hydrological sequences, $\bar{W}$ is the sequence average value. The test statistic T_0 is defined as:

$$T_0 = maxT(k) \;\; 1 \le k \le n \tag{4}$$

The test statistic T_0 is compared with the critical value for determining whether homogeneity exists.

Buishand' range test is an accumulative anomaly method and defined as:

$$S_0^* = 0 \tag{5}$$

$$S_k^* = \sum_{i=1}^{k}(W_i - \bar{W}) \; 1 \le k \le n \tag{6}$$

$$R = \frac{maxS_k^* - minS_k^*}{S} 0 \le k \le n \tag{7}$$

where R is the rescaled adjusted range and the value of $R/\sqrt{n}$ determines availability of breakpoints.

The Petttitt test is the non-parametric rank test and the results of these are assessed for the value of X_k with respect to the critical value. The statistic test is as follows:

$$X_k = 2\sum_{i=1}^{k} r_i - k(n+1) 1 \le k \le n \tag{8}$$

where the r_i means the ith rank of hydrological sequences.

The VNRT is a maximum likelihood estimate and assumes that the variables are randomly distributed. The test statistic is defined as:

$$N = \frac{\sum_{i=1}^{n-1}(W_i - W_{i+1})^2}{\sum_{i=1}^{n}(W_i - \bar{W})^2} \tag{9}$$

when hydrological sequence is homogeneous, the expected value of N is 2 (Buishand 1982).

The trend in a time series is susceptible to autocorrelation causing the trend to be over- or underestimated. Thus, it is crucial to reveal the autocorrelation present in the time series before performing hydrological trend and mutation analysis (Wang *et al.* 2021). The autocorrelation of sequences is usually checked by the Durbin-Watson test (Durbin & Watson 1951).

The test statistics are calculated as:

$$d = \frac{\sum_{t=2}^{n} (e_t - e_{t-1})^2}{\sum_{t=1}^{n} e_t^2} \tag{10}$$

where e stands for residuals. Generally, the value of d is distributed between 0 and 4, and near to the value of 2, meaning that the sequences are independent of each other.

3.2. Sliding accumulative anomaly method

The accumulative anomaly method is a kind of verification method that can visually judge the dispersion degree of hydrological values in the time series (Zhang *et al.* 2021a). When the value on the curve continues to increase, it means that the hydrological value is greater than the average value in the time period, and the time period is in the abundant year. Similarly, when the value on the curve continues to decrease, it means that the hydrological value is less than the average value in the time period, and the time period is in the depleted water year. In addition, the inflection point on the curve can be used to determine the characteristics of changes within the time series. Nevertheless, the hydrological observations are extremely volatile with time, since the accumulative anomaly method cannot accurately test the trend under the overall time series and stability in the local time. In this paper, the moving average was appended to make up for the deficiency of the accumulative anomaly method and to study the trends in precipitation and runoff variability.

For hydrological sequences W_i, the siding accumulative anomaly method is expressed as:

$$X_j = \sum_{i=1}^{j} (W_i - \bar{W})(j \leq n) \tag{11}$$

$$Y_{j+1} = \frac{1}{3}(X_j + X_{j+1} + X_{j+2}) \tag{12}$$

where X_j is the cumulative mean value of hydrological sequence in the jth year, and n is the sequence length, Y_{j+1} is the siding value in the $j+1$th year.

3.3. Mann-Kendall mutation analysis

The sliding accumulative anomaly method under hydrological series is limited in the inflection point judgment because of significant annual variation and autocorrelation, hence it is not accurate for the judgment of inflection point under time series and needs to be combined with other methods. The MK method is a commonly used nonparametric detection method (Mann 1945; Wu *et al.* 2021) that can analyze the long-term trend of time series and quantify the location of abrupt change points. Meanwhile, the MK method is widely used in the analysis of abrupt change detection in time series of runoff and precipitation owing to the advantage of not being easily disturbed by outliers.

The mutation detection statistics are defined as:

$$S_k = \sum_{i=1}^{k} \sum_{j=1}^{i} \text{sone}(W_i - W_j)(2 \leq k \leq n, 2 \leq j \leq i) \tag{13}$$

where $\text{sone}(W_i - W_j)$ is the value of 1 when W_i is greater than W_j, otherwise the value of 0.

$$UB_k = \frac{[S_k - E(S_k)]}{[Var(S_k)]^{\frac{1}{2}}} \quad 2 \leq k \leq n \tag{14}$$

where:

$$E(S_k) = \frac{n(n-1)}{4} \tag{15}$$

$$\mathrm{Var}(S_k) = \frac{n(n-1)(2n+5)}{72} \tag{16}$$

where S_k is the cumulative sequence, $E(S_k)$ is the mean value of the cumulative sequence, UB_k is a standard distribution, and $Var(S_k)$ is the variance of the cumulative sequence. Two-sided trend test was adopted by UB_k to construct inverse series UF_k. If the UB_k value is greater than zero, the sequence is on the rise, while the UB_k value is less than zero, which exhibits a downward trend. When the UB_k value exceeds the critical value of 1.96, it shows that the change of trend is significant. If the two curves of UF_k and UB_k appear at an intersection point in the confidence interval, the corresponding point of intersection is mutation initiation under the time series.

3.4. Wavelet functions

Precipitation is the main factor of runoff variation (Liu *et al.* 2018), thus analysis of the periodic performance of precipitation and runoff will help to determine river characteristics. Wavelet analysis is commonly used for periodic variation and can be represented by various functions. However, considering the non-stationary characteristics of hydrology under time series, the continuous wavelet transform is required to detect the presence of oscillations and periods, therefore the Morlet wavelet function was chosen in this study to analyze the multi-timescale variation of the precipitation and runoff time series of Langcang basin (Yao *et al.* 2021). The Morlet wavelet function is defined as:

$$\int_{-\infty}^{\infty} \psi(t)d_t = 0 \tag{17}$$

$$\psi(t) = e^{-\frac{t^2}{2}} e^{iwt}, \ w \in R \tag{18}$$

In Equation (17): ψ is the Morlet wavelet, which can form a transform function by scaling and shifting:

$$\psi_{m,n}(t) = |m|^{-\frac{1}{2}} \psi\left(\frac{t-n}{m}\right) \tag{19}$$

where m is a non-zero real number, representing the wavelet periodic scaling scale; n is a real number, indicating the wavelet translation scale. Then, the wavelet transform was obtained by the convolution of a wavelet function with awaiting signal:

$$W_f(m,n) = |m|^{-\frac{1}{2}} \Delta t \sum_{k=1}^{N} f(k\Delta t) \bar{\psi}\left(\frac{k\Delta t - n}{m}\right) \tag{20}$$

The magnitude of the period and fluctuation energy of the hydrologic time series was reflected by the wavelet variance at different scales:

$$Var(m) = \frac{1}{N} \sum_{k=1}^{N} W_f^2(m,n) \tag{21}$$

where $W_f(m,n)$ is the wavelet transform function, W_f is the signal to be processed; $\overline{\psi}$ is the complex conjugate function of ψ; N is the number of discrete points, k is a positive integer from 1 to N.

3.5. Hydro-sediment interrelation curve

The direction and shape of the flood noose curve depends mainly on the increase or decrease of the flow rate, when the river bed siltation is not considered (Ma *et al.* 2020). According to the hydrological characteristics of the research area in this paper, the daily average runoff and sediment load data in the Luozha River was analyzed from 1991 to 2019 and it was found that the relative variation amplitude of sediment has a greater variation than the runoff over the years with increasing flood, also the variation rates of sediment volume to runoff increases accordingly with the increase of runoff, therefore, this study derived the annual sediment prediction by integrating the relationship between runoff and sediment volume derivatives.

The relationship between runoff and sediment volume can be set as:

$$\mathrm{d}\tilde{G}_s/d\tilde{Q} = u(\tilde{Q}) \tag{22}$$

where $\tilde{G}_s$, $\tilde{Q}$ are dimensionless sediment load and runoff volume respectively; $u(\tilde{Q})$ is the function about $\tilde{Q}$.

4. RESULTS AND DISCUSSION

4.1. Analysis of homogeneity

The outcomes of the four tests for each precipitation, runoff and sediment load series are grouped in Table 2. Based on the number of tests rejecting the null hypothesis, Schönwiese & Rapp (1997) performed the classification 'useful' when one or zero tests reject the null hypothesis at the 1% level; 'doubtful' when two tests reject the null hypothesis at the 1% level; and 'suspect' when three or four tests reject the null hypothesis at the 1% level. If series labelled 'suspect' lack credibility., the hydrological dataset is not available for trend and variability analysis.

The hydrological data for homogeneous analysis is depicted in Table 2, in which annual average records for the precipitation and sediment load was found as 'useful', runoff records, however, are known as 'doubtful'. When signals of climate change are present in the time series, relative methods may mislead homogeneity tests (Aksu *et al.* 2022). The 'doubtful' signal breakpoints appear in correlation with the analysis of the precipitation MK mutation in Figure 2. River runoff and sediment load data show uneven distribution within the year. In 2019, for example, the homogeneity of daily average runoff and sediment load data was tested as 'suspect', while also demonstrating that fitting the runoff-sediment relationship equation with inhomogeneous data exclusively can cause bias in sediment predictions. Hence, this research selected the runoff and sediment load data available from the homogeneous testing of the flood period, and developed a theoretical relationship between runoff and sediment load for obtaining average annual sediment load.

4.2. Analysis of precipitation and runoff characteristics

4.2.1. Trend analysis results

Based on the precipitation and runoff data of the Luozha River in Lancang River Basin from 1964 to 2016, the annual precipitation and runoff of accumulative distance level process is plotted in Figure 1. The average annual precipitation is 1395.1 mm and the runoff is 18.6 m^3. The inter-annual precipitation and runoff variation coefficient C_v at the Luozha River of Lancang River Basin is 0.17 and 0.24 respectively, which is greater than the weak variation of 0.1 and less than the strong variation of 1, belonging to moderate variation. It can be clearly seen that the overall trend of annual precipitation and runoff in the time series has been consistent since 1969, and the overall variation of dryness and abundance was exhibited with long and short cycles, in which the same increasing trends can be observed in Figure 1 in at least three distinct periods, known as the abundant year, approximately from 1969 to 1976, 1982 to 1987, and 1989 to 2002. On the other hand, the same decreasing trends can also be observed at three distinct periods, approximately from 1976 to 1982, 1987 to 1989, and 2002 to

Table 2 | Summary of homogeneity results of the precipitation, runoff and sediment load

Stations	Hydrological sequences	Time scales	SNHT (*p*-value)	BRT (*p*-value)	PT (*p*-value)	VNRT (*p*-value)	Evaluation
Taipingguan	Precipitation (m^3)	1964–2016 (56 years)	0.075	0.062	0.121	0.358	Useful
	Runoff (m^3)	1958–2019 (59 years)	0.002* (2002)	0.007* (2002)	0.012	0.014	Doubtful
		2019 (365 days)	–	–	–	–	Suspect
		2019 (flood period)	0.516	0.561	0.985	0.151	Useful
	Sediment load (m^3)	1991–2010 (29 years)	0.393	0.397	0.389	0.467	Useful
		2019 (365 days)	0.083	–	–	–	Suspect
		2019 (flood period)	0.379	0.177	0.061	0.059	Useful

* and – indicate inhomogeneous at 1% significance level and values less than 0.0001, respectively; the values in parentheses represent the break point years.

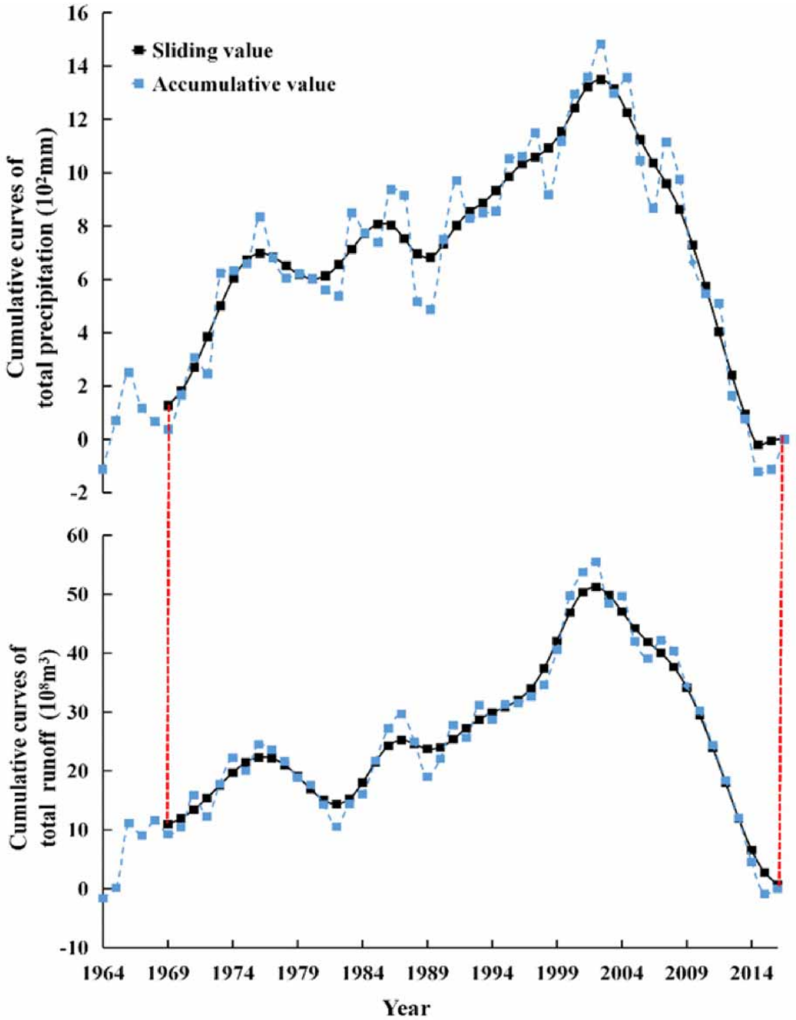


Figure 1 | Accumulation curves of total precipitation and runoff.

2014, which were describe as depleted water years. According to the comparison of accumulative curves precipitation and runoff in Figure 1, the annual precipitation series values declined rapidly from 1966 to 1970, whereas the relative accumulation value of annual runoff fell steadily in the same period. Guo *et al.* (2008) suggested that the stabilization of runoff volume change is related to the forest cover, which can affect the total evaporation and transpiration loss of soil moisture, thereby affecting the possibility of drought and flood. Liu *et al.* (2020b) studied the response of runoff to the various vegetation heights, indicating that runoff decreased with an increase in the forest area while increased with an increase in agricultural land or grassland. Thus, the slight differences for variables for precipitation and runoff in local time series was probably caused by spatial factors (Luo *et al.* 2020). Overall, precipitation and runoff trends are basically consistent, and no significant fluctuations were found for annual precipitation and runoff over time which demonstrates that the runoff of the Luozha River is mainly controlled by precipitation, with less influence from human factors.

4.2.2. Mutation analysis results

The Durbin-Watson test for precipitation and runoff data from 1964 to 2016 were 2.078 and 1.634 respectively, the results of which met the requirements for MK mutation detection analysis. As seen in Figure 2(a), the two curves of UB_k and UF_k intersected at 2002, indicating that the precipitation had changed significantly during this period, and 2002 was the mutation point of precipitation. Meanwhile, combined with the analysis of the cumulative distance level method, the runoff under the influence of precipitation appeared at the inflection point of abundance and dry in 2002. Yunling & Yiping (2005) found that the annual temperature gradually increased from 1960 to 2000 in the Lancang River Basin. Therefore, the mutation point of

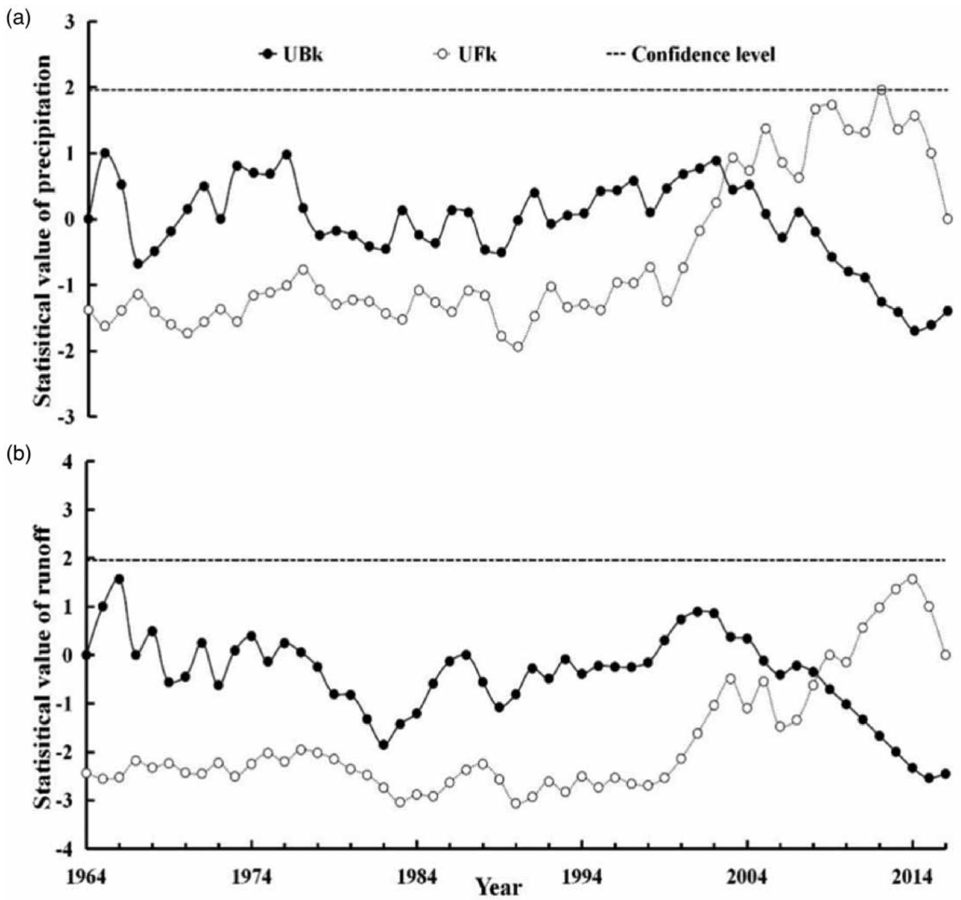


Figure 2 | (a) The MK mutation test curve in annual precipitation and (b) the MK mutation test curve in annual runoff.

precipitation is associated with climate change. As seen in Figure 2(b), the crossing point of UF_k and UB_k is located in 2008, indicating that the abrupt change for annual runoff appeared in early 2008 in this series. Based on the flooding information, it was found that extreme flood occurred on July 20, 2007 with a flow of 959 m^3/s, which exceeded the planned flow at the Taipingguan hydrological station and correlated with the abrupt point for annual runoff. The extreme flood caused severe soil erosion, and changed the underlying surface, thereby producing abrupt changes in annual runoff. Combined with the above trend analysis, the abrupt change point of runoff resulted in less volatility of runoff since 2008. Besides, the UB_k of precipitation and runoff under the study time series remains below 1.96, which reflects that the trend of precipitation and runoff was insignificant during 1964–2016, and the climate and topography of the area are stable in the natural state.

4.2.3. Periodic analysis results

The real contour of wavelet transform coefficient is shown in Figure 3(a) and 3(c), in which the solid and dashed lines means the positive and negative values of wavelet transform coefficients respectively, which can represent the abundant and depleted water periods. The real contour of wavelet can analyze the characteristics of precipitation and runoff of hydrological stations under time scale. The wavelet variance diagram of fluctuation energy with frequency domain intensity is shown in Figure 3(b) and 3(d), where the red point means the extreme point, indicating the stronger the fluctuation on the time scale, and the greater its contribution to the wavelet variance, which can determine the main time scale of periods.

The precipitation and runoff data of the Luozha River in Lancang River Basin from the period 1964 to 2016 were taken for wavelet analysis and the results are shown in Figure 3. The interannual variations and cycles in the annual precipitation series of the Luozha River are shown in Figure 3(a), in which the lower half of the contour density is much higher than the upper half, due to the fact that the lower half corresponds to a shorter period of oscillation with a higher frequency. As shown in Figure 3(b), the precipitation had four types of periodic variation rules with obvious peaks located at 5, 7, 17, and 28 years,

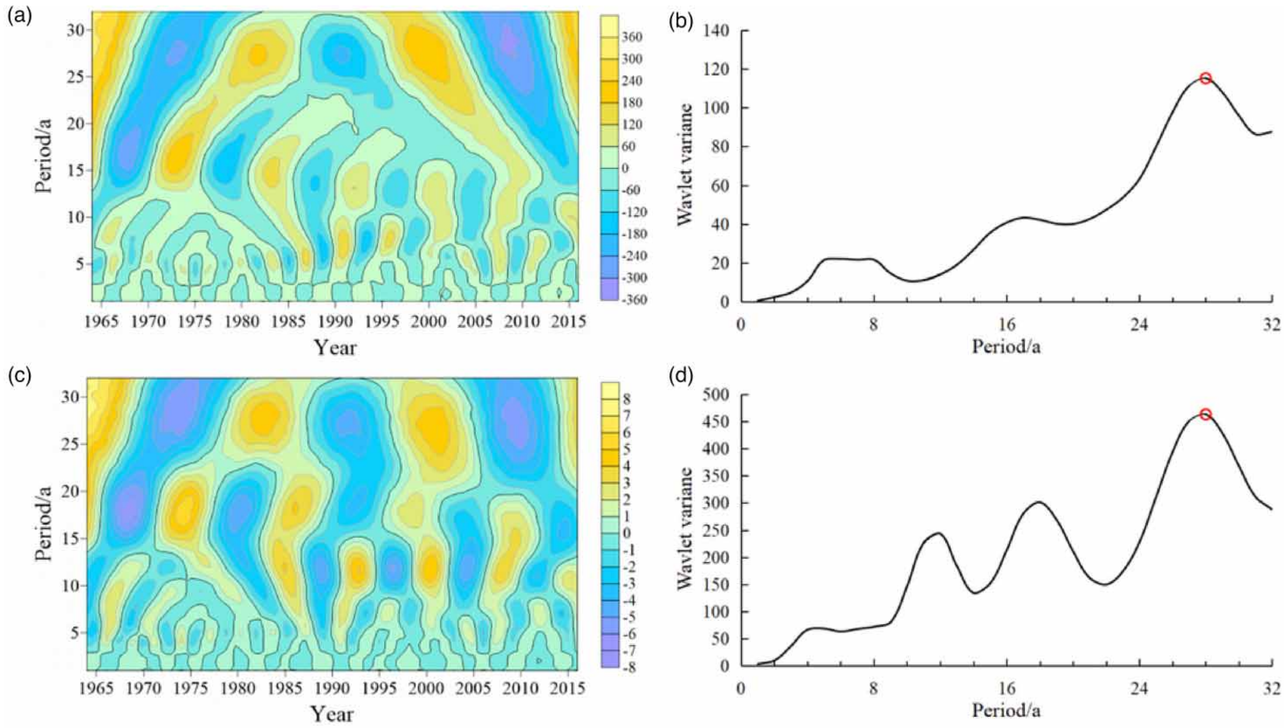


Figure 3 | (a) Real contours of precipitation wavelet transform coefficients, (b) Variance of precipitation wavelet variance, (c) Real contours of runoff wavelet transform coefficients and (d) Variance of wavelet variation of runoff.

respectively. Among them, the maximum peak value appears at the time scale of 28 years and the alternation between light and dark is obvious in the years 1964–2016, which suggests that the first main cycle of hydrological series was 28 years. Besides, these 28 years were stable in the whole-time domain, with a total of three abundance changes and significant alternations. The second main cycle corresponds to a time scale of 17 years, mainly representing three oscillations of alternating abundance and depletion from the period 1975–2002. The third main cycle is time scale of seven years, with two oscillations of alternating abundance and depletion from 2002–2016, with regional characteristics. The four main cycles have a time scale of five years, with a more significant performance from years 1988 to 2005.

Runoff variation is constituted at different time scales and can be found in Figure 3(c), presenting more complex small-scale oscillations nested in the large-scale oscillations. Annual runoff exhibited four main period variations of 5, 13, 18 and 28 years in Figure 3(d). As shown in Figure 3(c) and 3(d), the maximum peak occurs at the position of 28 years, which reveals that the main cycle of this hydrological series variation is 28 years, and experienced three times of abundance and depletion variation in the whole-time domain. The second main cycle corresponds to the time scale of 18 years, which indicates the strongest vibration of this cycle occurred in the period of 1966–2002, with three times of alternating abundance and depletion oscillation. The third cycle with a 13a time scale was mainly in the period 1985–2016, which was regional in nature with four times of alternating abundance and depletion. The four main cycle with five years was more significant in the period 1972–1985 and 2003–2008, experiencing alternating abundance and depletion of light and dark.

4.3. Interrelation of runoff and sediment load

In this paper, the author extracted the data of the first increasing floods in 2019 at the Luozha River hydrological station and calculated the derivative of dimensionless sediment load and runoff, then the function of $u(\tilde{Q})$ was obtained:

$$u(\tilde{Q}) = \frac{15}{8}\tilde{Q}^{\frac{3}{2}} \tag{23}$$

Substituting $u(\tilde{Q})$ into function (9), thus, there is:

$$\tilde{G}_s = \int \frac{15}{8}\tilde{Q}^{\frac{3}{2}} d\tilde{Q} \tag{24}$$

By solving the above equations, the expression of power function can be acquired:

$$\tilde{G}_s = \frac{3}{4}\tilde{Q}^{\frac{5}{2}} \tag{25}$$

Based on the existing 20-year annual sediment load data from the Taipinguan hydrologic station, the annual sediment load predicted by Equation (12) is compared with the measured data, as shown in Figure 4, in which the blue line refers to a perfect match and the red line means 50% error, and if the point lies in between the blue lines, this indicates a well applied prediction formula. As shown in Figure 4, 85% data points predicted from the present formula lie within 2/3 ~ 3/2 folds, 5% within 1/2 ~ 3/2 folds, 10% under 0.5 folds. Meanwhile, the predicted value is in good agreement with the measured with the exception of two anomalies, which were the annual measured data in 2003 and 2009. Depending on the presented results of hydrological variation in the Luozha River, the outliers generated in 2003 were affiliated with sudden precipitation mutations. Likewise, the outliers incurred in 2009 are linked to the runoff mutations. The article results in a bias of the prediction results to the actual value when the mutation point is generated.

In general, the prediction function on annual sediment load was the power function, and its form corresponds to the former recognition formula (Zhao *et al.* 2014). The coefficient reflects the variation rates of sediment under the average runoff annually, and the index represents the influence of variation between runoff and sediment load (Asselman 2000). The verification results showed that the new theoretical formula can be used to predict annual sediment load, and the new formula has such merits as theoretical derivation by integrating runoff and sediment load derivatives during flood augmentation, so that exponents of each item are a rational number. The proposed formula in this paper provides a theoretical reference for sediment prediction under natural conditions in other basins.

5. CONCLUSION

The present objective facts suggest that precipitation and human activities directly influence the generation of runoff in river areas, whereas variations in runoff lead to changes in the sediment load. Based on such facts, the measured data about annual

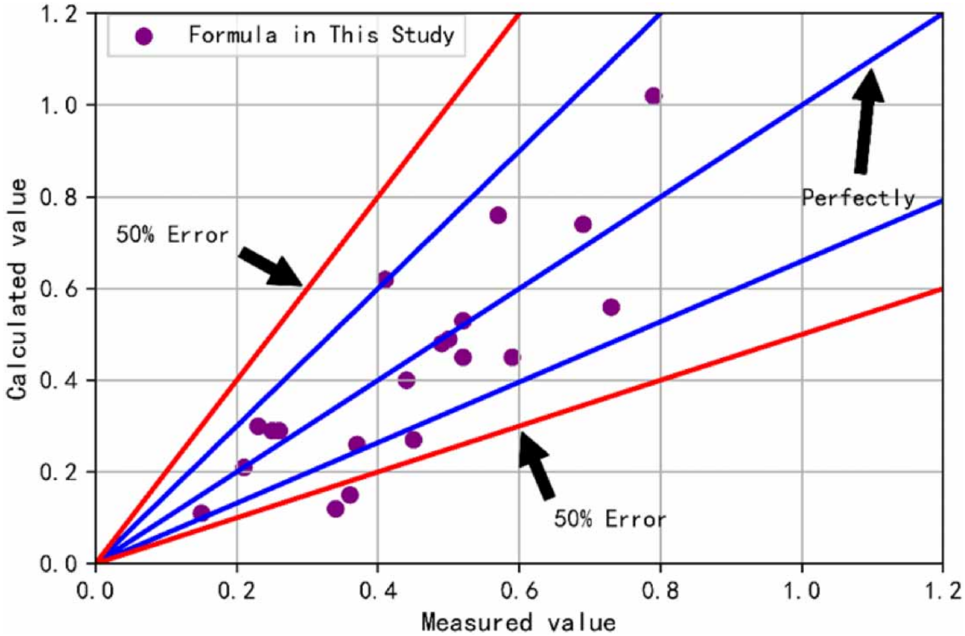


Figure 4 | Comparison between dimensionless calculated and measured sediment load.

precipitation and runoff in the Luozha River of the Lancang River Basin from 1964 to 2016 were analyzed. We found that the overall trends of annual precipitation and runoff are consistent and both have a 28-year principal cycle. Furthermore, the mutation of annual precipitation appeared in 2002 and led to the change from abundance to dryness, which was associated with climate change. The mutation of annual runoff in 2008 resulted in less fluctuation of annual runoff afterwards, which was related to extreme floods. These results illustrated that the runoff variation in the Luozha River is less influenced by human factors and will contribute to the enrichment of knowledge within the Lancang River Basin.

For sediment load, based on the difference in the magnitude of runoff and sediment load variability during the flood period a new method for obtaining annual sediment load was established. The research results show the formula of relationship between annual runoff and sediment load in Luozha River of Lancang River basin, with the equation coefficient and index of 0.75 and 2.5 respectively. The formula on annual sediment load was the power function, and its form corresponds to the former recognition formula. Meanwhile, the existing 20 years of annual sediment measurements was compared with the calculated values, showing the annual sediment load generated by this formula have more compliance with the measured data.

In summary, the relationship between rainfall, runoff and sediment in the natural state was explored by using the data measured at the Luozha River of the Lancang River Basin. The findings have important implications for achieving better comprehensive understanding in the river, and provide basic references for other areas of the basin for future water resource management. In addition to the above-mentioned results found under time series, regularities of spatial and temporal variations are different in natural conditions, which requires further research in the future.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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