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# Study on Variation Characteristics and Annual and Temporal Patterns of Water and Sediment in the Yellow River

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**Abstract.** The Yellow River, known as the mother river of the Chinese nation, the study on the variation patterns of its water and sediment flux holds significant theoretical guiding significance for the environment, climate, people's livelihood, and optimal allocation of water resources. This paper first focuses on the annual characteristic evaluation of sediment concentration and water-sediment flux in the Yellow River. Through the analysis of actual monitoring data from the Yellow River hydrological station over the past six years, it is found that sediment concentration has significant correlations with time, water level, and water discharge. On this basis, a multiple linear regression model between sediment concentration and water discharge is established using the stepwise regression method. Based on this model and the calculation relationship between total water discharge and total sediment discharge, the annual total water discharge of the hydrological station in the past six years (2016-2021) is estimated to be approximately 197.952 billion $m^3$, and the annual total sediment discharge is approximately 1211.364 billion kg.Subsequently, this paper delves into exploring the temporal variation patterns of water and sediment flux in the Yellow River. The M-K test method is used to analyze the mutation of monthly data of water discharge and sediment discharge over the past six years. The results show that the overall water discharge and sediment discharge exhibit a trend of slow fluctuation first and then significant increase, with the substantial growth mainly occurring after 2018. Through the seasonal decomposition model, the seasonal characteristics of water and sediment flux are revealed, which significantly increase in spring and summer and gradually decrease in autumn and winter. To further identify its periodicity, a wavelet analysis model is established, which clarifies that the variation period of water and sediment flux is one year. These research results provide a scientific basis for the management of water and sediment in the Yellow River and future trend prediction.

**Keywords:** Linear regression; M-K mutation test; Seasonal decomposition.

## 1. Introduction

The Yellow River, as the mother river of the Chinese nation, the dynamic changes of its water and sediment flux are of great theoretical significance for environmental governance, climate change, people's livelihood [1-2], and water resource management. Against the backdrop of increasingly significant global climate change and the impact of human activities, it is particularly urgent to deeply understand the evolution patterns of water and sediment in the Yellow River [3-4]. This study is based on the monitoring data of water and sediment in the Yellow River from 2016 to 2021, aiming to systematically analyze various characteristics of the water and sediment flux in the Yellow River.

This paper mainly addresses the following two core issues: Firstly, the annual characteristic evaluation of sediment concentration and water-sediment flux in the Yellow River, that is, analyzing the actual monitoring data of the Yellow River hydrological station in the past six years, studying the relationship between sediment concentration and time, water level, and water discharge, and estimating the annual total water discharge and annual total sediment discharge of the station in the past six years accordingly. Secondly, the exploration of the temporal variation patterns of water and sediment flux in the Yellow River, aiming to analyze the characteristics of water and sediment flux of the hydrological station in the past six years and study its variation patterns [5-6].

To achieve the above goals, this study will adopt a combination of multivariate statistics and time series analysis methods. Specifically, we will establish a regression model between sediment concentration and hydrological elements through correlation analysis and stepwise regression to estimate the annual total water and sediment. Meanwhile, the M-K test method is used to analyze the mutation of water and sediment flux, the seasonal decomposition model is used to reveal its seasonal characteristics, and the wavelet analysis model is used to explore its periodic variation patterns. This study is committed to providing a scientific basis for the regulation and management of water and sediment in the Yellow River. This paper assumes that: 1. It is assumed that the changes in water and sediment flux have certain time series characteristics. 2. It is assumed that the variation trend of water and sediment flux in the next two years can be predicted through historical data. 3. It is assumed that the formulation of sampling monitoring plans needs to consider data collection frequency and cost-effectiveness. 4. It is assumed that the "water and sediment regulation" of the Xiaolangdi Reservoir has an actual impact on water and sediment flux and riverbed elevation. 5. It is assumed that the water flow is uniform when water and sediment regulation is not carried out in June-July. The symbol descriptions are as follow Table 1:

**Table 1.** Symbol Descriptions

| Symbol | Description |
|---|---|
| $X_1$, $X_2$, $X_3$ | Year, month, day |
| $\Delta T$ | Time (second/) |
| Q | Total water discharge |
| S | Sediment discharge |
| Y | Sediment concentration |
| q | Water discharge |
| H | Riverbed elevation |

## 2. Evaluation of Annual Characteristics of Sediment Concentration and Water-Sediment Flux in the Yellow River

### 2.1. Data Preprocessing

To study the relationship between the sediment concentration of the Yellow River water at the hydrological station and time, water level, and water discharge, this paper selects the monitoring data of water and sediment in the Yellow River from 2016 to 2021 and analyzes its monitoring values. Before establishing the model, this paper preprocesses the required data [7]. Firstly, this paper processes the missing values in the data. It is understood and analyzed that the frequency of water and sediment monitoring in the Yellow River is determined by the intensity of changes. The main reason for missing data is that the changes in the river water are relatively stable, and there is no need for monitoring. Therefore, to eliminate the impact of missing values in the data, the fillna function is used to fill in the missing values.

### 2.2. Model Establishment

To exclude multicollinearity between variables, this paper adopts the stepwise analysis method. Firstly, a multiple linear regression model between the sediment concentration of the Yellow River and year, month, water level, and water discharge is established.

Let the sediment concentration be the dependent variable y, and year, month, water level, and water discharge be the independent variables $x_1$, $x_2$, $x_3$, $x_4$ respectively. Then the form of the multiple linear regression model is:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \varepsilon \quad (1)$$

Where $\beta_0$, $\beta_1$, $\beta_2$, $\beta_3$, $\beta_4$ are the parameters of the equation, and ε is the error term, which satisfies:

$$cov(\epsilon_i, \varepsilon_j) = \begin{cases} \delta^2 & i = j \\ 0 & i \neq j \end{cases} \quad (2)$$

For the known sample data, the regression equation can be written as:

$$\hat{y}_i = \hat{\beta_0} + \hat{\beta_1} x_{1i} + \hat{\beta_2} x_{2i} + \hat{\beta_3} x_{3i} + \hat{\beta_4} x_{4i} \quad (3)$$

Where $\hat{\beta_0}$, $\hat{\beta_1}$, $\hat{\beta_2}$, $\hat{\beta_3}$, $\hat{\beta_4}$ are the estimated values of the parameters. The above regression equation can be expressed in matrix form:

$\hat{Y} = XB$

Where:

$$Y = \begin{pmatrix} \hat{y}_1 \\ \hat{y}_2 \\ \vdots \\ \hat{y}_n \end{pmatrix}, x = \begin{pmatrix} 1 & x_{11} & x_{21} & x_{31} & x_{41} \\ 1 & x_{12} & x_{21} & x_{3n} & x_{4n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_{1n} & x_{2n} & x_{3n} & x_{4n} \end{pmatrix}, \hat{B} = \begin{pmatrix} \hat{\beta}_0 \\ \hat{\beta}_1 \\ \hat{\beta}_2 \\ \hat{\beta}_3 \\ \hat{\beta}_4 \end{pmatrix} \quad (4)$$

The estimated values of the parameters can be obtained by the least square method: $B = (X'X)^{-1}X'Y$.

### 2.3. Model Solution

By observing the scatter plots of sediment concentration with water discharge, time, and water level, it can be known that there may be correlations between sediment concentration and water discharge, time, and water level. There may be a linear relationship between sediment concentration and water discharge, water level, and a periodic relationship between sediment concentration and time. Further Spearman correlation analysis is conducted on the above variables to preliminarily understand the relationship between each independent variable x and the dependent variable y. From the results of the correlation analysis, year, month, water level, and water discharge have a significant positive correlation with sediment concentration. Finally, stepwise regression is used for analysis.

The model is solved using SPSS software, and the parameter estimates of the model are obtained as $\beta_0 = -0.229$ and $\beta_4 = 0.004$.

The regression equation is $y_i = 0.004q - 0.229$, ($i = 1,2,3, \ldots, n$)

$F = 1378.451$ is obtained. The F test for the model shows that $P < 0.05$, indicating that the model is highly significant, and $R^2 = 0.390$ is calculated, indicating that the model has a good goodness of fit. Therefore, this model can better reflect the relationship between sediment concentration and year, month, water level, and water discharge [8-10].

Through the analysis of the regression equation, it can be known that for the sediment concentration of the Yellow River, year, month, water level, and water discharge are all positively correlated with sediment concentration, and water discharge has a greater impact on annual sediment concentration. This is reflected in the actual monitoring data of water and sediment in the Yellow River: the greater the water discharge, the higher the sediment concentration; the smaller the water discharge, the lower the sediment concentration. This is also closely related to the scouring and silting characteristics of the Yellow River.

The variables $x_1$, $x_2$, $x_3$ represent year, month, day respectively, T represents time point, Q represents water discharge, S represents sediment discharge, Y represents water content. The formulas for calculating total water discharge and total sediment discharge using the above symbols are as follows:

Annual total water discharge = Σ water discharge × time

Annual total sediment discharge = Σ sediment concentration × annual total water discharge

$$Q = \sum_{i=1}^{n} q_i \Delta T \tag{5}$$

$$S = \sum_{i=1}^{n} Y_i Q \tag{6}$$

After calculation, the sum of total water discharge and total sediment discharge from 2016 to 2021 can be obtained, as listed in the following Table 2:

**Table 2.** Schematic Table of Total Water Discharge and Sediment Discharge

| Year | Total Water Discharge ($m^3$) | Total Sediment Discharge (Kg) |
|---|---|---|
| 2016 | 14369500800 | 18328813999.2 |
| 2017 | 15338538000 | 19047051414.0 |
| 2018 | 38889187200 | 293539431582 |
| 2019 | 38723788800 | 304010272620 |
| 2020 | 43375467600 | 350911312786.8 |
| 2021 | 47255094000 | 225527339538 |
| Total | 197951576400 | 1211364221940 |

## 3. Exploration of Temporal Variation Patterns of Water and Sediment Flux in the Yellow River

### 3.1. Analysis of Mutation of Water and Sediment Flux

#### 3.1.1. Establishment of Mutation Model Based on M-K Test

The M-K test can analyze the variation trend and mutation of a set of data and is widely used in the water conservancy field. It does not require the data to be normally distributed, individual outliers will not affect the analysis results, and it is a non-parametric test method with simple calculation. Through analysis, water and sediment flux are closely related to two factors: water discharge Q and sediment discharge S. The analysis principles are described as follows:

(1) Establishment of mutation model for water discharge

Let the water discharge sequence $x_n$ be an independent random time series, and construct an order sequence for it:

$$s_k = \sum_{i=1}^{k} r_i \,, \qquad k = 2,3, \dots, n \tag{7}$$

$S_k$ represents the cumulative number of times the i-th value in the time series x is greater than the j-th value, where:

$$r_i = f(x)\begin{cases} 1, x_i > x_j \\ 0, \quad x_i \le x_j \end{cases}, j = 1,2, \dots, i \tag{8}$$

Using the time series x, construct the following statistic:

$$UF_K = \frac{s_k - E(s_k)}{\sqrt{Var(s_k)}}, k = 1,2, \dots, n \tag{9}$$

Where, $UF_1 = 0$, $E(S_k)$ is the mean value of the order sequence $S_k$, and $var(S_k)$ is its variance.

Under the condition that each sample value of the time series x is continuously distributed and independent of each other, there is:

$$E(s_k) = \frac{n(n-1)}{4} \tag{10}$$

$$Var(s_k) = \frac{n(n-1)(2n+5)}{72} \tag{11}$$

It is obvious that the statistic $UF_i$ follows a standard normal distribution. A significance test with a significance level of α is conducted on it. If $|UF_i| > U\alpha$, it indicates that the time series x has an obvious variation trend. Inverting the sample data of the time series x can obtain a new time series, i.e., $x_n, x_{n-1}, \dots, x_1$. The same operation is performed on the new time series to obtain a new order sequence:

$$UB_k = -UF_k \tag{12}$$

Where $UB_1 = 0$, $k = n, n-1, \dots, 1$.

The test for mutation can be carried out with the help of a curve graph. For the two curves $UB_k$ and $UF_k$, if either of their values is greater than 0, it indicates that the time series x shows an upward trend; if either is less than 0, it indicates that x has a downward trend; under a given significance level α, if the curves $UB_k$ and $UF_k$ exceed the significance level line, it indicates that the time series x has a significant variation trend, and the part exceeding the significance level line is the time range where the mutation point exists; if the curves $UB_k$ and $UF_k$ intersect within the range of the significance level line, the intersection point is the time point when the mutation occurs in the time series [2].

(2) Establishment of mutation model for sediment discharge

The establishment of the mutation model for sediment discharge is similar to that for water discharge. Let the sediment discharge sequence $x_n$ be an independent random time series, construct an order sequence for it, conduct a significance test, and analyze.

### 3.1.2. Solution of Mutation Model Based on M-K Test

(1) Solution for mutation of water discharge

First, we analyze the mutation of water discharge. Based on the above principle of the M-K model, we use MATLAB software to analyze and calculate the data in the problem and draw the two curves UB and UF, as shown in the following Figure 1:

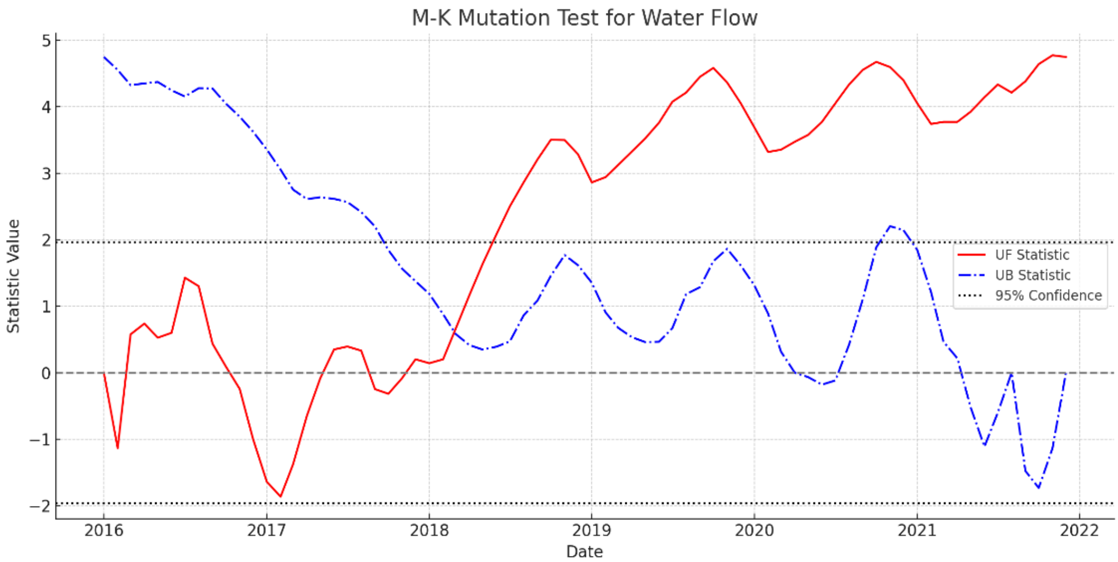


**Figure 1.** Schematic Diagram of M-K Water Discharge Mutation Test

Using the M-K test method, the water discharge of the hydrological station in the past 6 years is analyzed, with a significance level of 0.05. Observing the UF curve, before the intersection of the UF and UB curves, although there are slight fluctuations, the UF curve is within the critical line and does not exceed the confidence level line. This indicates that the water discharge was relatively stable during 2016-2017. During 2017, the UF curve dropped below the confidence level line, indicating that there was a phenomenon of reduced water discharge in this year, but the downward trend was not significant. The UF and UB curves intersect in 2018. Since 2018, the UF value has increased significantly, and all values are greater than 0, so the mutation time point of water discharge appears in 2018. Moreover, the UF curve passes the sliding t-test with a significance level of 0.05, indicating that 2018 is the starting point of the sudden increase in water discharge.

To sum up, the water discharge of the hydrological station in the past 6 years has shown an overall trend of slow fluctuation first and then significant increase, with the substantial growth mainly occurring after 2018, which is consistent with the fact that the abnormal atmospheric circulation in 2018 caused abnormally heavy precipitation in the Yellow River Basin. In July 2018, the average precipitation in the Yellow River Basin was 140.3mm, 41.5% more than the same period of the normal year, ranking the eighth highest since 1961 and the second highest since 2000. The South Asian high abnormally strengthened and extended eastward, the East Asian subtropical westerly jet was abnormally northward, and most of the Yellow River Basin was located in the divergent area south of the jet; the circulation in the middle and high latitudes of East Asia showed a "west low and east high" pattern, the area from the Balkhash Lake to Lake Baikal was controlled by a low-pressure trough, the Northwest Pacific subtropical high was abnormally westward and northward, overlapping with the high-pressure ridge in Northeast Asia in the same phase, and the cold air continuously splitting and moving southward in the middle and high latitudes converged with the warm and humid air flow on the northwest side of the subtropical high in the Yellow River Basin, resulting in overall more precipitation in the basin.

(2) Solution for mutation of sediment discharge

Secondly, we analyze the mutation of sediment discharge. Based on the above principle of the M-K model, we use MATLAB software to analyze and calculate the data in the problem and draw the two curves UB and UF, as shown in the following figure 2:

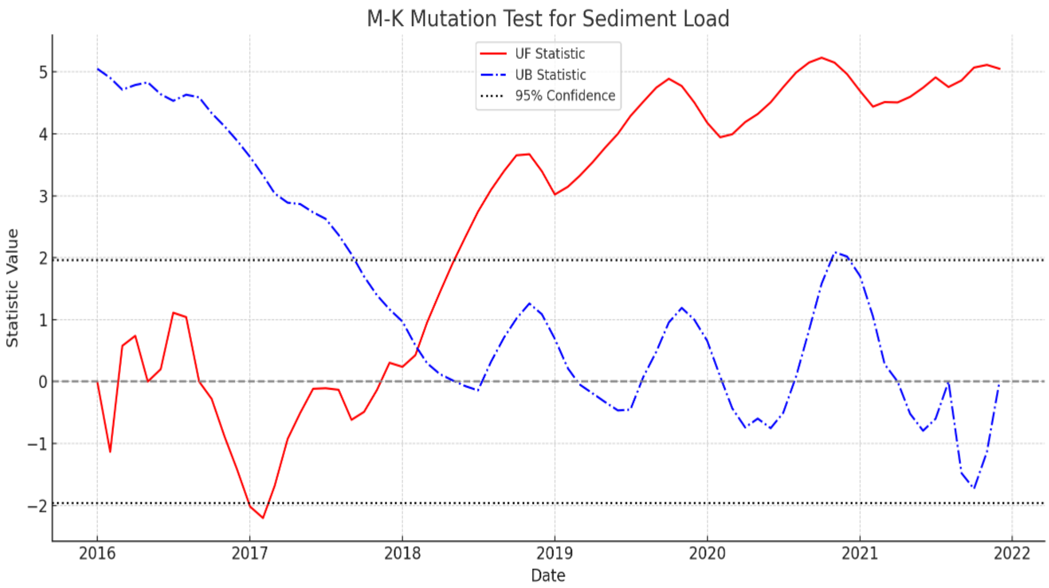


**Figure 2.** Schematic Diagram of M-K Sediment Discharge Mutation Test

Using the M-K test method, the sediment discharge of the hydrological station in the past 6 years is analyzed, with a significance level of 0.05. The overall variation of sediment discharge is closely related to water discharge. Observing the UF curve, before the intersection of the UF and UB curves, the UF curve is within the critical line and does not exceed the confidence level line. This indicates that the sediment discharge was relatively stable during 2016-2017. Similarly, the UF and UB curves intersect in 2018. Since 2018, the UF value has increased significantly, and all values are greater than 0, that is, with the sudden increase of water discharge, the sediment discharge also mutated. Moreover, the UF curve passes the sliding t-test with a significance level of 0.05, indicating that 2018 is the starting point of the sudden increase in sediment discharge.

To sum up, the sediment discharge of the hydrological station in the past 6 years has shown an overall trend of slow fluctuation first and then significant increase, with the substantial growth mainly occurring after 2018, which is consistent with the fact that the water discharge was more in 2018 and the scouring and silting characteristics of the Yellow River.

### 3.2. Analysis of Seasonality of Water and Sediment Flux

#### 3.2.1. Establishment of Seasonal Model Based on Seasonal Decomposition Model

The seasonal decomposition model is a statistical model used to analyze seasonal variations in time series data and is widely used in analyzing river characteristics. The additive model ("additive" model) in the model can decompose time series data into three different components: trend, seasonality, and residual, so as to better understand the characteristics of the data. Its analysis principle is as follows:

Let the observed value $y_t$ be the observed value of the time series at a specific time point t, that is, the water discharge and sediment discharge data from 2016 to 2021 for 6 years; the trend component $T_t$ is the long-term trend of the time series; the seasonal component $S_t$ is 365 days; the residual component $R_t$ is the component of the time series data that cannot be explained by the trend and seasonality.

Since this time series is relatively stable and the amplitude of the seasonal component remains relatively constant between different seasons, by using the additive model, adding the trend, seasonality, and residual components, we can obtain an approximate reconstruction of the original data:

$$Y_t \approx T_t + S_t + R_t \tag{13}$$

### 3.2.2. Solution of Seasonal Model Based on Seasonal Decomposition Model

We still split the water and sediment flux into water discharge Q and sediment discharge S, and analyze the seasonal variation trends of water discharge and sediment discharge from 2016 to 2021 (6 years) at a hydrological station downstream of the Xiaolangdi Reservoir in the Yellow River.

(1) Solution for seasonality of water discharge

Based on the principle of the above additive model ("additive" model), we use Python software to analyze and calculate the data in the problem and draw a comparison chart of the original data, trend, seasonality, and residual, as shown in the following figure 3:

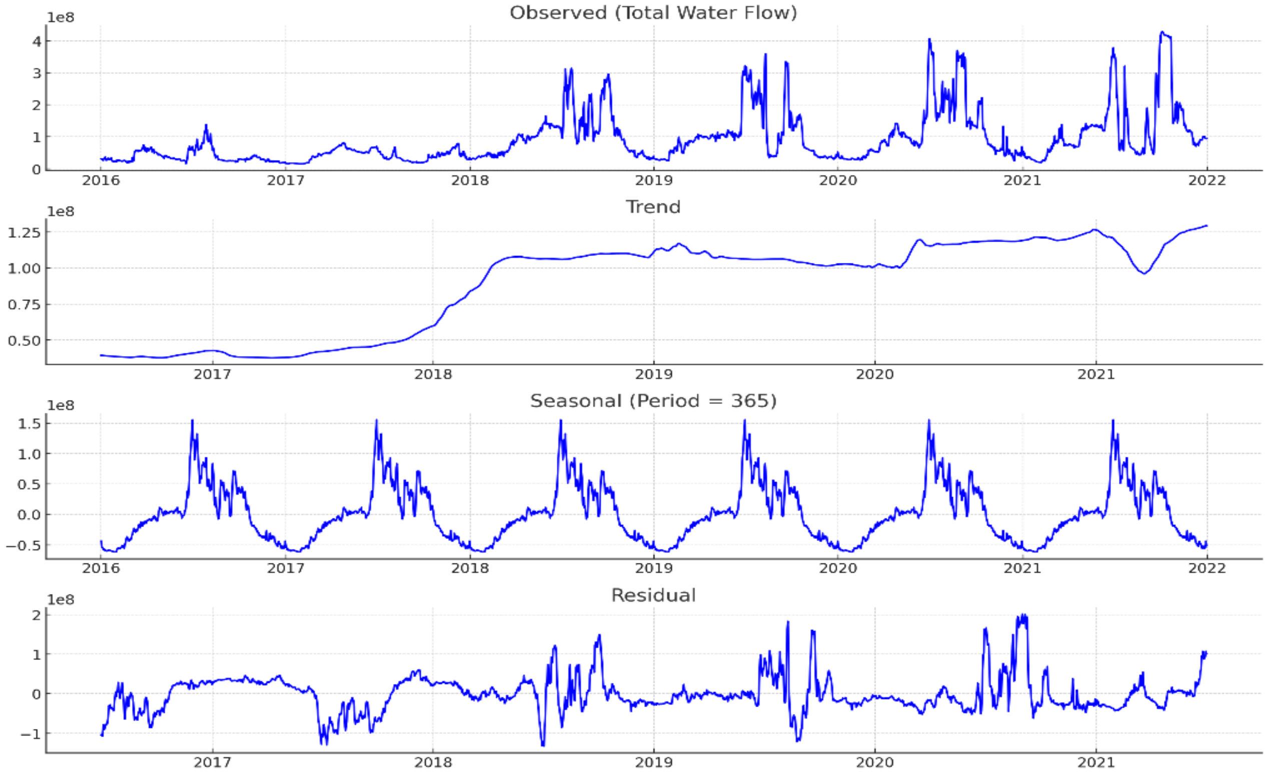


**Figure 3.** Schematic Diagram of Water Discharge Seasonality Test

By observing the trend chart, partially, in 2018, since late August, the Northwest Pacific subtropical high was abnormally strong and northward, the southwest warm and humid air flow and the southeast warm and humid air flow moved northward along the subtropical high, and at the same time, the cold air activities in the westerly belt were frequent. The cold and warm air continuously and violently converged in the middle reaches of the Yellow River, forming extremely rare autumn rain, and global warming led to serious melting of ice and snow in the source of the Yellow River, resulting in a significant increase in the overall water discharge in 2018; on the whole, although the trend of water discharge fluctuates over time, it is still rising.

Observing the seasonal chart, the water discharge shows an upward trend in spring, with a rapid upward trend caused by ice flood; there will be a peak in summer, caused by increased precipitation and significant melting of ice and snow in summer; autumn and winter show a downward trend, caused by reduced precipitation and river freezing; on the whole, it presents a periodic repeating pattern, which can confirm that the data is significantly affected by seasonality.

(2) Solution for seasonality of sediment discharge

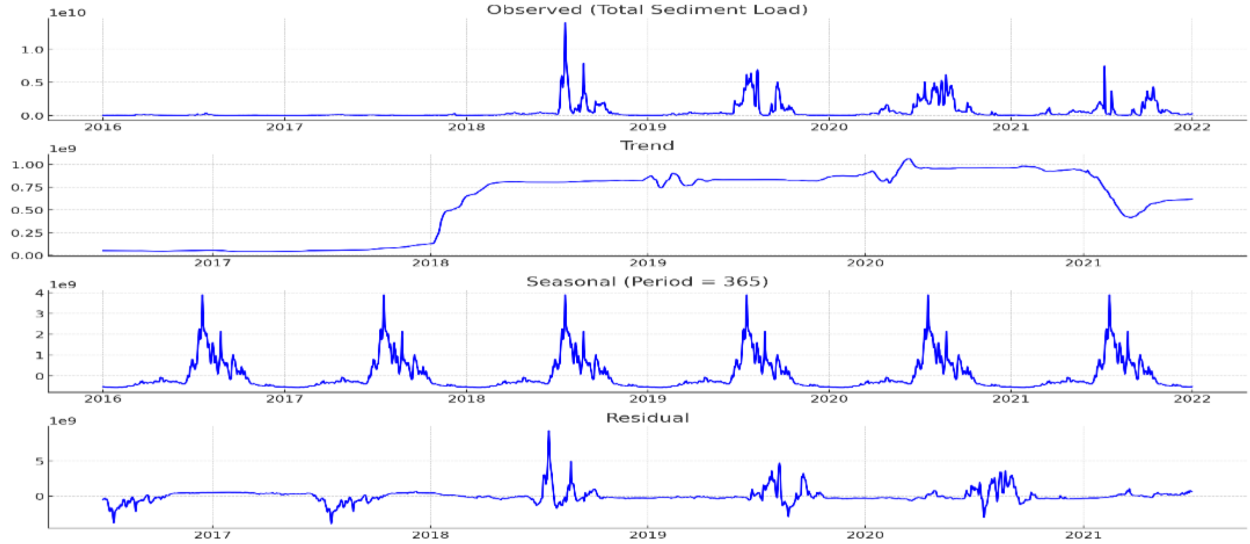


**Figure 4.** Schematic Diagram of Sediment Discharge Seasonality Test

Schematic Diagram of Sediment Discharge Seasonality Test is shown in figure 4. Using the same model, we can obtain that the trend, seasonality, and residual of sediment discharge are highly consistent with those of water discharge. The trend increased rapidly in 2018, corresponding to the increase in rainfall caused by global climate anomalies in 2018, the increase in water discharge, the fast flow rate, and the strong scouring force, resulting in the enhancement of the river's sediment transport capacity and the increase in sediment discharge, but the overall trend is still rising year by year. In terms of seasonality, peaks appear in spring and summer, and valleys appear in autumn and winter.

### 3.3. Analysis of Periodicity of Water and Sediment Flux

#### 3.3.1. Establishment of Periodic Model Based on Wavelet Analysis Model

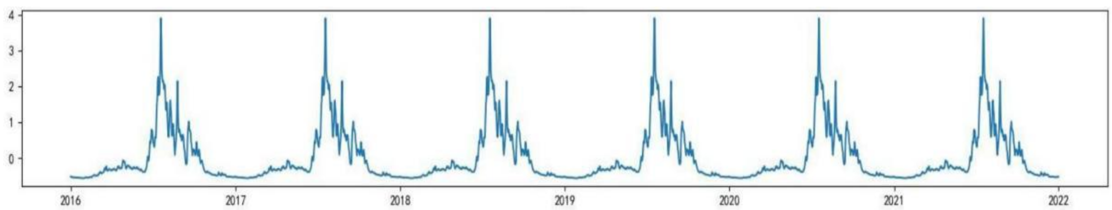

**Figure 5.** Schematic Diagram of Water Discharge Periodicity Test

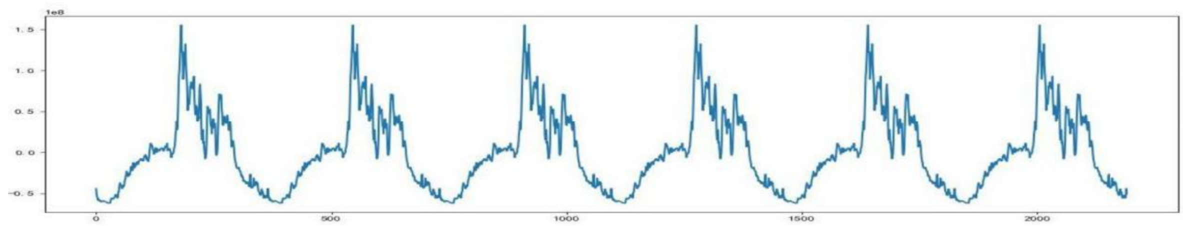

**Figure 6.** Schematic Diagram of Sediment Discharge Periodicity Test

Schematic Diagram of Water Discharge Periodicity Test and Sediment Discharge Periodicity Test are shown in figure 5 and figure 6. Based on the solution of the additive model in the seasonal decomposition model, it can be observed that the water discharge and sediment transport increase significantly during the spring flood and summer flood every year, that is, there is a correlation between different time series, which conforms to the "wavelet correlation analysis" model, so as to reflect the consistency of the periodic variation trends between the sequences. Schematic Diagram of Periodicity Analysis of Water Discharge and Sediment Discharge is shown in figure 7.

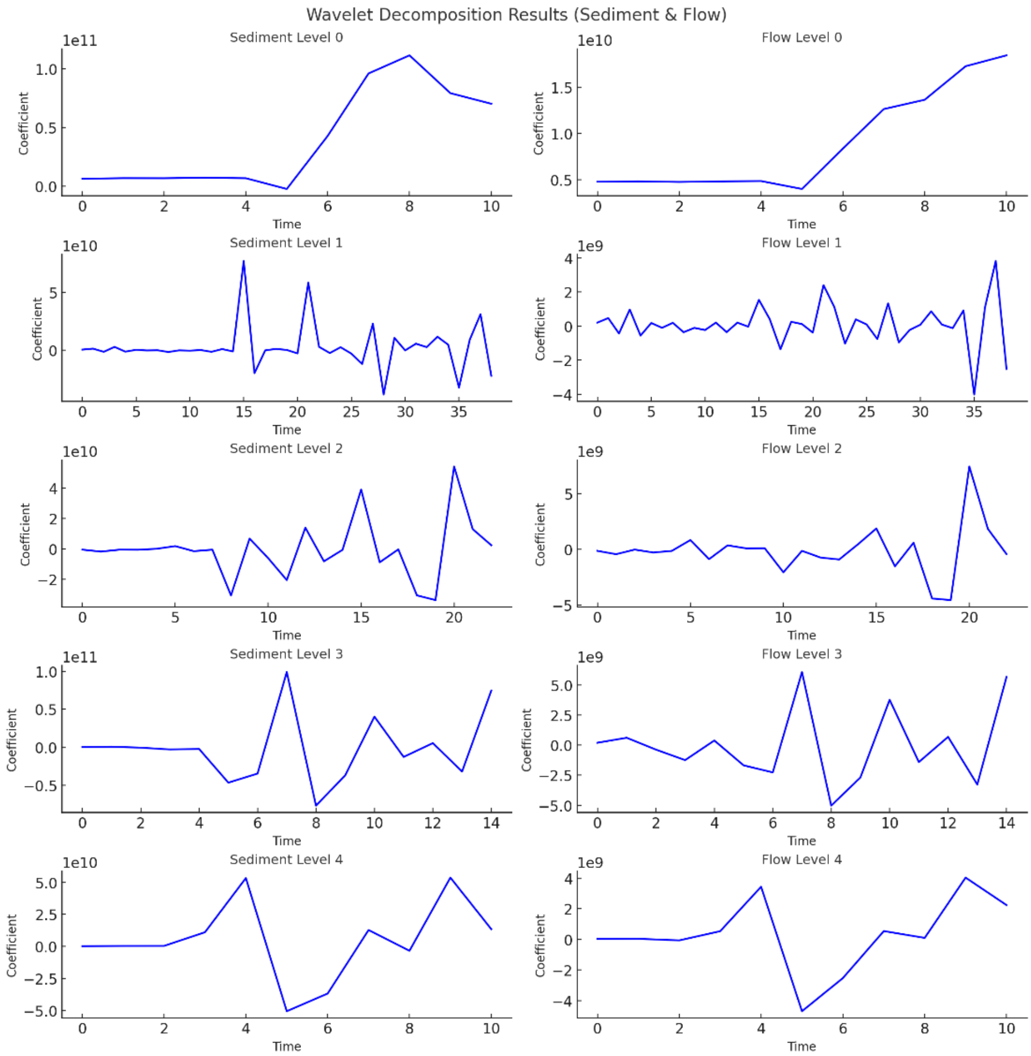


**Figure 7.** Schematic Diagram of Periodicity Analysis of Water Discharge and Sediment Discharge

Through wavelet analysis, it can be concluded that there is a significant correlation between the periodicity of water discharge and sediment discharge. And as the level selected in wavelet decomposition is higher, that is, the decomposed frequency range is more detailed, it can be seen that the consistency of their periodic variation trends is stronger, that is, the periodicity of water and sediment flux is: spring flood (April to June): during this period, the temperature rises, rivers in the north gradually thaw, and alternating cold and warm air flows form rainfall, resulting in a significant increase in river water discharge, forming spring flood; summer flood (July to September): during this period, the temperature rises significantly, leading to the melting of snow in the Bayan Har Mountains on the Qinghai-Tibet Plateau, the source of the Yellow River, and during this period, China is affected by the summer monsoon, which is the rainy season, and the river water discharge reaches a peak, forming summer flood.

To sum up, by analyzing the mutation, seasonality, and periodicity of the water and sediment flux of the hydrological station in the past 6 years, we can conclude that the water and sediment flux has a period of one year; the water and sediment flux in spring and summer increases significantly, and decreases gradually in autumn and winter; in case of special climate, the water and sediment flux will change accordingly.

## 4. Conclusions

This paper conducts an in-depth analysis of the monitoring data of water and sediment in the Yellow River from 2016 to 2021, aiming to reveal the annual characteristics and temporal variation patterns of water and sediment flux in the Yellow River, and on this basis, predict future trends, formulate optimal sampling monitoring plans, and evaluate the actual effect of "water and sediment regulation" of the Xiaolangdi Reservoir and its impact on riverbed elevation.

In the evaluation of annual characteristics of sediment concentration and water-sediment flux in the Yellow River, the study found that there is a significant positive correlation between sediment concentration and water discharge, and a linear regression model is established. Based on this model, the annual total water discharge and annual total sediment discharge of the hydrological station in the past six years are estimated.

Regarding the temporal variation patterns of water and sediment flux in the Yellow River, the M-K test results show that the water discharge and sediment discharge show a significant upward mutation trend after 2018, which is related to the abnormally heavy precipitation in the Yellow River Basin in that year. The seasonal decomposition model reveals the seasonal characteristics of water and sediment flux, which significantly increase in spring and summer and gradually decrease in autumn and winter. Wavelet analysis further confirms that the water and sediment flux has a periodicity of one year.

In terms of future trend prediction and optimal sampling monitoring plans, the SARIMA time series model predicts the water and sediment flux in the next two years, showing that it is generally stable and continues to have periodicity and seasonality. Based on this, the study formulates an optimal sampling monitoring plan for water level, flow, and sediment concentration, and proposes that the monitoring frequency should be increased during the flood season of the Yellow River (especially in July).

Finally, the evaluation of the actual effect of "water and sediment regulation" shows that the method of increasing the flow rate through artificial water storage can effectively scour the sediment at the river bottom, with good results. It is also predicted that if "water and sediment regulation" is not carried out in the next ten years, the riverbed elevation will increase.

This study comprehensively uses various statistical and time series analysis models, providing a scientific basis for the management of water and sediment in the Yellow River and future trend prediction.

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