Trend and attribution analysis of water and sediment variations in sandy rivers
Dangwei Wang, Junhong Zhang, Anjun Deng, Yong Jin, Tianjie Lei and Yuhai Wang

ABSTRACT

Human activities and climate change have led to significant changes in the flow and sediment of sandy rivers in northern China. The key work to reveal the changes of river water and sediment conditions is to quantitatively study the changes of precipitation, water and soil conservation in river basins, and the effect of reservoirs on sediment containment. Taking the Yongding River as a case study, we analyze the changing trend of the water and sediment into the Yongding River and find that their amount has greatly decreased. In particular, the sediment yield has decreased by more than 90% and its trend has changed, and the turning point occurred in the 1980s. Based on the statistical data analysis model, the influences of human activities on the sediment inflow of the Guanting Reservoir were quantitatively evaluated. The results show that sand retention of the upper cascade reservoirs is the main reason for the sharp reduction in sediment loads, but the sand retention effect of reservoirs has a certain time limit. Water and soil conservation played a vital role in the sediment loads reduction during the present stage. The present studies may provide insights into understanding the integrated reclamation of the river basin.

Key words | attribution analysis, changing trend, sediment retention, water and soil conservation, Yongding River

HIGHLIGHTS

- Influences evaluation of human activities on water and sediment transport.
- Reservoir regulation influences were found evident only before sedimentation balance.
- Erosion and torrent control works were found as the principal cause of recent hydrological variations.
- Time-effect of different factors on hydrological changes was evaluated.
- Ecological restoration was considered as a sustainable sediment reduction measure.
INTRODUCTION

Global climate change and human activities have affected water and sediment transport with varying degrees in the major rivers worldwide. Runoff and sediment load both change significantly in the Nile River, Egypt (Gebremicael et al. 2013), Colorado River, USA (Painter et al. 2010), Yangtze River (Yang et al. 2015), and Yellow River (He et al. 2016) as well as rivers in other regions. River systems are a type of important and highly active natural system of the earth, and their variations in runoff and sediment load are the direct river system responses to climate change and human activities (Zhang et al. 2022). Under intensifying impact of global climate warming and human activities (such as dam construction, water diversion, sand excavation, and vegetation restoration), the runoff and sediment yields of many rivers have changed significantly, directly affecting the reasonable allocation, development, and utilization of water resources in their basins and greatly influencing the geomorphological evolution of river basins and riparian ecosystems (Alexiadis 2007; Laghari et al. 2012; Mi et al. 2016).

Variations in runoff and sediment load in river basins have always been a research focus in fluvial geomorphology and water conservancy projects. Many studies have been conducted on the factors that influence the variations in runoff and sediment load in river basins, including human activities, whose impact on variations in runoff and sediment load has been extensively investigated (Farnsworth & Milliman 2003; Downs et al. 2013). The impact of human activities on river runoff and sediment load is studied primarily by investigating land use, sediment retention in reservoirs, and soil and water conservation (Pan et al. 2020). For example, Zhang et al. analyzed the trends of runoff and sediment load in the Pearl River and Yangtze River basins and believed that human activities (water conservancy facilities) play an important role in sediment reduction (Zhang et al. 2011; Zhang et al. 2012b). Chen & Li (2009) believed that the reservoir impoundment is the main cause for the drastic drop in sediment yield in the Yangtze River. By statistical analysis, Frihy et al. (1998) found that the sediment load in the Nile Delta declined by
nearly 98% after the completion of the Aswan Dam. Khan et al. (2016) discovered a close relationship between climate change and the variations in runoff and sediment load in the Ganges River in India.

In recent years, the impact of human activity and the cascade exploitation of water resources on water and sediment transport in rivers at basin scale has received widespread attention from scholars (Granados et al. 2006; Burt & Allison 2010; Yadu et al. 2018; Ling et al. 2021). Soil and water conservation measures play an important role in reducing sediment transport in river basins because they can reduce sediment yield in the river basin. For example, the large-scale soil and water conservation projects upstream of the Fenhe reservoir in 1988–2004 reduced the sediment input into the reservoir by 103 million tons, accounting for 53.4% of the total sediment input during this period (Li et al. 2013). The Rhine River basin once suffered considerably from flooding, and the 9 countries in the basin jointly implemented flood risk management plans, including measures such as restoring riparian wetlands and setting up flood diversion and storage areas to adjust land use, reduce water and soil loss, and restore and construct habitable aquatic and terrestrial ecosystems (Keruzoré et al. 2013). Although the effectiveness of soil and water conservation in sediment reduction has been demonstrated by catchment experiments, its influences on sediment reduction in the mainstreams of large rivers, especially its recovery cycle and effectiveness, remain controversial (Nie et al. 2011).

A variety of research methods have been applied in the analysis of influencing factors, such as land-use change, sediment retention in reservoirs, and soil and water conservation measures. For example, the Mann-Kendall (M-K) trend test, rescaled range (R/S) analysis, wavelet analysis, sliding t-test, and double cumulative curves are widely used to examine the trends of runoff and sediment load. However, previous research methods mainly focused on the analysis of the trends of runoff and sediment load in river basins and rarely involved attribution analyses of variations in runoff and sediment load or attribution analyses of influencing factors. River runoff and sediment yield are important factors that quantify variations in basin runoff and sediment load (Pandey et al. 2019; Singh et al. 2019). The evolution of river runoff and sediment load in different periods and different basins can reflect the characteristics of river sediment transport and deposition within these periods in these basins (Sun et al. 2021).

Because the rivers are the main channels for the transport of surface water and sediment, the changes in runoff and sediment load in river channels reflect the basic situation of water and soil loss in river basins. More importantly, the relevant research is helpful for the in-depth exploration of the mechanism of interactions between natural factors and human activities, thus providing a basis for decision-making in sustainable regional development strategies (John et al. 2021; Pu et al. 2021). In particular, the research on runoff and sediment load variations in river basins has become an important component of global change research, and the understanding of their changing process and driving mechanism is conducive to the management of the ecological environment of river basins (Pourshahbaz et al. 2020).

This study aims to analyze the water and soil loss situations and their multi-year trend, the cumulative effect of reservoir operation on sediment transport in river basins, and to reveal the relevant causes and patterns. Taking the Yongding River as a study case, we present the influences of soil and water conservation measures on variations in runoff and sediment load at the basin scale. Besides, this study also explores the dynamic relationship between reservoir operation and variations in basin sediment transport and reveals the influences of human activities (soil and water conservation measures and reservoir operation) and climate change on the variations in runoff and sediment load in the Yongding River basin.

STUDY AREA AND DATA COLLECTION

The Yongding River is one of the seven major river systems in northern China. This river is in the transition zone from the coastal plains of north China to the mid-temperate arid Inner Mongolia Plateau. The river water flows through the three provinces (Inner Mongolia, Shanxi, and Hebei) and two municipalities (Beijing and Tianjin), with a total length of 747 km, an average gradient of 2.85‰, and total basin area of 47,000 km². The river basin covers a mountainous area of 45,063 km² (95.8% of the total basin
area) and a plain area of 1,953 km² (4.2% of the total basin area). The regional climate is characterized by short summers and long winters, mean annual temperatures of 6–8 °C, mean annual precipitation of 405 mm (precipitation in June–September accounts for 64%–76% of the annual precipitation), and mean annual water surface evaporation of 1,200–1,400 mm, which is greater than the mean annual precipitation (Lei et al. 2010). The Sanggan River and Yang River are the two major tributaries of the Yongding River and are also the main sources of runoff and sediment load in the upper reaches of the Yongding River. The mean annual natural runoff in the mountainous area in the Yongding River basin is 2.08 billion m³. The flooding events of the Yongding River are mainly caused by rainstorms in the flood season, and maximum flood discharge generally occurs in July–August. The water in the upper Yongding River flows through the Loess Plateau and thus has high sediment concentrations, which results in sediment accumulation and riverbed raise in the lower reaches. Consequently, the lower Yongding River formed a ‘suspended river’ with ever-changing courses. The Yongding River is one of the rivers in the Haihe River system, its starting point being the conference area of the Sanggan River and the Yang River. The river flow enters the Guanting Reservoir downstream 8 km east from its starting point (Figure 1). The water discharges from the Guanting Reservoir and enters the middle and lower reaches, located in Beijing and Tianjin. Therefore, the variations in water and sediment inputs into the Guanting Reservoir can reflect the variations in runoff and sediment load in the upper reaches of the Yongding River.

To analyze the variations in runoff and sediment load in the Yongding River and the variations in precipitation in its basin over the years, we collected the 1952–2020 annual suspended sediment load data and annual runoff data from the Xiangshuihu gauging station in the Yang River basin and Shixiali gauging station in the Sanggan River basin upstream from the Guanting Reservoir. In addition, annual precipitation data were collected, which cover the period of 1952–2020 from 84 precipitation stations in the Yongding River basin. To analyze the human activities within the basin, we collected the area data (1988–2000) of regions in which the soil and water conservation measures were implemented (Haihe River Water Resources Commission of the Ministry of Water Resources of the People’s Republic of China), the water conservancy project data (1952–2020), and the water consumption data during the period of 1984–2005 (the Planning Office of the Hebei Provincial Department of Water Resources). The detailed information of the collected data is shown in Table 1.

Table 1 | Data collection from the gauging stations along the Yongding River and its tributaries

<table>
<thead>
<tr>
<th>Data type</th>
<th>River</th>
<th>Data series years</th>
<th>Management unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff</td>
<td>Yang River</td>
<td>1952 – 2018</td>
<td>Hydrologic Year Book of the Haihe River Basin</td>
</tr>
<tr>
<td>Sediment load</td>
<td>Yang River</td>
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</tr>
<tr>
<td>Runoff</td>
<td>Sanggan River</td>
<td>1952 – 2018</td>
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</tr>
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<td>Yongding River</td>
<td>1952 – 2018</td>
<td>Hydrologic Year Book of the Haihe River Basin</td>
</tr>
</tbody>
</table>

Figure 1 | Location of the Yongding River and the gauging stations in the river basin.
METHODOLOGY

Mann-Kendall test

The Mann-Kendall (M-K) test is a nonparametric test method recommended by the World Meteorological Organization for trend analysis of time series (Yue & Wang 2004). In this study, the M-K test was used to detect abrupt changes and analyze the variation trend based on the data series of hydrological processes.

Trend analysis

It was assumed that for an independent and identically distributed time series $X_i(n)$ ($n = 1, 2\ldots, N$), the statistical variable $S$ is defined as follows:

\[ S = \sum_{k=1}^{N-1} \sum_{j=k+1}^{N} \text{sgn}(X_i(j) - X_i(k)) \]  

where $\text{sgn}(X_i(j) - X_i(k)) = \begin{cases} 1, & X_i(j) - X_i(k) < 0 \\ 0, & X_i(j) - X_i(k) = 0 \\ -1, & X_i(j) - X_i(k) > 0 \end{cases}$

$N$ is the length of the time series data; $X_i(j)$ and $X_i(k)$ are the observed values at time $j$ and $k$, respectively.

The statistical variance in $S$ is

\[ \text{Var}(S) = \frac{N(N-1)(2N+5)}{18} \]  

When $N > 10$, the statistical variable $Z$ with a standard normal distribution is described as follows:

\[ Z = \begin{cases} \frac{S - 1}{\sqrt{\text{Var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S + 1}{\sqrt{\text{Var}(S)}}, & S < 0 \end{cases} \]

If $Z > 0$, the time series exhibits an uptrend; otherwise, it exhibits a downtrend. When the absolute value of $Z$ is greater than or equal to 1.28, 1.64, and 2.32, it indicates that there is an uptrend or downtrend of this data series at 90, 95, and 99% confidence levels respectively; if the absolute value of $Z$ is less than 1.28, 1.64, and 2.32, it means that the significance test of the corresponding confidence has not been passed, which means that the corresponding upward and downward trends are not obvious.

Analysis of turning points

A new time series needs to be constructed when using the M-K algorithm to calculate the turning point of the time series.

\[ S_k = \sum_{i=1}^{N} r_i \]  

where $r_i = \begin{cases} 1, & X_i(j) > X_i(k) \\ 0, & X_i(j) \leq X_i(k) \end{cases}$, $(j = 1, 2, \ldots, i)$, and the statistic is defined on this $S_k$ series.

\[ UF_k = \frac{S_k - E(S_k)}{\sqrt{\text{Var}(S_k)}}, \quad (k = 1, 2, \ldots, N) \]  

where the mean value $E(S_k) = k(k - 1)/4$, and the variance $\text{Var}(S_k) = k(k - 1)(2k + 5)/72$. The statistic $UF_k$ follows the standard normal distribution. $UF_k > 0$ indicates that the time series follows an uptrend; otherwise, it follows a downward trend. At a given significance level $\alpha$, the reliability value (i.e., confidence level $U_\alpha$) can be found in a normal distribution table; if $|UF_k| > U_{0.05}$, there is a significant trend in the time series. Usually, $\alpha = 0.05$ and $\alpha = 0.01$ are used as the significance standard, and the corresponding reliability line is $U_{0.05} = 1.96$, $U_{0.01} = 2.57$. If $|UF_k| > U_{0.05}$, it indicates that the time series has a significant changing trend at the 95% significance level. If $|UF_k| > U_{0.01}$, it indicates that the time series has a significant changing trend at the 99% significance level. The above steps are repeated for the reverse time series of $X_i$: $X_i(N)$, $X_i(N - 1)$, ..., $X_i(1)$ based on the numerical conditions: $UB_k = -UF_k$, $(k = N, N - 1, \ldots, 1)$, and $UB_1 = 0$. The original time series is arranged in the reverse order, and then the $UB_k$ is calculated according to the above method. The $UF_k$-time and $UB_k$-time curves are plotted in the M-K test and the intersection point of $UF_k$ and $UB_k$ is calculated. If the intersection point is below the confidence level line, this intersection point is the turning point of the series, which is the starting point of the new changing trend.
Rescaled range analysis

The Rescaled range analysis (R/S analysis) is an analysis method for the long-time memory of time series proposed by H. E. Hurst in a long-term study on the Nile River basin (Bassingthwaighte & Raymond 1984). Additionally, Hurst proposed the use of the R/S analysis to establish the Hurst index \( H \) as an indicator to distinguish whether the time-series data follow a random walk or a skewed random walk. The specific principle of R/S analysis is described as follows: for a certain time series \( X_t (i) (i = 1, 2 \ldots) \), the calculated mean value \( y(n) \) and cumulative deviation \( f(i, n) \) are defined as follows:

\[
y(n) = \frac{1}{n} \sum_{i=1}^{n} X_i (n = 1, 2, \ldots)
\]

(7)

where: \( y(n) \) is the arithmetic mean of the daily observation sequence of \( n \) periods, and \( X_i (i) \) is the observation value at the \( i \)th time

\[
f(i, n) = \sum_{j=1}^{i} (X_i (j) - y(n))(1 \leq i \leq n)
\]

(8)

where: \( f(i, n) \) is the cumulative deviation of \( n \) periods, and \( X_i (j) \) is the observation value at the \( j \)th time.

Thus, the range and standard deviation are calculated as follows:

\[
R(n) = \max_{1 \leq i \leq n} f(i, n) - \min_{1 \leq i \leq n} f(i, n)
\]

(9)

\[
S(n) = \left[ \frac{1}{n} \sum_{i=1}^{n} (X_i (i) - y(n))^2 \right]^{\frac{1}{2}}
\]

(10)

where: \( \max_{1 \leq i \leq n} f(i, n) \) is the maximum value of \( f(i, n) \), \( \min_{1 \leq i \leq n} f(i, n) \) is the minimum value of \( f(i, n) \).

Generally, the following relationship exists:

\[
\frac{R(n)}{S(n)} = (c \cdot n)^H
\]

(11)

where \( c \) is a constant, \( H \) is a Hurst index, and \( 0 < H < 1 \).

Taking the logarithm of this expression \( y = ax + b \) as follows:

\[
\lg \left( \frac{R(n)}{S(n)} \right) = H \lg n + H \lg c
\]

(12)

The equation can be rewritten as the following general linear equation:

\[
y = ax + b
\]

(13)

where \( y = \lg(R(n)/S(n)) \), \( a = H \), and \( b = H \lg c \). The \( H \) values can be obtained through a linear least-squares fitting.

\[
a = \frac{\sum_{n=1}^{N} (x_n - \bar{x})(y_n - \bar{y})}{\sum_{n=1}^{N} (x_n - \bar{x})^2}
\]

(14)

\[
b = \bar{y} - a \bar{x}
\]

(15)

when \( H > 0.5 \), this series has the characteristics of persistence, and the future changing trend of the series is the same as that in the past; when \( H < 0.5 \), the series has anti-persistence, and the future trend of the series is opposite to its past trend; and when \( H = 0.5 \), the time series is random and does not have any trend.

Evaluation of sediment control within the river basin

Estimation of sediment retention in water conservancy projects

The efficiency of sediment retention is commonly estimated using the Brune curve (Brune 1953). Based on the Brune curve, the sediment retention efficiency calculation method can be generalized as follows (Eizel-Din et al. 2010):

\[
\lambda = 100e^{-\beta W/V}
\]

(16)

where \( \lambda \) is the sediment retention efficiency of the reservoir (\%), which represents the proportion of sediment deposited in the reservoir to the sediment that entered the reservoir; \( V \) represents the reservoir capacity (m³), and \( W \) represents the runoff into the reservoir (m³).
Estimation of sediment reduction by soil and water conservation measures

When the measures of soil and water conservation were conducted, the sediment retention in this area should also be estimated. The volume of sediment retention based on the different soil and water conservation measures was obtained by multiplying the sediment data obtained in the survey with the area. Moreover, it is assumed that the annual progress of soil erosion control is the same, and the amount of sand blocked for the project measures is calculated as part of the total amount of sand blocked in the region according to the progress of soil erosion control. The sediment retention capacity of the comprehensive control measures implemented in the Yongding River basin was calculated using the following formula:

\[
\Delta W_w = \Delta W_{wb} + \Delta W_{wg} = \sum M_{wb} \cdot A_i \cdot I_{wi} + \sum V_{wg} \cdot m_i \tag{17}
\]

\[
\Delta W_s = \Delta W_{sb} + \Delta W_{sg} = \sum M_{sb} \cdot I_{si} + \sum V_{sg} \cdot m_i \tag{18}
\]

where \(\Delta W_w\) and \(\Delta W_s\) are the water retention capacity (m³) and sediment reduction (t) after the implementation of soil and water conservation measures; \(\Delta W_{wb}\) and \(\Delta W_{sb}\) are the water retention capacity (m³) and sediment reduction (t) after the implementation of the slope control measures, respectively; \(\Delta W_{wg}\) and \(\Delta W_{sg}\) are the water retention capacity (m³) and sediment reduction (t) after the implementation of the water conservation measures in valleys; \(M_{wb}\) and \(M_{sb}\) represent the runoff modulus (m³/km²) and soil erosion modulus (t/km²) before the implementation of the \(i\)-th slope control measures, respectively; \(A_i\) is the protection area of the \(i\)-th slope control measures (km²); \(I_{wb}\) and \(I_{sb}\) are the mean water retention capacity (m³) and sediment retention capacity (m³) of the soil and water conservation measures, respectively; and \(m_i\) is the number of water conservation measures for valleys.

RESULTS

Variations in runoff and sediment load in the basin

The water and sediment inputs into the Yongding River mainly come from two tributaries, the Sanggan River and the Yang River. The hydrological stations along two tributaries upstream from the Guanting Reservoir are Shixiali station and Xiangshuipu station, respectively. The annual runoff, annual mean sediment load, and annual mean sediment concentration at Shixiali and Xiangshuipu stations significantly decreased from 1952 to 2018, as shown in Figure 2(a)–2(c). In particular, the runoff and sediment load were drastically decreased by more than 90% after 2,000 comparing with the initial operation period of the Guanting Reservoir.

Figure 3(a)–3(d) shows the variations in the runoff and sediment load in the mainstream Yongding River. The runoff and sediment load inputs into the mainstream were represented by the sum one monitored at the Shixiali and Xiangshuipu stations. It was shown that the annual runoff input was approximately 141.4 millionm³ and the average annual sediment input was 150,000 tons since the beginning of the 2000s. The curve of runoff input into the Guanting Reservoir shows that the lowest water inflow occurred in approximately 2009, since its first record. The total runoff input into the Guanting Reservoir from the Sanggan River and Yang River in 2009 was approximately 50 million m³. Then the total runoff input of the Guanting Reservoir gradually recovered mainly due to the increase in the runoff of the Sanggan River. In contrast, there were few changes in the runoff of the Yang River (Figure 2).

Trends of runoff and sediment loads

The M-K method was used to analyze the variation patterns of the runoff and sediment processes in the Guanting Reservoir (Shixiali and Xiangshuipu stations) during 1952–2018. The \(Z\) values of the annual runoff and sediment inputs into the Guanting Reservoir and annual average sediment concentration are \(-9.037, -9.009,\) and \(-7.237,\) respectively. It indicated that the
runoff and sediment inputs into the Guanting Reservoir showed distinct downward trends at the 99% confidence level. The $UK_k$ and $UB_k$ curves representing the variations in runoff input into the Guanting Reservoir were obtained using the M-K method, as shown in Figure 4(a). There was a rising trend of $UF$ curve during 1952–1954, while it presented a downtrend during 1955–1961. However, the $UF$ was greater than 0 from 1952 to 1961, which indicates that the runoff input into the Guanting Reservoir was increasing before 1961. On the contrary, the $UF$ decreased to less than 0 and constantly declined since 1962, which demonstrated that the runoff input into the Guanting Reservoir began to show an increasingly prominent downtrend. The $UF$ and $UB$ curves intersect in the year 1984, where $UF = -4.33$, and the confidence level exceeds 99%. This indicated that the runoff input into the Guanting Reservoir had a highly significant downtrend since 1984.

Figure 4(b) shows the $UF_k$ and $UB_k$ changing curves of the annual sediment input into the Guanting Reservoir. The $UF$ was greater than 0 during 1952–1956, which indicated that there was a rising trend in the annual sediment input during this period. Conversely, the $UF$ was below zero and kept declining after 1957, indicating that the annual sediment input into the Guanting Reservoir began to show an increasingly prominent downtrend since 1957. The $UF$ and $UB$ curves intersect in 1986, where $UF = -4.89$, and the confidence level exceeds 99%, indicating that the annual sediment input into the Guanting Reservoir has had a highly significant downtrend since 1986.

Figure 4(c) shows the $UF_k$ and $UB_k$ curves of the variations in annual mean sediment concentration of the Guanting Reservoir. The $UF$ was always below 0, with a downtrend from 1952 to 2018, indicating that the annual mean sediment concentration in the Guanting Reservoir showed an increasingly prominent decrease since 1952. The $UF$ and $UB$ curves intersect in 1996, where $UF = -3.35$, and the confidence level exceeds 99%, indicating that the annual mean sediment concentration in the Guanting Reservoir had a highly significant downtrend since 1996.

The runoff and sediment inputs into the Guanting Reservoir are mainly from the Sanggan River and Yang River. However, the trends of runoff and sediment inputs into the Guanting Reservoir from these two rivers are not completely consistent. Therefore, it is necessary to separately analyze the trends of runoff and sediment load in these
two tributaries to accurately examine that of the Guanting Reservoir.

The $UK_k$ and $UB_k$ curves of runoff variation at Shixiali station on the Sanggan River were obtained using the M-K test. The results are shown in Figure 4(d). The $UF$ was greater than 0 and rising during 1952–1954. In contrast, although the $UF$ was still greater than 0 from 1955 to 1959, it showed a downward trend. These variation results indicated that the runoff at Shixiali station has an uptrend during 1952–1959. The $UF$ was always lower than 0 and constantly declining after 1960, indicating that the runoff at Shixiali station had an increasingly prominent downtrend. The $UF$ and $UB$ curves intersect in 1980, where $UF = \frac{1}{C_0} 4.73$, and the confidence level exceeds 99%, indicating that the runoff at Shixiali station had a highly significant downtrend since 1980.

Figure 4(e) shows the $UF_k$ and $UB_k$ curves of the annual sediment load at Shixiali station. The $UF$ was greater than 0 with a rising trend from 1952 to 1954, indicating that the annual sediment load at Shixiali station had an uptrend during this period. The $UF$ was equal to 0 in 1955. Then the $UF$ was constantly below zero and kept declining, indicating that the sediment load at Shixiali station showed an increasingly prominent downtrend after 1955. The $UF$ and $UB$ curves intersect in 1983, where $UF = -5.32$, and the confidence level exceeds 99%, indicating that the annual sediment load at Shixiali station had a highly significant downtrend since 1983.

Figure 4(f) shows the $UF_k$ and $UB_k$ curves of annual mean sediment concentration at Shixiali station. The $UF$ was always below 0 with a downtrend from 1952 to 2018, indicating that the annual mean sediment concentration at
Shixiali station had an increasingly prominent decrease after 1952. The $UF$ and $UB$ curves intersect in 1992, where $UF = 4.27$, and the confidence level exceeds 99%, indicating that the annual mean sediment concentration at Shixiali station had a highly significant downtrend since 1989.

Figure 4(g) shows the $UF_k$ and $UB_k$ variation curves of runoff at Xiangshuipu station on the Yang River. From 1952 to 1959, the $UF$ was greater than 0 and rising. Then the $UF$ was still greater than 0 until 1964 but with a downward trend. This finding indicates that the runoff at Xiangshuipu station exhibited an uptrend before 1964. On the contrary, the $UF$ was always lower than 0 and constantly declining, indicating that the annual runoff at Xiangshuipu station showed an increasingly prominent downtrend after 1965. The $UF$ and $UB$ curves intersect in 1989, where $UF = -3.76$, and the confidence level exceeds 99%, indicating that the annual runoff at Xiangshuipu station had a highly significant downtrend since 1989.

Figure 4(h) shows the $UF_k$ and $UB_k$ curves of annual sediment load for Xiangshuipu station. The $UF$ was greater than 0 during 1952–1959, indicating an uptrend of annual sediment load at Xiangshuipu station during this period. Then the $UF$ was always lower than 0 and constantly declining, indicating that the annual sediment load at Xiangshuipu station showed an increasingly prominent downtrend after 1960. The $UF$ and $UB$ curves intersect in 1989, where $UF = -3.76$, and the confidence level exceeds 99%, indicating that the annual sediment load at Xiangshuipu station had a highly significant downtrend since 1989.

Figure 4(i) shows the $UF_k$ and $UB_k$ curves of annual mean sediment concentration at Xiangshuipu station. From 1952 to 2018, the $UF$ was always lower than 0 and exhibited a downtrend, indicating that the annual mean sediment concentration at Xiangshuipu station showed an increasingly prominent downtrend during this period. The $UF$ and $UB$ curves intersect in 1990, where $UF = -3.38$,
and the confidence level exceeds 99%, indicating that the annual mean sediment concentration at Xiangshuipu station had a highly significant downtrend since 1990.

**Analysis of the sustainability of runoff and sediment load trends in the basin**

The $H$ value variations in runoff and sediment load at the Guanting Reservoir, Shixiali station on Sanggan River, and Xiangshuipu station on the Yang River were calculated based on the R/S analysis; the results are shown in Table 2. The $H$ values of the annual runoff and sediment inputs into the Guanting Reservoir and its annual mean sediment concentration are 1.00, 0.88, and 0.80 respectively, which are all greater than 0.5, indicating the future trends of runoff and sediment load will be the same as the past trends. The $H$ values of annual runoff, sediment load, and sediment concentration at Shixiali station on the Sanggan River are 1.00, 0.85, and 0.83 respectively, which are all greater than 0.5, indicating the future trends of runoff and sediment inputs into the reservoir from the Sanggan River will be the same as the past trends. Moreover, the $H$ values of the annual runoff, sediment load, and sediment concentration at Xiangshuipu station on the Yang River are 1.00, 0.92, and 0.79 respectively, which are all greater than 0.5, indicating that the future trends of runoff and sediment inputs into the reservoir from the Yang River will show few changes in the future.

Based on the above analysis results, the variations and the future trends in runoff and sediment load in the Guanting Reservoir, Shixiali station on the Sanggan River, and Xiangshuipu station on the Yang River were obtained, as shown in Table 3. From 1952 to 2018, the runoff and sediment inputs into the Guanting Reservoir and the runoff and sediment load at Shixiali and Xiangshuipu stations all exhibited downward trends, which became increasingly prominent in the mid-1980s to mid-1990s. Until 2000, the runoff and sediment load transport gradually reached a dynamic balance.

**DISCUSSION**

There are several possible reasons for the drastic reduction in runoff and sediment inputs into the Guanting Reservoir. First, climate change may result in an abrupt change in precipitation and thus causes variations in runoff and sediment load in the river basin. Second, reservoirs constructed in the upper reaches intercept large volumes of sediments and store massive volumes of water for industrial, agricultural, and urban water use. Third, a large number of measures for soil and water conservation that have been conducted on the river basin may also result in runoff and sediment yield reduction.

Climate changes are mainly reflected in the precipitation variations. Precipitation in the Yongding River basin from 1953 to 2000 is shown in Table 4. During the statistical period, the average annual precipitation was 411 mm. It can be seen that there were precipitation changes in different
periods, but the variations were not more than 10% compared with the annual average, and there is no trend change in precipitation. Therefore, climate change is not the main reason for the dramatic changes in inflow water and sediment in the Guanting Reservoir.

Many reservoirs have been constructed on the upper reaches of the Yongding River since 1958. By the year 2018, a total of 275 reservoirs had been built on the upper reaches of the Yongding River basin with a total volume capacity of 1.398 billion m$^3$. Most of these reservoirs were built before the 1980s; the statistical data are shown in Table 5. According to Equation (16), there is a nonlinear relationship between the sediment retention efficiency of a reservoir and the reservoir capacity, actual water input into the reservoir. In particular, the sediment retention efficiency of a large-scale reservoir is far greater than that of a small one. The reservoirs with the largest volume on the Sanggan River and the Yang River are the Cetian Reservoir (capacity of 580 million m$^3$, built in 1960) and the Youyi Reservoir (capacity of 117 million m$^3$, built in 1962), respectively. The two reservoirs held up all sediment that comes from the upper basin areas of the Sanggan River and the Yang River (see Figure 1). According to Equation (16), their sediment retention efficiency is estimated to be above 90%. As a result, the sediment loads in the Sanggan River and the Yang River were significantly reduced after 1960. Therefore, sediment retention in reservoirs is the leading cause of the sediment load downtrend in the Yongding River basin since the 1960s.

By the year 2000, the reservoirs upstream from the Guanting reservoir had intercepted a total of 490.7 million tons of sediment, and the total retained sediment volume reached 1.4 times the sediment retention capacity of these reservoirs. Consequently, the main sediment retention period of the reservoirs on the upper reaches of the Yongding River has been over and they reached a fluvial equilibrium. Therefore, the reservoirs in the upper basin are no longer available for a large number of sediment retention. Although some small- and medium-scale reservoirs have been newly built in recent years, these reservoirs have few regulatory effects on the river due to their low sediment retention capacity. Thus, there has been no major change in sediment retention of reservoirs since 2000. Therefore, the cause for the drastic reduction in the current sediment input into the Guanting Reservoir is not closely related to the upstream reservoir operation.

The sediment load of the Yongding River has experienced a considerable reduction since the 1980s. In particular, the sediment concentration had also decreased drastically, which indicated that the erosion-caused sediment yield of the basin decreased. This result was related to the implementation of soil and water conservation measures in the basin.

By the end of 1980, the total basic farmland area was 3,912 km$^2$, afforestation area was 497.9552 km$^2$, and the area of regions implementing integrated regulation was 6,273 km$^2$, accounting for 25.9% of the original water and soil loss areas. In addition, there were 704 small reservoirs,

| Table 4 | Precipitation variations in the Yongding River basin |
|---|---|---|---|---|---|---|---|---|
| Annual precipitation (mm) | 444 | 412 | 427 | 370 | 403 | 387 | 411 |

| Table 5 | Data statistics for the upstream reservoirs and their sediment retention volume |
|---|---|---|---|---|
| The capacity of a single reservoir (million m$^3$) | Number of reservoirs | Total storage capacity (million m$^3$) | Sediment retention capacity (VR, million m$^3$) | Sedimentation volume (VS, million m$^3$) | VS/VR |
| >100 | 2 | 696.0 | 220.2 | 271.7 | 1.2 |
| 10–100 | 16 | 489.6 | 111.7 | 169.6 | 1.5 |
| <10 | 257 | 212.8 | 22.6 | 49.4 | 2.2 |
| Total | 275 | 1,398.4 | 354.5 | 490.7 | 1.4 |
145,000 check dams, more than 20,000 small-scale channels, and numerous water conservancy projects, such as reservoirs and irrigation facilities, which played an important role in controlling water and soil loss in the basin.

The soil and water conservation measures resulted in the retention of 351 million tons of sediment in this basin from 1983 to 2000. These measures were implemented in Datong city of Shanxi Province, Zhangjiakou city of Hebei Province, and the Guishui River Basin of Yanqing County, of Beijing city, upstream from the Guanting reservoir in the Yongding River basin. The calculated sediment retention in different regions is shown in Table 6.

The restored area of the Yongding River basin has been greatly increased since the strict and effective regulation measures were put into operation in 1983. Moreover, the management and protection for work related to soil and water conservation measures have been strengthened to ensure that the integrated regulation measures can be sustained for a long time. Therefore, the runoff and sediment load conditions of the Guanting Reservoir are still sustainable.

### CONCLUSIONS

1. The annual runoff, sediment yield, and sediment concentration in the Yongding River basin declined in the 1960s and showed a significant decrease at the end of the 20th century. The runoff and sediment load after 2000 were 90% less than those in the 1960s, and the decrease in sediment load was greater than that in the runoff. The sediment concentration in the river considerably decreased. The water input, sediment input, and mean sediment concentration have remained stable since 2010.

2. The runoff and sediment inputs into tributaries of the mainstream varied with the intensity of human activities. The runoff and sediment inputs into the mainstream from the Sanggan River accounted for a larger proportion than those from the Yang River during 1952–1972 and 2002–2018, while the runoff and sediment inputs into the mainstream from the Yang River accounted for a larger proportion during 1972–2002. The sediment input into the Guanting Reservoir in recent years originated almost entirely from the Sanggan River.

3. The M-K test and the R/S analysis was conducted to analyze the variation characteristics and future trends of the runoff and sediment load inputs into the Guanting Reservoir. The results showed that the runoff and sediment load inputs into the Guanting Reservoir and the two tributaries all indicated downtrends during 1952–2018, which were more prominent from the mid-1980s to the mid-1990s.

4. As demonstrated by the analysis of sediment retention efficiency of reservoirs and soil and water conservation measures in the basin, the runoff and sediment input into the Guanting Reservoir started to decrease at the beginning of the 1960s. However, these reservoirs basically reached sedimentation equilibrium after 2000, and their current sediment retention efficiency is fairly low, contributing little to the reductions in runoff and sediment inputs to the Guanting Reservoir. The soil and water conservation measures were first implemented in the 1980s, and drastic reductions in runoff and sediment inputs to the Guanting Reservoir occurred after the 1980s. This coincidence indicates that the sediment reduction after the 1980s is closely related to the implementation of soil and water conservation measures. The time differences of sediment

### Table 6 | Sediment retention by different soil and water conservation measures in the basin during 1983-2000

<table>
<thead>
<tr>
<th>Regions</th>
<th>Terrace (×10⁴ tons)</th>
<th>Check dam (×10⁴ tons)</th>
<th>Arid plain (×10⁴ tons)</th>
<th>Planting trees (×10⁴ tons)</th>
<th>Planting grass (×10⁴ tons)</th>
<th>Restoration of vegetation (×10⁴ tons)</th>
<th>Subtotal (×10⁴ tons)</th>
<th>Total sediment retention (×10⁴ tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Datong city, Shanxi Province</td>
<td>570.67</td>
<td>215.54</td>
<td>404.83</td>
<td>2,883.25</td>
<td>131.51</td>
<td>383.5</td>
<td>4,589.3</td>
<td>15,695.41</td>
</tr>
<tr>
<td>Zhangjiakou city, Hebei Province</td>
<td>1,424.69</td>
<td>51.95</td>
<td>/</td>
<td>3,135.52</td>
<td>287.79</td>
<td>259.57</td>
<td>5,159.52</td>
<td>17,999.04</td>
</tr>
<tr>
<td>Yanqing County, Beijing city</td>
<td>61.73</td>
<td>1.53</td>
<td>/</td>
<td>260.4</td>
<td>2.93</td>
<td>95</td>
<td>421.6</td>
<td>1,410.08</td>
</tr>
</tbody>
</table>
transport changes in the Yongding River significantly contributed to identifying the real causes of the hydrological changes, which can provide new insights into the understanding of the water and sediment variations in sandy rivers.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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