Recent Change of Runoff and Sediment Characteristics of the Jinshajiang River

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Abstract. Sediment load of the Yangtze River is mainly from the upper reaches. The mean annual runoff of the Yichang hydrometric station, where the Three Gorges Project locates, is 436.4 billion m$^3$, and the annual sediment discharge is 470 billion kg. The suspended sediment mainly comes from the Jinshajiang River and the Jialingjiang River. The total mean annual sediment load of these two rivers occupies about 75% of the Yichang station. Compared with the years before 1990, the region composition of the runoff at Yichang station has no obvious variations, while the composition of the sediment source changes distinctly. Due to a large number of hydraulic constructions, the sediment transportation of the Jialingjiang River reduced greatly, whose proportion of the Yichang station has dropped from about 27% to around 10%. The Jinshajiang River basin has become the major area, from which the sediment into the Three Gorges Project comes. In this paper, a long time series of runoff and sediment observations from 1955 to 2011 of the Jinshajiang River is used for characteristics analysis, including trend, jumpy point and the sediment transportation properties. Besides descriptive statements, some statistical analysis techniques, such as Mann Kendall rank correlation test, Fisher ordered clustering, and double mass curves analysis are applied. The results illustrate that the sediment discharge varies with the runoff, displaying a decrease tendency over long time, especially in recent years, the sediment load drops significantly. Meanwhile, the sediment transportation efficiency reduces obviously in recent 10 years, which means much less sediment load can be carried with the same runoff. The construction of the large-scale water conservancy project is the main reason for such drastic change.

1. Introduction

The volume of runoff and sediment load of the Yangtze River ranks fourth and fifth respectively in the world [1]. The upper reach of the Yangtze River covers the segment from river head to Yichang city, with a mainstream length of 4540 km and a catchment area of about 1 million km$^2$, which accounts for about 55% of the whole Yangtze River basin. The upper reach is the main sediment yielding area of the Yangtze River. The measured mean annual runoff and suspended sediment discharge at Yichang station, the control station of the upper stream of the Yangtze River, are 430 billion m$^3$ and 452 billion kg, respectively.
The Three Gorges Project almost controls the entire upstream region of the Yangtze River. The runoff and sediment inflow upstream, which mainly comes from the Jinshajiang River and the Jialingjiang River, is one of the most important boundary conditions for the operation of the Three Gorges Project. The total mean annual sediment discharge of the Jinshajiang River and the Jialingjiang River covers more than 70% of sediment inflow into the Three Gorges Reservoir, and the Jinshajiang River accounts for a great proportion of all the tributaries. Especially in recent years, due to the sediment load decrease of the Jialingjiang River, the Jinshajiang River has become the largest source of sediment inflow into the Three Gorges Reservoir with the percentage of about 80% after the 1990s.

The design and demonstration of the Three Gorges Project is based on the hydrological series of the years 1950-1986, derived from statistical data of the runoff and sediment load series of 1961-1970. However, resulting from the continuous exploitation to the hydropower resources of the Yangtze River, its runoff and sediment discharge characteristics, especially the sediment characteristics, has changed greatly since the year around 2000. Overall, although there is no obvious change of the runoff, the measured sediment discharge drops observably, and the particle size also decreases greatly. Different characteristics of the runoff and sediment have distinct impact on the erosion and deposition of sediment at the backwater zone, the dam area, as well as the reach downstream the dam of the Three Gorge Reservoir, and thus affect the operation significantly.

In this paper, the hydrologic and sediment data of the years 1955-2011 at Pingsha station, which is the controlling hydrometric station of the mainstream of the Jinshajiang River, is taken to analyze statistically about the trends, catastrophe point and the relations between runoff and sediment. The results illustrate that although there is no tendency change for the runoff at Pingshan station, the sediment discharge performs a significant decrease tend. The main turning points of the tendency change of the runoff and sediment appear in the year of 1998 and 2001 respectively. For the value of the runoff and sediment, the jumpy points divided by Fisher ordered clustering are 2001 and 2011. Although the runoff does not vary greatly, there is a dramatic change for the sediment with the percentage of -77.32% before and after the jumpy point. The sediment transportation characteristics changes in the year of 2000, from then on less sediment can be carried with the same amount of runoff. Due to such a sudden transition, the human activities like reservoir constructions are supposed to be the key factors influencing sediment transportation.

2. Spatial and Temporal Characteristics of the Runoff and Sediment

2.1 Spatial Distribution

Jinshajiang River is the upper reach of the Yangtze River, which originates from Batang estuary, and ends at Yinbin of Sichuan Province, with a length of about 2300 km, accounting for 2/3 of the upper reaches of the Yangtze River, as shown in Fig. 1. The catchment area of the Jinshajiang River is around 362,000 km², taking up about 36% of the total area of the upper reaches of the Yangtze River, with a drop height of 3,300 m and an average slope of 1.45 ‰. Pingshan hydrological station, the export control station of the Jinshajiang River has a control drainage area of 459,000 km².

There are many tributaries of the Jinshajiang River, of which, 18 tributaries are with a catchment area over 1,200 km², and 9 of them have a catchment area above 10,000 km².
Rainfall and runoff of the Jinshajiang River mainly come from the Yalongjiang River tributary and the reaches downstream Shigu hydrometric station. The section from Batang estuary to Shigu station is narrow and locates in the longitudinal river valley with little rainfall, which is below 600 mm. The reaches below this section has more precipitation, and the largest tributary, the Yalongjiang River feeds into the mainstream of the Jingshajiang River, resulting in increasing runoff. The mean annual runoff of Panzhihua station is 57.2 billion m$^3$, while that of the Yalongjiang River is 52.4 billion m$^3$, which are almost equal. The runoff of the Jinshajiang River is relatively abundant and stable, constituting quite stable basic flow of Yangtze River. The runoff of the Pingshan station accounts for about 1/3 of the total runoff of the upper reaches of the Yangtze River.

The sediment yield condition and soil erosion of the upper and lower reaches of the Jinshajiang River basin varies significantly with different geographical situation, vegetation and rainfall characteristics. The sediment load increases from the headstream to the downstream of the Jinshajiang River, and the water and sediment comes from different source areas. This spatial variation is quit prominent for Jinshajiang River. Taking Panzhihua as the boundary, the Jinshajiang River is divided into two sections, and the main sediment source area of the Jinshajiang River basin is the lower reach with a natural head of 700 m and an average gradient of 1%. There are high mountains and deep valleys in this area with degrading stream and complex geological structure. Most of the tributaries and creeks have strong gully erosion, which can easily develop to landslide or debris flow under the effect of gravity and hydraulic power. Meanwhile, the original forest is destructed seriously in this area, and both sides of the river are covered by farmland. Storm in flood season results in serious soil erosion, which makes this area be the most serious regions of soil erosion of the whole Yangtze River basin, as well as the key soil and water conservation area.

Figure 1. Stream network of the Jinshajiang River.
2.2 Temporal Distribution

Pingshan hydrometric station is the control station of the mainstream of the Jinshajiang River. In this study, runoff and sediment data at the Pingshan station is taken as the study objective. Fig. 2 shows the annual runoff and sediment load process from 1955 to 2011, during which period the mean annual runoff at Pingshan station is 144.2 billion m$^3$ with the coefficient of variation Cv 0.16, while the mean annual sediment load is 250 billion kg with the coefficient of variation Cv 0.34. The mean annual sediment concentration is 1.73kg / m$^3$, and the maximum annual sediment load is 501 billion kg, occurred in the year of 1974. However, it should be clarified that when considering sediment block effect of Ertan Reservoir of over 80 billion kg, the maximum annual sediment load happened in 1998, and the amount is likely to exceed 550 billion kg. The minimum annual sediment load is 54 billion kg, occurred in 2011. In general, the sediment changes corresponds to the runoff variation, which means that more sediment comes with large runoff, and less sediment occurs with small runoff. Nevertheless, amplitude of variation of the sediment is much smaller than that of the runoff.

Figure 2. Annual runoff and sediment load process during 1955 to 2011.

Fig. 3 is given to compare the average value of runoff and sediment for different decades, from which it can be seen more clearly that although the runoff fluctuates, the sediment load reduces obviously. Especially after the 1970s, there is a distinct drop of the sediment load.
3. Analysis on Runoff and Sediment Characteristics of the Jinshajiang River

3.1 Trend Analysis

In this study, linear fitting trend line is firstly used to estimate the general trend of the runoff and sediment variations, as shown in Fig. 2. The given trend lines indicate that there is almost no change of trend for the runoff, while the sediment load performs a slight trend of decrease.

Linear regression is simple, but can hardly provide a persuasive result for such a dramatically changed process. Accumulated anomaly analysis [2], a frequently-used approach to judge the variation trend, is then adopted to estimate a general trend of runoff and sediment variation of the Jinshajiang River, as shown in Fig. 4. For a time sequence \( x_i \), the accumulated anomaly at moment \( t \) is:

\[
S_t = \sum_{i=1}^{t} (x_i - \bar{x}) \quad t = i, \ldots, N
\]  

(1)

where \( \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \) with the values of \( S_t \) at \( N \) moments. The accumulated anomaly curves are presented in Fig. 4 to analyze the tendency.
Fig. 4 shows that the biggest turning point of the trend of runoff happens in the year of 1997. Before then, there is a general trend of descending of the runoff, which increases dramatically after 1997. Besides, there are also some remarkable turning points appear in other years, such as the year of 1961, 1968, 1984, 1991, and 2005. It is worth noting that the runoff gets to another decline cycle after 2005, and continues its decrease trend in recent years. Although the sediment load basically shows a synchronous trend with the runoff, the trend changes relatively smooth. The major turning point of the sediment load occurs in the year of 2000, before which the sediment load increases generally with some minor rise and falls. However, three years after the runoff began the increase tendency sharply, the sediment discharge achieves its peak of increase trend, and starts the decrease tendency even though the increase trend of the runoff continues. In the most recent decade, the sediment discharge shows a distinct drop trend although there are still some random fluctuations of the runoff. From the above it can be seen that accumulated anomaly analysis can also be used to divide the phases of the variation.

Finally, to corroborate the trend analysis above and verify the specific tendency by index based on statistical theory, Mann-Kendall rank correlation test is applied [3], which is the most popular due to its less requirements on data, and less impacts on results when data deviating from normality. The ultimate principle of Mann-Kendall rank correlation test is that: for time series \( x_1, x_2, \ldots, x_N \), firstly find out their dual price \( P \); i.e. for all the \((x_i, x_j, i < j)\), the numbers of \( x_i < x_j \) is \( P \). If \((x_i < x_j, \text{ if } i < j)\) is hold for all the values in this time series, there is an uptrend, and \( P = (N - 1) + (N - 2) + \ldots + 1 = (N - 1)N/2 \), while if \((x_i > x_j, \text{ if } i < j)\), there is a downtrend and \( P = 0 \). Therefore for a sequence without any trend \( E(P) = N(N - 1)/4 \). If \( P < E(P) \), a downtrend might exist, and if \( P > E(P) \) there might be an uptrend. Statistic of \( U \) is adopted in this test:

\[
U = \frac{\tau}{\sqrt{Var(\tau)}}
\]  (2)
where \( \tau = \frac{4P}{(N(N-1))} - 1; \) \( \text{Var}(\tau) = \frac{2(2N+5)}{(9N(N-1))} \) and \( U \) converges fast to standardized normal distribution when \( N \) increases. Confidence level is set as \( \alpha = 0.05 \), critical value \( U_{0.05/2} = 2.576 \) is obtained from normal distribution table (Kendall, 1990).

Taking confidence level \( \alpha = 0.05 \) and \( N = 57 \), the result from Mann-Kendall rank correlation test of runoff at Pingshan station is \( U = -0.474 \), the absolute value of which is below \( U_{\alpha} = 1.96 \), presenting there is no obvious trend of change. Meanwhile, for sediment at Pingshan station \( U = 0.867 \), also implying no apparent variation trend.

### 3.2 Jumpy Points Analysis

Hydrological process consists of two components, one is the deterministic composition, shown as the trend and cycle; the other is the random composition. "Jump" is a performance of the randomness, which refers to a jumpy change at a certain moment for time series, with a performance of steep increase or steep drop of the values before and after jump points. The essence of the jump analysis is ordered clustering. First the jump point is found, and then a test is carried out.

Jinshajiang River has a large drainage area with complicated runoff and sediment yield conditions, which are affected by vegetation conditions of the catchment, the precipitation, the reservoir blocking effects and so on. Among them, the occurrence of mudslides, landslides are strongly random with more complex change. These factors make the runoff and sediment discharge of the Jinshajiang River have jumpy characteristics.

The accumulated anomaly analysis before can be used for observing jump points. Besides, Fisher's ordered clustering method is one of the most popular approaches for jump analysis. Fisher's ordered clustering method is dividing \( N \)-sample sequence \( \{x_i\} \) into \( k \) classes, and searching an optimal clustering scheme to make the sum of the dispersion minimum [4]. There are two features of this method: one is that these \( N \) samples are ordered, and the other characteristic is that the continuity of the sample order should be maintained during the clustering without any jump. When splitting the sample sequence, the data within a certain class are supposed to be close. Variance of the class is used to represent the deviation of the data in this segment. The optimal clustering criterion is to get the minimum variance within class, and maximum variance among different classes. The segment result by Fisher's ordered clustering method of 57 runoff and sediment sequence over the year 1955 to 2011 at Pingshan station is shown in Fig. 5, which implies the year of 2010 and 2001 should be the optimal jump point for runoff and sediment clustering respectively. The average runoff of the two periods before and after 2010 is presented in Table 1, as well as the average sediment of the two periods before and after 2001.
Figure 5. Fisher’s ordered clustering curves of runoff and sediment at Pinshan Station.

Table 1. Mean annual value of different periods of the runoff and sediment of the Jinshajiang River.

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<tbody>
<tr>
<td>Runoff ((x10^9) m(^3))</td>
<td>143.99</td>
<td>139.16</td>
<td>-4.83 (-3.35%)</td>
<td>238.10</td>
<td>54.00</td>
<td>-184.10 (-77.32%)</td>
<td></td>
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<tr>
<td>Sediment ((x10^9) kg)</td>
<td>143.14</td>
<td></td>
<td></td>
<td>234.87</td>
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3.3 Sediment Runoff Relations

Sediment transporting relationship between runoff and sediment load of a catchment reflects the changing properties of the tributary system. For the changes of sediment yield caused by the transformation of the underlying surface condition, if there is tendency change of the sediment
transporting characteristics, the relationship between runoff and sediment will alter, and there will be a significant turning point in the double mass curve with different slope before and after that.

Fig. 6 shows the double mass curve of runoff and sediment of the Pingshan station, as well as the fitting curves, fitting equations and the coefficients of correlation $R^2$. A distinguishing turning point at the year of 2000 can be seen, divided by which, the fitting linear functions have two different gradients.

![Double mass curve](image)

**Figure 6. Double mass curve.**

The sediment load increases with the increase of runoff before the year of 2000 in Fig. 6, but after then, the increase rate becomes low, which means after the year of 2000, even if the runoffs are the same, less sediment load are transported than the years before. According to this result, Fig. 7 presents the relations between runoff and sediment load at Pingshan station with different color for the years before and after 2000, and the curves are fitted with different quadratic functions respectively.

![Relations between runoff and sediment](image)

**Figure 7. Relations between runoff and sediment.**

Both Fig. 6 and Fig. 7 imply that the sediment transporting relationship is basically stable during the years from 1955 to 2000, while the sediment transporting efficiency after the year of...
2000 is slightly drops. The main reason for this is the completion and impoundment of Ertan reservoir in 1998. The sediment blocking effect of the reservoir is so obvious that there is a distinct turning point around the year of 2000 on the double mass curve, and the slope of the curve decrease significantly after 2000. Thus, the water conservancy projects are an important factor influencing the sediment transporting in the Jinshajiang River basin.

4. Conclusions

Jinshajiang River carries the largest amount of sediment load among all the rivers in the upper reach of the Yangtze River, which is also the main source of sediment into the Three Gorges Reservoir. The mean annual suspended sediment load of the Jinshajiang River is $234.87 \times 10^9$ kg. The stream segment from Panzhihua to Yibin is the lower reach of the Jinshajiang River, which is the main sediment yield area of the Jinshajiang River, as well as the most serious soil erosion region of the Yangtze River basin with complex geological structure, developed fault, and rock destruction. Researching on the hydrological data from 1955 to 2011 at Pingshan hydrometric station, the controlling station of the mainstream of Jinshajiang River, the following conclusions are obtained: (1) Although the fluctuation of the annual runoff is relatively intense, there is no obvious tendency change. Generally, before the year of 1998, the runoff has a declining trend. A few years after then, a rising trend is shown, and the runoff is currently in a downward trend beginning in 2005. However, all the trends above are not remarkable. Meanwhile, sediment load performs a slight increasing trend during the years before 2001, but in the following 10 years, it shows a significant decrease trend; (2) For the absolute values of the runoff and sediment discharge, the jumpy points appear in 2001 and 2011 respectively according to the Fisher’s ordered clustering. But the change of the runoff is much smaller with the percentage of -3.35%, while the sediment has a significant decrease after the jumpy point with the percentage of -77.32%. (3) The turning point of the sediment transportation characteristics changes in the year of 2000, after which time, the sediment transporting efficiency drops greatly. It means that from 2000, the amount of sediment carried by the same flow rate is significantly reduced. The construction of large-scale water conservancy projects is the most likely explanation for such a dramatic change of the sediment characteristics.

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References

