
WATER RESOURCES AND THE REGIME OF WATER BODIES

Multi-Timescale Variations in Water and Sediment Discharge of Mountainous Rivers in Southern Zhejiang Province, China

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Abstract—The rivers in southern Zhejiang Province are typical mountainous rivers that are impacted by various climatic and anthropogenic factors. In this study, the annual, seasonal and flood peak variations of water and sediment discharge, as well as their causes, are investigated using the Mann-Kendall test, accumulative curve, and wavelet analysis based on data from six hydrological stations and nine meteorological stations over the past 40–60 years. Insignificant increasing trends, occur in the water discharge for most rivers due to increased precipitation, while the observed significant decrease in the sediment load can be attributed to anthropogenic impacts (i.e., reservoirs constructions, sand mining). The greatest decrease in sediment load (64%) occurred in the Feiyun River (1968–2019). The water and sediment discharge during the plum rain season (April–June) and typhoon seasons (July–September) collectively account for ~75 and ~90% of the annual totals, respectively. Due to the differing rainfall patterns between these two seasons, the maximum monthly water discharge occurs in the plum rain season in most rivers. Meanwhile, the maximum flood peak discharge and daily sediment load, as well as the maximum monthly and daily sediment loads, occur more frequently during the typhoon season. Owing to reservoir construction, the maximum flood peak discharge and daily sediment discharge decreased by 13–50 and 18–74%, respectively, and the intra-annual distribution of water discharge became uniform. The dominant periodicities of annual water and sediment discharge for most rivers are ~22 years under the impacts of precipitation, while those in the Feiyun River are ~13 years due to human activities (the ratio of the total storage capacity and annual average water discharge reaches 84%).

Keywords: mountainous river, water discharge, sediment load, anthropogenic change, climatic change

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INTRODUCTION

Rivers serve as the primary routes for transporting freshwater and terrigenous sediment into the sea [16]. In the last decades, the water discharge and sediment load of the world's rivers have exhibited marked changes as a result of human activities, particularly the construction of dams and reservoirs [15, 16]. The contributions of sediment from small and medium-sized mountainous rivers to coastal ocean have been enlarged as the decrease of sediment from large rivers [25, 26]. Given that mountainous rivers often have steep gradients, they are extremely sensitive to rainfall resulting in a large increase in water flow during periods of rainfall and a subsequent rapid reduction. Hence, these characteristics, as well as the presence of small basin areas, make small and medium-sized mountainous rivers prone to flooding [7].

In this study, the selected four small and medium mountainous rivers (i.e., the Jiao, Ou, Feiyun, and Ao rivers) located in Zhejiang Province, China belong to East Asia. Although this area experiences low precipi-

tation during the dry season from October to March, the heavy rainfall associated with the plum rain and typhoon seasons significantly increases the water levels in basins, causing frequent flooding. In fact, floods are considered the most serious natural disaster in Zhejiang Province as they account for ~40% of the total losses caused by natural disasters [8]. To minimize the losses caused by flooding, various measures have been undertaken, including construction of reservoirs in the river basins. Indeed, reservoirs have been built for most small cities along China's coast. Moreover, despite their low discharge during the dry season, the average runoff of the four rivers is ~1118 mm/yr, which is approximately 3× the global average [16]. Thus, a better understanding of the changes in water and sediment delivery from the small and medium-sized mountainous rivers is required to inform the development of effective strategies for minimizing the effects of anthropogenic and climatic influences.

The main aims of this study are: (1) to identify the annual variations, including trend and abrupt

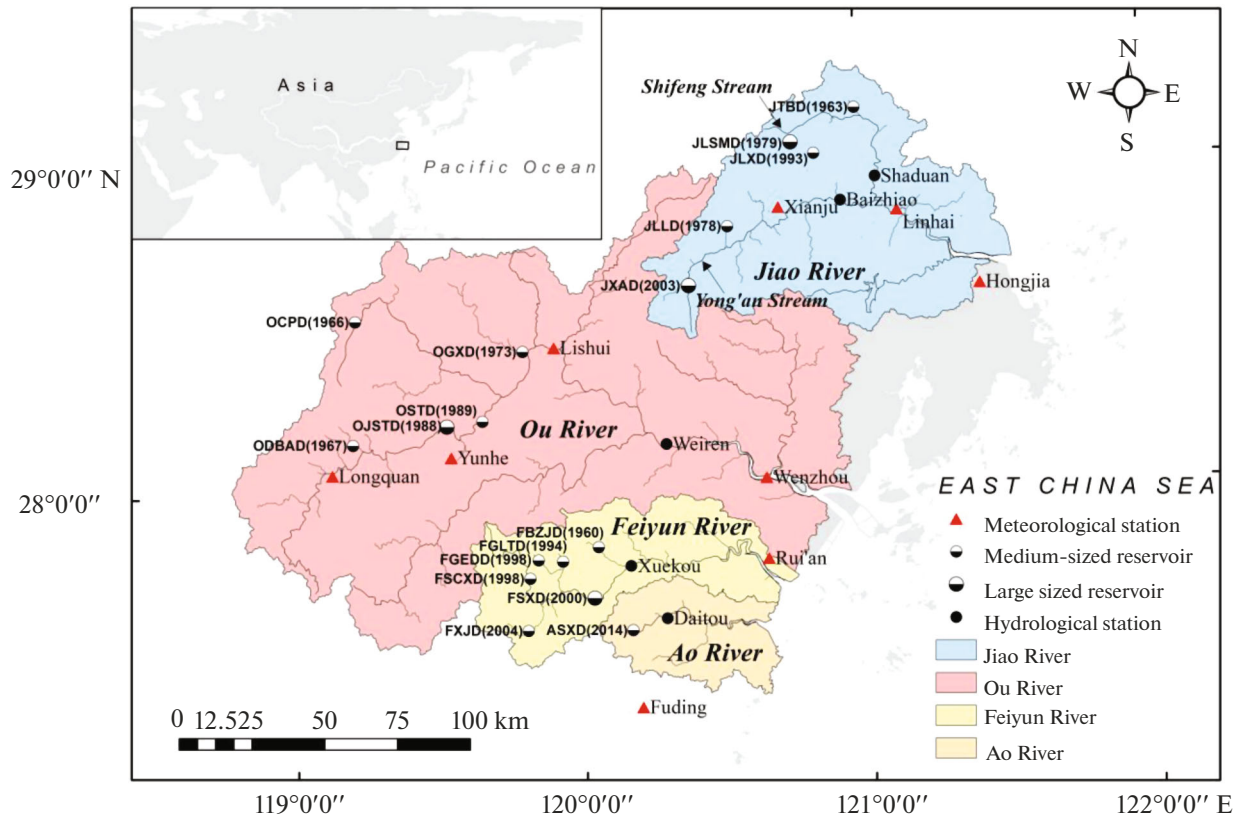


Fig. 1. Location of the study area. The first letters of the code for reservoirs represent the catchment. Namely, “J,” “O,” “F,” “A” represents Jiao River, Ou River, Feiyun River and Ao River, respectively. The “D” at the end of the code represents reservoir.

changes, for the water and sediment discharge from four mountainous rivers in southern Zhejiang Province; (2) to compare the seasonal distribution and changes in water and sediment discharge among these four rivers; (3) to identify the characteristics and changes of flood peaks for water and sediment discharge; (4) to detect the periodicity of water and sediment discharge; and (5) to discuss climatic and anthropogenic impacts on annual, seasonal, flood peaks, and periodic changes in water and sediment discharge.

STUDY AREA

Located in southern Zhejiang Province, the four rivers in this study, namely the Jiao, Ou, Feiyun, and Ao rivers, flow through the mountainous areas and eastward to the East China Sea. The Jiao, Ou, Feiyun and Ao rivers have catchment areas of 6613, 17900, 3700 and 1640 km², and a total length of 209, 388, 199, and 92 km, respectively. Shifeng Stream and Yong’an Stream are the two major tributaries of Jiao River.

Plum rain season and typhoon season are the two rainy seasons in Zhejiang Province, which collectively account for approximately 70% of the annual precipitation. Affected by the front of Asian summer mon-

soon staying, this region enters plum rain season between April and June, during which the rainfall events are long. The typhoon season occurs from July to September, during which the rainfall events are heavy and of short duration.

Many reservoirs have been built in the four rivers in recent decades. The locations of large and medium-sized reservoirs upstream of the hydrological stations are shown in Fig. 1. Other types of human activities that occur in this region include sand mining and water diversion.

DATA AND METHODS

Data

Water and sediment discharge data were collected from five gauging stations across the four rivers in this study. Monthly data in the past ~40–60 years were employed to analyze the annual, seasonal, and periodic variations in water and sediment discharge. Daily data for Ao River collected from 4/01 to 9/30 in 2009 were used as a typical example to compare the flood peaks between plum rain season and typhoon season. The annual maximum data for flood peak discharge and daily sediment load over the past ~40–60 years were used to analyze the variations in water peaks and

Table 1. Detailed information of meteorological and hydrological records in the four catchments

| Catchment | Hydrostation | Percentage, % | Precipitation | | Water discharge | | Sediment load | |
|--------------|----------------|---------------|---------------|-----------|--|-----------|----------------------------------|-----------|
| | | | mean, mm/a | period | mean, $\times 10^8 \text{ m}^3/\text{a}$ | period | mean, $\times 10^7 \text{ kg/a}$ | period |
| Jiao River | Baizhiao | 37.4 | 1531.01 | 1961–2019 | 23.11 | 1958–2019 | 37.25 | 1958–2019 |
| | Baibu/Shaduan* | 20.3/22.4 | | | 12.14 | 1958–2019 | 24.01 | 1958–2019 |
| Ou River | Weiren | 75.4 | 1576.93 | 1960–2018 | 137.26 | 1956–1998 | 187.26 | 1956–1998 |
| Feiyun River | Xuekou | 59.3 | 1635.55 | 1960–2019 | 23.83 | 1958–2019 | 27.82 | 1958–2019 |
| Ao River | Daitou | 22.5 | 1659.34 | 1960–2019 | 5.07 | 1958–2019 | 6.46 | 1958–2019 |

* Baibu Station was shut down and Shaduan Station was set in 1980 on Jiao River. Two stations distance is approximately 9 km. The data were combined with the separated record from Baibu Station (1958–1979) and Shaduan Station (1980–2019).

sediment discharge. The above data were obtained from government agencies, including the Hydrologic Management Center of Zhejiang, the Water Resources Bureau of Taizhou, and the Hydrological Management Center of Lishui. Due to the lack of bed-load data, only the suspended load is discussed in this paper. The detailed information regarding hydrological records is presented in Table 1. It should be noted that the Daitou station is the control station within the middle and upper reaches of the Ao River mainstream with the longest time series records for water and sediment discharge, although its percentage is less than 50% [23]. Data collected by the Baibu Station and Shaduan Station for the Shifeng Stream of the Jiao River were combined as the drainage basin areas changed by only a few percentages. Missing sediment load data (10/1962, 11/1962, 7/1979, 8/1979, 10/2013–12/2013, 1/2014–6/2014 in Jiao River; 1961–1962, 1968–1970 in Ou River; 1968–1970, 5/1987 in Feiyun River; 1968–1969, 2016 in Ao River) were interpolated using a power function of monthly water and sediment discharge by compiling all available data over the observation period. This is a popular method employed to estimate the suspended sediment load from water discharge records [1, 22, 24]. The coefficients of determination for the power function were >0.9 , apart from three abnormal months in the dry season with sediment load approached zero.

Monthly precipitation data in the past ~60 years from nine meteorological stations in the four river basins were provided by the National Meteorological Information Center of China Meteorological Administration and are available at <http://data.cma.cn/>. The area precipitation was calculated through the Thiessen polygon method in ArcGIS 10.8. The meteorological stations in each river basin were applied as follows: Xianju, Linhai, Hongjia, and Lishui represent precipitation in the Jiao River basin. Lishui, Yunhe, Longquan, Rui’an, Wenzhou, and Xianju represent the precipitation in the Ou River basin. Fuding, Wenzhou, Rui’an, Lishui, and Yunhe represent the precipitation in the Feiyun River basin. Fuding and Rui’an represent precipitation in the Ao River basin.

Methods

(i) Mann-Kendall Test

Mann-Kendall test (M-K test) is a popular non-parametric and rank-based approach to assess the significance of the trends in time series data owing to its robustness for non-normally distributed and censored data [12, 14]. When assessing standardized Z test results, an upward trend corresponds to a positive value, while a downward trend corresponds to a negative value. The local significance levels of the Z statistics for each trend were assessed using probability value p . The existing trend was assessed to be statistically significant at a significance level of 10% ($p \leq 0.1$) here. A detailed description of Z/p calculation is available in Panda et al. [17].

(ii) Double Accumulative Curve

A double accumulative curve widely used to identify the changes of hydrological regimes [13, 29] is a plot of the cumulated values for one variable against the cumulated values for another related variable for a concurrent period of time [18]. The double accumulative curve exhibits a straight line if the relationship between the two variables is constant. Alternatively, a break in the slope occurs when a change in the relationship occurs [29]. In this study, double accumulative curves were employed to identify changes in the relationship between water discharge and sediment load.

(iii) Wavelet Analysis

Wavelet transform is a multi-resolution method that is useful for characterizing changes in power of time series [21]. Given that it focuses on localized variations on power time and frequency, it has been used in a number of geophysical and hydrological studies [27, 28]. Selection of the function depends on the desired analysis and characteristics of the time series being analyzed [27]. Morlet wavelet is an effective tool for feature extraction as it provides an appropriate balance between time and frequency localization [4];

Table 2. Summarized results of Mann–Kendall test (M–K–test) for the time series of annual water discharge, sediment load, precipitation and C_V for water and sediment discharge

| Catchment | Water discharge* | | Sediment load* | | Precipitation* | | C_V for water discharge** | | C_V for sediment load** | |
|--------------|------------------|------|----------------|------|----------------|------|-----------------------------|------|---------------------------|------|
| | Z | p | Z | p | Z | p | Z | p | Z | p |
| Jiao River | 1.04 | 0.15 | −1.30 | 0.10 | 1.95 | 0.03 | −2.49 | 0.01 | −0.87 | 0.19 |
| Ou River | 0.75 | 0.23 | −1.21 | 0.11 | 0.90 | 0.19 | −1.99 | 0.02 | 0.31 | 0.38 |
| Feiyun River | 0.77 | 0.22 | −3.76 | 0.00 | 1.27 | 0.10 | −4.59 | 0.00 | −1.55 | 0.06 |
| Ao River | −0.50 | 0.31 | −0.88 | 0.19 | 1.18 | 0.12 | 0.02 | 0.49 | 0.09 | 0.47 |

* The statistical period is 1961–2019, 1960–1998, 1960–2019, 1960–2019 in Jiao, Ou, Feiun and Ao rivers, respectively.

** The statistical period is 1958–2019, 1956–1998, 1958–2019, 1958–2019 in Jiao, Ou, Feiun and Ao rivers, respectively.

Table 3. Days of annual maximum flood peak discharge and maximum daily sediment load occurring in plum rain and typhoon seasons (the statistical period is consistent with Fig. 3)

| Season | Days of annual maximum flood peak discharge | | | | | Days of annual maximum daily sediment load | | | | |
|-----------|---|---------------|----------|--------------|----------|--|---------------|----------|--------------|----------|
| | Jiao River | | Ou River | Feiyun River | Ao River | Jiao River | | Ou River | Feiyun River | Ao River |
| | Baiz-hiao | Baibu/Shaduan | | | | Baiz-hiao | Baibu/Shaduan | | | |
| Plum rain | 20 | 15 | 21 | 15 | 9 | 18 | 18 | 17 | 13 | 6 |
| Typhoon | 39 | 42 | 14 | 40 | 44 | 39 | 39 | 17 | 42 | 48 |

hence, Morlet wavelet was employed to analyze the periodicities of water and sediment discharge in the current study.

RESULTS AND DISCUSSIONS

Temporal Variations in Annual Water and Sediment Discharge

(i) Trend Variations in Annual Water and Sediment Discharge

The trends in annual water and sediment discharge from the five hydrological stations were examined. The trends in water discharge, sediment load, and precipitation were analyzed over time (Table 2). Increasing trends were observed in the annual water discharge for the Jiao, Ou, and Feiyun rivers (Fig. 2; Table 2), however, the trends were not significant in any of the rivers ($p > 0.1$; Table 3). More specifically, water discharge increased by 0.20, 0.17 and 0.08%/yr in the Jiao, Ou, and Feiyun rivers, respectively, while decreasing by 0.23%/yr in the Ao River. Regarding the sediment load, declining trends were detected in all rivers, in which the Jiao River and Feiyun rivers exhibited significant trends ($p < 0.1$). Specifically, sediment load decreased by 0.77, 0.95, 1.80, and 0.44%/yr in the Jiao, Ou, Feiyun, and Ao rivers, respectively. Meanwhile, upward trends were observed in precipitation levels in all rivers (0.25, 0.17, 0.15, and 0.13%/yr in the Jiao, Ou, Feiyun, and Ao rivers, respectively). These results suggest that the increase in water discharge can

be attributed to changes in climate, while the reduction in sediment load may result from human disturbance.

(ii) Climatic and Anthropogenic Impacts on the Temporal Variations in Annual Water and Sediment Discharge

Climate impact (i.e., precipitation) is typically the largest contributor to water discharge [3, 29]. In this study, water discharge exhibited increasing trends in the Jiao, Ou, and Feiyun rivers, which are consistent with the precipitation trends (Fig. 2; Table 2). Hence, the increase in water discharge may have resulted from precipitation. However, water discharge trends can also be impacted by anthropogenic activities, such as water diversion [19, 20]. In this study, the decrease of water discharge in Ao River was contrary to the increase of precipitation (Fig. 2; Table 2). This may be attributed to the water division of the ASXD built in 2014. According to the design requirements, it supplies 2.3×10^7 m³/yr of water to nearby towns [8], accounting for approximately 4.56% of the average annual water discharge of the Daitou Station.

Climate and human activities can also make great impact on sediment load [5, 7]. Large floods (typically caused by a typhoon) can markedly increase the annual sediment load. As the red line of accumulative curves shown in Fig. 3, the significant one-year increases in the slope of the accumulative curves may have been caused by a large amount of sediment being

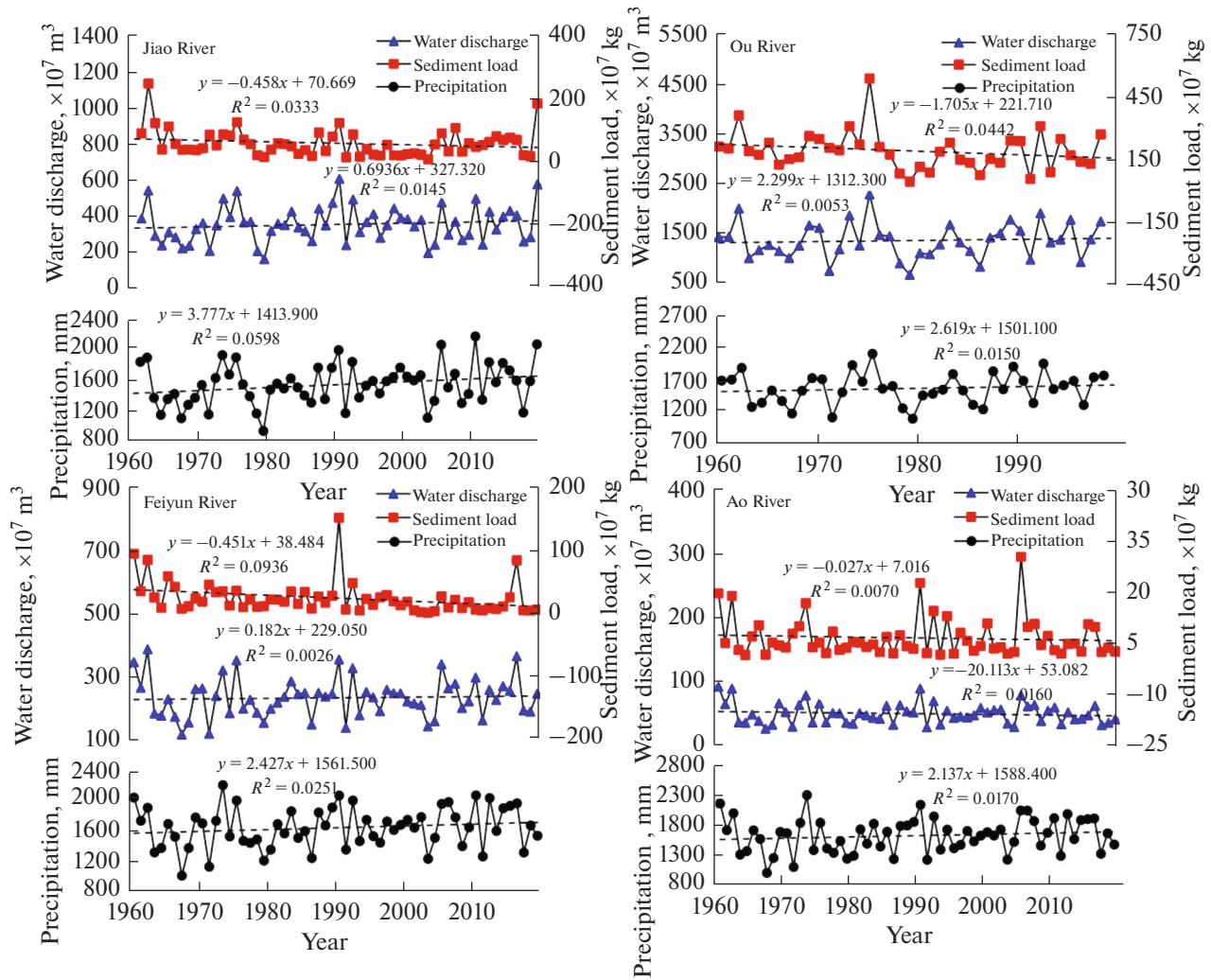


Fig. 2. Temporal variations in the annual water discharge, sediment load, and precipitation.

washed into the river following large floods. In addition, the sediment load for the four rivers varied during different time periods owing to the different types of human activities (marked by blue or green lines of accumulative curves in Fig. 3). Based on the observed points of change, the study period in the Ou and Feiyun rivers were divided into two periods, whereas, that in Jiao River was divided into four periods. Without changed point related to human activities, the study period in Ao River was divided into two period based on the construction year of the only medium-sized reservoir (ASXD). Phase 1: Minimal human activities, with small reservoirs constructed (storage capacity <0.1 km³). This period was used as the baseline period. In the Jiao, Ou, Feiyun, Ao rivers this period occurred in 1958–1965, 1956–1974, 1958–1967, and 1958–2013, respectively. Phase 2: Large and medium-sized reservoirs constructed quickly (total storage capacity of the Jiao, Ou, and Feiyun rivers was 0.4, 1.5, and 1.9 km³, respectively). This period was considered the

reservoir impact period, which occurred in 1966–1990, 1975–1998, 1968–2019 and 2014–2019 for Jiao, Ou, Feiyun and Ao rivers, respectively. Reservoirs would reduce the sediment load via trap sediment. Owing to the intensity of reservoir construction, the annual sediment load among the four rivers decreased by different extents during the study period with numerous reservoirs built (reservoir impact period). A relatively large reduction in sediment load (~64%) occurred in the Feiyun River. Phase 3: Sand mining had a significant impact on sediment load in Jiao River (1991–2003). During 1990s, sand mining occurred more frequently in the Jiao River due to urban construction [2]. The sediment load in Jiao River further decreased to 27 × 10⁷ kg/yr, which was ~53% lower than that during 1966–1990. Phase 4: The government took measures to limit sand mining (2004–2019), resulting in sediment load returning to the level in 1966–1990 (Figs. 3a, 3e).

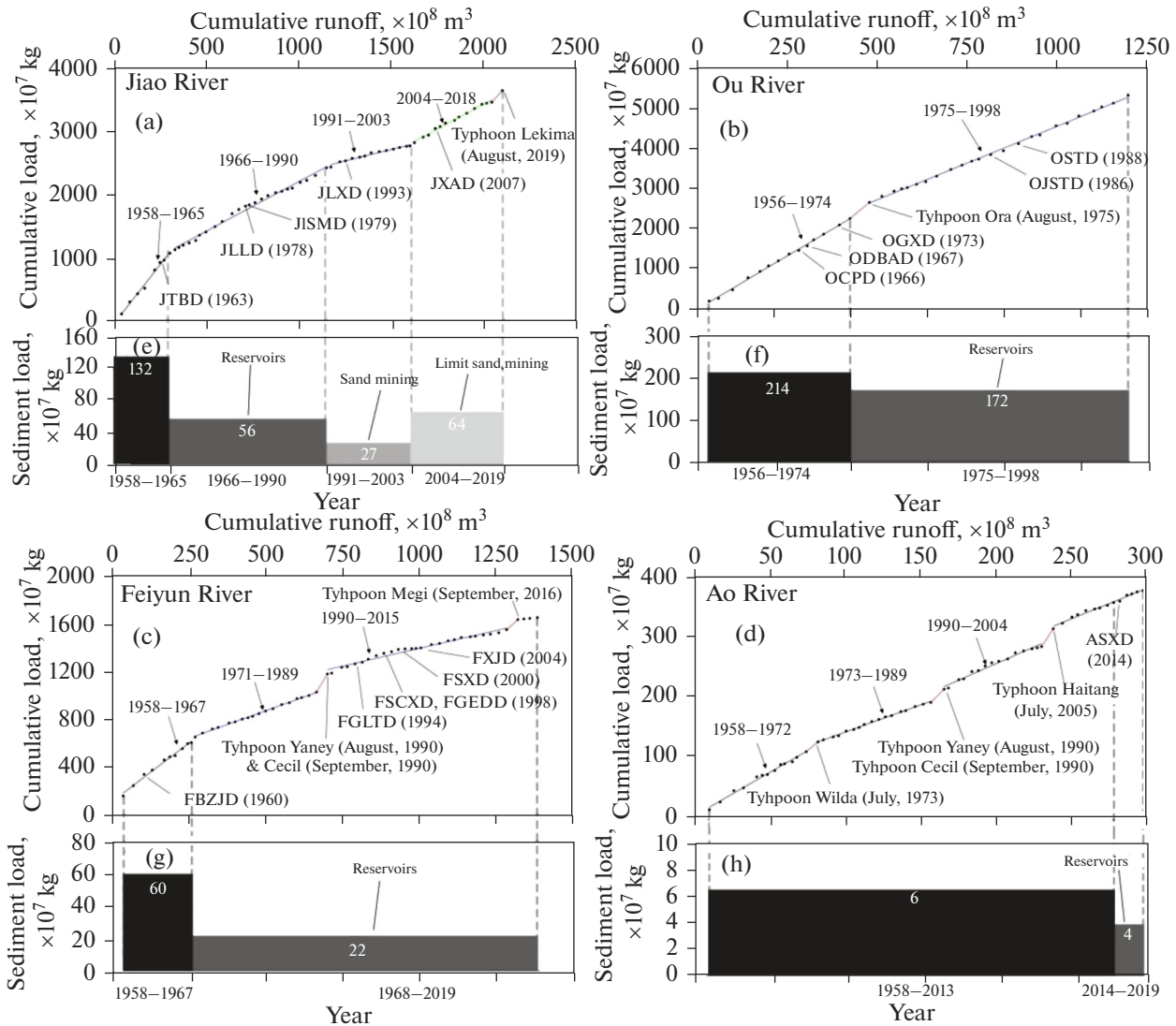


Fig. 3. Accumulative curves of annual water discharge and sediment load (a–d) and mean annual sediment loads for the Jiao, Ou, Feiyun, and Ao rivers during different periods (e–h). The red lines represent the one-year increase in the slope of the accumulative curves; the blue and green lines represent the gradual decrease and increase in the slope of the accumulative curves, respectively.

Seasonal Variations in Water and Sediment Discharge

(i) Comparison of Seasonal Distribution for Water and Sediment Discharge Among the four Rivers

Figure 4 shows the percentage of the multi-year average for monthly water discharge, sediment load, and precipitation. Overall, the monthly water and sediment discharge both exhibited a seasonal pattern of relatively high values in the plum rain season (April–June) and typhoon season (July–September), and relatively low values in the dry season (October–March). The water discharge in the flood season (including plum rain and typhoon seasons) accounted for ~75% of the total annual amount, while the sediment load was ~90%.

Furthermore, the water and sediment discharge peak months differed among the different rivers. The highest monthly water discharge of most rivers occurred in June (in plum rain season) while that of the Ao River occurred in August (in typhoon season). This is consistent with precipitation, which indicates that precipitation is the dominant factor for water discharge. However, the distribution of the sediment load differed. The highest monthly sediment load in most rivers occurred in August (in typhoon season), whereas that of the Ou River occurred in June (in plum rain season). The difference may be related to the quantity of heavy rains, the intensity of which can cause serious sediment erosion. In addition, the regular operations of hydraulic flushes during heavy rain

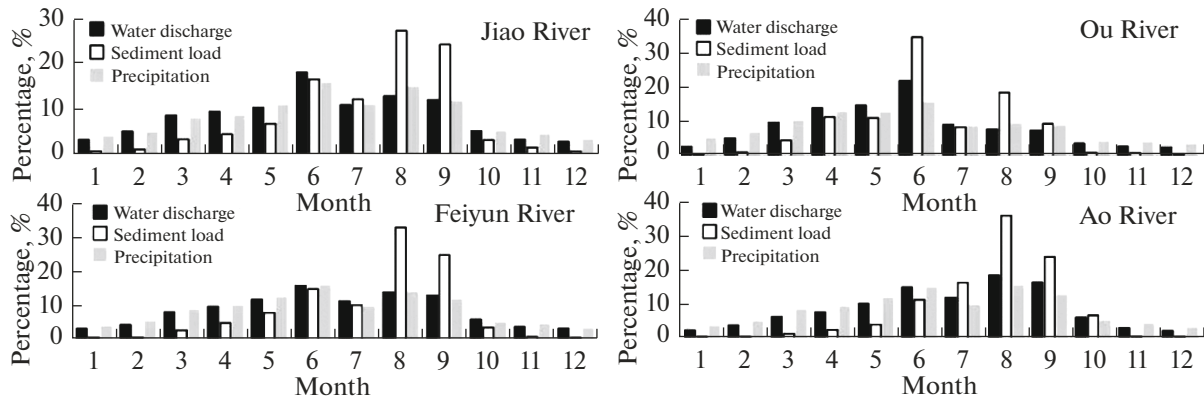


Fig. 4. Inter-annual distribution ratio of average monthly water discharge, sediment load, and precipitation (the statistical period is consistent with Fig. 2).

can flush the sediment impounded in the reservoirs and increase the sediment load during flood seasons with heavy rainfall. The heavy rains in the Ou River primarily occur during the plum rain season, while that in the Jiao, Feiyun, and Ao rivers mainly occur during the typhoon season [10].

(ii) Anthropogenic Impacts on the Changes of Seasonal Distribution in Water and Sediment Discharge

Reservoir construction can affect the intra-annual distribution of water and sediment discharge [13]. The coefficient of variation (C_V) is widely applied to describe the unevenness of water and sediment discharge [11]. It is calculated using the following equations:

$$C_V = \delta/\bar{R} = \sqrt{\frac{1}{12} \sum_{i=1}^{12} (R(i) - \bar{R})^2} / \frac{1}{12} \sum_{i=1}^{12} R(i)}. \quad (1)$$

In Eq. (1), $R(i)$ represents the mean of the i th month. C_V ranges in $[0, +\infty)$. A value of 0 indicates an even distribution, while larger values indicates more uneven distribution [11]. In this study, the monthly water and sediment discharge in each year was used to calculate the C_V series. To quantify the variations in intra-annual unevenness for water and sediment discharge, the M-K test was applied to estimate the trends of the C_V series (Table 2).

For the water discharge, the C_V value showed a significant decrease in the Jiao, Ou, and Feiyun rivers, indicating that the intra-annual distributions of the three rivers tended to be more uniform. This is likely related to the operation of reservoirs, which store water during the flood season and discharge water during dry season, leading to water discharge decreases during the flood season and increases during the dry season. However, the C_V value of water discharge in the Ao River showed a statistically insignificant increasing trend, indicating that its intra-

annual distribution of water discharge became more uneven and the change was indistinctive. This is likely due to fewer reservoirs having been built in the Ao River with the only medium-sized reservoir constructed in 2014, resulting in a slight impact on water discharge in the Ao River.

For the sediment load, the C_V value showed downward trends for the Jiao and Feiyun River, while opposite trends were observed for the Ou and Ao rivers. The most significant trend was observed in the Feiyun River, which may be related to its high reservoir construction intensity (ratio of the total storage capacity and annual average water discharge reached 84%). On the contrary, the C_V of sediment load in the other rivers showed insignificant changes, particularly in the Ou and Ao rivers, indicating that the impact of the reservoir on the intra-annual distribution in sediment load was relatively low, unlike the inter-annual distribution.

Variations in the Peaks of Water and Sediment Discharge

(i) Peaks of Water and Sediment Discharge during Flood Season

The four rivers were typical mountainous rivers, whose water and sediment discharge can increase by 2–3 orders of magnitude in 1–2 days following heavy rain, and subsequently return to normal levels rapidly. In the four rivers, the annual maximum daily sediment discharge had disproportionately large contributions of 25–35% to the annual values. Due to the different types of rainfall in plum rain and typhoon seasons, the peak flow and peak sediment transport process exhibited obvious differences between the two seasons. Here, we consider the daily data of Ao River from 4/01 to 9/30 in 2009 as an example. As shown in Fig. 5, the quantity of peaks for water and sediment discharge was relatively larger in the plum rain season, while the intensity was relatively stronger in the typhoon season. In addition, variations in sediment load were more

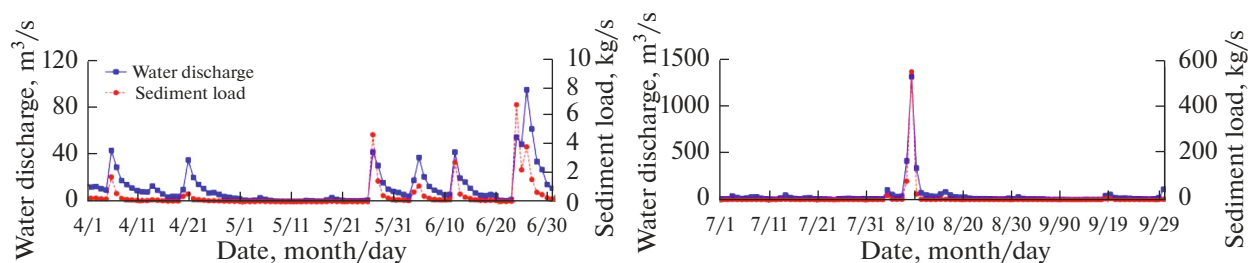


Fig. 5. Typical peak flow process and peak sediment transport process of Ao River during plum rain season and typhoon season in 2009.

severe. This is likely due to increases in erosion with increased water discharge, leading to significant increase in sediment load.

According to statistical, the maximum annual flood peak discharge of the Jiao, Feiyun, and Ao rivers occurred more frequently in typhoon season than plum rain season (Table 3). In contrast, the maximum monthly distribution of water discharge occurred more regularly in the plum rain season (Fig. 4). Hence, the long duration of rainfall and more flood peaks in the plum rain season may lead to a greater total water discharge, although the flood peaks are smaller than those in typhoon season. In addition, since large water discharge tends to generate high sediment, the seasonal distribution of maximum daily sediment load is similar to that of maximum flood peak discharge, which occurs more frequently during the typhoon season.

(ii) Anthropogenic Impacts on Water and Sediment Discharge Peaks

The average annual maximum flood peak discharge and maximum daily sediment load during the baseline period and reservoir impact period, as well as their change rates for all four rivers are listed in Table 4. The average annual maximum flood peak discharge decreased by 13–50% in the four rivers, indicating that the water discharge peaks were weakened following reservoir construction. These results were contrary to the increasing trend in annual water discharge (Fig. 2; Table 2), which likely resulted from the reservoirs diversifying the water from the flood season to dry season. This could further account for the remarkably uniform intra-annual distribution in water discharge (Table 2). Decreases were also observed in the annual maximum daily sediment load with change rates of 18–74%, which may result from the sediment impoundment of reservoirs.

Table 4. Mean for annual maximum flood peak discharge and maximum daily sediment load in baseline and reservoir impact periods and their change rates (based on the division in Fig. 3)

| Catchment | Station | Period | Annual maximum flood peak discharge | | Annual maximum daily sediment load | |
|--------------|---------------|------------------|-------------------------------------|----------------|------------------------------------|----------------|
| | | | mean, m ³ /s | change rate, % | mean, ×10 ⁷ kg/day | change rate, % |
| Jiao River | Baizhiao | Baseline | 4943 | −46 | 28.24 | −59 |
| | | Reservoir impact | 2649 | | 11.69 | |
| | Baibu/Shaduan | Baseline | 2597 | −50 | 26.19 | −74 |
| | | Reservoir impact | 1309 | | 6.85 | |
| Ou River | Weiren | Baseline | 10875 | −27 | 54.53 | −18 |
| | | Reservoir impact | 7929 | | 44.60 | |
| Feiyun River | Xuekou | Baseline | 4972 | −47 | 16.21 | −47 |
| | | Reservoir impact | 2658 | | 8.64 | |
| Ao River | Daitou | Baseline | 1428 | −13 | 2.73 | −46 |
| | | Reservoir impact | 1241 | | 1.47 | |

Table 5. Dominant periodicities of the annual water discharge, sediment load, and annual and flood season precipitation (the statistical period is consistent with Fig. 2)

| Catchment | Dominant periodicities | | | |
|--------------|------------------------|----------------------|----------------------|--------------------------------|
| | annual water discharge | annual precipitation | annual sediment load | precipitation in flood season* |
| Jiao River | 20 | 20 | 23 | 22 |
| Ou River | 23 | 23 | 19 | 23 |
| Feiyun River | 12 | 21 | 14 | 22 |
| Ao River | 24 | 22 | 24 | 22 |

* The flood season represents the plum rain season in the Ou River and represents the typhoon season in the remaining rivers.

Periodic Variations in Water and Sediment Discharge

(i) Periodicity in Annual Water and Sediment Discharge

The periodicity in annual water and sediment discharge, as well as annual and flood season (the flood season represents the plum rain season in the Ou River and the typhoon season in the other rivers) precipitation time series for the four rivers were examined using wavelet analysis (Supplementary material: Figs. 1S, 2S, Table 5). The dominant periodicity of annual water and sediment discharge was ~22 years in the Jiao, Ou, and Ao rivers, whereas the dominant periodicities of annual water and sediment discharge in the Feiyun River were ~13 years (Table 5).

In addition, the ~22-year periodicities of annual water discharge in the four rivers had weakened since the 1980s, which was similar to the characteristics of annual precipitation (Fig. 1S). However, the ~22-year periodicities of sediment load in the Jiao and Ou Rivers had weakened since the 1980s, while those of the Feiyun and Ao rivers remained relatively constant over the observation periods, which differs from the periodic changes in annual water discharge and precipitation (Fig. 1S).

(ii) Climatic and Anthropogenic Impacts on Periodic Change in Annual Water and Sediment Discharge

Climatic and anthropogenic impacts can control the periodicities of water and sediment discharge [23, 28]. In this study, the dominant periodicities of annual water discharge were similar to those of annual precipitation in the Jiao, Ou, and Ao rivers, indicating that annual precipitation is the primary factor affecting the dominant periodicity of their annual water discharge. High sediment yield during heavy rains is an important characteristic of mountainous rivers [7]. Thus, the flood season in this section represents the flood season with more heavy rains. The dominant periodicities of annual sediment load are consistent with those of flood season precipitation in most rivers, except Feiyun River. However, the dominant periodicities would change under the high reservoir construction intensity (the ratio of the total storage capacity to mean annual water discharge reached 84% in the Feiyun River) as the regulation of reservoirs leading to the weakening of

~22-year periodicity and the strengthening of ~13-year periodicity for water and sediment discharge in the Feiyun River (Figs. 1S; 2S).

The weakening of the ~22-year periodicity of annual precipitation and water discharge indicates that the weakening of periodic oscillation in annual water discharge is related to that of annual precipitation. Furthermore, the Asian summer monsoon is the dominant factor for precipitation in East China. The land-sea thermal contrast within Asia (including East China) and its neighboring oceanic region have consistently decreased in the summer, which likely results in weakening of the Asian summer monsoon and the periodicity of precipitation [6]. Different from water discharge, the weakening of the ~22-year periodicity for sediment load is consistent with that of flood season precipitation instead of annual precipitation (Fig. 1S).

CONCLUSIONS

Based on five hydrological stations and nine meteorological stations, we analyzed the annual, seasonal, flood peaks, and periodic changes in water and sediment discharge as well as their causes in four small and medium-sized mountainous rivers in southern Zhejiang Province, China. The primary findings can be summarized as follows:

(1) Insignificant increasing trends were observed in water discharge for the Jiao, Ou, and Feiyun rivers due to the influence of climate change (i.e., precipitation), while the reduction in the Ao River was caused by anthropogenic influences (i.e., water diversion). Meanwhile, decreasing trends were observed in sediment load for the four rivers, which can be attributed to anthropogenic impacts (i.e., reservoir construction and sand mining). The greatest decrease (~64%) occurred in the Feiyun River (1968–2019). Due to the relatively small reservoir size, the sediment load in the four rivers decreased by cumulative effect rather than an abrupt change caused by a single reservoir, as is observed for large rivers in China.

(2) The four rivers show typical mountainous characteristics so that their water and sediment discharge are sensitive to rainfall events. Among the four rivers,

the annual maximum daily sediment load accounted for 25–35% to the annual value. Thus, a large flood (typically caused by a typhoon) can markedly increase the annual sediment load. The maximum flood peak discharge, and maximum daily sediment load, as well as maximum monthly sediment load primarily occur in the typhoon season due to the high frequency of heavy rainfall events. However, the maximum monthly water discharge occurs in the plum rain season for most river, due to the long duration of the rainfall events and higher number of peaks, although the peaks are smaller. Owing to reservoir construction, the maximum peaks of water and sediment discharge decreased (~13–50 and 18–74%, respectively), and the intra-annual distribution of water discharge tended to be more uniform.

(3) The dominant periodicities of the annual water and sediment discharge in the Jiao, Ou, and Ao rivers are ~22 years under the impacts of precipitation, while that in the Feiyun River is ~13 years due to human activities (the ratio of the total storage capacity and annual average water discharge reaches 84%). In addition, the ~22-year dominant periodicities of annual water discharge in the four rivers have weakened since the 1980s owing to the periodic change in annual precipitation. However, a similar weakening of annual sediment load only occurs in the Jiao River and Ou River as the periodic changes in annual sediment load is determined by the flood season with more heavy rain.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

SUPPLEMENTARY INFORMATION

Fig. 1S. Morlet time frequency distribution of annual water discharge (a), annual sediment load (b), annual precipitation (c), precipitation during plum rain (d) and typhoon season (e) in the four rivers.

Fig. 2S. Wavelet variance of annual water discharge, sediment load and precipitation (the statistical period is consistent with Fig. 2).

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