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# Variation of runoff and sediment inflows to the Three Gorges Reservoir: Impact of upstream cascade reservoirs

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ABSTRACT

The construction of cascade reservoirs upstream of the Three Gorges Reservoir (TGR) has been greatly intensified in the 21st century. While research attention is dedicated to the downstream effects of the TGR, few studies have been focused on the radical change of upstream inflows to the TGR. In this study, we reveal the impact of upstream cascade reservoirs on the annual runoff and sediment load inflows to the TGR based on the data in 1956–2016. The measured sediment load at control hydrological stations shows a drastic decrease (59%) while the runoff only had a slight decrease (6%). The similarity of these characteristics for that measured at Yichang indicates the leading effects of TGR inflows on its outflow. We develop a macroscopic quantification method utilizing double mass curves to separate the contribution from climate effects and human activities. Results show that precipitation (climate factors) dominated the runoff change, while human activities were the main driving factors for sediment load reduction in the studied area. In the four sub-basins upstream of the TGR, the sediment retention induced by large reservoirs was the major reason for sediment load reduction, especially in the Jinsha River Basin and the Jialing River Basin, which contributed 70% (or 347 Mt/yr) of the total sediment retention in the whole upper Yangtze River Basin (YRB) since 2015, much larger than that of the TGR (19% or 94 Mt/yr). As the total storage capacity of the cascade reservoirs increased to more than twice the TGR's capacity in the 2010s, the regression relationship between runoff and sediment load broke down. The unprecedented situation in the upper YRB may have profound impacts on the morphology and ecology of the TGR as well as the downstream Yangtze River including its delta.

## 1. Introduction

Rivers are the major pathways to deliver water and sediment from land to oceans, supplying 36000 km$^3$ of freshwater and more than 20 billion tons of solid and dissolved materials per year (Milliman and Farnsworth, 2013). While they play a key role in the earth's surface system, human activities have been exerting intensive interference in recent decades. According to The World Commission on Dams (WCD), about 45000 large dams over 15 m high and an estimated $8 \times 10^5$ small dams had been built worldwide in the second half of the 20th century (World Commission on Dams, 2000), holding back more than 6500 km$^3$ freshwater (about 18% of the total annual runoff) and intercepting 4–5 billion tons sediment load (25% - 30% of the total value) in the reservoirs annually according to the statistics investigated in the early 21st century (Vörösmarty et al., 2003; Nilsson et al., 2005). Side impacts may be arisen in a riverine and coastal environment with intensive damming, for example, freshwater impoundment influences the hydrologic pattern and alter the regional biological cycle (Yuan et al., 2015); declining sediment supply leads to the erosion of channels and coastal deltas and may also disturb the ecosystem (Syvitski et al., 2005; Yang et al., 2005; Zhang et al., 2010, 2016).

China has been in full swing of dam construction since 1950 for electricity power generation, flood control, as well as water supply, etc. (Yang and Lu, 2014). Most of the reservoirs with high dams were built in the Yangtze River, which is the largest river in Asia and also ranks third in the world. Besides, the hydropower resource endowment in the Yangtze River Basin (YRB) accounts for almost half of the total potential capacity of technically exploitable hydropower in China and ranks first in the world, and most of which is contributed by the upper reach where there is large elevation drop (Zhang et al., 2014; Chu et al., 2019). There

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exist over 5000 reservoirs in the YRB (Gao et al., 2018), and the construction of large reservoirs (capacity $> 10^8 m^3$) has been greatly intensified since the late 1990s especially in its upper reach, with a prospective persistence in future (Chu et al., 2019). A great amount of research effort has been paid to reveal the critical influence of dams/reservoirs on the hydrology patterns in the middle and lower reaches of the YRB (including the Yangtze Delta), particularly in terms of annual runoff and sediment load (Hu et al., 2009; Yang et al., 2011, 2014, 2015; Dai et al., 2015; Zhao et al., 2017; Guo et al., 2018); the construction and operation of large dams/reservoirs are identified as the main reason for the drastic decline of sediment flux to the downstream Yangtze and even to the East China Sea (Hu et al., 2009; Yang et al., 2015, 2011).

In recent years, growing research attention is being attached to the cascade reservoirs in the upper YRB including the TGR in altering the runoff and sediment load pattern. Guo et al. (2020) investigated the cumulative effect of newly constructed dams and observed the accelerated reduction of annual sediment load as well as the decrease of mean sediment particle diameter. With the data only up to 2013, Zhao et al. (2017) quantitatively assessed the contribution of natural and anthropogenic factors on water discharge and sediment load for the whole YRB and found that for the upper YRB, after 1987 there was no significant abrupt change of runoff while the sediment load dropped more than 50% and human-induced drivers explained 86% of the change. Chen and Wang (2019) estimated the contribution of human activities to sediment reduction for the main sub-basins in the upper YRB in each decade since the 1970s using the hydrologic regression method. Although quite a few large reservoirs constructed in recent 10 years were not considered (e.g. the cascade reservoirs in the middle reach of the Jinsha River Basin), it showed that the reservoirs overall accounted for 88% of the sediment reduction among the quantity induced by human activities, way outstripping other factors such as soil conservation and river sand extraction. There are also detailed studies on the Jinsha River Basin (Li et al., 2018; Zhang et al., 2019) where damming is the most booming among all sub-basins, but the studies for other sub-basins seem to be scarce. For the inter-annual aspect, Ren et al. (2020) revealed the fact that the construction of cascade reservoirs reduced the peak discharge while increased the peak sediment transport time; the peak sediment hysteresis had become more obvious since the completion of the Three Gorges Dam (TGD) in 2003. The study by Wang et al. (2019) showed that while annual inflow to the TGR reduced by 6% (1990–2015), autumn inflow significantly decreased by 16%; climate change was the main contributor to both decreases (78% and 63%, respectively). The above studies have already highlighted the overwhelming impact of cascade reservoirs on the hydrological environment in the upper YRB particularly to the sediment transport and provided essential knowledge for further study. Despite this, considering the dramatic change of upstream water and sediment resources supplying the TGR, a systematic investigation involving the interaction between upstream sub-basins and the TGR under both spatial and temporal framework has yet to be reported by this stage.

The work presented by this paper tries to fill the above gap by first conducting hydrological analysis on the runoff and sediment load in recent 61 years (1956–2016) of main sub-basins upstream of the TGR, in terms of both annual and monthly variation. The quantification of the contribution of different driving forces (climate factors and human activities) is then carried out based on the runoff-sediment relationship in each sub-basin. In addition, the quantitative impact of the large reservoirs on annual sediment load as the main component of human activities is estimated for each sub-basin. The roles of cascade reservoirs together with the TGR are discussed under a spatial–temporal framework. As a whole, this study may serve as a piece of evidence to what extent upstream cascade reservoirs alter water and sediment supply regime to downstream; the framework of which can also be a reference for the environmental assessment and management of other large river basins with decadal time scales.

## 2. Material and methodology

### 2.1. Study area

The Yangtze River (also called Changjiang) ranks the third in length and the fourth in mean annual discharge in the world. It has a basin area of about $1.81 \times 10^6$ km$^2$ (18.8% of China's land area) and an annual runoff of about $9600 \times 10^8$ m$^3$ (36% of China's total runoff). It originates from the Qinghai-Tibet Plateau and flows 6387 km eastward to the East China Sea. Its upper reach (from river head to Yichang station, shown as Fig. 1) has a basin area of $1 \times 10^6$ km$^2$, which is 4504 km in length, covering a large elevation difference from over 5100 m to below 500 m near Yichang (with an average gradient of 1.1‰) (Yang et al., 2007), therefore, it contains abundant hydropower resources (89% of the whole basin; 42% of that in China in terms of technical exploitability) (Chu et al., 2019). The upper reach is also the major source of sediment: the mean sediment load at Yichang is 406 Mt/year, which is even 13% higher than that at Datong station (the control station of Yangtze River mouth).

Apart from the TGR Basin, there are four main sub-basins upstream that constitute the upper reach: Jinsha River Basin, Jialing River Basin, Min River Basin, and Wu River Basin (Fig. 1). Numerous large dams/reservoirs have been or are being constructed in the four sub-basins. Table 1 summarizes the reservoirs with a capacity larger than $1 \times 10^8$ m$^3$ that have been built or under construction. As is seen, the construction in the 21st century is greatly intensified compared to the 20th century; the total reservoir storage capacity by the end of 2016 has been already exceeded twice of the TGR ($393 \times 10^8$ m$^3$), and after the completeness of the Baihetan ($206 \times 10^8$ m$^3$), Wudongde ($74 \times 10^8$ m$^3$) and Lianghekou ($111 \times 10^8$ m$^3$) projects in the Jinsha River Basin in the future decade, this figure will even triple. In light of this, it is imperative to examine the impact of such human interference on water and sediment inflows to the downstream TGR.

### 2.2. Datasets

In this study, the precipitation data (1956–2016) downloaded from the website of the National Meteorological Information Center, China Meteorological Administration (CMA) (http://data.cma.cn/) are processed by the surface average method. The annual and monthly runoff and suspended sediment load data at Pingshan (Xiangjiaba), Gaochang, Zhutuo, Beibei, Wulong, and Yichang in 1956–2016 are collected for hydrological analysis, supported by the Hydrological Office of the Yangtze Water Resources Committee. The Pingshan (Xiangjiaba), Gaochang, Wulong, Beibei, and Yichang stations represent the control stations of the Jinsha River Basin, the Min River Basin, the Jialing River Basin, the Wu River Basin, and the TGR, respectively; the summation of the data at Zhutuo, Beibei and Wulong represent the inflows to the TGR.

### 2.3. Trend identification by Mann-Kendall test

The Mann-Kendall (M-K) test is adopted to identify the trend of hydrological time series (annual runoff and sediment load) in this study. It is a rank-based and nonparametric method commonly used in hydrological trend detection (Khaliq et al., 2009; Kumar and Jain, 2010; Wu et al., 2012). For a time series with independent identically distributed quantities $X_1, X_2, \ldots, X_N$ ($N$ is the length of the time series), the test statistic $S$, is calculated by

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} Sgn(X_j - X_i) \tag{1}$$

where $Sgn$ is the sign function. The test statistic $S$ approximately follows normal distribution when $N \geqslant 8$. Defining the standardized statistic value $Z$:

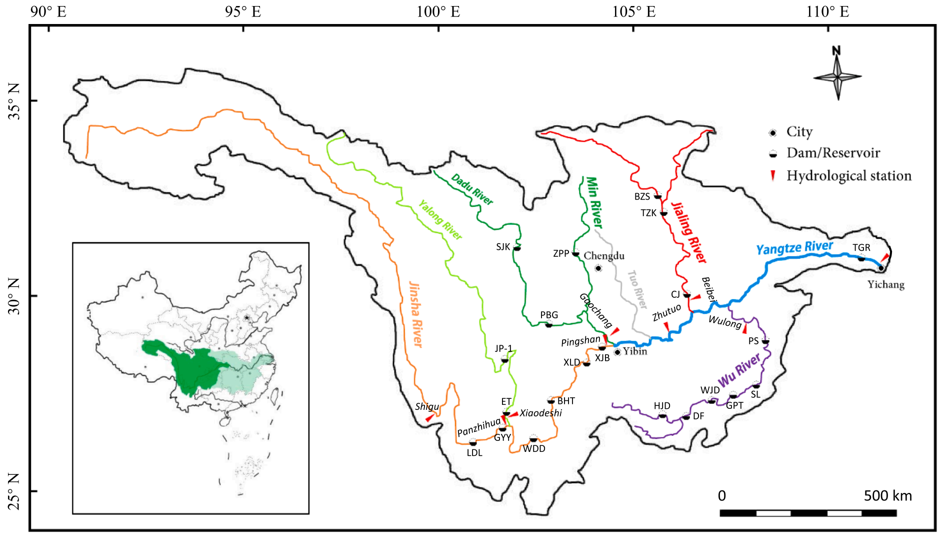


**Fig. 1.** Sketch map of the upper Yangtze River Basin with hydrological stations and large reservoirs (storage capacity lager than $10^9$ $m^3$).

**Table 1**
Summary of main reservoirs constructed upstream of the TGD.

| Basin | 20th Century | | 21st Century | |
|---|---|---|---|---|
| hline | Reservoir | Volume ($10^8 m^3$) | Reservoir | Volume ($10^8 m^3$) |
| Jinsha River | Ertan (ET) | 58 | Liyuan (LY), Ahai (AH), Jinanqiao (JAQ), Longkaikou (LKK), Ludila (LDL), Guanyinyan (GYY), Jinping-1 (JP1), Guandi (GD), Xiluodu (XLD), Xiangjiaba (XJB) | 330.8 |
| Min River | Gongzui (GZ), Tongjiezi (TJZ) | 5.1 | Zipingpu (ZPP), Luding (LD), Longtoushi (LTS), Pubugou (PBG) | 68.6 |
| Jialing River | Bikou (BK), Dongxiguan (DXG), Baozhusi (BZS), Xinzheng (XZ), Shengzhong (SZ) | 45.8 | Miaojiaba (MJB), Tingzikou (TZK), Jinyintai (JYT), Hongyanzi (HYZ), Jinxi (JX), Fengyi (FY), Qingju (QJ), Caojie (CJ) | 84.6 |
| Wu River | Puding (PD), Dongfeng (DF), Wujiangdu (WJD) | 37.5 | Yinzidu (YZD), Hongjiadu (HJD), Suofengying (SFY), Goupitan (GPT), Silin (SL), Shatuo (ST), Pengshui (PS), Yinpan (YP) | 160.2 |

$$Z = \begin{cases} \dfrac{S-1}{\sigma} & S > 0 \\ 0 \quad \text{if} & S = 0 \\ \dfrac{S+1}{\sigma} & S < 0 \end{cases} \tag{2}$$

where the standard deviation $\sigma$ is calculated as

$$\sigma = \sqrt{\frac{N(N-1)(N-5) - \sum_{p=1}^{n} t_p(p-1)(2p+5)}{18}} \tag{3}$$

where $n$ is the number of tied groups and $t_p$ is the number of ties in the $p$th tied group. For $Z$, if its absolute value is larger than the theoretical value $Z_{1-\alpha/2}$ where $\alpha$ is the significance level, the null hypothesis of no trend is rejected; positive $Z$ indicates an upward trend while negative $Z$ indicates a downward trend.

### 2.4. Macroscopic quantification of human and natural impacts by double mass curve

The double mass curve method is applied to quantify in a macroscopic sense that to what extent human activities and climate change (mainly the precipitation) contribute to the variation of annual sediment load inflow to the TGR. A double mass curve plots two cumulative quantities from a sequence of hydrologic observations, which exhibits a straight line if the relation between the two variables stays to be a fixed ratio (Searcy and Hardison, 1960). A break in the slope within a double mass curve indicates that a change in the constant of proportionality occurred (Searcy and Hardison, 1960; Li et al., 2016). The double mass curve method has been extensively applied to assess the alternation of precipitation-runoff and runoff-sediment relations in large basins such as the Yellow River Basin, the Yangtze River Basin, and the Pearl River Basin, where the proportionality assumption works reasonably well in terms of detecting the inconsistencies driven by climatic or anthropogenic factors (Xu, 2009; Gao et al., 2013; Li et al., 2016, 2018; Zhao et al., 2017). For example, a counterclockwise turning of the upper YRB rainfall(x)-sediment(y) double mass curve in the early 1980s was found to be associated with more frequent occurrence of landslide and debris flow in the Jinsha River Basin and the Jialing River Basin; while the clockwise turning in the early 1990s resulted from the water-soil conservation measures (Xu, 2009).

An illustrative example of applying the double mass curve method in the macroscopic quantification is shown in Fig. 2, which plots cumulative annual runoff v.s. cumulative annual sediment load. There are three time periods (1, 2 and 3) with the identifiable transition of water–sediment relation and three linear fitting curves of the discrete data points of the corresponding periods, the slopes of which are $\beta_1$, $\beta_2$ and $\beta_3$, respectively. Period 1 is chosen as the base period in which the water-sediment relation is assumed to be undisturbed by human or climatic changes. By the end of period 2, we can obtain the total amount of sediment load in period 2 if the water–sediment relation is unchanged (following the actual amount of runoff in the same period), $\Delta S_1$, as well as the actual total amount of sediment load in period 2, $\Delta S_2$:

$$\Delta S_1 = \beta_1 \Delta R_2 \tag{4}$$

$$\Delta S_2 = \beta_2 \Delta R_2 \tag{5}$$

where $\Delta R_2$ is the actual amount of accumulative runoff in period 2. Then

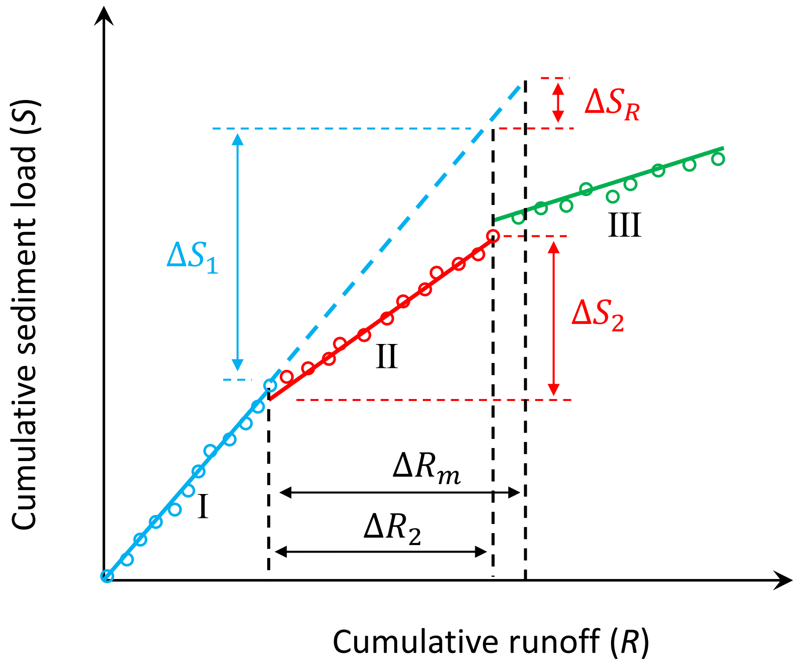


**Fig. 2.** A graphical illustration of quantifying human and natural impacts to sediment load by double mass curve.

the change of sediment load induced by the factors other than runoff, $\Delta S_{NR}$, is given as

$$\Delta S_{NR} = \Delta S_1 - \Delta S_2 \tag{6}$$

Note that positive value of $\Delta S_{NR}$ indicates effects of sediment reduction while negative value indicates sediment intensification. Further, the expected total amount of runoff in period 2 based on the average annual runoff of the whole period is $\Delta R_m$, which may be different from the actual amount, $\Delta R_2$. Positive value of $\Delta R_m - \Delta R_2$ means that period 2 is relatively dry and vice versa. Then, the amount of change sediment load due to the change of runoff as the result of climate change, $\Delta S_R$, is given as

$$\Delta S_R = \beta_1(\Delta R_m - \Delta R_2) \tag{7}$$

For a gross assessment, if the runoff change is dominated by the variation of precipitation, it is considered that the contribution of runoff can represent the natural driver of sediment change ($C_p$) while the contribution of factors other than runoff/precipitation is ascribed to human activities ($C_h$) as adopted by Zhao et al. (2017). Thus, the two contribution rates are calculated as

$$\begin{aligned} C_p &= \frac{\Delta S_R}{\Delta S_R + \Delta S_{NR}} \times 100\% \approx \frac{\Delta S_p}{\Delta S_p + \Delta S_h} \times 100\% \\ C_h &= \frac{\Delta S_{NR}}{\Delta S_R + \Delta S_{NR}} \times 100\% \approx \frac{\Delta S_h}{\Delta S_p + \Delta S_h} \times 100\% \end{aligned} \tag{8}$$

where $S_h$ = mean annual change of sediment load by human activities; $C_h$ = contribution of human activities to the change of sediment load; $S_p$ = mean annual change of sediment load by precipitation; $C_p$ = contribution of precipitation to the change of sediment load, respectively. In later context, sediment trapped in reservoirs per year on average, $I_s$, will also be estimated for a reference to $S_h$, which will be introduced in the next sub-section.

### 2.5. Reservoir trapping efficiency estimation by empirical formula

In this study, the cascade reservoirs upstream of the TGD play an important role in the reduction of annual sediment load. Besides the double mass curve, it is necessary to particularly estimate the ratio of annual sediment deposition to total sediment input to the reservoirs, or the trapping efficiency (*TE*). The widely used empirical formula, which is originally proposed by Brune (Brune, 1953) is applied in this study with an improved form (Vörösmarty et al., 2003; Garg and Jothiprakash, 2010):

$$TE = 1 - \frac{0.05}{\sqrt{\Delta\tau_r}} \tag{9}$$

$$\Delta\tau_r = \frac{\sum_{i=1}^{n} V_i}{Q} \tag{10}$$

where $V_i$ is the operational volume of the $i$th reservoir in the basin to be evaluated (and there are $n$ reservoirs in total), $Q$ is the average annual runoff at the outlet of the most downstream reservoir of the basin, $\Delta\tau_r$ is the reservoir residence time of the basin. The above equation deals with the situation that cascade reservoirs connect in series. For tributaries with reservoirs that join in parallel, the total trapping efficiency $TE_K$ can be expressed as (if there are $k$ sub-basins for example):

$$TE_K = \frac{\sum_{j=1}^{k} TE_j Q_j}{Q_K} \tag{11}$$

where $Q_K$ is the mean annual runoff at the outlet of the most downstream reservoir. More detailed application of the method in the upper YRB can be referred to Li et al. (2011) and Zhang et al. (2019).

## 3. Results and discussions

In this section, the annual variation of runoff as well as the suspended sediment load of the control stations upstream of the TGR, are analyzed, the characteristics of monthly distribution are also discussed. Then, the drivers of runoff and sediment load change in the interested sub-basins are identified and discussed, with particular attention paid to the effect of cascade reservoirs.

### 3.1. Annual variation

Fig. 3 shows the annual runoff and sediment load at Yichang station, the control station of the TGD. Both runoff and sediment load had a

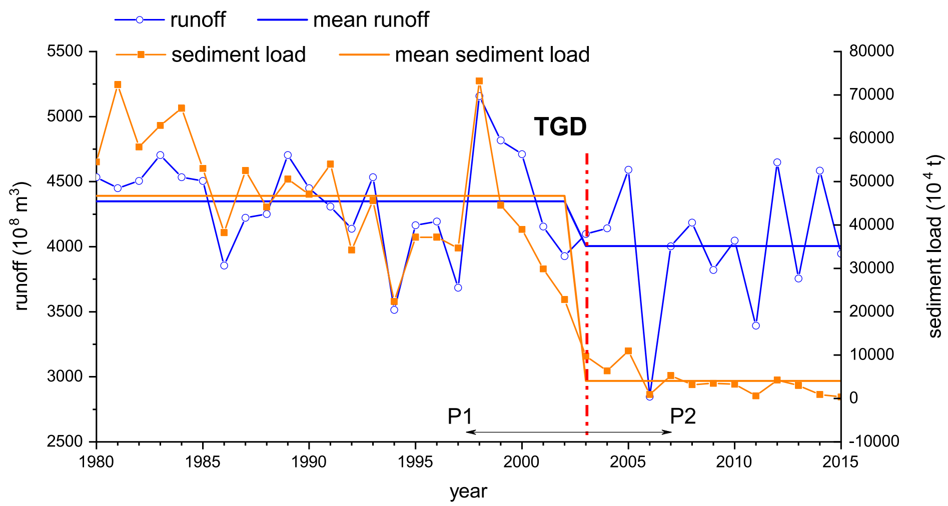


**Fig. 3.** Annual runoff and sediment load at Yichang station. P1 (1980–2002) is the pre-TGD period while P2 (2002–2015) is the post-TGD period.

decreasing trend during the investigated period, but the reduction of sediment load was much more significant, especially after the year of the commencement of the impoundment of the TGR (2003): comparing P2 (post-TGD, 2003–2015) to P1 (pre-TGD, 1980–2002), the mean runoff decreased about 8% from $4365 \times 10^8$ m$^3$ to $4005 \times 10^8$ m$^3$, while the rate of mean sediment load reduction was about 91% (Tables 2 and 3). Although the strength of sediment entrapment of TGD has been well illustrated (Hu et al., 2009; Tang et al., 2014), it is not adequate to completely attribute these changes to the TGD without analyzing the sources of water/sediment supply. The three control stations of the upper sub-basins, namely Zhutuo (the Jinsha River Basin and the Min River Basin), Beibei (the Jialing River Basin), and Wulong (the Wu River Basin), together contributed nearly 90% of the runoff and sediment load to Yichang station annually in P1. The sum of the annual runoff and sediment load of the three stations, which is regarded as the resources inflow to the TGR, are plotted in Fig. 4. The runoff inflow only showed a slightly decreasing trend (decreased 6% from $3818 \times 10^8$ m$^3$ to $3582 \times 10^8$ m$^3$), while the sediment load inflow decreased continuously and dramatically since the late 1990s. Comparing P2 with P1, the sediment inflow reduced 59% from 417 Mt/yr to 172 Mt/yr, which accounted for nearly 60% of the sediment reduction of Yichang on average in P2 according to Table 3. Therefore, apart from the effect of TGR itself, the variation of the upstream hydrology regime is also critical for the output of water and sediment at Yichang. The 3 stations are further analyzed individually as follows.

Shown as Fig. 5, there was no obvious change of annual runoff at Zhutuo station in 1980–2015 about its mean value $2615 \times 10^8$ m$^3$. The maximum value was $3170 \times 10^8$ m$^3$ (in 1998), the lowest value occurred in 2011 ($1934 \times 10^8$ m$^3$). However, a salient downward trend of yearly sediment load could be observed after the 21st century and it decreased to the lowest value of $2120 \times 10^4$ t in 2015, while the highest value was about 24 times larger ($48400 \times 10^4$ t in 1998). The M-K trend test (Fig. 5) consistently showed no significant trend of runoff, but the sediment load was detected to decrease with a significance level $\alpha <$ 0.05 since the year 2004.

**Table 2**
The mean annual runoff at the four hydrologic stations before and after TGR impoundment.

| Period | Runoff ($10^8$ m$^3$) | | | |
|---|---|---|---|---|
| | Zhutuo | Beibei | Wulong | Yichang |
| 1980–2015 | 2615 | 643 | 475 | 4235 |
| 1980–2002 | 2678 | 638 | 502 | 4365 |
| 2003–2015 | 2504 | 650 | 428 | 4005 |

The runoff at Beibei had a slight downward trend in the first half of the investigated period and then kept to be stable in the second half. The maximum value ($1070 \times 10^8$ m$^3$ in 1983) was three times larger than the minimum value ($308 \times 10^8$ m$^3$ in 1997). The M-K test justified the downward trend since the line broke through the significant level in 1995 for a period. The sediment load reduced significantly since 1981 to less than $1900 \times 10^4$ t in 1994 and then remained at a low level, except the year 1998 when the sediment load jumped to a peak of $9900 \times 10^4$ t.

The annual runoff and sediment load at Wulong station are less than the other two tributaries (on average $475 \times 10^8$ m$^3$ and $1679 \times 10^4$ t, respectively), but the total reservoir capacity is larger (Table 1). Similar to Zhutuo station, no significant trend of runoff could be observed or detected by M-K test, while the sediment load saw a decrease since the 21st century, which was no more than $1000 \times 10^4$ t in the last 9 years, and it remarkably dropped to only $94 \times 10^4$ t in 2013.

In general, the annual sediment load from the sub-basins upstream of TGD went through a considerable decrease since the late 1990s, while the annual runoff was relatively stable, with a slight decline.

### 3.2. Monthly variation

The change of monthly precipitation, runoff and sediment load at Zhutuo, Beibei, Wulong and Yichang is shown in Fig. 6. The precipitation is the average value in the basin upstream of the corresponding hydrological stations. Comparisons were made between the mean values in P2 (post-TGD period) and P1 (pre-TGD period) and were presented in terms of percentage. For precipitation, there was a slightly larger amount in Spring and less in Summer in P2; a negative change rate can be observed in winter months (December to February) except Wulong station, but the total amount of precipitation in these months accounted for no more than 5% of the annual quantity on average. There were no other obvious characteristics of the change of precipitation and the rate was fairly small compared to runoff and sediment load. The runoff in the flood season decreased at all of the 4 stations, while it increased in other seasons. This can be explained by the operation of the cascade reservoirs in the upper YRB, which evened the inner-year distribution of water discharge. In general, the statistics of the change rate of precipitation and runoff offered an impression that the total amount of annual water resources supply roughly kept unchanged (consistent with the annual data in the previous subsection), which was significantly different from the sediment load. The reduction of sediment load exhibited a more uniform manner compared to runoff: it became at least 70% smaller for all the months at Yichang, while a large rate of reduction mainly appeared in the flood season at other 3 tributary stations, and this is as

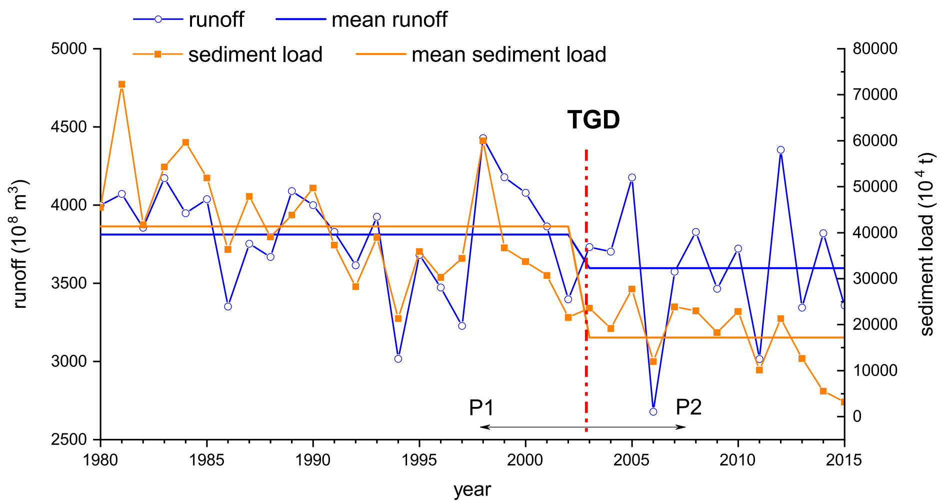


**Fig. 4.** Annual runoff and sediment load inflows to the Three Gorges Reservoir, obtained by the summation of data at Zhutuo, Beibei and Wulong. P1 and P2 have the same meaning as Fig. 3.

**Table 3**
The mean annual sediment load at the four hydrologic stations before and after TGR impoundment.

| Period | Sediment load ($10^4$ t) | | | |
|---|---|---|---|---|
| | Zhutuo | Beibei | Wulong | Yichang |
| 1980–2015 | 24846 | 6420 | 1581 | 31023 |
| 1980–2002 | 31052 | 8426 | 2189 | 46274 |
| 2003–2015 | 13867 | 2870 | 505 | 4040 |

expected because the reservoirs upstream of TGR could already intercept the major sediment supply mostly carried by the runoff in the flood season and hereby limited the further sediment retention in TGR. These patterns highlight the great impact of human activities on regional hydrologic characteristics not only in terms of overall quantity but also in the temporal distribution.

### 3.3. *The driving factors of the runoff variation*

The annual runoff imported to the TGR had little change over the decades, compared to the extent of sediment load. The average annual runoff in 2003–2015 decreased 6% at Zhutuo, increases 2% at Beibei and decreases 15% at Wulong relative to the average value in 1980–2002. Numerous studies have indicated the dominance of precipitation on basin runoff in the YRB (Chen et al., 2014; Guo et al., 2018; Wang et al., 2011); this is indeed the case in the sub-basins upstream of the TGR as revealed by our results. Fig. 7 plots the double mass curves between the annual runoff and annual precipitation in the four sub-basins upstream of TGR, the Jinsha River Basin, the Min River Basin, the Jialing River Basin and the Wu River Basin, respectively. The fitted functions are all almost linear and exhibit perfect correlation with $R^2$ larger than 0.99. This shows that the annual precipitation was still the major explanatory driving factor of the variation of annual runoff, while the influence of other factors were not identifiable in the first-order sense, although human activities in the upstream reach of the YRB have been playing an increasingly important role recently (Guo et al., 2018). The impact of the operation of dams or reservoirs was unclear from the double mass curves. A gross estimation of the total capacity of large reservoirs of the four sub-basins is given in Table 1: more than $600 \times 10^8$ m$^3$ of the volume of impoundment had been exerted in the 21st century. However, as many of the reservoirs are seasonally regulated (typically, they impound water during the latter half of the wet season and release water during the driest months (Yang et al., 2010)), for a gross estimation they only influence the intra-annual runoff except the first year of impoundment (Zhang et al., 2019). This is consistent with the result in the last section that, inflow runoff decreased in wet seasons while increased in dry seasons, becoming more regulated. As a whole, the annual runoff inflow to the TGR was governed by the annual precipitation in the studied period.

### 3.4. *The driving factors of the sediment load variation*

We analyze the contribution of different driving factors to sediment load variation via the method introduced in Section 2 based on the data in the four sub-basins upstream of the TGR. The driving factors that can be identified from the double mass curves are (i) the variation of annual runoff and (ii) the factors other than runoff (mainly considered to be influenced by human activities). As shown in Section 3.3, annual precipitation continuously dominated the annual runoff with a linear relation in all sub-basins within the studied period, hence we consider runoff to represent the change of precipitation reasonably well, so that the assumption in Section 2.4 can be applied. For each sub-basin, the studied period (1956–2016) is divided into 4 sub-periods (P1 to P4) demarcated by turning points observed in the double mass curve, and the quantification of the contribution is carried out for each sub-period. Additionally, the empirical method by Brune's formula is applied to estimate the trap efficiency of the cascade reservoirs in each sub-basin. The double mass curve is shown in Fig. 8, the corresponding results are summarized in Tables 4–7.

In the Jinsha River Basin, the turning of sediment-runoff relation mainly occurred in P3 and P4. First, the sediment load increased slightly in P2 (1963–1996) by $0.25 \times 10^8$ t/yr on average, despite the negative contribution of precipitation (−21%), which suggested that the increased sediment load due to human activities approximately equaled 6 times of the amount of sediment load reduction due to precipitation reduction. This may be caused by the land-surface disturbance such as land exploitation and road construction accompanied with the economic growth of China since the 1980s (Lu, 2005). In the next period, a considerable decrease of sediment load occurred ($0.71 \times 10^8$ t/yr) and human activities contributed 118 %, covering the positive effects of precipitation in sediment increase. This was probably because a series of soil conservation, as well as afforestation projects were launched since the 1990s in the middle and lower reaches of the Jinsha River Basin (Wei et al., 2011), also the newly constructed dams and reservoirs trapped a large amount of sediment. The gross estimation based on the empirical method showed that the large reservoirs on average trapped 31 Mt sediment per year in P3 (mainly due to Ertan reservoir), accounting for

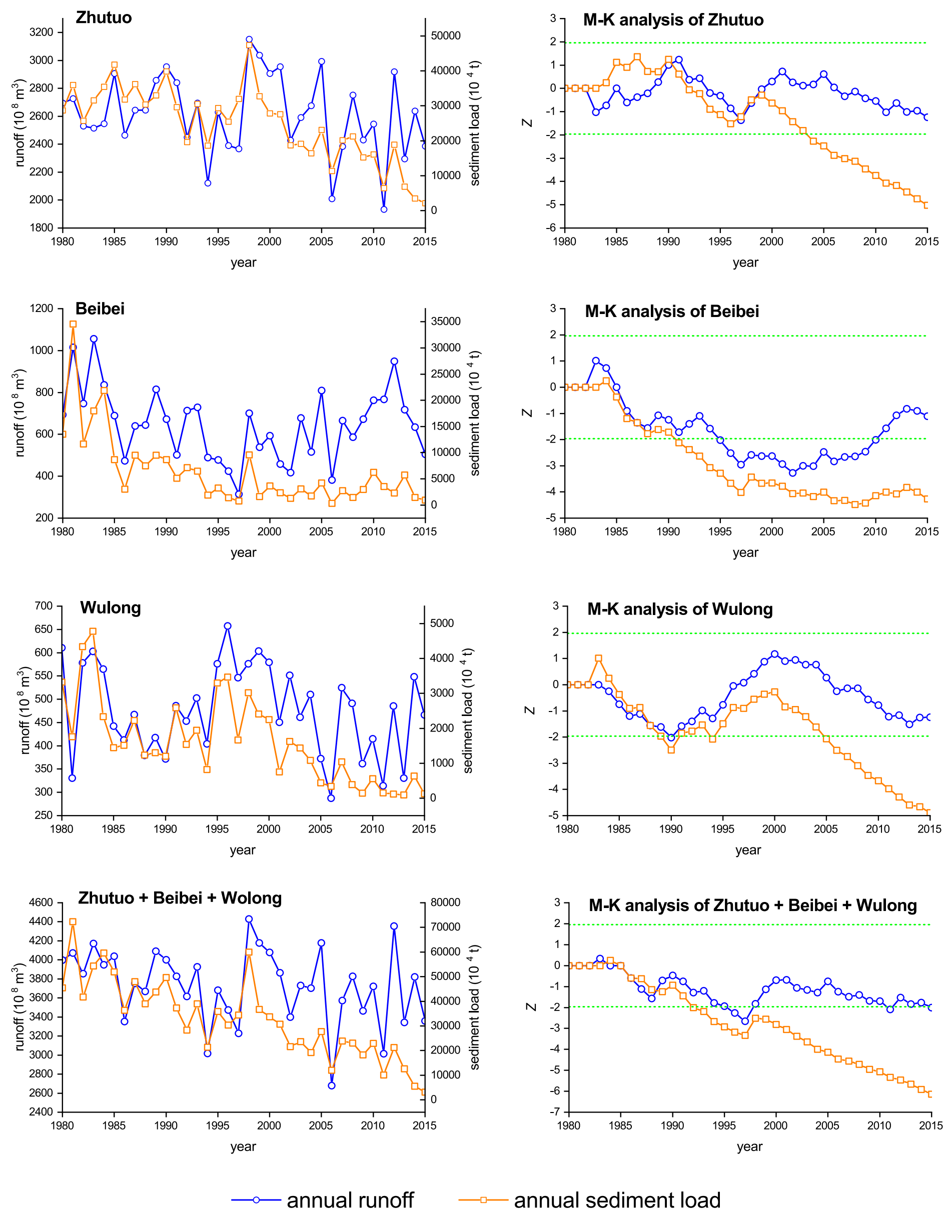


**Fig. 5.** Annual runoff and sediment load at 3 stations of the upper YRB in 1980–2015, as well as the M-K trend analysis of the corresponding time series. $Z$ = test statistics, which indicates the trend significance. The green dashed lines (±1.96) corresponds to the significance level 0.05.

more than 40 % of the mean annual reduction of the sediment load, 71 Mt. Actually, an investigation conducted by regression method by Feng et al. (2008) demonstrated that the actual sediment load trapped in Ertan reservoir (between 1998 and 2004) was between 50 to 65 Mt. In alignment with the massive construction of large reservoirs after 2010, the sediment load dramatically decreased in P4 (2012–2016), at a rate of $2.04 \times 10^8$ t/yr with a trapping efficiency of 90.1%, and 95 % was ascribed to human activities. The quantity roughly agreed with the value estimated sediment load trapped by the reservoirs ($2.19 \times 10^8$ t/yr, in agreement with Zhang et al., 2019), indicating the dominating role of reservoirs. In comparison, the influence of precipitation change on sediment load was negligible in P3 and P4.

The Jialing River Basin exhibited a continuous sediment reduction throughout the studied period (P2 to P4) and the amount of the change was comparable with the Jinsha River Basin. The influence of precipitation on sediment load was mainly observed in P2 when the increasing precipitation increased 9.1 Mt sediment load annually on average but was still offset by the decreasing amount (20.8 Mt/yr on average) due to human activities. From P3 onward, the influence of precipitation became less important, which was similar to the Jinsha River Basin. As for human activities, in every 10 years from 1967 to 2016, there were large reservoirs dammed in the mainstream, e.g. Bikou (5.2) in 1971, Shengzhong (13.4) in 1977, Baozhusi (25.5) in 1991, Caojie (22.2) in 2005 and Tingzikou (41.2) in 2010, where the numbers in brackets are the volume in $10^8$ $m^3$. From P2 to P4, the estimated sediment load trapped by reservoirs roughly agreed with the annual rate of sediment reduction; accordingly, the estimated trap efficiency increased from about 40% to 70% and then to 90%. The trapped sediment load per year was estimated to be comparable for the three sub-periods and was even higher than the measured value. Despite the roughness of the empirical formula for trap efficiency, the contribution of a series of water and soil conservation measures since 1989 (named as Changzhi Project) to the declining soil erosion (and thus the sediment load) could be the most probable reason (Xu, 2007; Dai and Lu, 2014). The conservation measures were estimated to reduce sediment load between 40% and 60% in the upper reaches, and 15% to 20% in the lower reaches (Yang and He, 2005). Assuming 30% of the total sediment yield in the Jialing River Basin was reduced due to water and soil conservation, the amount that

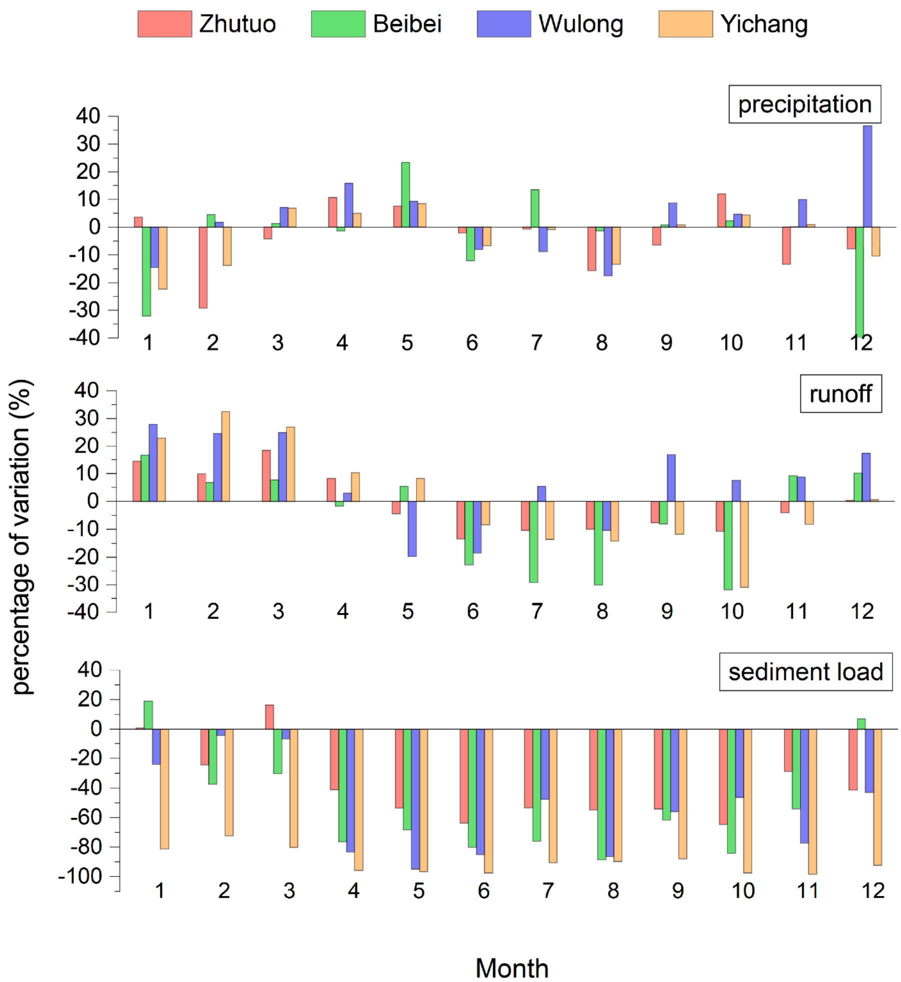


**Fig. 6.** The change of monthly distribution of precipitation, runoff and sediment load at Zhutuo, Beibei, Wulong and Yichang stations. The precipitation is the average value in the basin upstream of the corresponding hydrological stations. Comparisons are made between pre-TGD period P1 (1980–2002) and post-TGD period P2 (2003–2015).

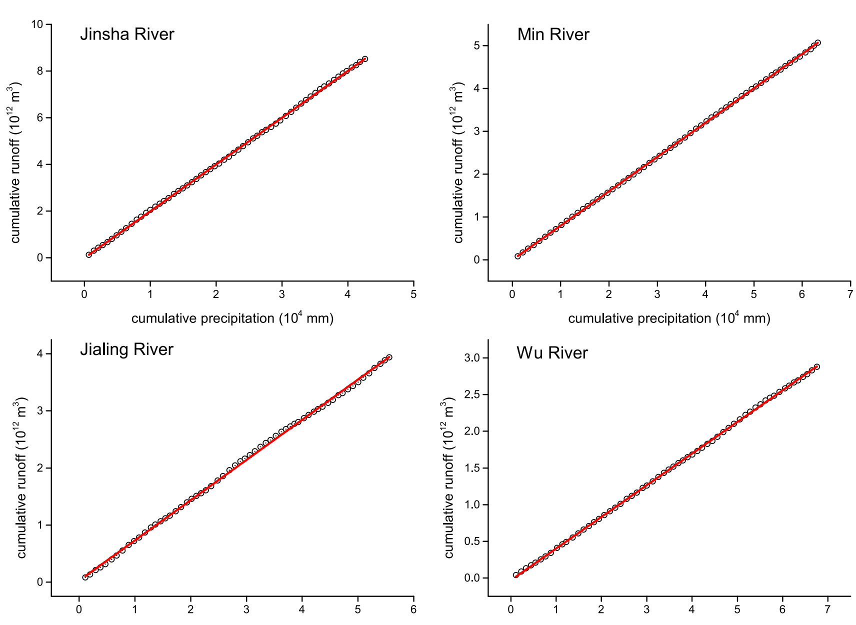


**Fig. 7.** Double mass curves between annual runoff and precipitation in the sub-basins of the upper YRB.

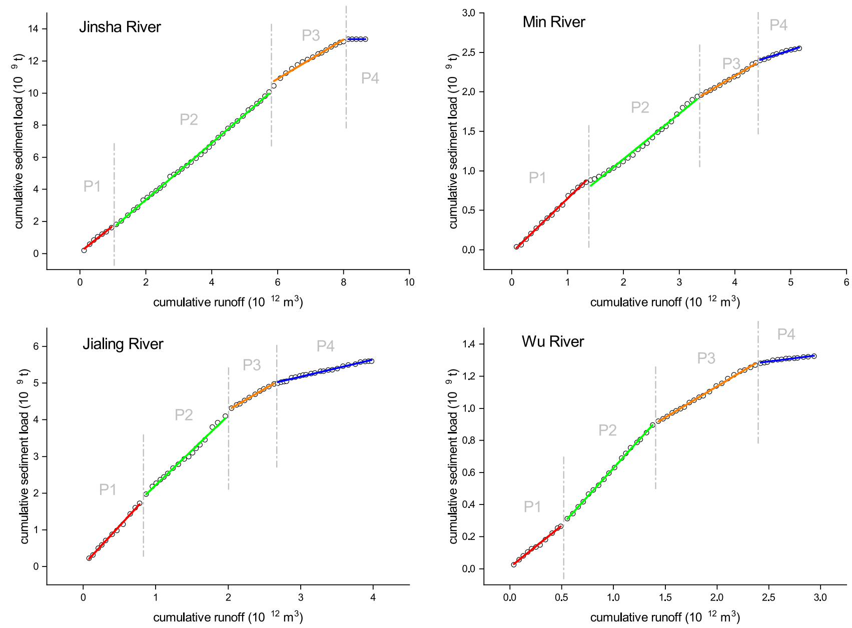


**Fig. 8.** Double mass curves between annual sediment load and runoff in the sub-basins of the upper YRB. *P*1 to *P*4 denote the different periods demarcated by the slope change of the double mass curve. The fitted functions can be found in Table 4–7.

**Table 4**
Impact of human activities and precipitation change on annual sediment load of the Jinsha River Basin. $x$ and $y$ in the fitted functions are the accumulated runoff and sediment load, respectively. $S$ = the total change of sediment load; $S_h$ = mean annual change of sediment load by human activities; $C_h$ = contribution of human activities to the change of sediment load; $S_p$ = mean annual change of sediment load by precipitation; $C_p$ = contribution of precipitation to the change of sediment load; $TE$ = trapping efficiency; $I_s$ = sediment load trapped in reservoirs per year.

| Period | | Fitted function | $S$ $10^8$ t | $S_h$ $10^8$ t/yr | $C_h$ % | $S_p$ $10^8$ t/yr | $C_p$ % | $TE$ % | $I_s$ $10^8$ t/yr |
|---|---|---|---|---|---|---|---|---|---|
| P1 | 1956–1962 | $y = 16.33x + 8187$ | | | | | | | |
| P2 | 1963–1996 | $y = 17.70x - 19477$ | 7.01 | 0.25 | 121 | −0.044 | −21 | 0 | 0 |
| P3 | 1997–2011 | $y = 12.24x + 354601$ | −8.99 | −0.71 | 118 | 0.11 | −18 | 25.5 | 0.31 |
| P4 | 2012–2016 | $y = 0.13x + 1325060$ | −10.72 | −2.04 | 95 | −0.1 | 5 | 90.1 | 2.19 |

**Table 5**
Impact of human activities and precipitation change on annual sediment load of the Min River Basin. The variable notations are the same as Table 4.

| Period | | Fitted function | $S$ $10^8$ t | $S_h$ $10^8$ t/yr | $C_h$ % | $S_p$ $10^8$ t/yr | $C_p$ % | $TE$ % | $I_s$ $10^8$ t/yr |
|---|---|---|---|---|---|---|---|---|---|
| P1 | 1956–1970 | $y = 6.84x - 3297$ | | | | | | | |
| P2 | 1971–1993 | $y = 5.75x - 186$ | −1.304 | −0.068 | 121 | 0.012 | −21 | 22.1 | 0.08 |
| P3 | 1994–2006 | $y = 4.13x + 54969$ | −3.45 | −0.24 | 88 | −0.032 | 12 | 34.7 | 0.12 |
| P4 | 2007–2016 | $y = 2.26x + 140029$ | −4.46 | −0.4 | 90 | −0.046 | 10 | 49.4 | 0.25 |

**Table 6**
Impact of human activities and precipitation change on annual sediment load of the Jialing River Basin. The variable notations are the same as Table 4.

| Period | | Fitted function | $S$ $10^8$ t | $S_h$ $10^8$ t/yr | $C_h$ % | $S_p$ $10^8$ t/yr | $C_p$ % | $TE$ % | $I_s$ $10^8$ t/yr |
|---|---|---|---|---|---|---|---|---|---|
| P1 | 1956–1966 | $y = 21.37x + 3178$ | | | | | | | |
| P2 | 1967–1983 | $y = 18.99x + 31703$ | −1.99 | −0.208 | 178 | 0.091 | −78 | 42.1 | 0.28 |
| P3 | 1984–1993 | $y = 11.43x + 198152$ | −6.27 | −0.96 | 105 | 0.045 | −5 | 69.4 | 0.99 |
| P4 | 1994–2016 | $y = 4.66x + 377752$ | −35.15 | −1.38 | 90 | −0.15 | 10 | 88.4 | 1.17 |

was trapped in large reservoirs in P4 still took up 60% of the total amount of reduction ($0.82 \times 10^8$ t/yr v.s. $1.38 \times 10^8$ t/yr), which remained to be the major reason for sediment reduction.

For the Min River Basin, the turning points in the double mass curve are not as evident as the Jinsha River Basin and the Jialing River Basin. However, there still existed tractable effects of human activities while

**Table 7**
Impact of human activities and precipitation change on annual sediment load of the Wu River Basin. The variable notations are the same as Table 4.

| Period | | Fitted function | $S$ $10^8$ t | $S_h$ $10^8$ t/yr | $C_h$ % | $S_p$ $10^8$ t/yr | $C_p$ % | $TE$ % | $I_s$ $10^8$ t/yr |
|---|---|---|---|---|---|---|---|---|---|
| P1 | 1956–1966 | $y = 5.18x + 947$ | | | | | | | |
| P2 | 1967–1983 | $y = 7.11x - 8373$ | 1.25 | 0.052 | 70 | 0.022 | 30 | 77 | 0.07 |
| P3 | 1984–2003 | $y = 3.87x + 36279$ | −1.907 | −0.099 | 104 | 0.004 | −4 | 83.2 | 0.25 |
| P4 | 2004–2016 | $y = 0.82x + 108637$ | −3.35 | −0.23 | 88 | −0.03 | 12 | 92.2 | 0.29 |

the impact of precipitation change was also a much smaller counterpart. The sediment load decreased continuously in the three sub-periods (P2–P4) and more than half of this quantity can be attributed to reservoirs, although the amount of the change was much less compared to the above two basins. The trap efficiency increased steadily from 22% to 35% and then to 50% in the three sub-periods; $0.25 \times 10^8$ t out of $0.4 \times 10^8$ t of sediment load was trapped in large reservoirs per year in the recent scenario, P4 (2007–2016).

The Wu River Basin had the second-largest capacity of large reservoirs (nearly 20 km$^3$) among the four basins, although its average annual runoff was the smallest. The large reservoirs could explain the entire sediment reduction by comparing $S_h$ to $I_s$. In P2 (1967–1983), while there were already reservoirs constructed (with a trapping efficiency of 77%), the rate of sediment load yielded by per unit volume of runoff still increased compared to P1 and the contribution from human activities accounted for 70%, probably suggesting vigorous exploitation of land surface; another 30% of sediment load increase was due to the increase of annual precipitation. Little information was available for soil and water conservation in this basin; excessive land exploitation and river channel mining might continuously happen in P3 and P4 so that the sediment reduction was offset to some degree. Further in P4 (2004–2016), after Goupitan, Pengshui and Shatuo reservoirs are completed, the sediment trapping efficiency increased to 92% (annually trapping 29 Mt), comparable with the result calculated by the double mass curve ($S_h = 23$ Mt), indicating the dominant role of human activities (mainly the cascade reservoirs) on the sediment load.

To summarize, the sediment load in the four sub-basins went through a drastic decrease in the recent two sub-periods, which was most significant in P4. Generally, it covers the time range after 2000, when large reservoirs were being intensely constructed and operated, and the total trap efficiency of the large reservoirs zoomed to nearly 90% for all of the four basins. Among them, the Jinsha River Basin and the Jialing River Basin especially played an important role since they on average contribute more than 80% of the total sediment load of the four basins (52% and 30% respectively, based on the data in 1956–1980). Precipitation was able to influence the sediment load as a secondary contributor compared to human activities. Especially since 2000, approximately 10% (or even less) of the sediment load variation in the four sub-basins could be explained by precipitation.

### 3.5. *The altered sediment flux pattern across the upper YRB*

The pattern of sediment flux across the upper YRB, which involves the sediment retention in the reservoirs as well as the sediment discharge downstream of the TGD, has changed remarkably in response to the emerging cascade reservoirs. Fig. 9 shows the gross estimation of the total reservoir capacity in the sub-basins as well as the trapped sediment load. It is obvious that the sediment trapped in the reservoirs increased in alignment with the capacity, which especially jumps with the appearance of some super large reservoirs such as Ertan, Xiangjiaba

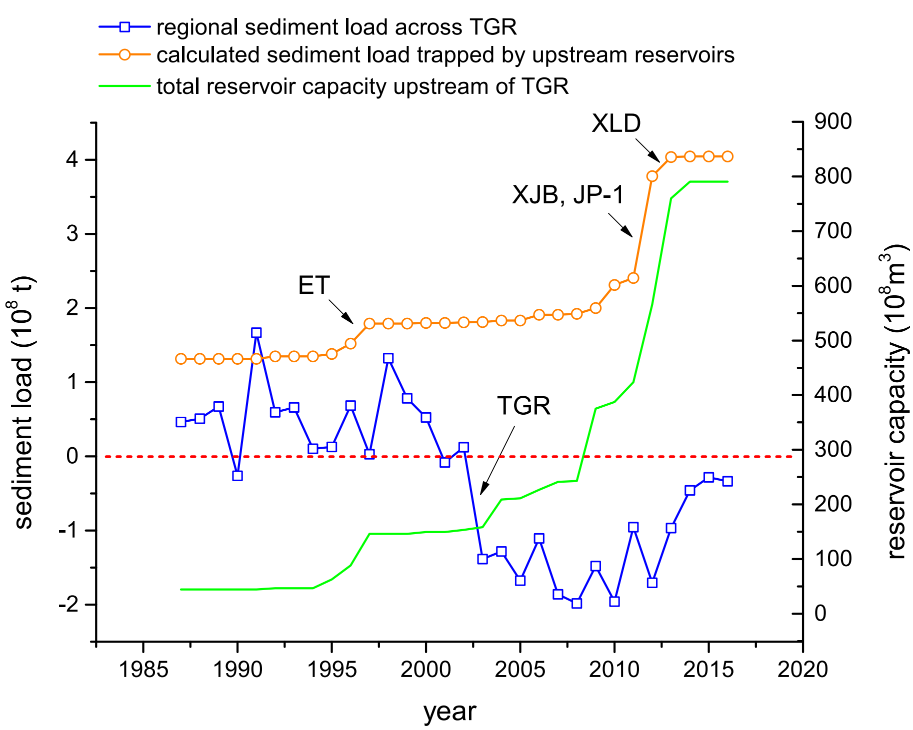


**Fig. 9.** Variation of regional sediment load across the TGR (obtained by the subtraction between Yichang station and upstream Zhutuo, Beibei and Wulong), total capacity of the reservoirs upstream of TGR as well as the calculated sediment load trapped by the reservoirs. The red dashed line marks the zero regional sediment load.

and Xiluodu. As the total reservoir storage capacity increased from 45 × $10^8$ $m^3$ in the 1980s to about 150 × $10^8$ $m^3$ in the 2000s and 790 × $10^8$ $m^3$ by the end of 2016, the sediment load trapped by large reservoirs upstream of the TGR roughly increased from 130 Mt/yr to 200 Mt/yr and to over 400 Mt/yr correspondingly. The reservoirs could lead to a sediment reduction of 3.9 × $10^8$ t/yr by the end of 2016, accounting for 86% of the total sediment yield of the four basins in 1956–1980 and 96% of the human-induced sediment reduction; the contribution from the Jinsha River Basin and the Jialing River Basin was 86%. The overall relation between annual sediment load and runoff in the upstream basins has been evaluated in a normalized manner, as shown in Fig. 10. The slopes of the curves, which means the amount of sediment load carried per unit runoff, tends to decrease over the three equal period time; the correlation coefficient also tends to decrease. This shows on one hand, reservoirs significantly reduced the strength of sediment yield for the basin, on the other hand, they exerted disturbance to the runoff-sediment relation owing to the dam operation. As a result, the resultant sediment load became more unpredictable and uncertain.

In the presence of the continuous sediment inflow reduction (Fig. 4), the sectional sediment load across the TGR (obtained by subtracting the inflows from the value at Yichang) went through an interesting alteration. First, from 2003 to 2010, the sectional sediment load dropped to a negative value and kept declining because of the sedimentation in the TGR. However, in the following years, the upstream sediment supply kept declining even to below 1 × $10^8$ t after 2014. Although the sectional sediment load was still negative so that the sedimentation in the TGR is continuing, such a trend started to rebound towards equilibrium, and thus the situation of retention in the TGR could be mitigated. In the meantime, the contribution of the TGR in sediment retention among all the large reservoirs in the upper Yangtze River was decreasing, as shown in Fig. 11. The result is obtained by performing the trapping efficiency calculation for the whole upper YRB in 2003–2016 by the method introduced in Section 2.5; historical (pre-dam) mean annual runoff and sediment yield are used. In 2005, the TGR contributed most of the total sediment retention ($I_s$), while in 2015 this situation was overturned by the dramatic increase of trapping efficiency of upper cascade reservoirs (especially the Jinsha River Basin, which accounts for 45%), and the sediment trapped in the TGR became less than one-fifth of the total amount. In the near future, other huge reservoirs such as Wudongde and Baihetan will be constructed and put into operation, the trap efficiency of the Jinsha River Basin will increase to 93.1% as estimated in Zhang et al. (2019) (95% according to Yang et al. (2007)). Therefore, the sediment load inflows to the TGR will further decrease, so will the relative contribution of the TGR in sediment retention for the whole upper Yangtze River. Under the current and future situation, the strategy of the TGR operation may change correspondingly to adapt to the new pattern of sediment supply from upstream, as suggested by Dai and Lu (2014) as an example, water storage can start from July instead of September to allow the storage of more silty water. Nevertheless, this may aggravate the riverbed incision downstream of the TGD. Comprehensive quantitative investigation for optimal management for the whole cascade reservoirs system requires future efforts.

## 4. Concluding remarks

This study provides a systematic analysis of the influence of cascade reservoirs on the variation of annual runoff and sediment load inflows to the TGR. The main conclusions are marked as follows:

(1) Comparing post-TGD years with pre-TGD years, a slight decrease (6%) of annual runoff inflow to the TGR occurred, together with a dramatic decrease of sediment load inflow (nearly 60% of the pre-TGD value). While the monthly pattern of precipitation had no obvious change, the runoff and sediment load (both upstream control stations and downstream Yichang) all went through a significant decrease in wet seasons; the runoff in dry seasons also saw an increase, implying the consequence of intense regulation.

(2) Perfect linear relationship between cumulative precipitation and cumulative runoff is found for all of the 4 sub-basins, indicating a reliable dominance of annual precipitation on annual runoff. Thus, the influence of human activities on annual runoff can be considered insignificant for the studied area; the annual runoff can be directly applied as an indicator of precipitation (climate effects) in the contribution analysis of sediment load.

(3) Human activities are found to be the dominant contributor to the variation of sediment load for both inflows and outflows of the TGR. The sediment load in all of the four sub-basin went through a drastic decrease particularly since the 1990s, with human activities explaining more than 90% of the reduction (comparable to the annual sediment

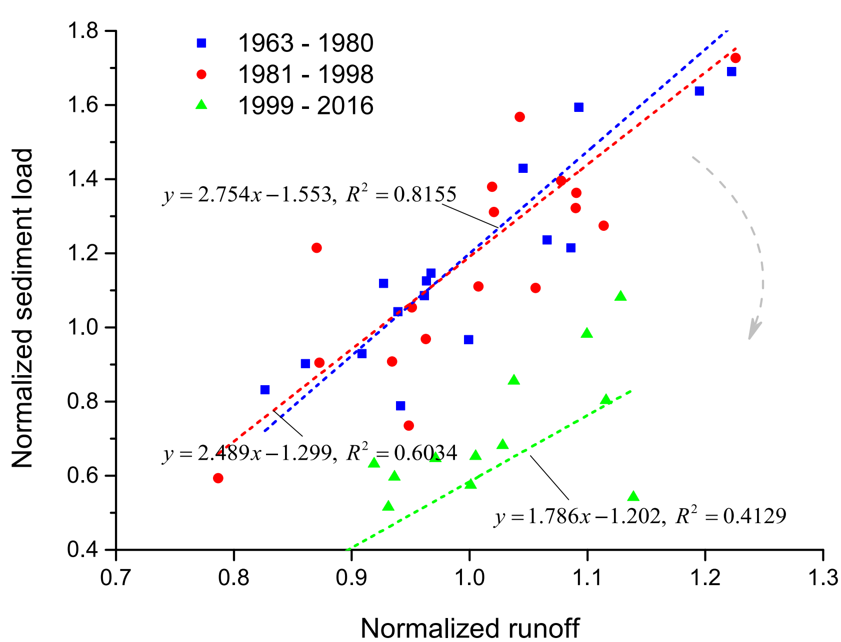


**Fig. 10.** Runoff-sediment relation of upstream TGR in different time periods. The runoff and sediment are the summation of the upstream four stations (Pingshan, Beibei, Gaochang & Wulong) and normalized by the average value during 1963–2016.

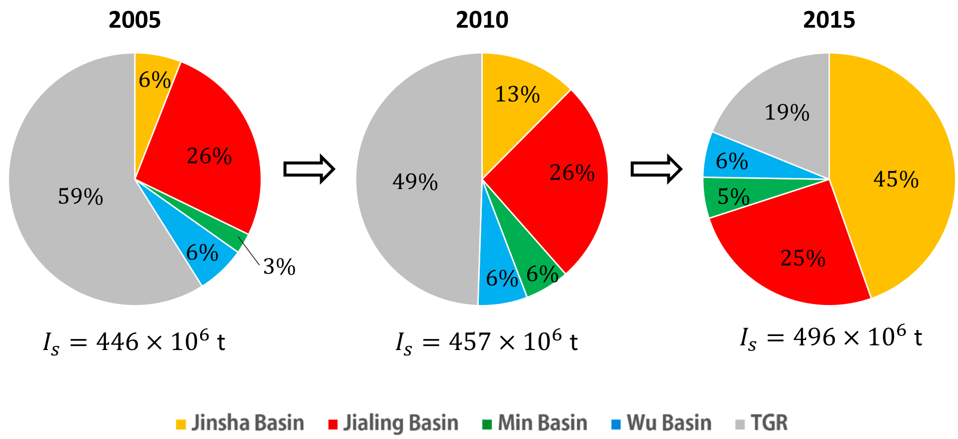


**Fig. 11.** The relative contribution of sediment retention in large reservoirs in different sub-basins (including the TGR) in the upper reach of the YRB in the years 2005, 2010 and 2015. $I_s$ is the total sediment load trapped in the large reservoirs, calculated based on the average sediment yield in pre-dam period.

yield). The amount of sediment load reduced in each sub-period is consistent with the estimated reservoir sedimentation, suggesting that the cascade reservoirs played a key role in human activities. By 2016, roughly 400 Mt/yr sediment load was trapped by the cascade reservoirs upstream of TGR; the relative contribution of the TGR in sediment retention for the whole upper YRB also decreased from 59% to less than 20% largely owing to the intensive damming in the Jinsha River Basin. The cascade reservoirs upstream of the TGR not only cut down the sediment load inflows, also break down the rating relation between annual runoff and sediment load.

## CRediT authorship contribution statement

**Haochen Yan:** Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Xiaofeng Zhang:** Conceptualization, Supervision, Writing - review & editing. **Q. Xu:** Resources.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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