*Pol. J. Environ. Stud. Vol. 32, No. 3 (2023), 2909-2923*
DOI: *10.15244/pjoes/157223* ONLINE PUBLICATION DATE: 2023-04-18

*Original Research*

# Analysis of Water and Sediment Characteristics of the Yellow River and Their Correlations

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*Received: 16 February 2022*
*Accepted: 6 December 2022*

## Abstract

The water and sediment characteristics of the Yellow River are related to the development of the river basin and have great significance in determining the future trends in sediment load. In this study, the water and sediment characteristics and influencing factors were analyzed. The correlations among hydrological and sediment parameters were further analyzed. The results showed that the annual average sediment concentration (AASC), the annual sediment load (ASL), the median grain size of sediment (MGSS) and the annual sediment transport modulus (ASTM) decreased. Therefore, the sediment control effect of the tributaries was significant. The annual runoff (AR) of the hydrological stations in the Yellow River increased from 2002 to 2019. Altogether, AASC and ASL of the Yellow River showed a downward trend. The sediment was reduced by water storage and sediment detention of reservoirs. AASC and ASL increased significantly due to water and sediment regulation tests and floods. However, the silt in the river channel could be washed with the help of current scouring and flood to slow down the silt. There was a strong correlation between AASC and ASL, whether the Yellow River or its tributaries. Besides, there was a significant impact of AASC and ASL of the tributaries on the sediment of the Yellow River, showing that the sediment control of the tributaries was essential. The sediment in the main tributaries and the Yellow River showed a decreasing trend from 2002 to 2019, which is conducive to the ecological harmony and stability of the Yellow River.

**Keywords**: the Yellow River, tributary, sediment, correlation, water and sediment characteristics

## Introduction

The Yellow River is the cradle of Chinese civilization. A significant quantity of sediment was carried because it flowed through the Loess Plateau with severe soil erosion. For example, ASL at the Sanmenxia hydrological station was approximately $1.52 \times 10^9$ t/year between 1919 and 1953 [1].

Many scholars have performed numerous studies on the sediment of the Yellow River. The suspended sediment concentration exceeds 500 $kg \cdot m^{-3}$ during floods, reaching 1 000 $kg \cdot m^{-3}$ in some tributaries [2]. About 70% of the sediment from the Yellow River has been deposited in the Bohai Sea, 14.1% in the

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north Yellow Sea, and 13.9% in the south Yellow Sea [3]. Approximately 90% of sediment of the Yellow River comes from the easily eroded Loess Plateau [4-6]. Moreover, about 80% of sediment load is deposited rapidly in the estuary delta [7-8]. Many sediments are deposited in the riverbed, affecting the stability of the water level of the Yellow River [9].

Erosion and deposition in the riverbed are automatically adjusted in the Tongguan reach, and the lower Yellow River, and water and sediment transport can form highly constrained equilibrium relationships [10]. The reduction of runoff in the reaches between the Toudaoguai and Sanmenxia hydrological stations accounted for 39.3% of the decrease in the sediment load of the Yellow River, and the other 60.7% of the decline has resulted from economic and social development [11]. Except for the upper reaches of the Tangnaihai hydrological station, AR and ASL exhibit significant declines. The variation in AR and ASL in the river source area can largely be attributed to the decreasing precipitation and increasing temperature [12].

The monitoring data of four main hydrological stations of the Yellow River from 1950 to 2005 showed a significant decrease trend of the sediment of the Yellow River due to the influence of artificial and natural in the past 56 years [13]. Since the 1970s, ASL of the Yellow River has decreased significantly. At present, the sediment load of the Loess Plateau is less than a quarter of that in 1980, and ASL of the Lijin hydrological station is only 10.7% of that in the 1950s, which has decreased by 90% [14]. The ASL had decreased by nearly 90% and 80% in the past 10 (2009-2018) and 20 years (1999-2018), respectively, compared with the annual average of 1919-1998 [15-19]. However, there was no significant change in the runoff or sediment loads in the headwater catchments of the Yellow River Basin from 1956 to 2001 [20].

The sediment grain size in the lower Yellow River decreased along the river course [21]. The sediment load of most rivers in the world has shown a significant change in the last decades due to human activities (sediment storage dams, land use, terraces, reservoirs and Green for Grain Project, urbanization, agricultural practices, and mining) [22]. From 2000 to 2015, the Xiaolangdi Reservoir was mainly to store water and block sand, intercept most medium and coarse sand in the reservoir, and control 90% of the net flow and sediment into the lower Yellow River [23-24].

The vegetation plays an active role in preventing and controlling water and gravity erosion. This is mainly because vegetation can reduce the erosional force and improve the erosion durability of soil. The roots of vegetation fix the soil, enhancing the permeability and stability of the soil [25-26]. Revegetation has been the most effective measure to decrease the sediment in the Yellow River Basin [27]. However, the Yellow River sediment is sandy in texture with a limited capacity to retain water and nutrients [28]. Sediments discharged from the Yellow River experience a high consolidation rate after deposition. Excess pore water pressure dissipates entirely after 45-51 h [29]. The Yellow River sediment can be used as a soil conditioner to repair the saline soil [30-31].

To summarize, the sediment source, water and sediment characteristics, influence factors of sediment (i.e., reservoir, vegetation, flood, etc.), and sediment utilization of the Yellow River have been studied. Nevertheless, studies should be advanced because there was little research on water and sediment characteristics of the Yellow River and its tributaries, influence factors of sediment and parametric correlations. The water and sediment characteristics of the Yellow River and its tributaries, influence factors of sediment, and parametric correlations are studied based on the hydrological and sediment monitoring data in the Yellow River and its tributaries.

## Overview of the Study Area and Data Sources

### Overview of the Study Area

The Yellow River is the second-longest river in China, with a length of 5464 km, and its drainage area is $75.2 \times 10^4$ km$^2$. The Yellow River and its tributaries were taken as the study area, including 17 hydrological stations (Fig. 1) [32-34]. The basic properties of the tributaries are listed in Table 1.

### Hydropower Stations in the Study Area

The Wanjiazhai Reservoir, Longkou Reservoir, Sanmenxia Reservoir, and Xiaolangdi Reservoir were built on the Yellow River [35-38], with general situations listed in Table 2.

### Data Sources

Data including AR, AASC, ASL, MGSS, and ASTM obtained from "Sediment Bulletin of the Yellow River" compiled by Yangtze River Water Resources Commission of the Ministry of Water Resources from 2002 to 2019 were reliable [39]. The water and sediment characteristics and the parametric correlations were studied systematically.

### Data Processing

The significance values (sig) of parameters were obtained by *SPSS* (Tables 3 and 4). Tables 3 and 4 show that the significance values of 16.18% parameters were less than 0.05, which cannot meet the normal distribution. Pearson correlation, a commonly preferred statistical method for correlation analysis, requires the data/parameters to satisfy the normal distribution. Therefore, Spearman rank correlation was used for the analysis. Spearman rank correlation coefficients ($\rho$, hereafter this text will be abbreviated as a correlation

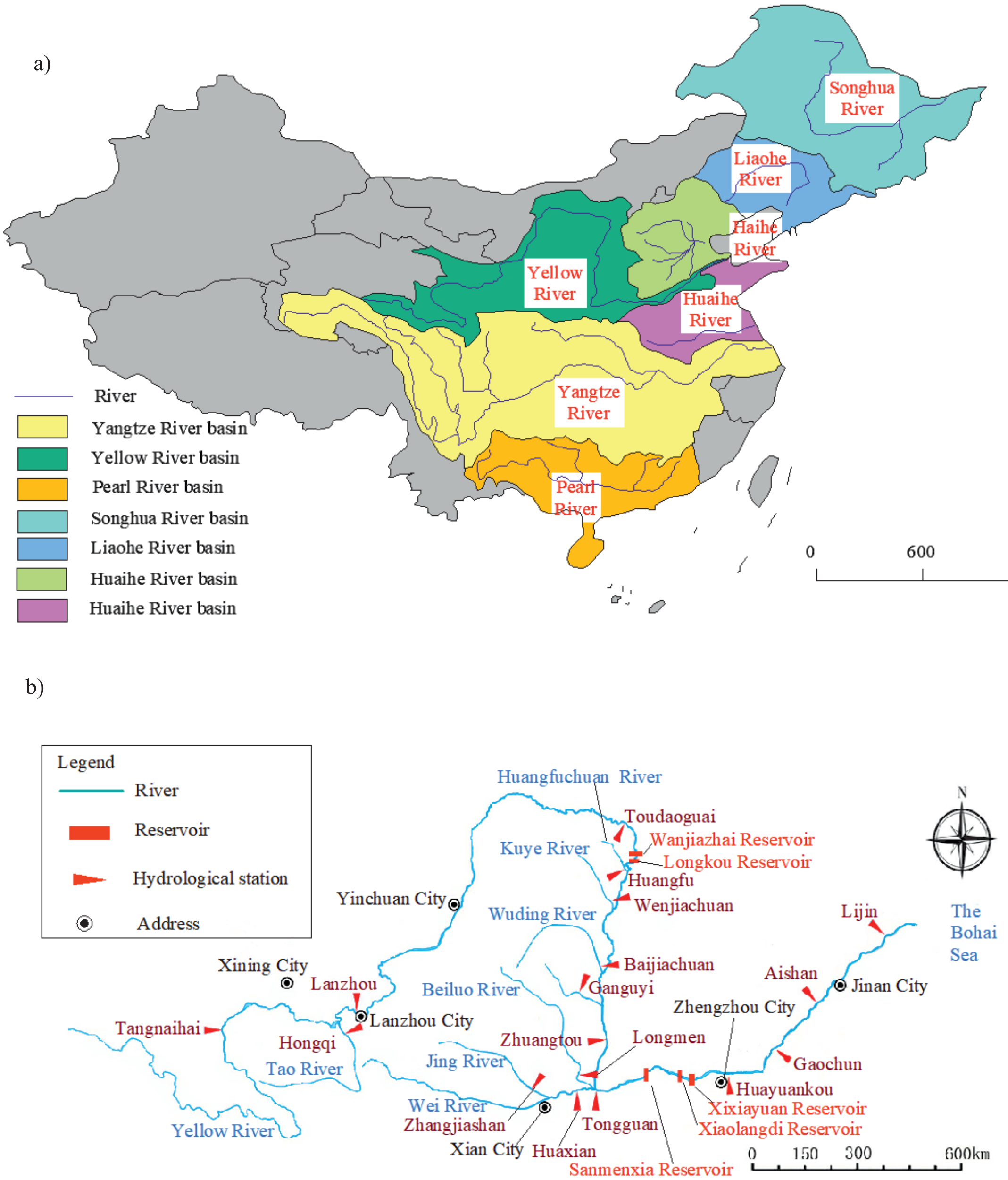


Fig.1. Distribution map of study area. a) Watershed distribution map of China, b) Distribution of the Yellow River and its main tributaries.

coefficient) were calculated to judge the correlation between parameters. $|\rho|\in(0.6: 1]$, $|\rho|\in(0.3: 0.6]$, and $|\rho|\in(0: 0.3]$ stand for strong correlation, correlation, and no correlation, respectively.

## Analysis of Water and Sediment Characteristics

Staple power for sediment transport is provided by flowing water. Therefore, The characteristics of AR should be studied first. In this section, the analysis order of parameters is AR, AASC, MGSS, and ASTM. In addition, the variation law of water and sediment of each tributary was analyzed first to study the impact of sediment of the tributaries on the Yellow River.

### Analysis of Water and Sediment Characteristics of the Tributaries of the Yellow River

The timing variability properties of AR of the tributaries of the Yellow River are shown in Fig. 2. It can be seen from Fig. 2 that the AR of Wei River and Tao River was significantly greater than those of other rivers, and their maxima occurred in 2018 and 2003 (i.e., $40.34 \times 10^8$ and $52.83 \times 10^8$ m$^3$). The maxima of other rivers were $0.33 \times 10^8$-$11.14 \times 10^8$ m$^3$. From 2002 to 2019, the AR of Tao River, Kuye River, Jing River, and Wei River increased by 126.48%, 99.77%, 55.84% and 150.22%, respectively, but the AR of other rivers decreased by 11.41%-50.83%. Furthermore, the water interception of the Huangfuchuan River occurred in 2011. The AR

Table 1. General situation of the tributaries and hydrologic stations of the Yellow River.

| Rivers | River sources | River mouths | Drainage area ($10^4$ km$^2$) | Length (km) | Drop (m) | The hydrological stations | Location of the hydrological stations |
|---|---|---|---|---|---|---|---|
| Tao River | Henan Mongolian Autonomous County, Huangnan Tibetan Autonomous Prefecture, Qinghai Province | Youngjing County, Gansu Province | 25527 | 673 | 2631 | Hongqi | Lintao County, Dingxi City, Gansu Province |
| Huangfuchuan River | Zhunge'er Banner, Inner Mongolia | Fugu County, Shaanxi Province | 3246 | 1251 | 520 | Huangfu | Fugu County, Shaanxi Province |
| Kuye River | Dongsheng District, Inner Mongolia Autonomous region | Shenmu county, Shaanxi Province | 8706 | 242 | 832.48 | Wenjiachuan | Shenmu county, Shaanxi Province |
| Wuding River | Dingbian county, Shaanxi province | Qingjian County, Yulin City, Shaanxi Province | 30260 | 491 | 883.8 | Baijiachuan | Qingjian County, Yulin City, Shaanxi Province |
| Yan River | Jingbian County, Shaanxi Province | Yanchang County, Shaanxi Province | 7725 | 286.9 | 935.29 | Ganguyi | Yanchang County, Shaanxi Province |
| Jing River | Jingyuan County, Guyuan City, Ningxia Hui Autonomous Region | Chenjiatan, Xi'an City, Shaanxi Province | 45421 | 455.1 | 2180 | Zhangjiashan | Wangqiao Town, Jingyang County, Shaanxi Province |
| Beiluo River | Baiyushan, Dingbian County, Shaanxi Province | Pucheng County, Shaanxi Province | 26905 | 680.3 | 1346.99 | Zhuangtou | Yongfeng Town, Pucheng County, Shaanxi Province |
| Wei River | Weiyuan County, Dingxi City, Gansu Province | Tongguan County, Weinan City, Shaanxi Province | 134766 | 818 | 1130 | Huaxian | Huaxian County, Shaanxi Province |

Table 2. Hydropower stations in the Yellow River.

| Reservoirs | Water storage time | Total reservoir capacity ($10^8$ m$^3$) | The maximum dam height (m) |
|---|---|---|---|
| Wanjiazhai | 1998 | 8.96 | 105 |
| Longkou | 2009 | 1.957 | 51 |
| Sanmenxia | 1960 | 162 | 106 |
| Xiaolangdi | 1999 | 162.5 | 154 |
| Xixiayuan | 2007 | 1.62 | 20.2 |

of Yan River tended to be stable except for the maxima in 2002 and 2013.

The change curves of water and sediment parameters of the tributaries of the Yellow River from 2002 to 2019 are shown in Figs 3-6. It can be seen from Fig. 3 that the AASC of each tributary generally indicated a decreasing trend. From 2002 to 2019, the AASC (from Tao River to Wei River) decreased by 81.31%, 82.92%, 96.06%, 70.82%, 95.53%, 87.39%, 94.1%, and 90.47% respectively. The AASC of Huangfuchuan changes with time in hyperfunction, whose expression is $\mathrm{AASC} = 0.49 \times \frac{t}{t - 1999.6}$, and the correlation coefficient is 0.63. The AASC of Taohe has a sine function relationship with time; the expression is $\mathrm{AASC} = 4.22 + 3.47 \times \sin(\frac{t}{7.57} + 436.1)$, and the correlation coefficient is 0.52.

Fig. 4 indicates that the ASL of each river decreased from 2002 to 2019. Taking Tao River as an example to illustrate the change law from 2002 to 2019, the ASL decreased from 0.086 × $10^8$ to 0.037 × $10^8$ m$^3$, decreasing by 56.98%. The ASL of other rivers (from Huangfuchuan River to Wei River) decreased by 90.43%, 92.11%, 74.14%, 97.75%, 80.35%, 95.7%, and 76.16%, respectively. The ASL of Wei River has a sine function relationship with time, whose expression is $\mathrm{ASL} = 21442 + 21441.55 \times \sin(\frac{t}{896.68} + 700.08)$, and the correlation coefficient is 0.63. The ASL of Jing River and Kuye River has a Gauss function relationship with time; the expressions are $\mathrm{ASL} = 77.32 - 76.83 \times e^{-2\left(\frac{t-2014.39}{133.29}\right)^2}$ and $\mathrm{ASL} = 0.01 + 0.12 \times e^{-2(\frac{t-2002.98}{1.87})^2}$, and the correlation coefficients are 0.54 and 0.89.

MGSS can be affected by AASC, ASL, and the type and particle gradation of rocks and soils in the basin. It can be seen from Fig. 5 that from 2002 to 2019, the MGSS of each tributary (from Huangfuchuan River to Wei River) decreased by 79.55%, 12.5%, 22.58%, 48.28%, 0%, 75%, and 27.27%, respectively. The maximum decrease was for Huangfuchuan River, which decreased from 0.088 to 0.018 mm. The maxima of the Kuye River and Beiluo River occurred in 2004 and 2011 (i.e., 0.059 and 0.028 mm), respectively. The relationship between MGSS of Huangfuchuan River and time is the Boltzmann function, whose expression is $\mathrm{MGSS} = \frac{70.91}{1+e^{(t-1996.05)/dt}} + 0.02$, and the correlation coefficient is 0.71. MGSS of Beiluo River has a sine function relationship with time, whose expression is $\mathrm{MGSS} = 0.9 + 0.9 \times \sin(\frac{t}{111.36} + 753.09)$, and the correlation coefficient is 0.4.

Fig. 6 indicates that the ASTM of each river decreased from 2004 to 2019. Taking the Tao River

Table 3. Significant critical values of parameters of the Yellow River.

| Parameters | The Yellow River | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Tangnaihai | Lanzhou | Toudaoguai | Longmen | Tongguan | Huayuankou | Gaocun | Aishan | Lijin |
| AR | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| AASC | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| ASL | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| MGSS | 0.08 | 0.14 | 0.01 | 0.15 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |

Table 4. Significant critical values of parameters of the tributaries of the Yellow River.

| Rivers | Tao River | Huangfuchuan River | Kuye River | Wuding River | Yan River | Jing River | Beiluo River | Wei River |
|---|---|---|---|---|---|---|---|---|
| AR | 0.01 | 0.01 | 0.09 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| AASC | 0.2 | 0.14 | 0 | 0.01 | 0 | 0.2 | 0.2 | 0.2 |
| ASL | 0.18 | 0 | 0.01 | 0.01 | 0 | 0.13 | 0.11 | 0.08 |
| MGSS | 0.01 | 0 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |

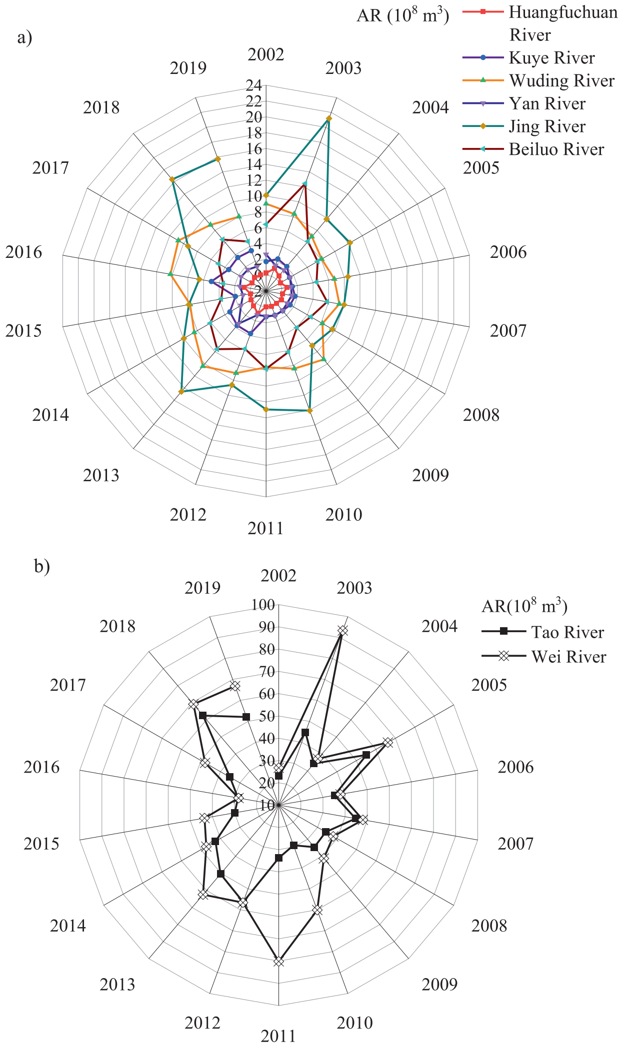


Fig. 2. AR of the tributaries of the Yellow River ($10^8$ $m^3$). a) Huangfuchaun River, Kuye River, Wuding River Yan River Jing River and Beiluo River, b) Tao River and Wei River.

as an example to illustrate the tendency of ASTM; from 2004 to 2019, the ASTM showed a fluctuating downtrend, which decreased from 268 to 146 t/year·km$^2$, with a decrease of 45.52%. ASTM of other rivers (from Huangfuchuan River to Wei River) decreased by 84.65%, 16.55%, 51.13%, 93.97%, 66.27%, 93.10%, and 47.45%, respectively.

## Analysis of Water and Sediment Characteristics of the Yellow River

The change curves of hydrological and sediment parameters of the hydrological stations in the Yellow River are shown in Figs 7-11. It can be seen from Fig. 7 that the various trends of each curve are similar. From 2002 to 2016, AR of hydrological stations (from Tangnaihai to Lijin) increased by 8193.29%, 102.42%, 187.46%, 142.66%, 137.89%, 133.95%, 158.59%, 242.45%, and 645.11%, respectively. AR of Gaocun, Aishan and Lijin hydrological stations reached the maxima in 2018 (i.e., 410.1 × $10^8$, 376.3 × $10^8$, and 333.8 × $10^8$ $m^3$). Besides, AR of other hydrological stations reached the maximum values in 2019 (i.e., 310.3 × $10^8$, 477.3 × $10^8$, 353 × $10^8$, 380 × $10^8$, 415.6 × $10^8$, and 457.6 × $10^8$ $m^3$).

It can be seen from Fig. 8 that from 2002 to 2019, the AASC of Toudaoguai, Huayuankou, and Gaocun hydrological stations increased by 86.3%, 20.91%, and 3.71%, respectively. However, the AASC of other hydrological stations decreased by 9.01-84.63%. In addition, the AASC of Tangnaihai, Aishan, and Lijin hydrological stations reached the maxima values in 2003 (i.e., 0.798, 15.1, and 19.2 kg/m$^3$). But AASC of Longmen and Tongguan hydrological stations reached the maxima in 2002 (i.e., 21.4 and 25.7 kg/m$^3$).

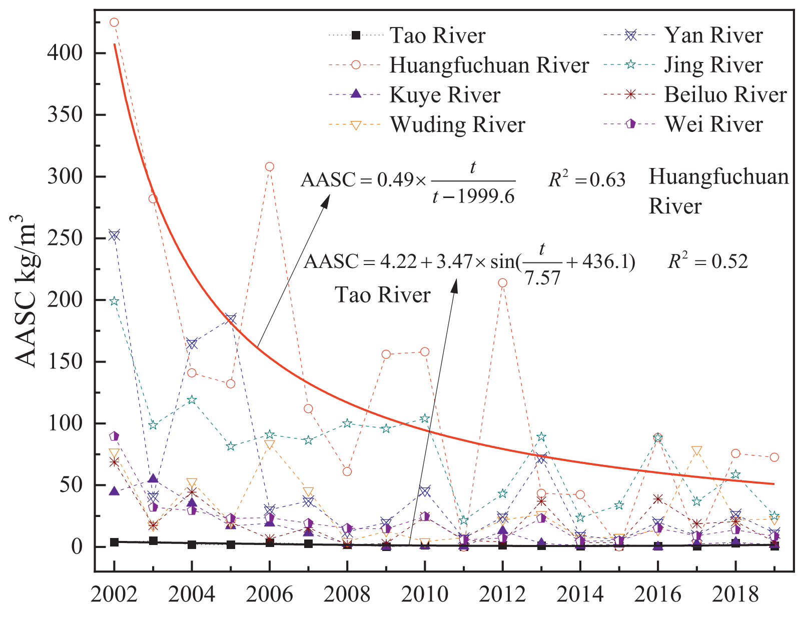


Fig. 3. AASC of the tributaries of the Yellow River.

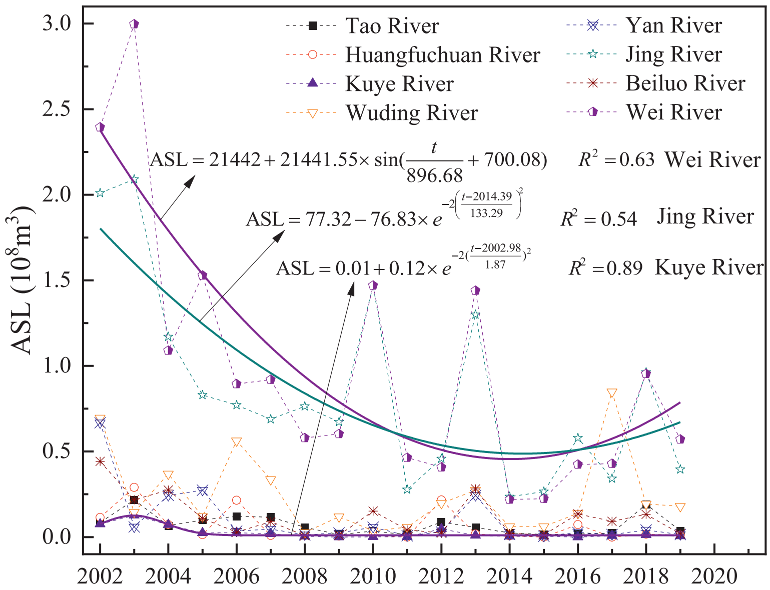


Fig. 4. ASL of the tributaries of the Yellow River.

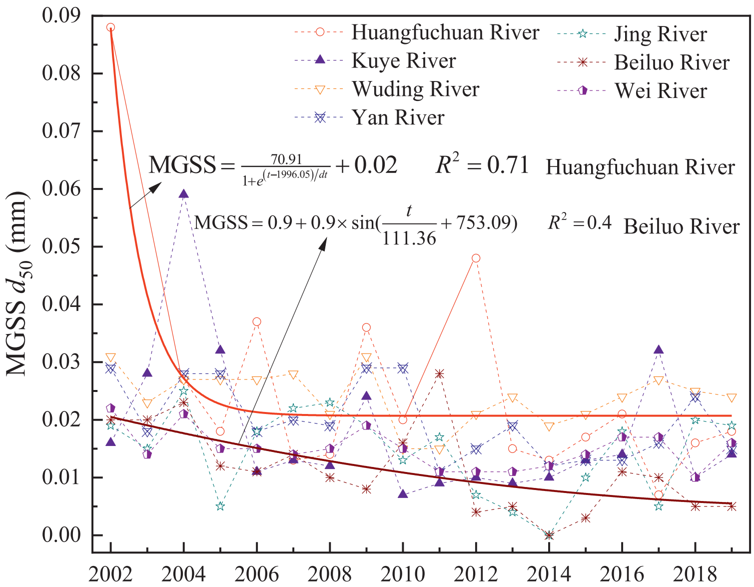


Fig. 5. MGSS of the tributaries of the Yellow River.

Among them, the AASC of Tonggun station is higher than other stations. AASC of Tonggun station has a lognormal function relationship with time, whose expression is $\mathrm{AASC} = 5.96 + \frac{48878.41}{t} e^{-\frac{\left(\ln\frac{t}{1999.25}\right)^2}{0.000008}}$, and the correlation coefficient is 0.9. AASC of Tangnaihai station has a sine function relationship with time, whose expression is $\mathrm{AASC} = 0.45 + 0.24 \times \sin(\frac{t}{1.13} - 130.97)$, and the correlation coefficient is 0.69.

It can be seen from Fig. 9 that ASL of Longmen and Tongguan hydrological stations generally showed a decreasing trend from 2002 to 2019, which decreased by 62.71% and 62.63%, respectively. However, ASL of other hydrological stations increased by 22.81%-437.31% from 2002 to 2019. In addition, the ASL of Tongguan station (0.55 × $10^8$-6.179 × $10^8$ $m^3$) is significantly higher than that of other hydrological stations, and the ASL of Tangnaihai station is the lowest (0.028 × $10^8$-0.211 × $10^8$ $m^3$). ASL of Tonggun station has a Boltzmann function relationship with time, whose expression is $\mathrm{ASL} = \frac{3.73}{1+e^{(t-2004.47)/dt}} + 1.72$, and the correlation coefficient is 0.61. ASL of Tangnaihai station

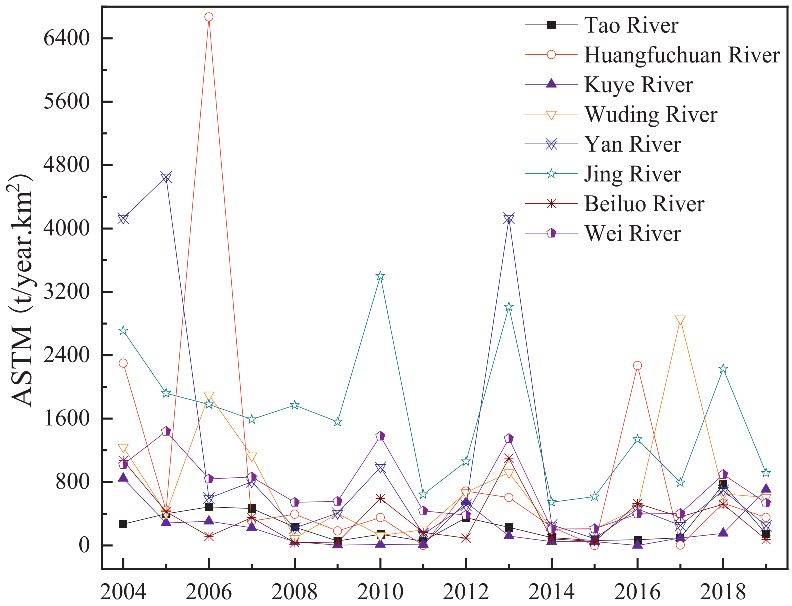


Fig. 6. ASTM of the tributaries of the Yellow River.

has a since function relationship with time, whose expression is $\mathrm{ASL} = 0.09 + 0.06 \times \sin(\frac{t}{1.23} - 239.43)$, and the correlation coefficient is 0.6.

Fig. 10 indicates that MGSS of Tangnaihai, Longmen, Tongguan, Gaocun, Aishan, and Lijin hydrological stations generally decreased by 50%, 38.24%, 20.83%, 15.38%, 18.52%, and 25% from 2002 to 2019, respectively. However, MGSS of Lanzhou, Toudaoguai, and Huayuankou hydrological stations generally showed an increasing trend, which increased by 9.09%, 237.5%, and 108.33%, respectively.

It can be seen from Fig. 11 that from 2003 to 2019, ASTM of Tangnaihai, Toudaoguai, Huayuankou, and Gaocun hydrological stations increased by 25.89%, 415.83%, 66.3%, and 20%, but ASTM of other hydrological stations decreased by 12.78%-72.85%. In addition, ASTM of Tongguan, Aishan, and Lijin hydrological stations reached the maximum values in 2003 (i.e., 906, 485 and 491 t/year·km$^2$). ASTM of Tangnaihai, Lanzhou, Longmen, and Huayuankou hydrological stations reached the maximum values in 2018 (i.e., 173, 431, 651, and 471 t/year·km$^2$). ASTM of Toudaoguai and Gaocun hydrological stations reached the maxima in 2019 (i.e., 391 and 450 t/year·km$^2$).

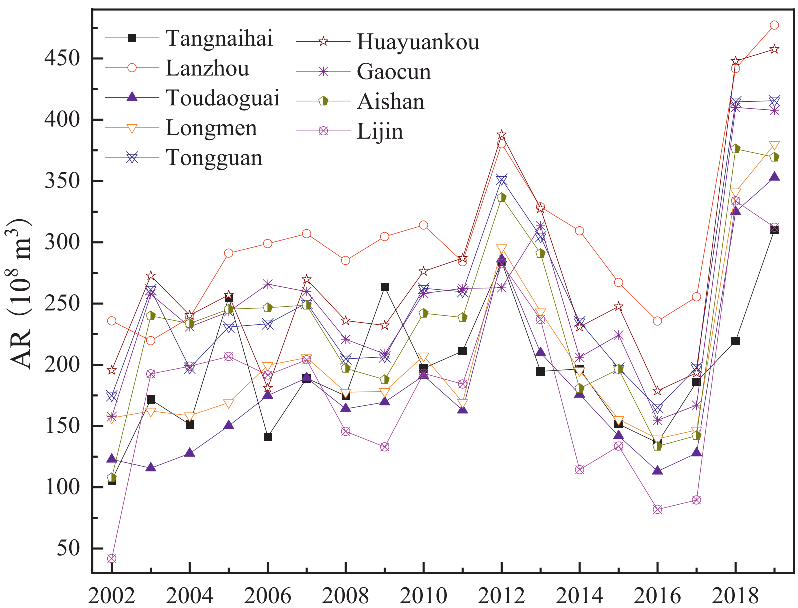


Fig. 7. AR of the Yellow River.

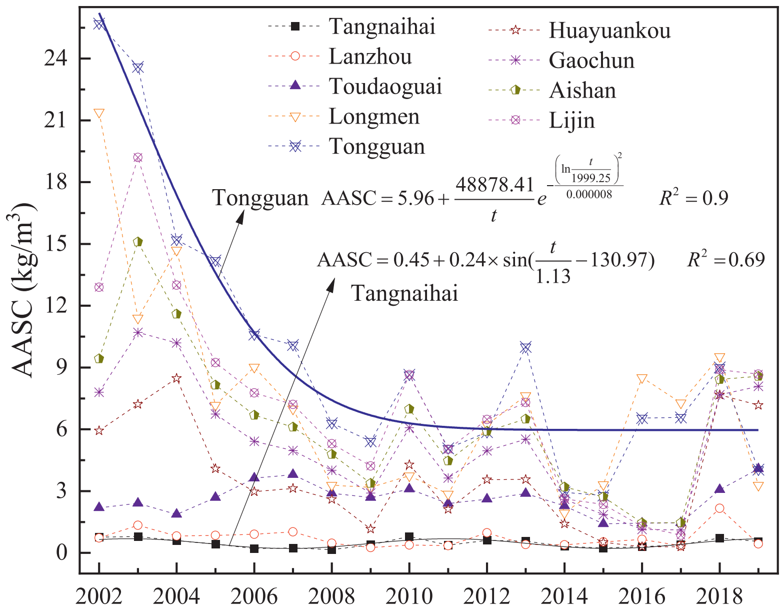


Fig. 8. AASC of the Yellow River.

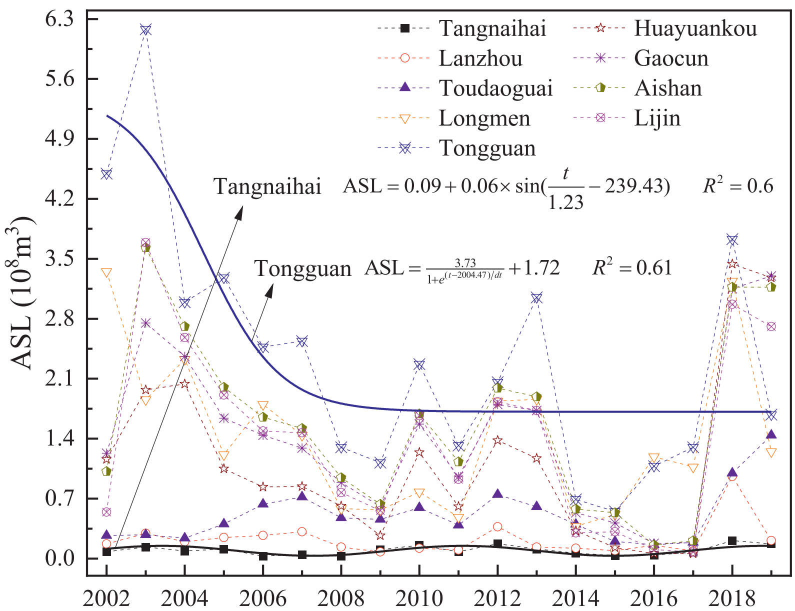


Fig. 9. ASL of the Yellow River.

## Correlation Analysis Among Parameters

### Correlation Analysis Among Parameters of the Tributaries of the Yellow River

Because ASL plays a decisive role in ASTM, the correlations among ASTM and other parameters were not analyzed separately. The correlation matrices of Tao River are shown in Fig. 12. The correlations among hydrological and sediment parameters of the tributaries are demonstrated in Fig. 13.

It can be seen from Figs 12 and 13 that (1) for AR and AASC: there is a strong correlation between the two parameters of Huangfuchuan River, and there is a correlation between the two parameters of Yan River and Beiluo River. There is no correlation between the two parameters of other rivers. (2) For AR and ASL: there is a strong correlation between the two parameters of Huangfuchuan River and Beiluo River, and there is a correlation between the two parameters of Tao River, Yan River, and Jing River, and there is no correlation between the two parameters of other rivers. (3) For AR and MGSS: there is a strong correlation between the two parameters of the Wei River. There is a correlation between the two parameters of the Huangfuchuan River and Beiluo River, and there is no correlation between the two parameters of other rivers. (4) For AASC and

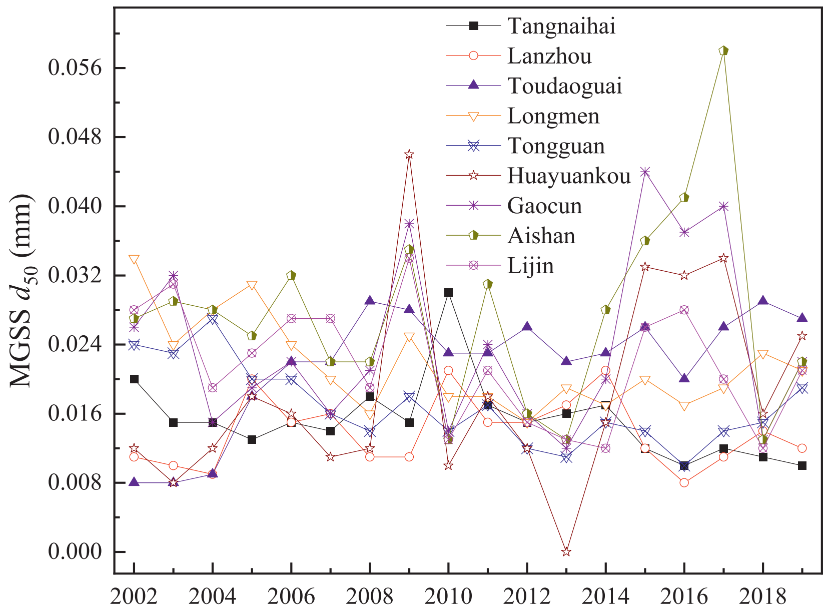


Fig. 10. MGSS of the Yellow River.

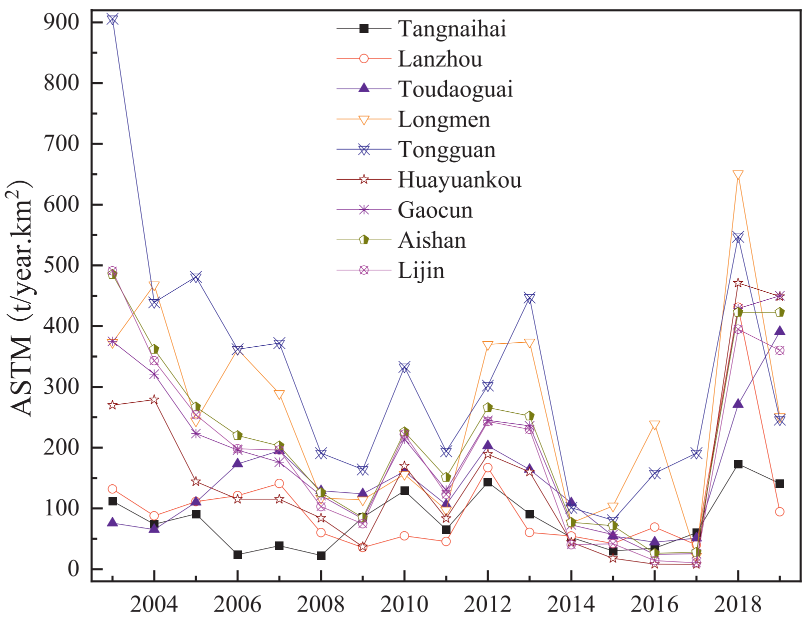


Fig. 11. ASTM of the Yellow River.

ASL: there is a strong correlation between the two parameters of all rivers. (5) For AASC and MGSS: there is a strong correlation between the two parameters of Huangfuchuan River, Wuding River, and Yan River, and there is no correlation between the two parameters of other rivers. (6) For ASL and MGSS: there is a strong correlation between the two parameters of the Wuding River and Yan River, and there is a correlation between the two parameters of the Huangfuchuan River, Kuye River, and Beiluo River, and there is no correlation between the two parameters of other rivers.

Collectively, there is a strong correlation between AASC and ASL in the tributaries of the Yellow River, and the correlations between AR and AASC, AR and MGSS are weak.

## Correlation Analysis Among Parameters of the Yellow River

The parametric correlations of the Yellow River (Figs 14 and 15) are studied based on the correlations among hydrological and sediment parameters of the tributaries of the Yellow River.

It can be seen from Figs 14 and 15 that (1) For AR and AASC: there is a strong correlation between two parameters of the Toudaoguai hydrological station, and

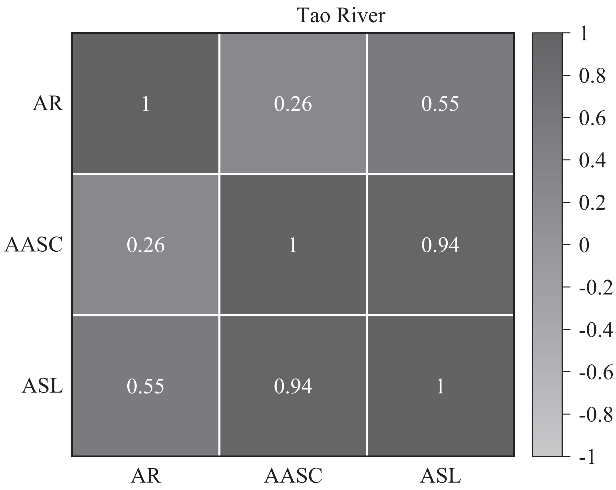


Fig. 12. Correlation matrices of Tao River (MGSS is not monitored).

there is a correlation between the two parameters of Huayuankou, Gaocun, Aishan, and Lijin hydrological stations, and there is no correlation between the two parameters of other hydrological stations. (2) For AR and ASL: there is a strong correlation between the two parameters of Tangnaihai, Toudaoguai, Huayuankou, Gaocun, Aishan, and Lijin hydrological stations, and there is a correlation between the two parameters of the Tongguan hydrological station, and there is no correlation between the two parameters of other hydrological stations. (3) For AR and MGSS: there is a strong correlation between the two parameters of Lanzhou and Aishan hydrological stations, and there is a correlation between the two parameters of Huayuankou, Gaocun, and Lijin hydrological stations, and there is no correlation between the two parameters of other hydrological stations. (4) For AASC and ASL: there is a strong correlation between the two parameters of all hydrological stations. (5) For AASC and MGSS: there is a correlation between the two parameters of Longmen, Tongguan, Huayuankou, Gaocun, and Aishan hydrological stations, and there is no correlation between two parameters of other hydrological stations. (6) For ASL and MGSS: there is a strong correlation between the two parameters of Gaocun and Aishan hydrological stations, and there is a correlation between the two parameters of Toudaoguai, Longmen, Tongguan, and Huayuankou hydrological stations, and there is no correlation between the two parameters of other hydrological stations.

To summarize, there is a strong correlation between AASC and ASL for the Yellow River. However, the correlations between AR and AASC, AR and MGSS are weak.

## Discussions

### Cause Analysis of Strong and Weak Parametric Correlations

According to the initial analysis of Section 4, there is a strong correlation between AASC and ASL whether for the Yellow River or its tributaries. However, the correlations between AR and AASC, AR and MGSS are weak.

AASC is strongly related to ASL due to the river sediment load being directly affected by river sediment

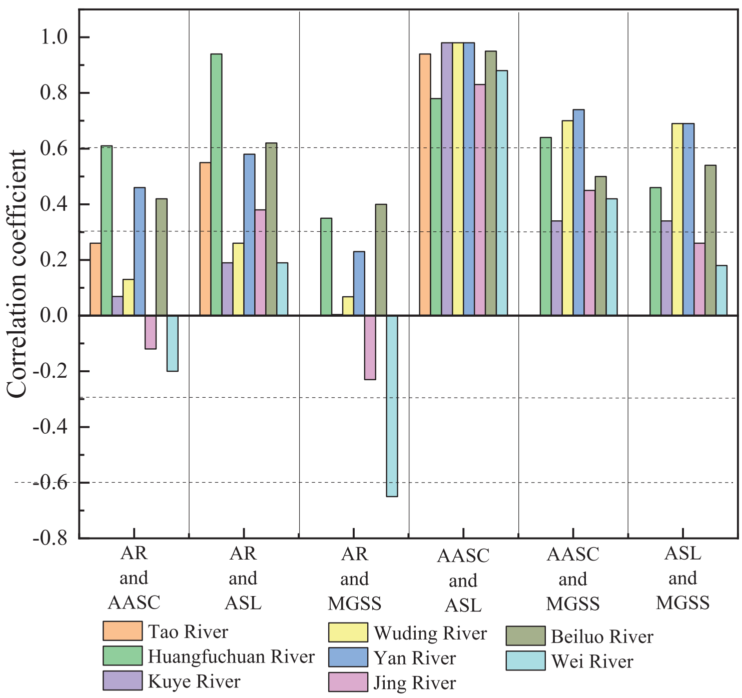


Fig. 13. Correlation coefficients between hydrological and sediment parameters of the tributaries of the Yellow River.

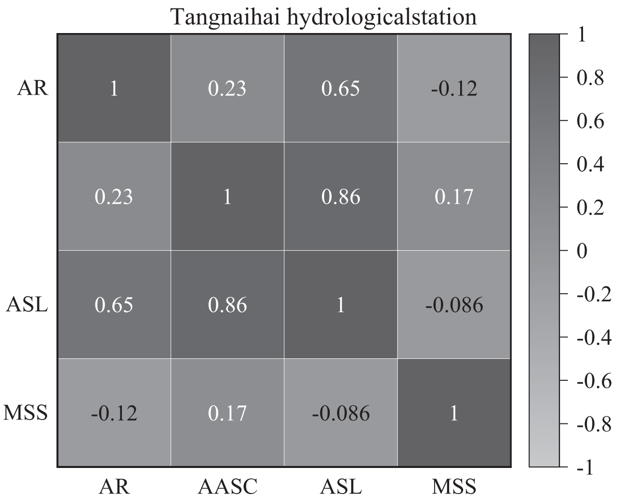


Fig. 14. Correlation matrices of Tangnaihai hydrological stations.

content. Besides, there are different sources in the river sediment, namely different sediment-producing areas. Since the main determinants of AASC and MGSS include the type, weathering degree, and particle size distribution of rock and soil mass at sediment sources, which are not directly related to AR, the correlations between AR and AASC, AR and MGSS are not strong.

## Impact of Sediment of the Tributaries on the Yellow River

The tributary water flows into the Yellow River, and the sediment carried by the water and not deposited in the tributary flow into the Yellow River. Part of the sediment is deposited in the Yellow River, and others flow downstream. Because the main eight tributaries are located at upstream of the Tongguan station, the sediment not deposited flows through Tongguan station, affecting the sediment monitoring data of the Tongguan station. Therefore, the influence of tributary sediment on the sediment of the Yellow River can be reflected by comparing and analyzing the variation characteristics of Tongguan station sediment and the total sediment of tributaries.

Therefore, the impact of the AASC of the tributaries on the Yellow River was analyzed. AASC of the Tongguan hydrological station and the sum of the AASC of the tributaries were taken as the left and right axes, respectively (Fig. 16).

Fig. 16 indicates that the variation laws of the two curves are similar. From 2002 to 2008, with a rapid decrease rate, the AASC of the Tongguan hydrological station and the sum of the AASC of the tributaries decreased by 75.49% and 82.86%, respectively. From 2008 to 2019, the AASC of the Tongguan hydrological station decreased by 35.87%, and the sum of AASC of the tributaries decreased from 198.96 to 146.551 kg/m$^3$, with a decrease of 26.34%.

Linear fitting was carried out for the AASC of the Tongguan hydrological station and the sum of AASC of the tributaries, whose equations are AASC = $-0.92t$ + 1852.87 and AASC = $-37.17t$ + 75080.47, respectively, and their correlation coefficients are 0.54. The two lines are approximately parallel. Besides, statistical analysis was performed by

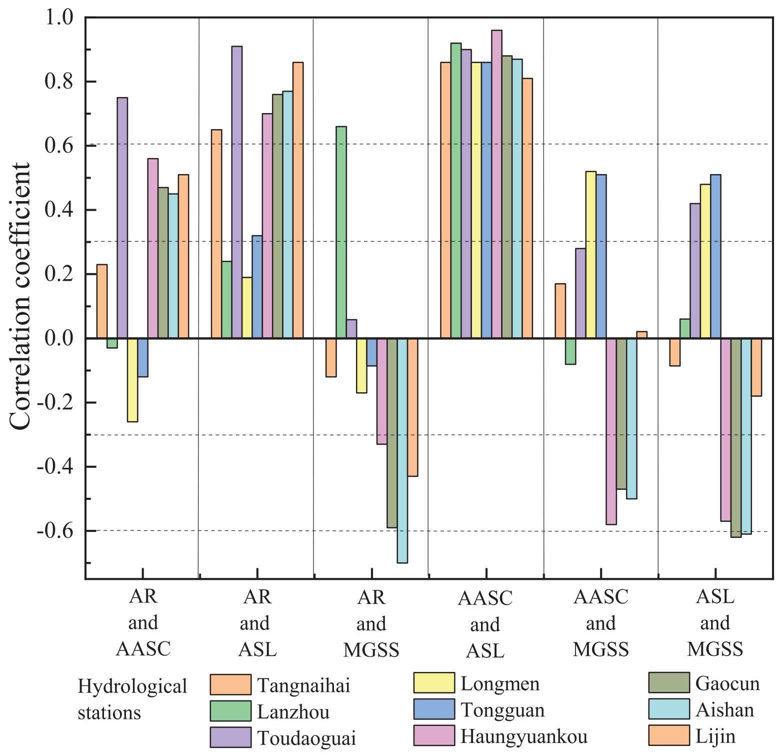


Fig. 15. Correlation coefficients between hydrological and sediment parameters of the Yellow River.

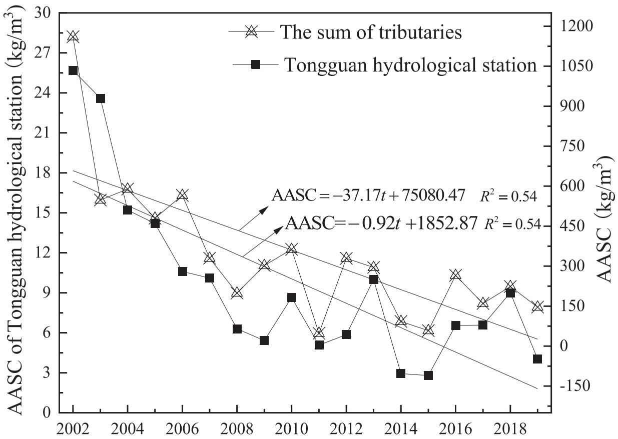


Fig. 16. AASC of Tongguan hydrological station and the sum of tributaries.

*SPSS*. The correlation coefficient between the AASC of the Tongguan hydrological station and the sum of the AASC of the tributaries is 0.87, and there is a strong correlation between the two parameters. It can be seen from it that there is a significant impact of the AASC of the tributaries on the Yellow River.

The change curves of the ASL of the Tongguan hydrological station and the sum of ASL of the tributaries were made (Fig. 17). It can be seen from Fig. 17 that the variation laws of the two curves are similar. From 2002 to 2009, with an overall decreasing trend, the ASL of the Tongguan hydrological station decreased from $4.496 \times 10^8$ to $1.12 \times 10^8$ m$^3$, with a decrease of 75.09%, and the sum of ASL of the tributaries decreased from $6.488 \times 10^8$ to $1.449 \times 10^8$ m$^3$, with a decrease of 77.67%. ASL of Tongguan hydrological station reached the maximum values in 2010, 2013, and 2018 (i.e., $2.27 \times 10^8$, $3.05 \times 10^8$, and $3.73 \times 10^8$ m$^3$). Similarly, the sum of ASL of the tributaries

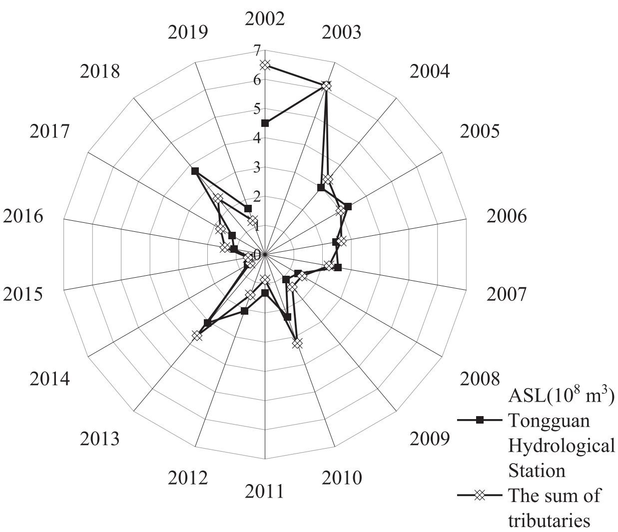


Fig. 17. ASL of Tongguan station and the sum of ASL of the tributaries.

reached the maximum values in 2010, 2013, and 2018 (i.e., $3.234 \times 10^8$, $3.623 \times 10^8$, and $2.506 \times 10^8$ m$^3$). Besides, statistical analysis was performed by *SPSS*. The correlation coefficient between the ASL of the Tongguan hydrological station and the sum of the ASL of the tributaries is 0.88, and there is a strong correlation between the two parameters.

Taken together, there is a significant impact of ASL of the tributaries on the Yellow River, sediment treatment of the tributaries is also essential. Common sediment treatment measures should be taken, including water and soil conservation, water storage and sediment retention of hydropower stations, rational utilization of Yellow River sediment, mechanical dredging of sediment, etc.

## Analysis of Sediment Influencing Factors

The variation characteristics of sediment of the Yellow River and its tributaries were systematically described in Sections 3.1 and 3.2, which were affected by the flood, dam storage and geological disasters, etc. [40-41].

### *Water Storage and Sediment Retention of Hydropower Stations*

The sediment data before and after the construction of the Longkou Reservoir were compared to discuss the impact of the reservoir on sediment. The AASC of the Longmen hydrological station decreased from 3.29 to 3.19 kg/m$^3$, with a decrease of 3.1%, due to the construction and operation of Longkou reservoir in 2009. ASL of the Longmen hydrological station decreased from $0.584 \times 10^8$ m$^3$ to $0.568 \times 10^8$ m$^3$, with a decrease of 2.74%. ASTM of Longmen hydrological station decreased from 117 to 114 t/year·km$^2$, with a decrease of 2.56%.

### *The Water and Sediment Regulation Tests*

The water and sediment regulation tests (2003/9/6 9:00-2003/9/18 18:30) of the Yellow River were carried out in 2003, and the AASC of the Huayuankou hydrological station increased from 5.93 to 7.22 kg/m$^3$, with an increase of 21.75%. Besides, the ASL of the Huayuankou hydrological station increased from $1.16 \times 10^8$ to $1.97 \times 10^8$ m$^3$, with an increase of 69.83%.

Similarly, the water and sediment regulation tests (2004/6/19 9:00-2004/6/29 0:00, 2004/7/2 12:00-2004/7/13 8:00) of the Yellow River were carried out in 2004. AASC of Huayuankou hydrological station increased from 7.22 to 8.48kg/m$^3$, with an increase of 17.45%, and ASL of Huayuankou hydrological station increased from $1.97 \times 10^8$ to $2.04 \times 10^8$ m$^3$, with an increase of 3.55%. MGSS of the Huayuankou hydrological station increased from 0.008 to 0.012 mm, with an increase of 50%.

ASTM of the Huayuankou hydrological station increased from 270 to 279 t/year·km$^2$, with a rise of 3.33%.

Likewise, the water and sediment regulation tests (6/19-7/7, 7/24-8/3, and 8/11-8/21) of the Yellow River were carried out in 2010, AASC of Huayuankou, Gaocun, Aishan, and Lijin hydrological stations increased by 268.97%, 108.93%, 106.51%, and 105.21%, respectively. Besides, ASL of Huayuankou, Gaocun, Aishan, and Lijin hydrological stations increased by 360.97%, 158.22%, 166.14%, and 197.68%, respectively. ASTM of Huayuankou, Gaocun, Aishan, and Lijin hydrological stations increased by 361.96%, 158.45%, 166.51%, and 197.59%, respectively.

*Floods*

There was significant rainfall in the flood season of 2018, resulting in an obvious flood process in the Yellow River, Jing River and Wei River. The flood discharge of the upstream reservoir was used to scour the river sediment to improve the channel shape of the Yellow River. Therefore, most of the upper reaches of the Ningmeng River and the lower reaches below Huayuankou were scoured.

AASC of nine hydrological stations (from Tangnaihai to Lijin) increased by 85.17%, 525.36%, 108.84%, 30.86%, 36.93%, 2460%, 585.71%, 472.79%, and 933.72%, respectively, and ASL of nine hydrological stations (from Tangnaihai to Lijin) increased by 189.04%, 978.65%, 430.32%, 202.80%, 186.92%, 5831.03%, 1584.49%, 1416.75%, and 3757.14%, respectively. ASTM of nine hydrological stations (from Tangnaihai to Lijin) increased by 189.78%, 982.91%, 430.33%, 2927.91%, 186.39%, 5824.53%, 1582.35%, 1416.13%, and 3772.55%, respectively.

The AASC of Jing River increased from 36.6 to 58.7 kg/m$^3$, with an increase of 60.38%. ASL of Jing River increased from $0.342 \times 10^8$ to $0.963 \times 10^8$ m$^3$, with an increase of 181.58%. ASTM of Jing River increased from 792 to 2230 t/year·km$^2$, with a rise of 181.57%. Similarly, AASC of Wei River increased from 8.95 to 13.8 kg/m$^3$, with an increase of 54.19%, and ASL of Jing River increased from $0.429 \times 10^8$ to $0.954 \times 10^8$ m$^3$, with a rise of 122.38%. ASTM of Jing River increased from 408 to 896 t/year·km$^2$, with an increase of 122.33%.

## Conclusions

In this paper, the water and sediment characteristics and influence factors of the Yellow River and its tributaries were analyzed, and the parametric correlations were further studied. The following conclusions were drawn:

(1) AASC, ASL, MGSS, and ASTM of tributaries showed a downward trend, and the AASC and ASL of the Yellow River decreased from 2002 to 2019.

(2) There is a strong correlation between AASC and ASL, whether the Yellow River or its tributaries. Therefore, the change characteristics of AASC can be indirectly reflected by ASL. However, the correlations between AR and AASC, AR and MGSS are weak. There is a significant impact of the ASL and AASC of the tributaries on the Yellow River.

(3) The correlation coefficients between AASC and ASL are 0.87 (the sum of tributaries) and 0.88 (Tongguan station), respectively, showing that the tributaries have a significant impact on the sediment of the Yellow River.

(4) Sediment detention of reservoirs, water and sediment regulation tests, and floods have an impact on sediment. Sediment detention of reservoirs effectively reduces the river sediment content. The water and sediment regulation tests and flood are used in combination, which can significantly reduce sedimentation.


## Acknowledgments

We thank the Scientific and Technological Research Program of Chongqing Municipal Education Commission (Grant No. KJQN202001210, KJQN201901240, KJQN201901209, KJQN202001219) and General Program of Chongqing Natural Science Foundation (Grant No. cstc2018jcyjA).


## Conflict of Interest

The authors declare that they have no conflict of interest.

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