Changes in streamflow and sediment for a planned large reservoir in the middle Yellow River

Binquan Li, Zhongmin Liang, Zhenxin Bao, Jun Wang, Yiming Hu

1 College of Hydrology and Water Resources, Hohai University, Nanjing 210098, PR China
2 State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing Hydraulic Research Institute, Nanjing 210029, PR China
3 Research Center for Climate Change, Ministry of Water Resources, Nanjing 210029, PR China

Correspondence
Dr Zhongmin Liang, Professor, College of Hydrology and Water Resources, Hohai University, 1 Xikang Road, Nanjing 210098, PR China.
Email: zmliang@hhu.edu.cn

Funding information
National Key R&D Program of China, Grant/Award Number: 2016YFC0402706; General Program of National Natural Science Foundation of China, Grant/Award Number: 41877147; Fundamental Research Funds for the Central Universities of China, Grant/Award Number: 2018B43314; Key Program of National Natural Science Foundation of China, Grant/Award Number: 41730750; China Postdoctoral Science Foundation, Grant/Award Number: 2017T100388

Abstract
Changes in streamflow and sediment runoffs would affect the reservoir’s functional operation and the construction of soil and water conservation measures in China’s Loess Plateau. In this study, the long-term changes in streamflow and sediment were analyzed for a main stem section of the middle Yellow River where the to-be-built large Guxian Reservoir is to be located. Results showed that both streamflow and sediment had significant downward trends with the rates of −9.4 m³ s⁻¹ yr⁻¹ and −16.8 million t yr⁻¹, respectively, during the period of 1961–2017. Using the range of variability approach, the change of streamflow regime in its postimpact period (1986–2017) was subjected to the moderate alteration, whereas the alteration of sediment regime was moderate and severe for the first (1980–1996) and second (1997–2017) postimpact periods. As an example, the attribution analyses of annual streamflow and sediment changes were conducted in a typical tributary catchment (Qingjian River) on the right bank of Guxian Reservoir. For the periods of 1980–2002 and 2003–2016, climate variability occupied the primary and secondary proportions to both streamflow and sediment reductions, respectively. Overall, human activities demonstrated the underlying contribution to the sharp declines of streamflow and sediment, accounting for 68% and 74%, respectively, during the period of 1980–2016. We suggest that, based on the operational life of warping dams (built on gully for mitigating gully erosion by raising the gully-bed step-by-step), there are risks of flash flood and high sediment concentration events in the future because the streamflow/sediment-reducing infrastructures may be damaged by extreme rainstorms and in turn become the flood and sediment amplifiers.

1 | INTRODUCTION

The Huang He or Yellow River is the mother river of the Chinese nation and has a very important strategic position in the overall structure of China’s economic and social development. In addition, the lower Yellow River is a world-famous ‘suspended river’ that brings a major threat to regional flood protection (Wang et al., 2016). The fundamental difficulty of Yellow River basin management lies in the phenomenon of water scarcity, high sediment concentration, and the uncoordinated process of rainfall-runoff and sediment yields. The Loess Plateau...
contributes nearly 90% of the total Yellow River sediment runoff, whereas most of the sediment runoff is produced in the coarse sandy hilly catchments of the middle Yellow River (Gao et al., 2017). Meanwhile, the middle Yellow River region is also one of the main sources of floods (Bai, Liu, Liang, & Liu, 2016; Li et al., 2018). Consequently, the reservoirs and large-scale soil and water conservation (SWC) projects built in the middle Yellow River region should be the key measures for streamflow and sediment regulation, such as the warping dam system. Warping dam is a dam built in a gully formed in a soil and water loss area for the purpose of creating newly arable land by silt deposition in front of the dam, decreasing gully slope, and mitigating gully erosion by raising the gully-bed step-by-step (Hu, Wu, Jayakumar, & Ajsawa, 2004). During the past 100 years, the streamflow and sediment transport in the Yellow River basin have considerably decreased mainly due to the interception function of anthropogenic engineering projects (e.g., reservoirs and SWC measures; Liu, 2016). In order to maintain the low sediment concentration and control floods, new reservoirs and SWC projects are planned to build in the Loess Plateau of the middle Yellow River. Thus, it is of great significance to study the changes in streamflow and sediment in the middle reaches of Yellow River and further to quantitatively assess their attributions.

Many previous studies have conducted to study the hydrological alteration (streamflow and sediment changes) and its attribution using different methods in different catchments of the Yellow River, mostly focusing on the separation of the effects of climate variability and human activities (Cui et al., 2018; Li et al., 2014; Liang, Liu, Liu, & Song, 2013; Liu, Dai, Zhong, Li, & Wang, 2013; Wang et al., 2018; Zhang, Mu, Wen, Wang, & Gao, 2013). Gao, Mu, Wang, and Li (2011) detected the transition year of streamflow and sediment discharge series (1950–2008) in the 1980s and inferred that human activities occupied a dominant role in the streamflow and sediment discharge reduction with the percentages of 17.8% and 28%, respectively, and in a typical tributary (Wei River basin), the corresponding contribution rates were estimated as 82.8% and 95.6% (Gao, Geissen, Ritsema, Mu, & Wang, 2013). Wang (2014) conducted an overview of 15 recent representative studies in separating two types of effects climate variability and human activity on stream discharge and suggested different methods for estimating absolute and relative magnitudes of these two type effects. Liang et al. (2015) stated that, in 14 catchments of the Loess Plateau, streamflow was more sensitive to changes in precipitation than that in potential evapotranspiration (PET), and ecological restoration contributing to streamflow reduction was much larger than that of climate change. Shi and Wang (2015) suggested that hydraulic structures may be an important cause for the sharp decrease in streamflow and sediment discharge in a catchment of middle Yellow River and further considered the impacts of the variation in rainfall patterns and the warping dam construction on hydrological regime changes. Gao et al. (2016) found that land use change and climate variability accounted for 70% and 30%, respectively, of the streamflow reduction in 17 catchments of Loess Plateau. Li et al. (2018) concluded a similar result (85.2–90.3% SWC measures vs. 9.7–14.8% climate variability) in the Wuding River basin located in the middle Yellow River. Although many case-studies have proved that anthropogenic activities accounted for more of streamflow decrease than climatic factors, there were also some exception, such as the Yan River and Beiluo River (Wu, Xiao, Yang, Duan, & Zhang, 2018; Zhao et al., 2014). For the sediment change in the middle reaches of Yellow River, a study of Gao et al. (2017) showed that over 70% of sediment load reduction can be attributed to human-induced land use/cover change, whereas less than 30% was associated with climate variability. Wang et al. (2016) found that landscape engineering, terracing, and the construction of warping dams and reservoirs were the dominating factors to sediment load decrease of Yellow River and suggested that the Yellow River's sediment load would increase in the future after the storage of existing dams and reservoirs approaching their capacities. Fu et al. (2017) suggested that despite some erosion in China's Loess Plateau has been successfully controlled with the implementation of the Grain-for-Green Programme in 1999, the whole regional ecosystem remains very fragile.

Most of previous studies focused on the separation of climate variability and human activities (or land use/cover), and results supported the statement that human activities are the dominant influencing factor of the reduction of streamflow and sediment. In this study, a more detailed analysis of different postimpact periods and the discussion on possible future changes were provided. The Guxian Hydropower Station is a planned large reservoir in the middle reach of Yellow River, and currently, the development of Guxian Hydropower Station has been in the stage of feasibility study. Guxian Reservoir is the core project in the regulation system of the Yellow River water and sediment. It is a major strategic project in China and related to the long-term stability of the Huang-Huai-Hai Plain. Thus, the analysis of changes in streamflow and sediment runoffs at the Guxian River section is important. In this study, we aimed to analyze the changes in streamflow and sediment load at the Guxian Reservoir section, to calculate their alteration degrees, and further to conduct a case-study of distinguishing human and climate influences on streamflow and sediment changes in a typical tributary catchment on the right bank of Guxian Reservoir. The future changes of SWC measures’ benefits were also discussed in this paper.

2 | MATERIALS AND METHODS

2.1 | Study area

This paper focused on the changes of streamflow and sediment runoffs at the Guxian River section in the middle reach of Yellow River, where a large hydropower station will be built. This river section controls 490,000 km² drainage area (about 65% of the whole Yellow River basin), among which more than 60,000 km² area is the coarse sandy hilly underlying surface of the Loess Plateau. We defined the study area as the interbasin between the upstream (Wubu) and downstream (Longmen) hydrological stations of the Guxian Reservoir site (Figure 1). The Wubu–Longmen drainage area is a main coarse sandy hilly region in the Loess Plateau and covers an area of 64,038 km², whereas more than 88% area is controlled by the to-be-built Guxian Reservoir. The drainage areas upstream and downstream and the hydrological station could be defined as ‘gaged area’ and ‘ungaged area’, respectively. In the drainage area between Guxian and Longmen stations (defined as ‘Guxian–Longmen drainage area’ hereafter), the Xinsihe, Dacun, and Jixian stations control the area of 1,662, 2,141, and 436 km², respectively. The ungaged area between Guxian and Longmen stations is 3,409 km².
The Wubu–Longmen drainage area is a typical semiarid region under the temperate continental monsoon climate. The average annual precipitation is 486 mm (1961–2017), decreasing from southeast to northwest. Precipitation distribution is uneven within the year, and precipitation in the flood season accounts for about 65% of its total yearly amount. The corresponding average annual streamflow is 2.718 billion m³, and average annual runoff depth is 42.4 mm. This region has a typical loess hilly and gully underlying surface with widely distributed loose loess, ravines, broken, and undulating ground. In the rainy season, rainstorm easily produces the high-content sediment floods. The average sediment concentration in the Wubu–Longmen drainage area reaches 126 kg m⁻³, which is 39% of that at Longmen station. Thus, the Wubu–Longmen drainage area is a main sediment yielding area in the middle Yellow River region. In addition, a typical tributary on the right bank, Qingjian River basin, was selected to demonstrate a case-study on streamflow and sediment change attribution. This tributary basin covers an area of 4,078 km², whereas its downstream hydrological station (Yanchuan) controls 85% of the total basin area. Its underlying surface is loess hilly and gully with the potential soil erosion area percentage >90%.

The harnessing of the Loess Plateau in the middle Yellow River basin has experienced different stages (Figure 2). Large-scale SWC measures (including terrace and warping dam construction, afforestation, and pasture reestablishment) were implemented in the Loess Plateau and the Yellow River basin since the 1950s. In addition, China central government launched a large ecological restoration campaign in the 1990s that increases the forest and pasture lands. Under these stages, different SWC project construction intensities would have different effects on streamflow and sediment.

![FIGURE 1](image1.png)  **FIGURE 1** Location of the Guxian Reservoir in the drainage area between Wubu and Longmen hydrological stations in the middle Yellow River, and the Digital Elevation Model (DEM) of the study area. The spatial distribution of backbone warping dams in a typical tributary (Qingjian River basin) as of 2009 was also shown [Colour figure can be viewed at wileyonlinelibrary.com]

![FIGURE 2](image2.png)  **FIGURE 2** The harnessing stages of the Loess Plateau in the middle Yellow River basin since the 1950s. SWC: soil and water conservation [Colour figure can be viewed at wileyonlinelibrary.com]
2.2 Forcing data

The 0.5 Degree Gridded Monthly China Surface Precipitation and Air Temperature Dataset (Version 2) was used as the forcing meteorological data in this study. In this dataset, monthly precipitation and maximum/mean/minimum air temperature is interpolated from 2,472 climate stations in the mainland China through the thin plate spline interpolation technique by the Climate Data Center, China Meteorological Administration. Monthly PET was estimated by the Thornthwaite method. Long-term streamflow and sediment concentration data were collected at two mainstream hydrological stations (Wubu and Longmen) and three downstream tributary hydrological stations (Xinshihe, Dacun, and Jixian) for the period of 1961–2017. It should be noted that the yearly streamflow and sediment data of the Xinshihe station from 1961 to 1965 were estimated from its upstream Linzhen hydrological station because the Xinshihe station was established in 1966. The Fenchuan River, Shiwang River, and Zhouchuan River are three main tributaries in the downstream of Guxian Reservoir. The streamflow and sediment data of these three tributaries were collected to estimate the streamflow and sediment runoffs of the drainage basin between Guxian and Longmen stations and further analyze the streamflow and sediment load at Guxian Reservoir section.

In the Qingjian River basin, daily precipitation from 16 rain gages were collected and processed to areal mean data series (1954–2016) using the Thiessen polygon interpolation method. Daily streamflow and sediment concentration data during the flood season (June–September) from 1954 to 2016 were also available at the Yanchuan hydrological station for the test of flow and sediment simulation models. The spatial distribution of all 274 backbone warping dams as of 2009 within the catchment was also demonstrated in Figure 1 and used for further analysis.

The land use data of the Qingjian River basin as at 1978, 1996, and 2015 was determined with Landsat MSS and TM remote sensing images. The random forest supervised classification method was used in the remote sensing image interpretation. Six land use types were classified, that is, cropland, forestland, grassland, waterbody, construction land, and barren land.

2.3 Trend test and abrupt change analysis

Annual time series of hydrometeorological variables were tested for the analysis of streamflow and sediment load of the study area. The trend-free prewhitening (TFPW) and Mann–Kendall (MK) coupled trend test framework was used to remove the autocorrelation and further analyze the trend of a time-series (Kendall, 1975; Mann, 1945; Yue, Pilon, Phinney, & Cavadias, 2002). A Z-statistic could be obtained from the TFPW–MK test to reflect the trend of a time-series, whereas a positive value of Z represents an upward (increasing) trend, and vice versa. The Z-statistic also indicates the significance of trend in a time series. The change rate could be estimated via the Sen's slope (Sen, 1968).

The climatic and human factors would affect the streamflow and sediment runoffs and produce the abrupt change points in streamflow or sediment time series. The order clustering (OC) analysis method (Li et al., 2014; Xie, Chen, Li, & Zhu, 2005) was employed to detect the change points in the streamflow and sediment time series and further was verified by the Pettitt test (Pettitt, 1979). The OC method constructs a time-variant statistic, \[ V = \{v_1, v_2, \ldots, v_n\}, \] as follows:

\[ v_j = \frac{\sum_{i=1}^{j} (x_i - \overline{x}_j)^2 + \sum_{i=j+1}^{n} (x_i - \overline{x}_{n-j+1})^2}{\sum_{i=1}^{n} (x_i - \overline{x})^2}, \]

where \( X = \{x_1, x_2, \ldots, x_n\} \) is an n-sized hydrometeorological time series to be tested, the subscripts \( i \) and \( j \) are the sequence numbers \( 1 \leq i \leq n \) and \( 1 < j < n \), and \( \overline{x}_j \) and \( \overline{x}_{n-j+1} \) represent the average values of two sub-series of \( X_1 = \{x_1, x_2, \ldots, x_j\} \) and \( X_2 = \{x_{j+1}, x_{j+2}, \ldots, x_n\} \), respectively. Furthermore, the change point \( j_0 \) would be detected through the objective function:

\[ V(j_0) = \min\{V(j)\}, \quad 1 < j_0 < n. \]

Because there may be more than one abrupt change points in the streamflow and sediment time series, especially for small-size catchments. In this study, Equation (2) was modified to detect both local and global minimum as the abrupt change points and further verified by the Pettitt test integrating with the binary segmentation (BS). Using BS algorithm, any single change point detection technique can be extended to multiple change points by iteratively repeating the single change point detection technique on different subsets of the sequence.

The alteration degrees of hydrological regimes (streamflow and sediment) between two subseries separated by the detected change point \( j_0 \) were assessed by the range of variability approach (RVA; Richter, Baumgartner, Wigington, & Braun, 1997). Thirty-one RVA parameters were calculated to characterize interannual variation of the streamflow and sediment data series. In an RVA analysis, the hydrological alteration degree of each RVA parameter is defined as follows:

\[ D_i = \frac{N_d - N_e}{N_e} \times 100\%, \quad (3) \]

where \( D_i \) is the ith RVA indicator's hydrologic alteration degree, \( N_d \) is the number of years with which the 'postimpact' annual values of RVA parameters actually fell within the target range, and \( N_e \) is the expected number of years with which the 'postimpact' values of the RVA parameters should fall within the target range \( = p \cdot N_T \), where \( N_T \) is the total number of observed years, and \( p = 50\% \) for the target range bracketed by the 25th and 75th percentile values. The values of \( |D_i| \) ranging between 0–33%, 33–67%, and 67–100% represent the low, moderate, and high alterations, respectively, for the ith indicator. Furthermore, the overall degree of hydrologic alteration could be calculated as follows (Shiau & Wu, 2004):

\[ D_o = \left( \frac{1}{n} \sum_{i=1}^{n} D_i^2 \right)^{1/2}, \]

where \( n \) is the number of RVA indicators. In this study, all RVA parameters except for the parameters of 'number of zero days' and 'base-flow index' in group number 2 were used to analyze the alteration degree of both streamflow and sediment regimes, and thus, \( n = 31 \).
2.4 Streamflow and sediment estimates at Guxian Reservoir section

Annual streamflow and sediment load at Guxian station are estimated by the streamflow or sediment load at Longmen station minus the corresponding values of the Guxian–Longmen drainage area. The downstream hydrological stations of these three tributaries in the Guxian–Longmen area are not exactly located at the catchment outlets and cannot completely collect all streamflow and sediment runoff within the catchments. In this study, the streamflow and sediment runoffs from the ungauged area between Guxian and Longmen stations were estimated through the runoff coefficient \(a = W/P\) and sediment runoff modulus \(M = S/A\) for both preimpact and postimpact periods separated at the change point \(\Delta\). The values of \(a\) and \(M\) were assumed to be invariant in space and calculated in the gaged areas (Fenchuan, Shiwang, and Zhouchuan Rivers), where \(P\) (mm), \(W\) (mm), and \(S\) (t) are annual precipitation, streamflow, and sediment runoff, respectively, and \(A\) (km²) is the drainage area. Furthermore, streamflow or sediment yield of the Guxian–Longmen drainage area could be resolved as the constituents from its gaged and ungauged drainage areas.

For annual streamflow, it could be estimated by assuming that runoff coefficient is uniform in the gaged and ungauged areas.

\[
W_{\text{Guxian-Longmen}} = (W_{\text{Guxian}} + W_{\text{Xinshihe}} + W_{\text{Dacun}}) + (\alpha_1 P_1 A_{\text{cal}} + \alpha_2 P_2 A_{\text{cal}}) U,
\]

where \(W_{\text{Guxian-Longmen}}\) is annual total streamflow of the Guxian–Longmen drainage area (m³ s⁻¹), and \(W_{\text{Guxian}}, W_{\text{Xinshihe}}\), and \(W_{\text{Dacun}}\) are annual streamflow at the Jixian, Xinshihe, and Dacun stations, respectively (m³ s⁻¹); \(\alpha_1\) is annual runoff coefficient of Zhouchuan River basin (calculated at Jixian station), and \(P_1\) is annual areal mean precipitation (mm) in the gaged area of the left bank of Yellow River (\(A_{\text{cal}} = 1, 477$ km²); \(\alpha_2\) represents the average annual runoff coefficient of the total area controlled by the Xinshihe and Dacun stations, and \(P_2\) is annual precipitation (mm) in the ungauged area of the right bank of Yellow River \((A_{\text{cal}} = 1, 932$ km²); \(U = 1/31536\) is a unit conversion variable.

Accordingly, annual sediment yield in the Guxian–Longmen drainage area, \(S_{\text{Guxian-Longmen}}\), could be estimated through the assumption that sediment runoff modulus uniform in the gaged and ungauged areas.

\[
S_{\text{Guxian-Longmen}} = (S_{\text{Guxian}} + S_{\text{Xinshihe}} + S_{\text{Dacun}}) + (M_1 A_{\text{cal}} + M_2 A_{\text{cal}}),
\]

where \(S_{\text{Guxian}}, S_{\text{Xinshihe}},\) and \(S_{\text{Dacun}}\) are annual sediment load at the Jixian, Xinshihe, and Dacun stations, respectively (t), and \(M_1\) and \(M_2\) are annual sediment runoff modulus (t km⁻²) in the gaged area of the left and right banks of Yellow River, respectively.

2.5 Attribution analysis methods for streamflow and sediment changes

The target hydrological time series are generally divided into the preimpact and postimpact periods separated at the change point \(\Delta\) for comparisons. It assumes that the target data series is ‘natural’ (without distinct disturbances) during the preimpact period, whereas for the postimpact period, both climatic and anthropogenic factors have obvious effects. For a multiyear time scale, many previous studies (Li et al., 2018; Liang et al., 2013) used Equation (7) to separate the contributions of climatic and anthropogenic factors to the changes in streamflow or sediment load.

\[
\begin{align*}
\Delta Y_{\text{climate}} &= Y_{2,\text{cal}} - Y_{1,\text{obs}} \\
\Delta Y_{\text{human}} &= Y_{2,\text{obs}} - Y_{2,\text{cal}}
\end{align*}
\]

where \(\Delta Y_{\text{climate}}\) and \(\Delta Y_{\text{human}}\) are the changes in streamflow (or sediment load) caused by climate variability and human activities, respectively; \(Y_{1,\text{obs}}\) is the average value of observed streamflow (or sediment load) for the preimpact period, whereas \(Y_{2,\text{obs}}\) and \(Y_{2,\text{cal}}\) are the observed and calculated streamflow (or sediment load) for the postimpact period, respectively. It could be expected that the uncertainty of streamflow/sediment simulation models would also introduce errors to the calculation of Equation (7). We assume the streamflow/sediment simulation models used in this study produce systematic underestimated or overestimated results for both preimpact and postimpact periods. It is on this premise that such systematic errors could be reduced as much as possible through the revision of Equation (7).

\[
\begin{align*}
\Delta Y_{\text{climate}} &= Y_{2,\text{cal}} - Y_{1,\text{cal}} \\
\Delta Y_{\text{human}} &= (Y_{2,\text{obs}} - Y_{1,\text{obs}}) - \Delta Y_{\text{climate}}
\end{align*}
\]

where \(Y_{1,\text{cal}}\) is the average value of calculated streamflow (or sediment load) in the preimpact period. This revised calculation method was first introduced by Dai (2002b) and proved to be applicable to produce more accurate results than Equation (7) in the arid/semiarid Wu River catchment in the middle Yellow River.

In this study, monthly streamflow and sediment runoffs were calculated using the model proposed by Dai (2002a).

1. Base flow. A linear statistical relation between base flow and precipitation on annual scale could be established as follows:

\[
W_b = A + B P_t,
\]

where \(W_b\) is annual base flow, and \(P_t\) is annual precipitation; \(A\) reflects the storage and recharge capacity of groundwater aquifer, and \(B\) represents the correlation between base flow and precipitation. Furthermore, monthly base flow \(W_{b,1}\) could be estimated using the proportion \(C_i\) as \(W_{b,1} = C_i \cdot W_{b}\) with the constraint of \(\sum_{i=1}^{12} C_i = 1\).

2. Surface flow. Monthly surface flow \(W_s\) could be calculated from the saturation excess and infiltration excess runoff components by establishing the exponential relations to monthly precipitation \(P:\)

\[
W_s = \begin{cases} 
  k_1 P_t^m, & P < D_1 \\
  k_2 P_t^{m_2}, & P \geq D_1 
\end{cases},
\]

where \(D_1\) is a precipitation threshold parameter, \(k_1\) and \(k_2\) are the model parameters related to the underlying surface condition, and \(m_1\) and \(m_2\) are the exponential coefficients.

Thus, the total monthly streamflow is estimated as \(W = W_s + W_{b,1}\).

3. Hillslope sediment yield. Sediment yield on the hillslope depends on rainstorm intensity, erosion resistibility, and sand carrying capacity of surface flow. The similar exponential function forms were established for estimating monthly hillslope sediment yield:

\[
S_h = \begin{cases} 
  k_3 W_s^m, & W_s < D_2 \\
  k_4 W_s^{m_4}, & W_s \geq D_2 
\end{cases},
\]
where \( S_h \) is monthly hillslope sediment yield; \( D_2 \) is the threshold parameter of surface flow; and \( k_3, k_4, m_3, \) and \( m_4 \) are parameters.

4. River sand scouring by base flow. Clear water of base flow could carry and transport deposition in the riverbed. Similarly, the river sand scouring by base flow could be estimated in the exponential forms:

\[
S_b = \begin{cases} 
    k_5 W_{bj}^{m_5}, & W_{bj} < D_3 \\
    k_6 W_{bj}^{m_6}, & W_{bj} \geq D_3
\end{cases},
\]

where \( S_b \) is monthly river sand scouring by base flow; \( D_3 \) is the threshold parameter of base flow; and \( k_5, k_6, m_5, \) and \( m_6 \) are parameters.

5. Channel sand carrying capacity. The empirical exponential relation of channel sand carrying capacity \( S_{\text{max}} \) for a specified streamflow flux \( W \) could be as follows:

\[
S_{\text{max}} = k_7 W^{m_7},
\]

where \( k_7 \) and \( m_7 \) are parameters.

6. Sediment transport. The actual monthly sediment transport \( S \) could be estimated as follows:

\[
S = \begin{cases} 
    S_h + S_b, & S_h + S_b < S_{\text{max}} \\
    S_{\text{max}}, & S_h + S_b \geq S_{\text{max}}
\end{cases}.
\]

3 | RESULTS

3.1 | Changes in hydrometeorological and sediment variables

3.1.1 | Climate variability analysis

Annual time series of hydrometeorological and sediment variables for the period of 1961–2017 were analyzed via the TFPW–MK trend test method. On the basin scale of Wubu–Longmen drainage area, the trends of precipitation, air temperature, and PET are demonstrated in Figure 3. During the entire study period, average annual precipitation was 486.4 mm with a downward slope of \(-0.30\) mm \(\text{yr}^{-1}\), but the change trend was not statistically significant. On the interdecadal timescale, the slowly decreasing and the relatively obvious increasing trends could be found with a separation in the late 1990s. In the context of global warming, this coarse sandy hilly region had undergone a remarkable warming trend at an increasing slope of \(0.02^\circ\text{C} \text{yr}^{-1}\) (with 99% confidence level), with the average annual air temperature of \(8.30^\circ\text{C}\). However, annual air temperature became stable or slightly decreased after the early 2000s according to the 5-year moving average series. Average annual PET experienced the stable or slightly decreased trend during the period from 1961 to the mid-1990s, and then a temporary and statistically significant increasing trend in the late 1990s. The stable trend of PET could also be found after the mid-2000s according to its 5-year moving average series. The average annual PET in the Wubu–Longmen drainage area was 626.3 mm with a slope of \(0.45\) mm \(\text{yr}^{-1}\) (with 99% confidence level) during the period of 1961–2017.

3.1.2 | Streamflow and sediment change analysis

Figure 4a shows the streamflow time series at Wubu and Guxian stations, and the streamflow difference between Guxian and Wubu stations for the study period. The streamflow difference could represent streamflow contribution from the Wubu–Guxian drainage area to the river section of Guxian Reservoir. The trend test suggested that streamflow at both Wubu and Guxian stations dramatically decreased with the slope rates of \(-8.5\) and \(-9.4\) m\(^3\) s\(^{-1}\) \text{yr}^{-1}, respectively, and the average values of these two streamflow time series were 707.7 and 767.5 m\(^3\) s\(^{-1}\), respectively. It should be noticed that the streamflow differences in 2008 and 2012 were negative. The most likely reason is that the streambed of the planned Guxian Reservoir site may have changed in the flood periods of these 2 years due to the severe sediment erosion. Streambed sediment scouring will

![FIGURE 3](https://wileyonlinelibrary.com)
cause the elevation of streambed to decrease, and thus the discharge converted from measured water level in the downstream sections would be less than its ‘real’ value. The ‘real’ discharge of the downstream would certainly be greater than that in the upstream sections. Figure 4b shows annual sediment load data series at the Guxian hydropower station and its upstream Wubu station for the study period. It was found that more than 60% of the sediment load at Guxian station (multiyear average of 5.41 × 10^8 t) was from the drainage basin above the Wubu station (multiyear average of 3.33 × 10^8 t). Furthermore, a coherent downward trend with 99% confidence level could be found at these two mainstream stations. The slope rates were −1.19 × 10^7 t yr^-1 and −1.68 × 10^7 t yr^-1 at Wubu and Guxian stations, respectively. The Wubu–Guxian area is only 11% of the cover area of the whole Guxian drainage basin but accounted for about 40% of its total sediment load. It suggests that this interval basin has very strong soil erosion characteristic and is one of the main sediment yielding areas of the Yellow River basin.

Despite the streamflow/sediment differences between Wubu and Guxian stations were decreasing, there were different from the time series at two mainstream stations in the change pattern. It reflected the characteristics of streamflow and sediment under different spatial scales and different disturbance intensities of human activities.

Furthermore, the trends of the streamflow and sediment at the Wubu station during the flood (June–September) and dry (October–May) seasons were also analyzed to better understand the hydrological changes (Figure 5). Results suggested that the significant downward trend (99% confidence level) could be found in all four streamflow and sediment data series during the flood and dry seasons. At the Wubu station, average streamflow was 928.6 and 603.1 m^3 s^-1, with the slopes of −14.3 and −6.1 m^3 s^-1 yr^-1, respectively, during the flood and dry seasons. Different from streamflow, the sediment load in flood season was much larger than that in dry season, that is, 188.2 versus 53.1 million t. The corresponding decreasing rates were −6.54 × 10^6 and −2.01 × 10^6 t yr^-1, respectively. It indicated that
the decline in streamflow and sediment during the flood season was greater than that in the dry season.

The modified OC method and BS-Pettitt test detected the possible abrupt change points in both streamflow and sediment load data series for the period of 1961–2017. Both mainstream stations (Wubu and Guxian) had the same abrupt point year in 1985 for the annual streamflow series, whereas in annual sediment data series, the abrupt points located in 1979 and 1996. This may reflect the different intercepting functions of SWC measures on streamflow and sediment processes. Thus, the preimpact and postimpact periods could be defined as 1961–1985 and 1986–2017 for streamflow, and for sediment, two postimpact periods of 1980–1996 and 1997–2017 were defined for comparisons with the preimpact period (1961–1979).

3.2 Hydrological alteration analysis using RVA

3.2.1 Monthly change analysis

From the preimpact to postimpact period, the streamflow values decreased in almost all months except for a slight increase (<7%) in February and March at the Wubu station (Figure 6). For the magnitude change of monthly streamflow condition, both Wubu and Longmen stations had obviously large decreases in the flood season with the largest magnitudes of ~66% and ~71%, respectively. In addition, the dispersion around a median flow value within the preimpact or postimpact period also reduced in the summer months as measured by coefficient of dispersion (COD). These could be explained by the peak-shaving role of human activities (e.g., large-scale SWC measures).

Figure 7 shows the comparison of monthly sediment concentration change between the preimpact and postimpact periods. In the first postimpact period (1980–1996), monthly sediment concentration at the Wubu station decreased by 7.2–53.1% from March to November and increased by 14.5–19.4% in other months when compared with the preimpact period. For the index of COD, the 12 months had inconsistent changes in increase or decrease. In the second postimpact period (1997–2017), monthly sediment concentration considerably decreased by 61.9–90.1% and the corresponding COD increased by 28.6–497.9% for all months at the Wubu station. For the downstream Longmen station, similar change characteristics of sediment concentration and its COD between the preimpact and

**FIGURE 6** Mean monthly streamflow values and the corresponding coefficient of dispersion at (a) Wubu station and (b) Longmen station for both preimpact and postimpact periods [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 7** Same as Figure 6, but for sediment concentration at (a) Wubu and (b) Longmen stations, respectively [Colour figure can be viewed at wileyonlinelibrary.com]
two postimpact periods could be observed in Figure 7. Overall, human activities retained locally larger proportion of sediment runoff during the flood season than in the low-flow season. Because soil erosion and sediment production are mainly associated to the flood processes in the rainy season, the overall sediment retention benefit of SWC measures is very significant in this region.

### 3.2.2 Alteration degrees of streamflow and sediment load

The alteration degree of the streamflow and sediment regimes were analyzed by using RVA between the preimpact and postimpact periods at the Wubu and Longmen stations. It should be noted that the RVA analysis here is different from the analysis of only the change in the amount of flow or sediment in Section 3.1.2. The hydrologic alteration factor for all 31 RVA parameters were calculated for both daily streamflow and sediment concentration series (Figure 8). Results showed that, for the streamflow at Wubu station, more than half of RVA parameters (52%) experienced the moderate alteration from the preimpact to postimpact periods, whereas the proportions of RVA parameters with low and severe alterations were 32% and 16%, respectively. The corresponding proportions for low, moderate, and severe alterations at Longmen station were 39%, 35%, and 26%, respectively. All minima flow indicators were subject to the low alteration degree except for a moderate negative alteration of 90-day minimum flow at Wubu station and a moderate positive alteration of 30-day minimum flow at Longmen station. As for the maxima ones, all indicators of two stations experienced the moderate or severe negative alterations. Consequently, the calculated overall flow alteration degrees, $D_w$, were 54% and 53% for Wubu and Longmen stations, respectively, which both were subject to the moderate alteration.

As for the sediment concentration changes, the proportions of RVA parameters undergoing the low, moderate, and severe alterations were (39%, 52%, and 10%) and (39%, 55%, and 6%), respectively, at the Wubu and Longmen stations in the first postimpact period (1980–1996). For the second postimpact period (1997–2017), the corresponding proportions of low, moderate, and severe alterations among all RVA indicators were (16%, 16%, and 68%) and (13%, 29%, and 58%), respectively, at the Wubu and Longmen stations. It was obvious that most RVA parameters of sediment concentration tended to transfer from low/moderate to severe alterations. Most indicators of monthly (and annual minima) sediment conditions demonstrated the moderate and severe alterations for the postimpact periods 1980–1996 and 1997–2017, respectively (Figure 8). The overall sediment alteration degrees, $D_v$, were 45% (46%) and 76% (74%) at the Wubu (Longmen) station for these two postimpact periods, respectively. Therefore, the first and second postimpact periods of sediment concentration belonged to the moderate and severe alterations, respectively.

### 3.3 Case study: Streamflow/sediment decline in the Qingjian River basin

It is very difficult to conduct the attribution analysis of streamflow or sediment decline in the whole Guxian drainage basin due to its extra-large basin area (about 490,000 km²). Therefore, we analyzed the effects of climate variability and human activities on streamflow and sediment from 1954 to 2016 in a typical tributary of Qingjian River basin as a case study. It is meaningful because this catchment locates at the typical coarse sandy hilly region near the Guxian Reservoir and has experienced all stages of the Loess Plateau harnessing as shown in Figure 2. Both modified OC method and BS-Pettitt test detected two abrupt change point years at 1979 and 2002 for both annual streamflow and sediment series at the Yanchuan station. Therefore, 1954–1979 was defined as the preimpact period, whereas 1980–2002 and 2003–2016 were the postimpact periods. In the preimpact period, the statistical models for calculating monthly streamflow and

![FIGURE 8](http://wileyonlinelibrary.com) The range of variability approach indicator’s hydrologic alteration degrees at the Wubu and Longmen stations between preimpact and postimpact periods [Colour figure can be viewed at wileyonlinelibrary.com]
3.3.1 Model setup

The streamflow and sediment runoff models described in Section 2.5 were established and tested with the data in the preimpact period with 1954–1969 and 1970–1979 for model calibration and validation, respectively. Table 1 listed the calibrated model parameters, and Figure 9 shows the observed and calculated monthly streamflow/sediment series. The performance indices of correlation coefficient and index of agreement were obtained for both comparisons, and results suggested that the streamflow and sediment models produced acceptable simulation accuracy. During the postimpact periods, observed streamflow or sediment runoff series for most of flood seasons was less than the reconstructed natural series. It indicated that the external factors such as climate variability and human activities reduced streamflow and sediment runoffs in the postimpact periods.

3.3.2 Attribution of streamflow and sediment decline

In the postimpact periods, annual precipitation slightly decreased by 5–8% when compared with the preimpact period (Table 2). Annual streamflow slightly decreased by 9% in the first postimpact period and considerably decreased by 42% in the second postimpact period. Accordingly, the reduction of sediment yield is much larger than that of streamflow with the ratio of ~37% and ~88% for these two postimpact periods, respectively. It suggested that the external factors (climate variability or human activities) had stronger effects on sediment yield than streamflow.

Figure 10 demonstrates the changes of annual streamflow and sediment due to climate variability and human activities. Results showed that the changes of streamflow and sediment in most years of the postimpact periods were negative. For the years with positive streamflow or sediment changes (ΔWtotal or ΔStotal), precipitation seemed to be relatively concentrated in time and thus would be likely to cause major flood and high-content sediment events. In the first postimpact period (1980–2002), 14 out of 23 years had the negative

### TABLE 1

Calibrated model parameters for the calculation of streamflow (mm) and sediment (t km⁻²) in the Qingjian River basin

| Wb  | Wi  | Sh  | Sb  | Smax |
|-----|-----|-----|-----|------|
| A   = 6.4, B  = 0.024 | k₁ = 0.0043 | k₃ = 133 | k₅ = 0.066 | k₇ = 380 |
| C₁  = 0.029, C₂  = 0.08, C₃  = 0.17 | m₁ = 1.98 | m₃ = 2.3 | m₅ = 4.3 | m₇ = 1.11 |
| C₄  = 0.08, C₅  = 0.053, C₆  = 0.034 | D₁ = 50 | D₃ = 3 | D₅ = 3.5 |
| C₇  = 0.088, C₈  = 0.126, C₉  = 0.089 | k₂ = 0.000101 | k₄ = 531 | k₆ = 14.42 |
| C₁₀ = 0.105, C₁₁ = 0.092, C₁₂ = 0.055 | m₂ = 2.35 | m₄ = 1.04 | m₆ = 0 |

### FIGURE 9

Calibrated and validated results of monthly streamflow and sediment runoffs of the Qingjian River basin in the preimpact period. CC: correlation coefficient; IOA: index of agreement [Colour figure can be viewed at wileyonlinelibrary.com]
streamflow changes with the average decrease of $\Delta W_{\text{total}} = -17.7$ mm (Table 3). In the decomposition of such streamflow decrease, climate variability and human activities contributed 54% and 46%, respectively. For the years of $\Delta W_{\text{total}} > 0$, climate variability still produced the decrease of streamflow ($\Delta W_{\text{climate}} = -2.9$ mm), whereas human activities promoted the release of streamflow stored in the catchment with an average increase of $\Delta W_{\text{human}} = 16.7$ mm. Overall, annual streamflow decrease in the first postimpact period could be basically explained by climate variability, and human activities contributed a moderate adverse effect of $-30\%$ on total reduction. In the second postimpact period, it was concluded that human activities occupied an absolute dominant position of annual streamflow decrease with an average reduction of $-24.2$ mm. On average, almost all streamflow decrease during this period could be explained by human activities, whereas climate variability contributed a slight adverse effect of $-3\%$. When statistics were made for both postimpact periods, the

TABLE 3  Annual streamflow change and its components in the postimpact periods in the Qingjian River basin (unit: mm)

| Period                      | Subseries               | $\Delta W_{\text{climate}}$ | $\Delta W_{\text{human}}$ | $\Delta W_{\text{total}}$ |
|-----------------------------|-------------------------|----------------------------|---------------------------|----------------------------|
| Postimpact Period 1 (1980–2002) | 14 years with $\Delta W_{\text{total}} < 0$ | $-9.6$ (54%)               | $-8.1$ (46%)             | $-17.7$                    |
|                             | 9 years with $\Delta W_{\text{total}} > 0$ | $-2.9$ (~21%)               | $16.7$ (121%)            | $13.8$                     |
|                             | All 23 years            | $-7.0$ (130%)               | $1.6$ (~30%)             | $-5.4$                     |
| Postimpact Period 2 (2003–2016) | 13 years with $\Delta W_{\text{total}} < 0$ | $-8.5$ (32%)               | $17.7$ (67%)             | $-26.3$                    |
|                             | Year 2013: $\Delta W_{\text{total}} > 0$ | $122.1$                     | $-120.0$                 | $2.1$                      |
|                             | All 14 years            | $0.8$ (~3%)                 | $-25.0$ (103%)           | $-24.2$                    |
| Both periods (1980–2016)     | 27 years with $\Delta W_{\text{total}} < 0$ | $-9.1$ (42%)               | $-12.7$ (58%)            | $-21.8$                    |
|                             | 10 years with $\Delta W_{\text{total}} > 0$ | $9.6$ (76%)                 | $3.0$ (24%)              | $12.6$                     |
|                             | All 37 years            | $-4.0$ (32%)                | $-8.5$ (68%)             | $-12.5$                    |
effects of climate variability and human activities on streamflow were consistent for three cases. Annual streamflow change in most years (27) was negative, and the decreasing percentages of climate variability and human activities were 42% and 58%, respectively. In the remaining 10 years with $\Delta W_{\text{total}} > 0$, 76% of streamflow increase could be attributed to climate variability. Overall, climate variability and human activities caused the reduction of streamflow with the contributions of $-4.0$ mm (32%) and $-8.5$ mm (68%), respectively. This finding is consistent with the results of some Loess Plateau's catchments in previous studies (Dai, 2002a; Dai, 2002b; Gao et al., 2016, 2017; Li et al., 2018; Xu, 2011).

All years experienced the decrease of sediment yield except for 5 years in the first postimpact period (Figure 10; Table 4). The sediment increases in 1995 and 2002 were significant with the amplitudes of 35% and 131%, respectively, comparing with the sediment in the preimpact period, and the changes in other 3 years with $\Delta S_{\text{total}} > 0$ were not obvious. In the first postimpact period, climate variability and human activities contributed 80% and 20% to the reduction of sediment yield, respectively. The primary and secondary contributions of these two factors were changed in the second postimpact period, whereas climate variability caused more sediment yield ($1.210 \text{ t km}^{-2}$) in the context of a drastic sediment reduction. Overall analysis suggested that human activities was the dominant factor of sediment decrease with the percentage of 74% in both postimpact periods.

4 | DISCUSSION

4.1 | The role of human activities on the reduction of streamflow and sediment

In general, human activities were the dominating influencing factor of both streamflow and sediment changes in the Qingjian River basin. This finding could be a positive demonstration of the benefits from SWC project that is the most important content of human activities related to hydrological processes in the Loess Plateau. On the time trend, one could find the decreasing negative effect of human activities on both streamflow and sediment, that is, more and more streamflow and sediment runoffs were intercepted within the basin except for the positive components of $\Delta W_{\text{human}}$ and $\Delta S_{\text{human}}$ in the late 1980s and 1990s (Figure 10). In most of these exceptions, the total streamflow or sediment yield was larger than that of the preimpact period. The reason was probably due to the fact that the water stored in the basin in the previous period was released by small reservoirs (including dam break). In addition, streamflow or sediment will also increase when the SWC project reaches its maximum capacity and fails. Two typical cases were analyzed to prove the rationality of the calculation results:

1. Rainstorm 2002. On July 4–5, 2002, a sudden high-intensity rainstorm occurred in the upstream of Qingjian River basin with rainfall amount of 463 mm at the rainstorm center. It caused various degrees of damage to large-scale SWC measures in the basin. The runoff coefficient $\alpha$ of this rainstorm event largely increased to greater than 0.6, whereas the normal value of $\alpha$ is less than 0.2 with the interception of SWC measures (Chen, Zhang, Dai, Zhao, & Wang, 2004). It suggested that the intercepting capacity of SWC measures in the basin had reduced and in turn largely increased the runoff generation capacity under such rainstorm condition. Similarly, sediment concentration was also increased considerably. According the local government investigation, up to 85 warping dams were destroyed by this rainstorm event and thus 1.36 million m$^3$ of earthwork, 7,394 m$^3$ of stonework were destroyed. The arable land by silt deposition in front of warping dam was reduced by 112.1 hm$^2$ in the upstream basin. In addition, mining of mineral resources and destruction of slope SWC measures also amplified of streamflow and sediment runoffs.

2. Rainstorm 2013. From July 1 to 26, 2013, there were continuous heavy rainfalls in the basin since the 1945 meteorological record, with the longest process, the strongest intensity, and the most rainy days, which exceeded the 100-year standard. The total precipitation of 2013 was significantly larger than that of 2002 (Table 5). However, the formed streamflow and sediment of 2013 were obviously less than those of 2002. It was indicated that the quality of SWC measures in 2013 was significantly better than that in 2002. Almost all extra water and sediment generated by the rainstorm 2013 were intercepted by the SWC measures.

Among the human activities affecting the natural hydrological processes, the SWC measures including terra and warping dam construction, afforestation, and pasture reestablishment have contributed considerably to the reduction of streamflow and sediment in different ages. Figure 11 shows the land use maps of the Qingjian River basin in 1978, 1996, and 2015. The cropland of the basin was reduced.

### TABLE 4 Annual sediment yield change and its components in the postimpact periods in the Qingjian River basin (unit: t km$^{-2}$)

| Period                  | Subseries                  | $\Delta S_{\text{climate}}$ | $\Delta S_{\text{human}}$ | $\Delta S_{\text{total}}$ |
|-------------------------|----------------------------|------------------------------|----------------------------|----------------------------|
| Postimpact Period 1     | 18 years with $\Delta S_{\text{total}} < 0$ | $-4.260$ (57%)               | $-3.223$ (43%)             | $-7.483$                   |
|                         | 5 years with $\Delta S_{\text{total}} > 0$  | $-2.261$ ($-$45%)            | $7.316$ (145%)             | $5.055$                    |
|                         | All 23 years               | $-3.825$ (80%)               | $-932$ (20%)               | $-4.757$                   |
| Postimpact Period 2     | all 14 years: $\Delta S_{\text{total}} < 0$ | $1.210$ ($-$11%)             | $-12.710$ (111%)           | $-11.500$                  |
| Both periods (1980–2016)| 32 years with $\Delta S_{\text{total}} < 0$ | $-1.867$ (20%)               | $-7.373$ (80%)             | $-9.240$                   |
|                         | 5 years with $\Delta S_{\text{total}} > 0$  | $-2.261$ ($-$45%)            | $7.316$ (145%)             | $5.055$                    |
|                         | All 37 years               | $-1.920$ (26%)               | $-5.388$ (74%)             | $-7.308$                   |

| Period/year             | Precipitation (mm) | Streamflow (mm) | Sediment (t km$^{-2}$) |
|-------------------------|--------------------|----------------|------------------------|
| Preimpact period        | 490.2              | 57.8           | 12.999                 |
| 2002                    | 523.4              | 85.6           | 29.992                 |
| 2013                    | 728.6              | 60.0           | 3.904                  |

### TABLE 5 Observed annual precipitation, streamflow, and sediment of 2002 and 2013 in the Qingjian River basin

| Period/year             | Precipitation (mm) | Streamflow (mm) | Sediment (t km$^{-2}$) |
|-------------------------|--------------------|----------------|------------------------|
| Preimpact period        | 490.2              | 57.8           | 12.999                 |
| 2002                    | 523.4              | 85.6           | 29.992                 |
| 2013                    | 728.6              | 60.0           | 3.904                  |
whereas the area of vegetation including both forestland and grassland gradually increased from 1978 to 2015. Thus, the basin’s intercepting capacity of streamflow or sediment certainly increased. This verified the above attribution analysis result that human activities were the governing factor of streamflow and sediment decline.

4.2 The possible changes of future SWC measures’ benefits

The warping dam is the last line of defense in the SWC measures system. It can intercept water and silt that cannot be stored or blocked by other measures and plays a leading role in streamflow and sediment reduction. A large number of investigations and studies have shown that under general rainfall conditions, the warping dam’s water-blocking, and sediment-blocking effects are very significant, and it has a large effect of water storage and sediment retention during the dry season and has little or even negative effect during the flood period (Liu, 2016). The remarkable situation is that as time goes by, the water storage and sediment blocking effect of the warping dam is gradually weakened. When these warping dams encounter the flood exceeding defensive standards, they often cause dam damages. Even the floods are within the defense standards, they can also cause a certain degree of dam damage due to poor engineering quality and negligence management of warping dams.

According to the China’s design specification of warping dam, for main warping dams, the sediment capacity is generally 60% of its total storage capacity. However, the reality is not the case. The Yellow River Conservancy Commission (YRCC) analyzed the relationship among the completion time, total storage capacity, and accumulated storage capacity of 4,157 main warping dams distributed in the middle Yellow River region (built before the 1980s), and results suggested that the total silted capacity basically accounts for 77% of the storage capacity (Liu, 2016; Liu, Gao, & Wang, 2017). This ratio (defined as sedimentation ratio hereafter) is higher than that from the design specification. Certainly, this ratio would be slightly different in a specific catchment within the middle Yellow River region. For instance, the average sedimentation ratio for main warping dams in the Wuding River basin is 0.795 (Liu, 2016). This phenomenon is related to the structure and utilization of warping dams. The storage position corresponding to sedimentation ratio = 77% is basically the spillway floor position of the current backbone dams. As for small and medium-size warping dams, YRCC also found the same phenomenon as backbone warping dams, but with a higher sedimentation ratio of 88% based on the data of 1,640 small and medium-size warping dams in Shaanxi Province (Liu, 2016; Liu et al., 2017). This sedimentation ratio is larger than that of backbone warping dams because most of the small and medium warping dams do not have spillways.

Using the data of completion time, total storage capacity and accumulated storage capacity of warping dams from YRCC, we fitted the empirical statistical equations of sedimentation ratio for both backbone and small/medium warping dams in Figure 12. It could be used to estimate the operation life of the basin warping dam system and further analyze the future changes of benefits of the dam system. Data of 274 backbone warping dams as of 2009 in the Qingjian River basin (as shown in Figure 1) were used to estimate the number of
effective warping dams and the corresponding total storage capacity from 1955 to 2009. A functionally effective warping dam is defined as its sedimentation ratio is less than its maximum (e.g., 0.77 for backbone dams). Since 1972, some of the backbone dams have reached their maximum sedimentation ratio and failed (Figure 13). By 1995, the number of failed backbone dams has been very impressive. As for the storage capacity of these dams, the effective storage capacity reached its peak in 1976 and then dropped significantly afterwards. As of 2009, 66% of the built backbone dams had been failed and more than 80% of the storage capacity had been silted up. Therefore, it can be expected that if there is no new warping dam construction plan, the effective storage capacity will be further reduced in the Qingjian River basin.

Throughout the middle Yellow River, up to 88% of small/medium dams and 20% of backbone dams have been fully filled with sediment according to the YRCC’s statistics in 2016 (Liu, 2016; Liu et al., 2017). Thus, we must maintain the risk awareness of flash floods considering that the streamflow/sediment-reducing infrastructures including warping dam, low-level road, and even small/medium reservoir may be damaged by extreme rainstorms and in turn become the flood and sediment amplifiers (Liu, Dang, & Zhang, 2016; Wang et al., 2016). This possibility has already happened, for example, the flash floods of Qingjian River in 2002. Therefore, in the middle Yellow River, some new planned reservoirs and SWC projects (e.g., the Guxian Reservoir) should be built to prevent the streamflow/sediment trends rebound. In the future SWC work; however, the practices should consider other aspects such as the impact of sediment starved water, balancing the sediment budget, and the natural aggradation/degradation processes. Otherwise, the sediment-starved water could again intensify the gully erosion as well as streambed change.

5 | SUMMARY AND CONCLUSION

In the past half-century or more, the streamflow and sediment load of Yellow River has been greatly reduced mainly due to the water conservancy project and large-scale SWC measures. This paper conducted an analysis of the changes in streamflow and sediment for a main stream section of the planned large Guxian Reservoir in the middle Yellow River and attempted to conduct the attribution analysis of streamflow and sediment changes in a typical tributary. In the Wubu–Longmen area where Guxian Reservoir is located, the TFPW-MK test found a nonsignificant downward trend of average annual
precipitation with a slope of $-0.30$ mm yr$^{-1}$ and a remarkable warming trend of average annual air temperature with a slope of $0.02^\circ$C yr$^{-1}$ for the period of 1961–2017. Meanwhile, the Thornthwaite-based PET series showed the increasing trend at a slope of 0.45 mm yr$^{-1}$. The annual streamflow and sediment load data were estimated from its upstream (Wubu) and downstream (Longmen) stations for the study period. The sharp decrease trends of both streamflow and sediment load at the Guxian Reservoir section could be detected with the rates of $-9.4$ m$^3$ s$^{-1}$ yr$^{-1}$ and $-1.68 \times 10^7$ t yr$^{-1}$, respectively, and the corresponding average annual values were 767.5 m$^3$ s$^{-1}$ and 541.24 million t during the period of 1961–2017.

For all three main stream sections (Wubu, Guxian, and Longmen), the abrupt change point at 1985 was detected for their annual streamflow series by the modified OC method and BS-Pettitt test, whereas two abrupt change points (1979 and 1996) were obtained for their annual sediment series. Using the abrupt points, the entire study period could be divided into the preimpact and postimpact periods. The RVA method estimated the hydrological alteration at the reservoir’s upstream (Wubu) and downstream (Longmen) stations between the preimpact and postimpact periods on the intermonthly scale. Results showed that streamflow was subject to the moderate alteration based on the index of overall alteration degree, whereas sediment concentration belonged to the moderate and severe alterations, respectively, in the first (1980–1996) and second postimpact (1997–2017) periods.

Selecting a typical loess tributary catchment (Qingjian River) on the right bank of Guxian Reservoir, the effects of climate variability and human activities on annual streamflow and sediment declines were separated for the period of 1954–2016. The attribution analysis suggested that both climate variability and human activities contributed to the decreases in streamflow/sediment, but human activities could be the dominating influencing factors. The contributions of human activities to the decreases in annual streamflow and sediment were 68% and 74%, respectively, throughout the postimpact period (1980–2016), whereas the remaining percentages were associated with climate variability. This finding is consistent with the results of other loess catchments in the middle Yellow River. In the first (1980–2002) and second (2003–2016) postimpact period, however, climate variability occupied the primary and secondary proportions respectively to the reductions of streamflow and sediment. The role of warping dams on streamflow and sediment interception was discussed with two rainstorm cases, which proved the importance of the quality of warping dam and the effective storage capacity. The case analysis of warping dam’s operation life indicated that there are flash flood risks because the streamflow/sediment-reducing infrastructures including warping dam, low-level road, and even small/medium reservoir maybe damage by extreme rainstorms and in turn become the flood and sediment amplifiers.

ACKNOWLEDGMENTS

This work was supported by the National Key R&D Program of China (2016YFC0402706), General Program of National Natural Science Foundation of China (41877147), Fundamental Research Funds for the Central Universities of China (2018B43314), Key Program of National Natural Science Foundation of China (41730750), and China Postdoctoral Science Foundation (2017T100388).

ORCID

Binquan Li https://orcid.org/0000-0002-9958-0396

REFERENCES

Bai, P., Liu, X., Liang, K., & Liu, C. (2016). Investigation of changes in the annual maximum flood in the Yellow River basin, China. Quaternary International, 392, 168–177. https://doi.org/10.1016/j.quaint.2015.04.053

Chen, J., Zhang, S., Dai, M., Zhao, Y., & Wang, C. (2004). Analysis on runoff and sediment variation by “2002.7” rainstorm in Qingjian River. Water Power, 30(1), 16–20. (in Chinese)

Cui, T., Yang, T., Xu, C., Shao, Q., Wang, X., & Li, Z. (2018). Assessment of the impact of climate change on flow regime at multiple temporal scales and potential ecological implications in an alpine river. Stochastic Environmental Research and Risk Assessment, 32(6), 1849–1866. https://doi.org/10.1007/s00477-017-1475-z

Dai, M. Y. (2002a). Runoff estimation model based on the separation from its cause of formation. In G. Wang, & Z. Fan (Eds.), Study of changes in runoff and sediment load in the Yellow River, vol. 1 (pp. 981–990), Zhengzhou: The Yellow River Water Conservancy Press. (in Chinese)

Dai, M. Y. (2002b). Water and sediment changes and the calculation comparison of hydrological methods in the Wuding River basin. In G. Wang, & Z. Fan (Eds.), Study of changes in runoff and sediment load in the Yellow River, vol. 1 (pp. 991–1009), Zhengzhou: The Yellow River Water Conservancy Press. (in Chinese)

Fu, B., Wang, S., Liu, Y., Liu, J., Liang, W., & Miao, C. (2017). Hydrogeomorphic ecosystem responses to natural and anthropogenic changes in the Loess Plateau of China. Annual Review of Earth and Planetary Sciences, 45, 223–243. https://doi.org/10.1146/annurev-earth-060316-020552

Gao, G., Zhang, J., Liu, Y., Ning, Z., Fu, B., & Sivapalan, M. (2017). Spatio-temporal patterns of the effects of precipitation variability and land use/cover changes on long-term changes in sediment yield in the Loess Plateau, China. Hydrology and Earth System Sciences, 21, 4363–4378. https://doi.org/10.5194/hess-21-4363-2017

Gao, P., Geissen, V., Ritsema, C. J., Mu, X.-M., & Wang, F. (2013). Impact of climate change and anthropogenic activities on stream flow and sediment discharge in the Wei River basin, China. Hydrology and Earth System Sciences, 14, 961–972. https://doi.org/10.5194/hess-17-961-2013

Gao, P., Mu, X.-M., Wang, F., & Li, R. (2011). Changes in streamflow and sediment discharge and the response to human activities in the middle reaches of the Yellow River. Hydrology and Earth System Sciences, 15, 1–10. https://doi.org/10.5194/hess-15-1-2011

Gao, Z., Zhang, L., Zhang, X., Cheng, L., Potter, N., Cowan, T., & Cai, W. (2016). Long-term streamflow trends in the middle reaches of the Yellow River Basin: Detecting drivers of change. Hydrological Processes, 30, 1315–1329. https://doi.org/10.1002/hyp.10704

Hu, C., Wu, D., Jayakumar, R., & Ajiawawa, S. (2004). Warping dams—Construction and its effects on environment, economy, and society in Loess Plateau region of China. UNESCO, Beijing: CN/2004/SC HYD/PI/1, IHP-UNESCO Office Beijing & IRTCES Beijing.

Kendall, M. G. (1975). Rank correlation methods. London: Charles Griffin.

Li, B., Liang, Z., Zhang, J., Wang, G., Zhao, W., Zhang, H., ..., Hu, Y. (2018). Attribution analysis of runoff decline in a semiarid region of the Loess Plateau, China. Theoretical and Applied Climatology, 131, 845–855. https://doi.org/10.1007/s00704-016-1816-2

Li, B., Yu, Z., Liang, Z., Song, K., Li, H., Wang, Y., ..., Acharya, K. (2014). Effects of climate variations and human activities on runoff in the Zoige alpine wetland in the eastern edge of the Tibetan Plateau. Journal of Hydrologic Engineering, 19(5), 1026–1035. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000868
Liang, K., Liu, C., Liu, X., & Song, X. (2013). Impacts of climate variability and human activity on streamflow decrease in a sediment concentrated region in the Middle Yellow River. Stochastic Environmental Research and Risk Assessment, 27(7), 1741–1749. https://doi.org/10.1007/s00477-013-0713-2

Liang, W., Bai, D., Wang, F., Fu, B., Yan, J., Wang, S., ... Feng, M. (2015). Quantifying the impacts of climate change and ecological restoration on streamflow changes based on a Budyko hydrological model in China’s Loess Plateau. Water Resources Research, 51, 6500–6519. https://doi.org/10.1002/2014WR016589

Liu, X. (2016). Cause of water and sediment sharp decline in the Yellow River in recent years. Beijing: Science Press. (in Chinese)

Liu, X., Dai, X., Zhong, Y., Li, J., & Wang, P. (2013). Analysis of changes in the relationship between precipitation and streamflow in the Yiluo River, China. Theoretical and Applied Climatology, 114(1–2), 183–191. https://doi.org/10.1007/s00704-013-0833-0

Liu, X., Dang, S., & Zhang, H. (2016). Possible incoming sediment amount of the Yellow River under the extreme rainfall scenarios in the future. Yellow River, 38(10), 13–17. (in Chinese)

Liu, X., Gao, Y., & Wang, F. (2017). Quantity and distribution of warping dams that still have sediment retaining ability in the Loess Plateau. Yellow River, 39(4), 1–6. (in Chinese)

Mann, H. B. (1945). Nonparametric tests against trend. Econometrica, 13, 245–259. https://doi.org/10.2307/1907187

Pettitt, A. (1979). A nonparametric approach to the change point problem. Journal of the Royal Statistical Society: Series C: Applied Statistics, 28(2), 126–135.

Richter, B., Baumgartner, J. V., Wigington, R., & Braun, D. P. (1997). How much water does a river need? Freshwater Biology, 37, 231–249. https://doi.org/10.1046/j.1365-2427.1997.00153.x

Sen, P. (1968). Estimates of the regression coefficient based on Kendall’s tau. Journal of the American Statistical Association, 63(324), 1379–1389. https://doi.org/10.1080/01621459.1968.10480934

Shi, H., & Wang, G. (2015). Impacts of climate change and hydraulic structures on runoff and sediment discharge in the middle Yellow River. Hydrological Processes, 29, 3236–3246. https://doi.org/10.1002/hyp.10439

Shiau, J. T., & Wu, F. C. (2004). Feasible diversion and in stream flow release using range of variability approach. Journal of Water Resources Planning and Management, 130(5), 395–404. https://doi.org/10.1061/(ASCE)0733-9496(2004)130:5(395)

Wang, S., Fu, B., Piao, S., Lü, Y., Ciais, P., Feng, X., & Wang, Y. (2016). Reduced sediment transport in the Yellow River due to antropogenic changes. Nature Geoscience, 9, 38–41. https://doi.org/10.1038/ngeo2602

Wang, X. (2014). Advances in separating effects of climate variability and human activity on stream discharge: An overview. Advances in Water Resources, 71, 209–218. https://doi.org/10.1016/j.adwatre.2014.06.007

Wang, X., Yang, T., Yong, B., Krysanova, V., Shi, P., Li, Z., & Zhou, X. (2018). Impacts of climate change on flow regime and sequential threats to riverine ecosystem in the source region of the Yellow River. Environmental Earth Sciences, 77(12), 465. https://doi.org/10.1007/s12665-018-7628-7

Wu, J., Miao, C., Yang, T., Duan, Q., & Zhang, X. (2018). Modeling streamflow and sediment responses to climate change and human activities in the Yanhe River, China. Hydrology Research, 49(1), 150–162. https://doi.org/10.2166/nh.2017.168

Xie, P., Chen, G., Li, D., & Zhu, Y. (2005). Comprehensive diagnosis method of hydrologic time series change-point analysis. Water Resources Power, 23(2), 11–14. (in Chinese)

Xu, J. (2011). Variation in annual runoff of the Wudinghe River as influenced by climate change and human activity. Quaternary International, 244, 230–237. https://doi.org/10.1016/j.quaint.2010.09.014

Yue, S., Pilon, P., Phinney, B., & Cavadias, G. (2002). The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrological Processes, 16, 1807–1829. https://doi.org/10.1002/hyp.1095

Zhang, G., Mu, X., Wen, Z., Wang, F., & Gao, P. (2013). Soil erosion, conservation, and eco-environment changes in the Loess Plateau of China. Land Degradation & Development, 24, 499–510.

Zha0, G., Tian, P., Mu, X., Jiao, J., Wang, F., & Gao, P. (2014). Quantifying the impact of climate variability and human activities on streamflow in the middle reaches of the Yellow River basin. China. Journal of Hydrology, 519, 387–398. https://doi.org/10.1016/j.jhydrol.2014.07.014

How to cite this article: Li B, Liang Z, Bao Z, Wang J, Hu Y. Changes in streamflow and sediment for a planned large reservoir in the middle Yellow River. Land Degrad Dev. 2019;30:878–893. https://doi.org/10.1002/ldr.3274