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On the cumulative dam impact in the upper Changjiang River: Streamflow and sediment load changes

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ABSTRACT

Climate change and anthropogenic activities such as dam construction alter basin-scale hydrological regime of a river. The upper Changjiang River (uCR) stands out as one of the most heavily dammed rivers in the world after the construction of the Three Gorges Dam (TGD) and other large dams in its mainstem. Quantification of the cumulative dam impact is prerequisite for better river management. In this work, we provide a rigorous appraisal of the changes in streamflow, sediment load, and sediment composition at multiple time scales throughout the uCR based on data in 1950–2017. We observed that a decreasing trend in annual streamflow has emerged since 2015 at Yichang, the outlet of the uCR basin, although the changes were statistically insignificant for the first 65 years. The annual sediment load has decreased progressively and substantially, e.g., by 97% in 2010s compared to 1950s at Yichang. The Three Gorges Dam and the new large dams in the upstream mainstem accelerated the sediment load reduction in 2003 and 2014, respectively. As a result, the suspended sediment became finer, with a decrease in mean diameter from 17 μm in the 1960s to 8 μm in the 2010s at Yichang. We established a reservoir storage capacity index, which is the ratio of the total reservoir storage capacity to annual streamflow, and identified a threshold of 4% larger than which the cumulative dam impact will induce profound sediment load reduction. We concluded that climate change and anthropogenic activities, in particular the large dams in the mainstem, have transformed the uCR system from a turbulent and muddy river to a placid one, which can affect fluvial processes as well as aquatic ecosystems by altering sediment and nutrient concentrations and ratios. These hydro-morphological changes merit the urgent attention of concerned authorities.

1. Introduction

Terrestrial river discharge and sediment load are a worldwide concern as they substantially impact deltaic geomorphology, biogeochemical cycling, and land-ocean interactions (Syvitski et al., 2005; Wang et al., 2011; Best, 2019). Due to global climate change and increasing human activities, river discharge and sediment load in large rivers around the world have undergone significant changes, especially the decline in sediment load (Walling and Fang, 2003; Liu et al., 2014, 2017; Yang et al., 2015). Over long time scales (e.g., the geological scale), climate patterns play a vital role in controlling rainfall, river discharge, and sediment yield. Hence, the phenomenon of global warming could accelerate hydrological circulation and lead to an increase in the frequencies of extreme floods and droughts (Arnell and Gosling, 2013). Over an intermediate time scale (e.g., decadal scale), human activities in terms of water consumption, land-use change, dam construction, and sand mining etc. are the driving forces that accelerate basin-scale hydrological changes. Hence, a site-specific study is necessary to uncover the controlling effects of human activities on these hydrological changes (Syvitski et al., 2005; Wang et al., 2010; Dai and Lu, 2014; Guo et al., 2018). Over a short time scale (e.g., monthly scale), climate oscillations such as the El Niño cycle have significant impacts on sediment load variations (Wang et al., 2011; Liu et al., 2017).

To mitigate river floods, store water for irrigation and hydropower generation, and support navigation, dams are constructed across big rivers around the world (The World Commission on Dams, 2000). The number of dams in the world was estimated to be > 16 million, with a total storage volume of approximately 8000 km^3 (Lehner et al., 2011). These dams disrupt river continuity and sediment transport, which in turn affect the fluvial hydro-geomorphological and ecological processes as well as the ecosystems in estuaries and deltas of the river (Gong

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et al., 2006; Gupta et al., 2012; Gao et al., 2015). Dams have become one of the most concerning human interference in river systems as the number of dams and total storage capacity increase rapidly. Therefore, knowledge of dam construction and its regulating effects on river discharge and sediment load is crucial for river and delta management and restoration.

The Changjiang River (CR) in China is one of the most human-altered river systems in the world, with > 50,000 dams (including both big and small ones) as of 2010 (Yang et al., 2011), and the number increases year by year (see SubSection 3.1 for more information on dams). Thus far, numerous studies have been undertaken on the changes in precipitation, river discharge and sediment load in the CR basin, especially on the sharp decline in sediment load since 2003 when the world's largest concrete gravity dam, the Three Gorges Dam (TGD), was commissioned (Yang et al., 2007, 2014; Wang et al., 2008; Gao et al., 2013; Tan et al., 2016; Yang et al., 2018). It has been reported that the annual precipitation and river discharge have remained relatively stable in the past 60 years, while the sediment load has experienced a substantial decline in the mainstem downstream of the TGD (Dai and Lu, 2014; Zhao et al., 2017). The sharp decrease in sediment load since 2003 was attributed to the TGD, which has a massive storage capacity and high sediment retention ability (Yang et al., 2007, 2011, 2014; Dai et al., 2008; Gao et al., 2013; Tan et al., 2016; Zhao et al., 2017). Previous studies had mainly focused on the hydrological changes in the middle-lower CR basin downstream of TGD (Yang et al., 2014; Zhao et al., 2015, 2017). Hence, it is necessary to clarify the changes occurring in the upper basin, in order to assess the disruptive impact of dams.

Following the completion of the TGD in 2009, more hydropower dams have been constructed along its mainstem and tributaries upstream (Fig. 1). The combined storage capacity of these new reservoirs is a few times larger than the capacity of the TGD, and their effects on river discharge regulation and sediment delivery are expected to be immense. Thus far, few works have examined the effects of these newly built dams on the river discharge and sediment regime of the river. Moreover, the combined influence of these dams is only partially understood (Zhao et al., 2017; Yang et al., 2018; Guo et al., 2019). The lack of knowledge of the cumulative impact of dams will lead to overestimation of TGD's influences, an underestimation of the total anthropogenic impact, and misinterpretation of future trends. In addition, while most of the previous studies have focused on the inter-annual variations of river discharge and sediment load, few attempts have been made to detect the intra-annual (seasonal) variations and sediment composition changes, which are also important for river management and protection (Xu and Milliman, 2009; Li et al., 2011; Zhao et al., 2015). To address these knowledge gaps, we evaluate the combined impact of dams on the flow and sediment transport in the upper Changjiang River (uCR), based on a long time series and more recent data (1950–2017). We examine the spatiotemporal variations throughout the upper basin at both decadal and seasonal time scales. To quantify the cumulative dam impact and predict future trends, we use a reservoir storage capacity index (RSCI), which is the ratio of the total reservoir storage capacity in a certain year to the annual streamflow. The main objectives of this work are (1) to quantify the latest inter-annual and seasonal variations of river discharge and sediment load after the construction of a series of large dams along the TGD's upstream, (2) to demonstrate the changes of sediment composition and its potential effects on the transportation of nutrients and contaminants, and (3) to systematically uncover the cumulative dam impact along the mainstem and in the tributaries.

2. Study area and methods

2.1. Study area

The CR is the third longest river by length (~6300 km), the fifth largest in terms of river discharge, and the fourth largest in terms of sediment load in the world (Milliman and Farnsworth, 2013). It is a river of great socio-economic and environmental importance to China given it is home to a population of ~480 million. The river has a drainage area of 1.9×10^6 km^2, accounting for approximately 20% of the territory of China. The CR originates from the Qinghai-Tibet Plateau

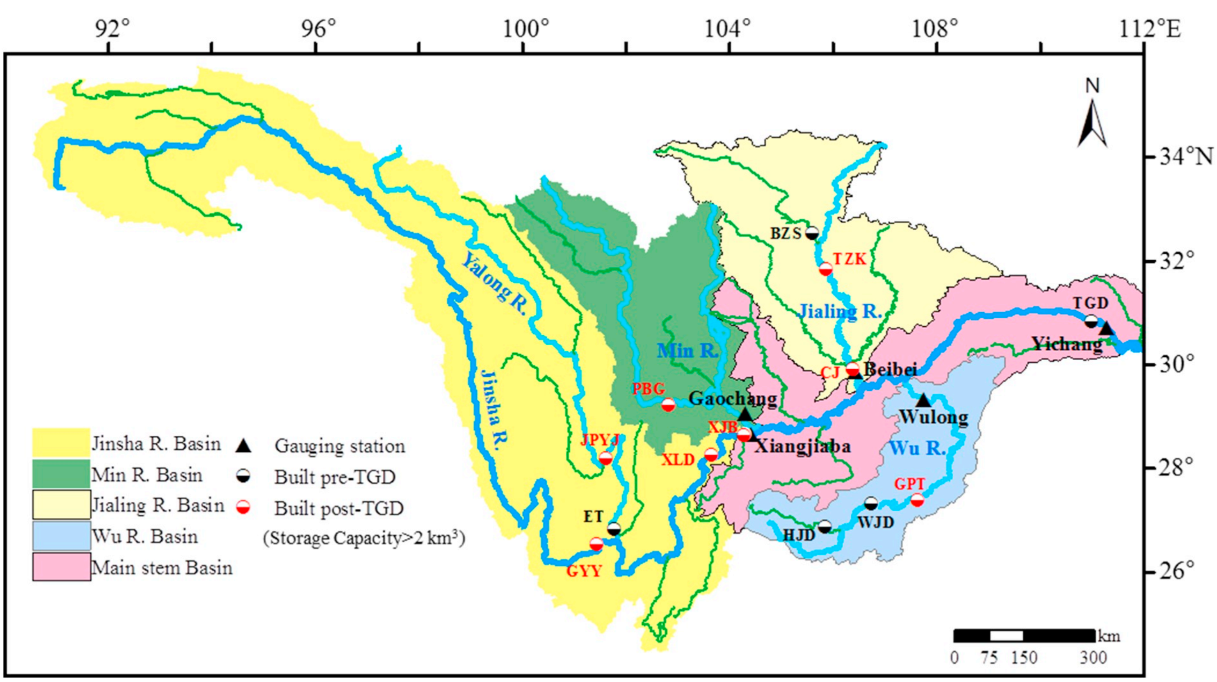

Fig. 1. A sketch map of the upper Changjiang River basin with the gauges (triangles), and dams with a storage capacity > 2 km^3 built before (black circles) and after (red circles) the Three Gorges Dam. TGD: Three Gorges Dam; XJB: Xiangjiaba Dam; XLD: Xiluodu Dam; GYY: Guanyinyan Dam; CJ: Caojie Dam; TZK: Tingzikou Dam; BZS: Baozhusi Dam; GPT: Goupitan Dam; WJD: Wujiangdu Dam; HJD: Hongjiadu Dam; PBG: Pubugou Dam; ET: Ertan Dam; JPYJ: Jinpingyiji Dam. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and stretches west-eastward from central China to the East China Sea. It is divided into three sub-basins, i.e. the upper, middle, and lower reaches, primarily based on its spatially varying landscape and climate patterns (Fig. 1).

The uCR is the basin from the headwater to Yichang, the outlet of the upper basin (Fig. 1). It is approximately 4500 km in mainstem length and has a drainage area of nearly 1.08×10^6 km^2. The terrain of uCR is mainly mountainous, with an average riverbed gradient of 1.1‰, and it is the primary sediment source zone in the CR (Chen et al., 2001). The mainstem of the uCR is joined by four large tributaries, namely the Jinsha River, the Min River and Jialing River from north, and the Wu River from south. The Jinsha River and Jialing River account for 61% of the drainage area of the uCR basin, and they are the main sediment source zones, contributing approximately 80% of the sediment load at Yichang (Wei et al., 2014). Being controlled by the Asian Monsoon, the uCR experiences significant temporal variations in precipitation, i.e., a major portion of river discharge (~75%) and sediment load (~85%) are discharged in the wet season between May and October at the outlet of the whole basin (about 1200 km downstream of Yichang) (Chen et al., 2001).

Amid the rapid socio-economic development, the sediment regime in the uCR has been strongly affected by human activities. For instance, reforestation had played a vital role in the decrease of sediment load until the mid-1980s. Since 1989, a series of soil conservation projects (named the Changzhi Project) have been implemented in the uCR basin, which has substantially reduced soil erosion and sediment yield (Xu and Milliman, 2009; Dai and Lu, 2014). Meanwhile, a large number of dams has been constructed since the 1950s, and the cumulative reservoir storage capacity has been increasing since 1990 (Yang et al., 2011; Gao et al., 2015).

2.2. Data acquisition

Data on annual and monthly streamflow, sediment load and suspended sediment concentration, and the median size (D_{50}) of the suspended sediment were obtained from the main hydrological gauges along the mainstem and at the mouths of the four major tributaries, Jinsha River (Xiangjiaba), Min River (Gaochang), Jialing River (Beibei), and Wu River (Wulong) (Fig. 1). The data were obtained from the Changjiang Water Resources Commission (CWRC) (www.cjw.gov.cn/zwzc/bmgb/), and their consistency was verified. Bed load was excluded from this study, because bed load transport is much smaller than the suspended sediment load and accounts for only a small portion (< 2%) of the total sediment load in the CR (Li et al., 2011). Air temperature and precipitation data were taken from past publications (Yang et al., 2015; Guo et al., 2018).

Information of dams were gathered from government bulletins and reports published by the Ministry of Water Resources of China (www.mwr.gov.cn/zwzc/hygb). The dams were classified according to their storage capacity, i.e., large dams (a storage capacity > 10^8 m^3), medium dams (a storage capacity between 10^7 and 10^8 m^3), and small dams (a storage capacity between 10^5 and 10^7 m^3). The details of super big dams with a storage capacity > 2×10^9 m^3 are presented in Table 1 in SubSection 3.1.

2.3. Analysis methods

We employed the Mann-Kendall (MK) test (Kendall, 1975) and the double mass curve (DMC) method to detect the changes and associated significance. The MK analysis is a non-parametric statistical test method for trend and abrupt change-point detection in a time series which does not need to assume the normality of distribution. In this study, a significant level of 5% was used. This method is widely recommended and has been generally applied in hydrological and meteorological data analyses (Li et al., 2016; Zhao et al., 2017). Detailed of the MK test can be found in Li et al. (2016) and many other references, and thus are not repeated here.

The DMC method is a common and effective method used to determine the consistency of two proportional correlation parameters and associated changes. It involves a plot of two cumulative parameters for a concurrent time, and the results usually manifest as a straight line if the proportionality between those two parameters remains unchanged. A change in the slope of the DMC indicates a change in the ratio of sediment load to river discharge, and an abrupt change in the slope indicates the time at which the mutation occurs. Due to its simple application and intuitive interpretation, the DMC method has been widely used to detect the impact of anthropogenic activities on river flow and sediment regime changes (Walling, 2006; Gao et al., 2015; Zhao et al., 2017).

We further calculate a reservoir storage capacity index (RSCI) to describe the actual effect of dams on river discharge regulation. The RSCI is defined as the ratio of the total reservoir storage capacity in a certain year to the annual streamflow (Xu and Yan, 2010). The variability of a typical parameter is indicated by the coefficient of variation (CV), which is estimated by calculating the standard deviation over the mean value of a data series.

3. Results

3.1. Dams in the uCR

In this section, we briefly introduced the dam statistics and temporal changes of the cumulative storage capacity of dams in the uCR in the period of 1950–2017 (Figs. 2 and 3). Information on the big dams was listed in Table 1, and a summary of the total number of dams and their storage capacity was listed in Table 2. The uCR is perfectly suitable for hydropower generation because of its mountainous terrain and large relief variations (Fig. 2a). Specifically, as of the late 1980s, there were 11,931 dams in the uCR, accounting for 80% of the dams in the whole basin at that time (Gu and Ian, 1989), with a total storage capacity of 20.5 billion m^3 (CWRC, 2001). The number of hydropower dams has increased to ~52,000 throughout the CR as of 2016, and their total storage capacity increased to approximately 360 billion m^3, ranking it as one of the world's most heavily dammed large rivers. The cumulative flood control capacity (FCC), i.e., the reservoir volume between the lowest and highest flood control water levels, was > 77 billion m^3. The majority of dams are in the uCR region. As of 2017, there were a total of 14,624 dams in the uCR with a storage capacity > 10,000 m^3. The large, medium, and small reservoirs accounted for 0.7%, 3.4%, and 95.9%, respectively. Although the number of large reservoirs was much smaller than that of the medium and small ones, their storage capacity was immensely significant, i.e., accounting for 86.6% of the total storage capacity.

The TGD constructed at a site approximately 40 km upstream of Yichang during 1994 and 2009 is the largest dam within the CR, with a storage capacity of 39.6 km^3 (~5% of the annual streamflow at the dam site). Following the TGD, a dozen of other large dams were built on the mainstem, including the Xiangjiaba, Xiluodu, Baihetan, Wudongde, and Guanyinyan dams (Fig. 2). The total storage capacity of the first four dams is 44.3 km^3, which is even larger than that of the TGD. The mainstem of the Jinsha River has become heavily dammed with a cumulative storage capacity of 90.7 km^3. Hydropower dams were also broadly constructed in the tributaries of the uCR. The Ertan and Jingpinyiji dams were built across the Yalong River, while the Lianghekou dam is yet to be constructed. There are Pubugou and Shuangjiangkou dams across the Min River. The total storage capacity of the dams in the Min River was 13.85 km^3, which was by far the smallest one compared to the other tributaries (Table 2). The Jialing River is another heavily dammed tributary, with large dams such as Baozhusi, Tingzikou, and Caojie dams. The Wu River was dammed by the Wujiangdu, Hongjiadu and Goupitan dams etc.

Based on the increasing trend of the total reservoir storage capacity

Table 1
Statistics of big dams in the uCR with a total storage capacity > 2 km^3.

Dam name	Position	Operation time	Controlled drainage area (km^2)	Storage capacity (km^3)	Flood control capacity (km^3)
Wujiangdu	Wu R.	1983	27,790	2.30	0
Hongjiadu	Wu R.	2001	9900	4.95	0
Goupitan	Wu R.	2009	43,250	6.45	0.40
Ertan	Yalong R.	1998	116,400	5.80	0.07
Jinpinyiji	Yalong R.	2014	103,000	7.76	0
Lianghekou	Yalong R.	[a]	/	10.77	2.00
Pubugou	Min R.	2010	68,510	5.39	0.73
Shuangjiangkou	Min R.	[a]	/	2.90	0.66
Baozhusi	Jialing R.	2001	28,430	2.55	0.73
Caojie	Jialing R.	2011	156,100	2.22	0
Tingzikou	Jialing R.	2013	62,550	4.12	1.26
Guanyinyan	Jinsha R.	2012	256,520	2.25	0.54
Xiangjiaba	Jinsha R.	2012	458,800	5.16	0.90
Xiluodu	Jinsha R	2013	454,380	12.67	4.65
Baihetan	Jinsha R.	[a]	/	20.63	7.50
Wudongde	Jinsha R.	[a]	/	7.41	1.45
Lawa	Jinsha R.	[a]	/	2.07	0
TGD	Mainstem	2003	1,084,000	39.60	22.15

[a] The dams are under construction. Note that most of the big dams are constructed after the TGD.

in the uCR, we identified three phases of changes, i.e., 1950–1979, 1980–2002, and 2003–2017 (Fig. 3). In the first period, the total storage capacity increased slowly, i.e., a mean increase of 0.49 $km^3 yr^{-1}$. The RSCI of the mainstem and tributaries was below 10%. The total storage capacity increased fast in the second period, with a rate of increase 1.6 times larger than that in the first period. By the end of 2002, the total storage capacity of the dams was approximately 44.02 km^3.

The RSCI of the Jialing River and Wu River increased significantly in the second phase, reaching 28% and 21%, respectively. The third period witnessed a dramatic rise in the total storage capacity, especially after the construction of mega-dams including the TGD in 2003, Goupitan Dam in 2009, and Xiluodu Dam in 2013 (Fig. 2 and Table 1). The increase rate of the total storage capacity in the uCR basin in the third period was 8.33 $km^3 yr^{-1}$, which was 5.5 times larger than that in the second period. The total storage capacity reached 168.9 km^3 in 2017, and another 39.7 km^3 is expected after the construction of upcoming dams. Except the Min River (18%), the overall RSCI of the mainstem and tributaries exceeds 30%. The maximum RSCI of 62% occurred in the Wu River. Taking the mean streamflow in the past 10 years (2008–2017) as a reference, we estimated an increase of 70% in the RSCI of the Jinsha River and the Wu River, and an increase of 55% after the completion of the new dams. The large number of dams and their storage capacities rank the uCR as one of the most heavily dammed large rivers in the world. Hence, their cumulative impact on the river system merits in-depth examination.

3.2. Inter-annual changes of precipitation, streamflow, and sediment load

Fig. 4 shows the changes in mean annual temperature and precipitation based on data from 1961 to 2012 in the uCR. The mean annual temperature varied between 11.7 °C and 13.5 °C, with an average value of 12.4 °C and a small CV of 3.3%. The mean annual temperature has exhibited an increasing trend since 1995, and this trend became statistically significant ($p < 0.05$) in 2003. The mean annual precipitation varied in the range of 790 to 1025 mm, with a mean value of 915 mm. Precipitation has followed an overall negative trend in the past decades, with a rate of decrease of 1 mm yr^{-1}. However, the decreasing trend in precipitation was statistically insignificant ($p < 0.1$).

The inter-annual variations in streamflow and sediment load in the mainstem and the four major tributaries (Xiangjiaba, Gaochang, Beibei, and Wulong) in the uCR are presented in Fig. 5. The annual streamflow varied between 350 and 500 km^3 at Yichang, and between 30 and 100 km^3 in the major tributaries. The CV values of the streamflow exhibited moderate variations, e.g., 11–25%. Overall the streamflow has not shown any significant increasing or decreasing trend over a time scale of 68 years. The MK trend analyses, however, exposed statistically significant changes in streamflow in 2015, 2006, and 2016 at Yichang ($p < 0.04$), Gaochang ($p < 0.05$), and Beibei ($p < 0.03$), respectively (Fig. 6). The changes at Xiangjiaba and Wulong were insignificant over the 68-year time scale. The MK test results suggested that there is an emerging decreasing trend in annual streamflow in the uCR, which merits the acquisition of data to further confirm and verify this trend in the future.

The sediment load exhibited consistently decreasing trends at all stations, particularly in the recent two decades. The CV values of sediment load were much higher than those of streamflow, particularly in the Jialing River (76%) and Wu River (68%), suggesting a much more profound variability in sediment load than streamflow. The MK test results indicated that the decrease in sediment load at Yichang, Gaochang, and Wulong started in around 1990, and the decreasing trend has been statistically significant ($p < 0.05$) since 2001, 2007, and 2003, respectively. The sediment load at Beibei of the Jialing River has been exhibiting a reducing trend since 1969, and has become statistically significant ($p < 0.05$) since 1988. The MK test results have been showing a decreasing trend at Xiangjiaba since 2009, but only became significant after 2015 (Fig. 6). The largest sediment load decrease rate was 8.48 Mt yr^{-1} at Yichang, which was approximately 4.4 times larger than the smallest one at Xiangjiaba. The trend analyses demonstrated that the decrease in sediment load has been the dominant trend in the uCR.

Specifically, the average sediment load at Xiangjiaba was 254 Mt yr^{-1} in 1953–2000, followed by a sharp decline. Recent years have been marked by a very low sediment load, i.e., 1.7 Mt yr^{-1} in 2013–2017, which was < 1% of the previous mean value. The recently constructed Xiangjiaba Dam, a few kilometers upstream of the Xiangjiaba Gauge, was responsible for this rapid decrease in sediment load. In the Min River, the sediment load at Gaochang exhibited fluctuations at decadal time scales prior to 1990, with a mean value of 52.4 Mt yr^{-1} in 1953–1990. A stepwise decline occurred until a mean load of 18.0 Mt yr^{-1} in 2006–2017. In the Jialing River, the mean sediment load was 155.3 Mt yr^{-1} in 1956–1984, and it declined to 29.7 Mt yr^{-1} in 1994–2014 and further to 5.4 Mt yr^{-1} in 2015–2017. Stepwise reduction occurred in the Wu River also, and the sediment load at Wulong had decreased from 23.7 Mt yr^{-1} in 1956–1966 to 5.5 Mt yr^{-1} in 2001–2017. In the 1950s, the average sediment load at the outlet of the uCR in Yichang was 519.8 Mt yr^{-1}; however, it had declined to 17.1 Mt yr^{-1} during 2010–2017, which was a reduction of 97%. Overall, a progressive and substantial decrease in sediment load has been

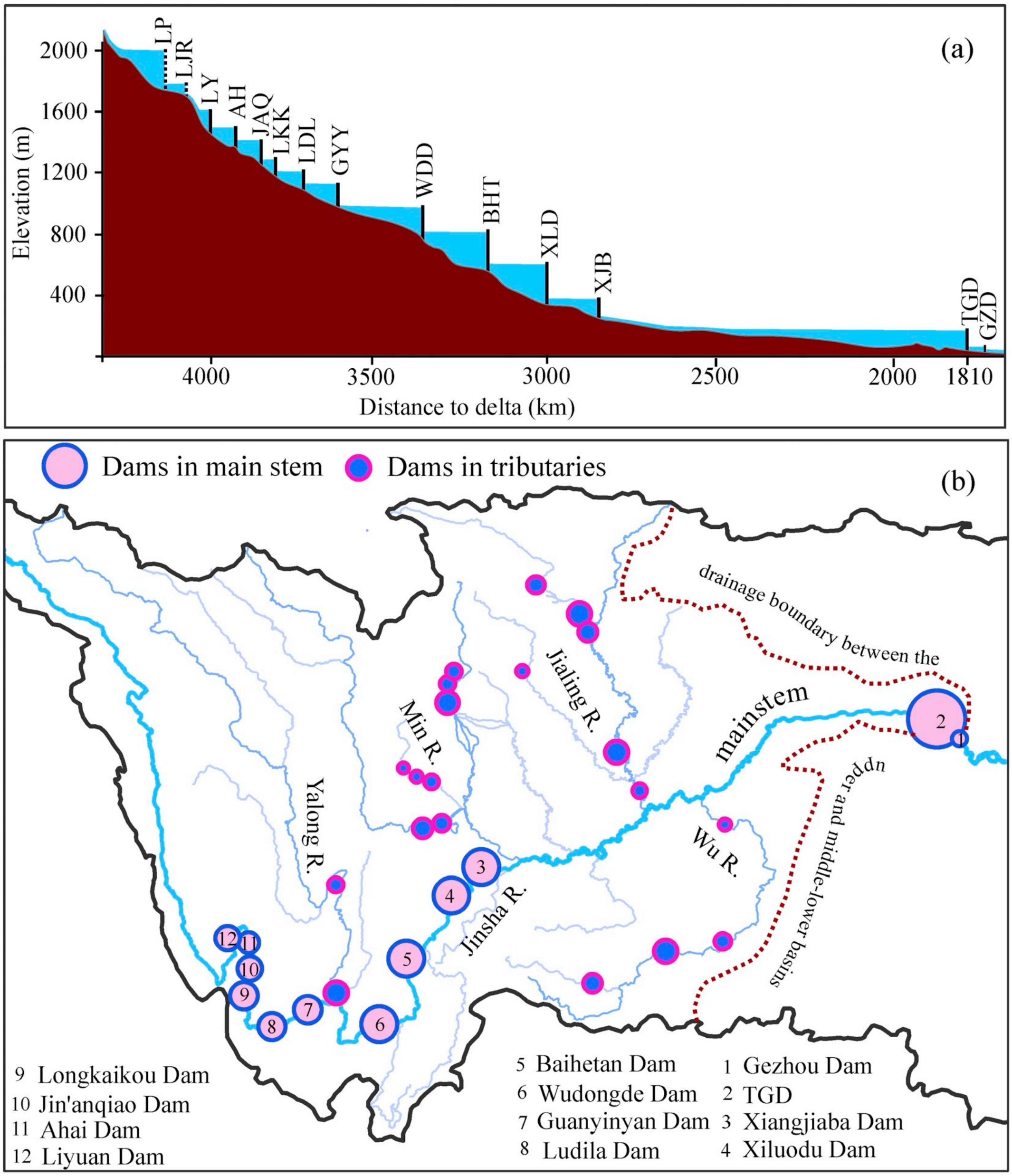

Fig. 2. (a) Elevation and the dams along the upper main stem, and (b) distribution and location of big dams in the upper Changjiang River. GZD: Gezhou Dam; XJB: Xiangjiaba Dam; BHT: Baihetan Dam; WDD: Wudongde Dam; GYY: Guanyinyan Dam; LDL: Ludila Dam; LKK: Longkaikou Dam; JAQ: Jin'anqiao Dam; AH: Ahai Dam; LY: Liyuan Dam. Constructions of the Liangjiaren Dam (LJR) and the Longpan Dam (LP) have not been commissioned yet because of a dispute regarding their environmental and ecological impact.

observed throughout the uCR in the 68 years and the reduction has been accelerating in the recent decade.

3.3. Differentiated contribution of the tributaries

In this section we quantified the contributions of streamflow and sediment load from different tributaries to the flux at the outlet of the uCR (Fig. 7). We observed that the total streamflow of the four tributaries and their contributions were relatively stable over time, with the variations being basically < 10% (Fig. 7a and b). The Jinsha River contributed the largest percentage of streamflow, followed by the Min, Jialing, and Wu rivers. Their average contributions were 33%, 20%, 15% and 12%, respectively. The remaining 20% of the streamflow was from the ungauged zones and small tributaries.

The absolute magnitude of sediment load and the relative contribution of the four tributaries had significantly changed over time, especially in the recent years (Fig. 7c and d). Prior to 2003, the sediment load at Yichang was predominantly larger than the total flux of the four major tributaries, suggesting significant sediment supply from the ungauged area and small tributaries. The ungauged in-reach sediment supply was estimated to be 58.0 Mt yr^{-1} in 1956–2000. Channel erosion may also contribute to this in-reach sediment supply, but its impact was not expected to be large because the overall bottom sediment (grain size > 1 mm) was much coarser than the suspended sediment (grain size < 1 mm). The Jinsha and Jialing rivers stand out as two important sediment suppliers, with averaged contributions of 46% and 24%, respectively, in 1956–1989. The sediment loads from the Min and Wu rivers were relatively small (10% and 6% on an average, respectively). The ungauged source accounts for approximately 14% of the sediment load at Yichang in the same period. In the period of 1990–2002, the relative contribution of the Jinsha River became larger, i.e., an increase to 70%, while the other tributaries delivered a smaller

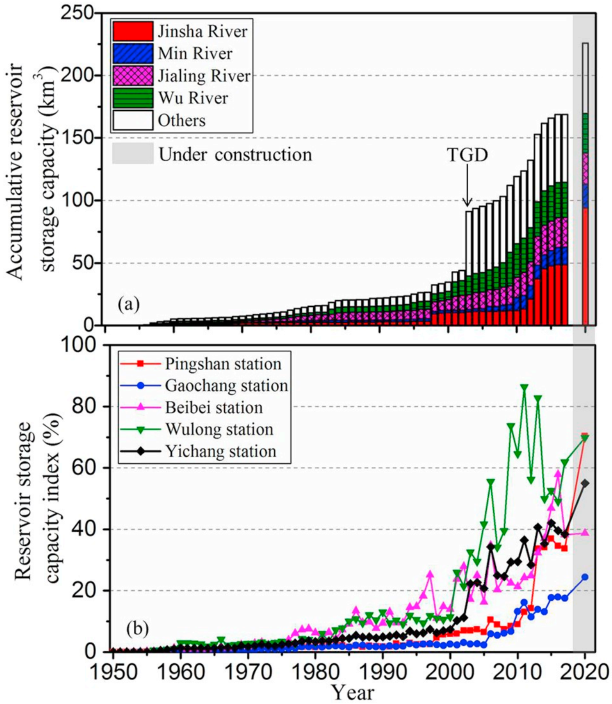

Fig. 3. Variations in the accumulated reservoir storage capacity (a) and reservoir storage capacity index (b) for the main stem and four major tributaries in the upper Changjiang River.

percentage of sediment to the mainstem. One remarkable change was in the early 2000s, after which the sediment load at Yichang became smaller than the total sediment load of the four tributaries, let alone the in-reach sediment supply (Fig. 7c). This indicated an in-reach sediment deposition as a result of reservoir sedimentation in the TGD. Another significant change occurred since 2013 when more dams were put into operation in the Jinsha River (e.g., Xiangjiaba and Xiluodu dams). The sediment load from the Jinsha River decreased to a very low quantity, i.e., 1.7 Mt yr^{-1} on average, in 2013–2017. In the same period, the sediment load of the Jialing River also decreased to a new low, i.e., 7.7 Mt yr^{-1}. As a result, the Min River stands out as an important sediment source. Therefore, the sediment load reduction in the Jinsha River and Jialing River were responsible for the much smaller sediment load gauged at Yichang since 2013. Overall, these changes suggest a sediment load regime shift in the uCR.

3.4. Intra-annual changes of streamflow and sediment load

Fig. 8 shows the monthly streamflow and sediment load at Yichang during three periods, i.e., 1950–1989, 1990–2002, and 2003–2017, given the change points detected on the annual time series of data. It shows that a major portion of the streamflow (~77%) was discharged in the wet seasons between May and October, and the contribution of the single July month was up to 18%. Over time, the percentage of streamflow in the wet seasons decreased slightly from 80% in 1950–1989 to 74% in 2003–2017. In the wet-to-dry transition seasons (between July and November), the streamflow exhibited a progressive reduction; whereas, in the dry seasons from December to May of the next year, it exhibited a gradual increase. These inter-annual changes were ascribed to dam regulations, which predominantly store water and reduce downstream river discharge in the wet seasons, but flush more water downstream in the dry seasons in order to empty the reservoir before the next flood season.

The sediment load was more concentrated than the streamflow in the wet seasons (Fig. 8b). More than 92% of the sediment load was delivered in the wet seasons between June and October at Yichang, and the peak percentage in July was up to 31% in 1950–1989. The sediment load had decreased throughout the course of the year, and the decline in the recent decade (2003–2017) has been particularly remarkable. The sediment load reduction in the wet seasons was much more profound at the absolute magnitude, and it dominated the reduction in the annual sediment load. For instance, the sediment load in the months between June and October had decreased from 472.9 Mt on average in 1950–1989 to 34.8 Mt in 2003–2017 at Yichang, i.e., a reduction of 93%. However, the relative percentage of sediment load in the wet seasons only had increased slightly from 92% in 1950–1989 to 99% in 2003–2017. These trends were consistent with the operation scheme of the dams and their significant sediment trapping effects (see SubSection 4.2 for more discussion).

3.5. Sediment rating curves

The sediment rating curves based on the annual river discharges and suspended sediment concentrations (SSC) show that the mainstem, i.e., at Yichang gauge, was generally less sediment-loaded compared to the tributaries (Fig. 9). In the four tributaries, the Jialing River (Beibei) and the Wu River (Wulong) were characterized by larger SSC under the same river discharge. The sediment loading rates have been decreasing both in the mainstem and the tributaries, particularly since the late 2000s. The sharp decline at Yichang around 2003 and the decline at Xiangjiaba around 2013 were substantial. It implies that the temporal changes between river discharge and SSC were out of phase, i.e., drastic sediment load reduction and insignificant streamflow change. Specifically, the mean river discharge in 2003–2017 is only 7% lower than in 1950–2002, while the mean SSC in the same period had declined by > 90%.

3.6. Sediment grain size changes

Besides the sediment mass reduction, the composition of the suspended sediment has also changed. The median diameters (D_{50}) of the suspended sediment particles in the mainstem and tributaries have exhibited decreasing trends in the past ~60 years (since 1960)

Table 2
Statistics of different sized reservoirs in the upper Changjiang River basin in 2017.

Regions		10^7 > SC ≥ 10^5 m^3		10^8 > SC ≥ 10^7 m^3		SC ≥ 10^8 m^3		Total no.	Total SC (10^8 m^3)	Total FCC (10^8 m^3)
		No.	SC (10^8 m^3)	No.	SC (10^8 m^3)	No.	SC (10^8 m^3)			
Main stem	Yibin-Yichang	2998	18.56	95	22.82	10	479.87	3103	521.25	230.01
Major tributaries	Jinsha R.[a]	2408	15.95	93	22.06	26	449.50	2527	487.46	88.32
	Min R.	797	6.85	53	10.81	23	120.79	873	138.45	14.40
	Jialing R.	4986	24.42	130	43.35	25	170.31	5141	238.08	46.20
	Wu R.	1322	11.62	95	29.00	21	239.22	1438	279.84	9.24
Other tributaries		1506	12.23	35	9.27	1	2.29	1542	23.87	9.04
Total		14,017	89.63	501	137.31	106	1461.98	14,624	1688.95	397.21

[a] The Yalong River is included in the Jinsha River basin. SC stands for storage capacity, and FCC is flood control capacity.

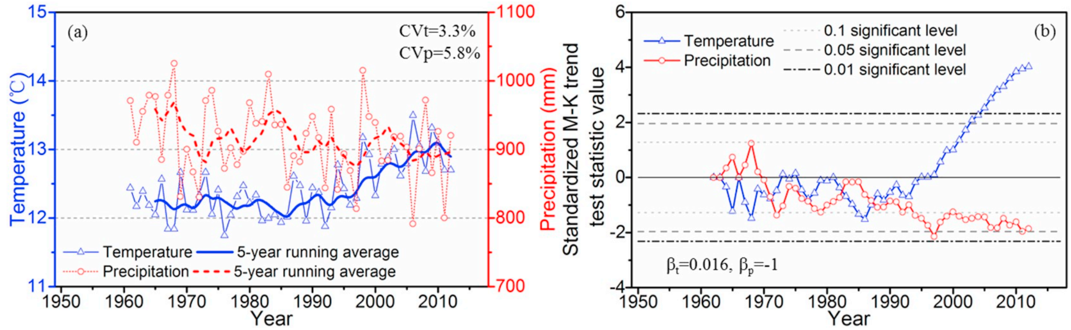

Fig. 4. Changes of mean annual temperature and precipitation (a), and variations of standardized MK-test statistics for temperature and precipitation (b) in the upper Changjiang River basin.

(Fig. 10). The mean D_{50} at Xiangjiaba, Gaochang, and Beibei were approximately 34 µm in the 1960s (1960–1969), and declined by about 71% to ~10 µm in the 2010s (2010–2017). The D_{50} at both Wulong and Yichang were smaller compared to those at the other tributaries. At Yichang, it reduced by 53%, i.e., from 17 µm in the 1960s to 8 µm in the 2010s. However, in the recent years, since 2010, the D_{50} at Beibei, Wulong, and Yichang were slightly larger compare to those in the previous decade (Fig. 10). Moreover, we see that the suspended sediment at Yichang were composed of 74% primary particles with a diameter < 0.031 mm, 17% with a diameter between 0.031 and 0.125 mm, and 9% with a diameter > 0.125 mm in 1986–2002 (Table 3). It implies that the fine sediment particles (< 0.125 mm) dominated the suspension transport. Since 2003, the percentage of particles < 0.031 mm in grain size increased gradually to 92% in the first few years since the TGD operation, when the percentages of particles in the range of 0.031–0.125 mm and > 0.125 mm reduced to 6% and 2%, respectively. This was in line with an overall fining trend of the suspended sediment because coarse sediment was deposited in the TGD and only the fine sediment was flushed downstream. Thereafter, the proportion of sediment < 0.031 mm decreased to 83% in 2014–2017, with the proportion of sediment with a grain size of 0.031–0.125 mm increased to 14%. The percentage of sediment > 0.125 mm was relatively stable in a low range of approximately 1–3%.

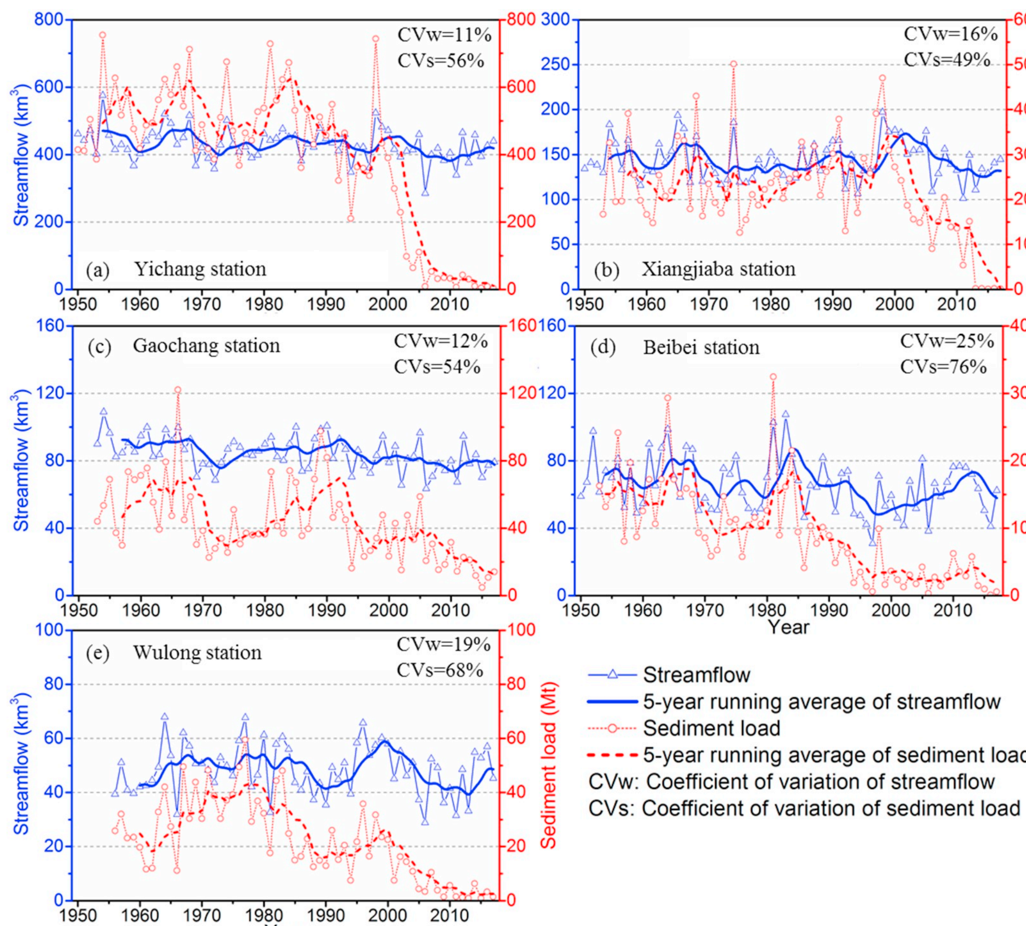

Fig. 5. Annual streamflow and sediment load changes in the upper Changjiang River: Yichang (a, outlet of the uCR); Xiangjiaba (b, outlet of the Jinsha River), Gaochang (c, Min River), Beibei (d, Jialing River), and Wulong (e, Wu River). The bold solid and dash lines are 5-y running averages of streamflow and sediment load, respectively.

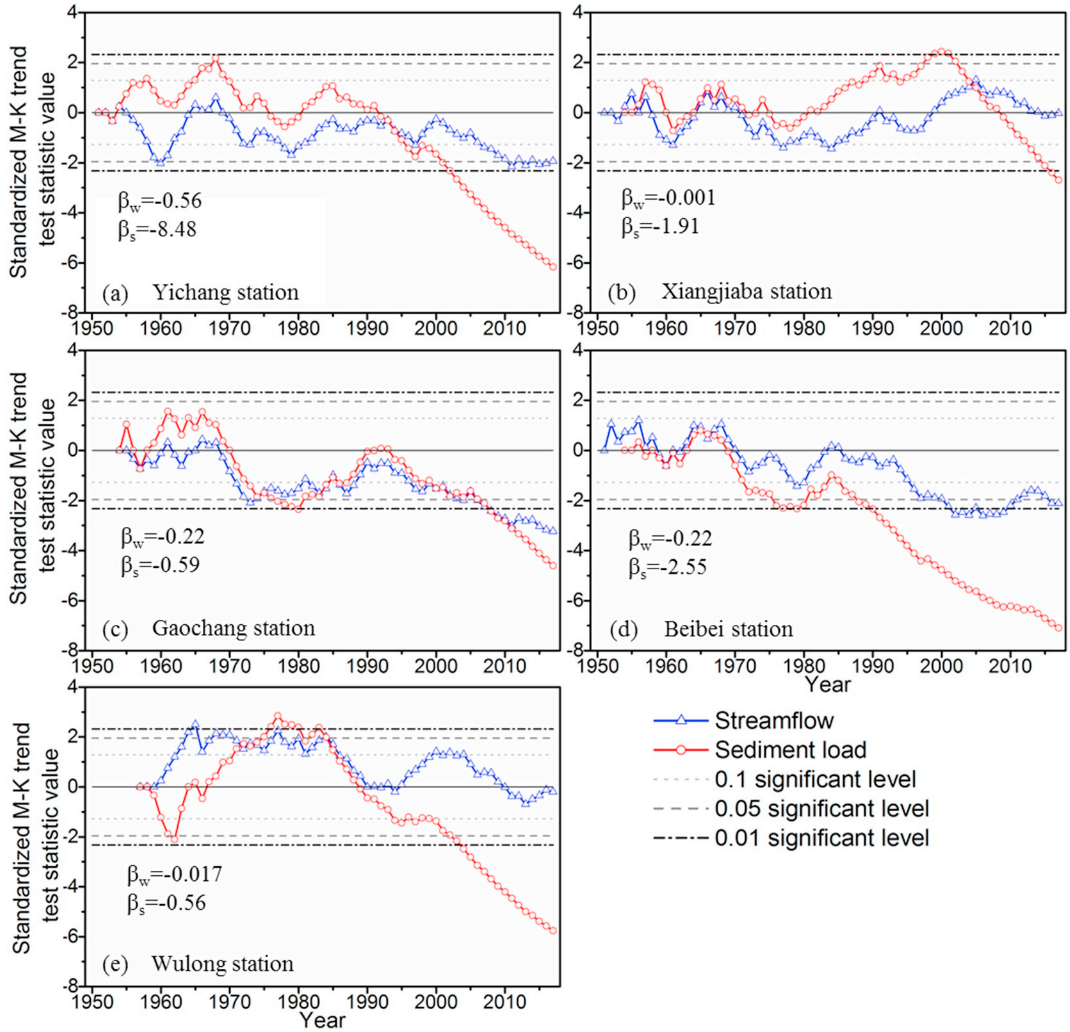

Fig. 6. Variations of standardized MK-test statistics for streamflow and sediment load at five gauges in the upper Changjiang River: Yichang (a); Xiangjiaba (b), Gaochang (c), Beibei (d), and Wulong (e). β_w and β_s are the rates of change of annual streamflow and annual sediment load, respectively.

4. Discussion

4.1. Causes of river discharge changes

Climate change and human interference are the two main driving forces affecting river discharge and sediment load (Walling and Fang, 2003). Air temperature in the uCR basin has increased significantly since 2003, despite the inter-annual fluctuations, with an increasing rate of 0.16 °C per decade. The increase in air temperature has two contrasting consequences–greater evapotranspiration and melting of more glaciers and permafrost in the headwater zone. For example, Yang et al. (2015) estimated that the temperature increase in the uCR basin caused a ~2% decrease in the river discharge due to greater evapotranspiration over the past decades, but a ~7% increase in discharge in the headwater as a result of the accelerating glacial and permafrost thaw. The two impact may cancel each other; therefore, it becomes difficult to quantify the net influence. Moreover, the precipitation pattern changes also play a role in inducing river discharge changes (Naik and Jay, 2011; Xu et al., 2013; Zhao et al., 2015). Chen et al. (2016) showed that approximately 90% of the inter-annual fluctuations in streamflow in the CR could be ascribed to precipitation. The mean precipitation over the entire length of the CR follows a significantly decreasing trend between 1950 and 2015 ($p < 0.02$), i.e., a rate of decrease of approximately 13 mm per decade (Guo et al., 2018). However, no statistically significant trend was detected in the mean annual precipitation in the uCR basin, although it showed an overall negative trend over the past ~40 y (Fig. 4). The long-term impact of a warming climate on the regional hydro-meteorological circulation, e.g., precipitation, evapotranspiration, and river discharge, still needs better quantification.

The influence of human activities in altering river discharge has profoundly increased in the recent decades. For example, water consumption for domestic usage and industrial and agricultural activities has increased by approximately 5 times to 90 $km^3 yr^{-1}$ between 1949 and 2000, accounting for approximately 10% of the annual streamflow in the CR (Guo et al., 2018). This may result in a more significant streamflow decline than the precipitation trends in the northern subbasins, e.g., the Min River and Jialing River (Xu et al., 2007; Zhao et al., 2017). Although the decrease in the annual streamflow over a 68–year time scale was statistically insignificant (Yang et al., 2011; Gao et al., 2013; Chen et al., 2016; Zhao et al., 2017), our analysis suggested that a significant decreasing trend is emerging at Yichang since 2015 (Fig. 6a). It may demonstrate a regime shift in the streamflow of the uCR, which merits future monitoring and study.

Dams influence variations in river discharge, particularly over seasonal time scales (Chen et al., 2016; Guo et al., 2018). The TGD is responsible for the significant increase and decrease in river discharge during the driest months (i.e., January to April) and the wet-to-dry transition seasons (i.e., July to November), respectively (Fig. 8a). Note that changes in river discharge over the seasonal time scales have taken

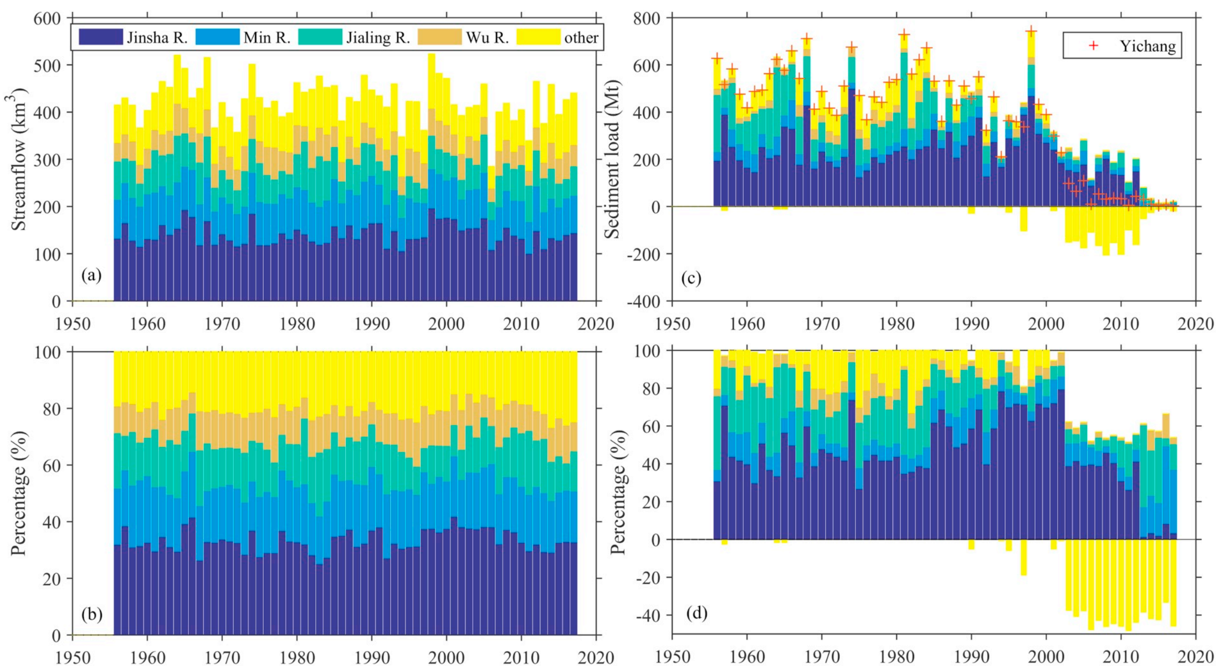

Fig. 7. Contributions of streamflow and sediment loads from the tributaries to the flux at Yichang: Streamflow contributions at (a) absolute and (b) relative magnitudes, and sediment load contributions at (c) absolute and (d) relative magnitudes. The negative values in panels (c) and (d) indicate in-reach (Xiangjiaba to Yichang) sediment deposition, mainly the deposition in the TGD.

place before the commissioning of the TGD (1990–2002). Meanwhile, monthly changes of precipitation in the uCR basin have been insignificant over the past 60 years (Chen et al., 2016). Thus, seasonal modification of streamflow was likely due to the combined influence of the dams in the tributaries and climate change. Especially, the total reservoir storage capacity had almost doubled by the end of 2002 compared to that in 1990, reaching 44.0 km^3 (Fig. 3a). Controlled by the same East Asian monsoon, the operation scheme of all these large dams in the uCR is almost the same, i.e., the dams will store water in the wet-to-dry transition seasons and release it mostly in the dry-to-wet transition seasons. Therefore, their cumulative regulating impact on river discharge regulation becomes much greater. Thus an integrated management and system process must be envisioned to develop an optimized operational strategy for all dams. Such an integrated process will help to gain a maximum benefit and mitigate their cumulative impact on the river. Overall, the decline in streamflow of the uCR is mainly ascribed to the precipitation decrease and anthropogenic activities including water consumption and dam construction, and the cumulative dam impact has become a significant, or even dominant, factor in river discharge regulation within the course of a year.

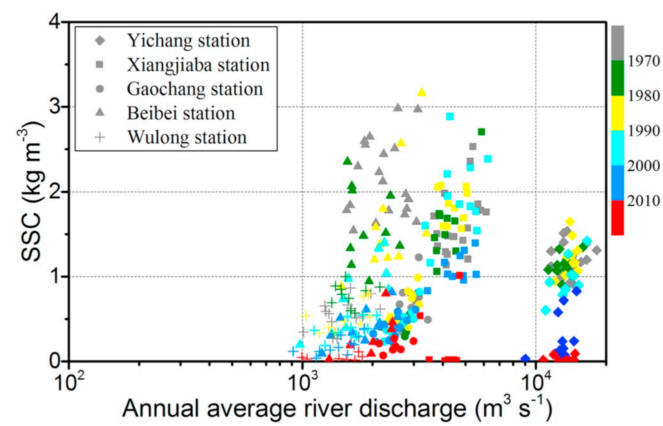

Fig. 9. Sediment rating curves at Xiangjiaba, Gaochang, Beibei, Wulong, and Yichang based on the annual mean values of river discharge and suspended sediment concentration.

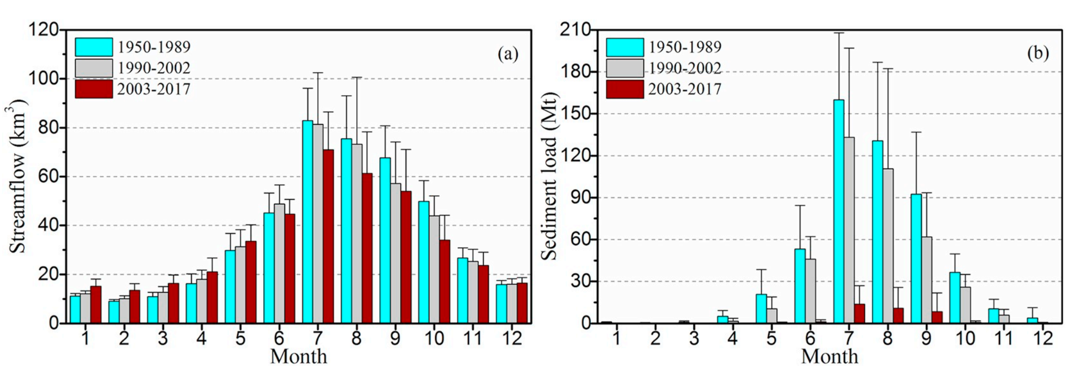

Fig. 8. Monthly streamflow (a) and sediment load (b) at Yichang during three periods. The columns are the mean results of every month, and the error bars indicate the standard deviations.

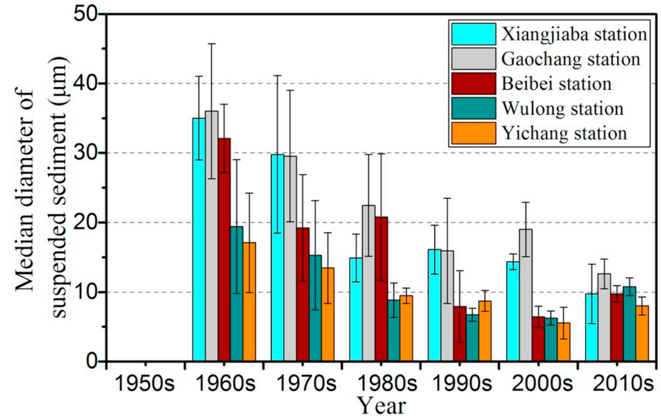

Fig. 10. Changes in median diameter of the suspended sediment in different decades at different gauges.

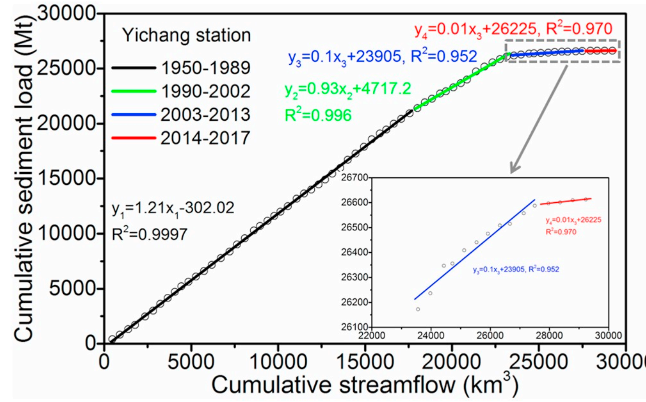

Fig. 11. Double mass curve relating cumulative streamflow and sediment load at Yichang, and the three change points.

Table 3
Sediment composition changes at Yichang.

Year	Percentages (%)		
	≤0.031 mm	0.031–0.125 mm	> 0.125 mm
1986–2002[a]	**73.9**	**17.1**	**9.0**
2003	81.0	10.0	9.0
2004	84.0	7.1	8.9
2005	86.7	7.9	5.4
2006	90.0	7.8	2.2
2007	91.5	6.0	2.5
2008	92.2	6.5	1.3
2009	92.1	6.4	1.5
2010	91.0	7.6	1.4
2011	89.3	9.6	1.1
2012	90.4	8.3	1.3
2013	91.9	7.7	0.4
2014	87.4	10.7	1.9
2015	78.8	17.3	3.9
2016	84.9	12.2	2.9
2017	81.5	16.6	1.9
2003–2013	**89.1**	**7.7**	**3.2**
2014–2017	**83.2**	**14.2**	**2.6**

The bold parts indicate the averaged results.
[a] Sediment composition data prior to 1986 are not available.

4.2. Causes of sediment load reduction

The reduction in sediment load in the uCR was much more pronounced than river discharge (Fig. 5). This implied that the changes in sediment load were not only influenced by river flow, but also by other human interference like land-use changes, soil and water conservation, and dam construction. Although rainfall intensity and duration influence the surface erosion and sediment yield, human activities such as deforestation and reforestation also affect the sediment yield and sediment runoff (Hu et al., 2009; Yang et al., 2015). Zhao et al. (2017) found that the forested land cross the whole CR basin had increased by approximately 0.1% (704 km^2), while the irrigated land and dry farmland that could be easily eroded had decreased by 4% (10,191 km^2) and 1.4% (3484 km^2) from the 1980s to 2010, respectively. The land-use changes mainly occurred in the uCR where large-scale anti-deforestation measures were implemented. Meanwhile, sediment yield in the uCR was highly correlated with population density, because extensive socio-economic activities result in strong land-use changes (Du et al., 2011). For example, implementation of anti-deforestation measures in the Jinsha River and Jialing River since the late 1980s was responsible for the gradual decrease in sediment load in the two rivers (Yang et al., 2006; Guo et al., 2018).

The double mass curve between sediment load and streamflow at Yichang exhibited a stepwise reduction of sediment load with three obvious and abrupt change points in 1990, 2003, and 2014 (Fig. 11). The first two change points have been illustrated and discussed by Gao et al. (2015) and Zhao et al. (2017), and they were attributed to reforestation and dams in the tributaries and the TGD, respectively (Yang et al., 2011; Gao et al., 2015).

Yang et al. (2006) had attributed two-thirds of the sediment load reduction at Yichang since the mid-1980s to hydropower dams. It was estimated that 31% of the total sediment load decline and 65% of the decline since 2003 were due to the TGD. They also noted that soil conservation and precipitation decline accounted for approximately 6% and 5% of the total sediment load decrease, respectively (Yang et al., 2015). Especially, the Ertan Dam was responsible for the sediment load reduction at the Yalong River in 1998. The Gongzui Dam in the Min River had caused approximately 58% of the sediment load reduction at the dam site (Gu and Ian, 1989), while the Tongjiezi and Zipingpu dams further exacerbated the reduction at Gaochang (Fig. 6). Similarly, the Baozhusi Dam in the Jialing River resulted in a profound sediment load reduction in the mid-1980s. Overall, the obvious sediment load reduction in the tributaries was generally related to dam construction, implicating dam impact on sediment delivery.

Due to increasing human interference, e.g., the water and soil conservation measures and dam construction, particularly the construction of large dams in the Jinsha River and Jialing River (Table 1), a new change point has emerged in 2014. The slope of the double mass curve decreased from approximately 0.1 in the third stage (2003 – 2013) to 0.013, because of the new low sediment load regime since 2014. The mean annual sediment load at Yichang was 46.6 ± 31.4 Mt yr^{-1} between 2003 and 2013, and it has plummeted to only 6.3 ± 2.7 Mt yr^{-1} since 2014, indicating a reduction of 86%. The sharp decline of sediment load at Yichang since 2014 was mainly attributed to the decreasing sediment load in the Jinsha River and Jialing River (Fig. 7). After the initial phase of operation of the Xiangjiaba Dam (storage capacity of 5.16 km^3) in 2012, the mean annual sediment load at the Xiangjiaba station decreased by 95%, i.e., from 140.9 Mt yr^{-1} in 2003–2012 down to 1.7 Mt yr^{-1} between 2013 and 2017. Similarly, the mean annual sediment load at the Beibei station declined by two-thirds, from 37.7 Mt yr^{-1} in 2003–2013 to 7.7 Mt yr^{-1} thereafter, owing to the impoundment of the Tingzikou Dam (storage capacity of 4.12 km^3) in 2013. The newly built large dams in the Jinsha River and Jialing River upstream of the TGD were mainly responsible for the sediment load decline at the outlet of uCR since 2014. When taking the period prior to 1990 as a reference, we estimated the relative contribution of climate change and human factors on the sediment load reduction to be 15.3 Mt yr^{-1} and 304.4 Mt yr^{-1}, respectively. Hence, the human factor has become the dominant one (a contribution of 95%) in causing the sediment load reduction in the post-major dam construction era.

Table 4
Sediment inflow and outflows, and deposition in the TGD from 2003 to 2017.

Year	Sediment inflows (Mt)	Sediment outflows (Mt)	Reservoir sedimentation (Mt)	Trapping efficiency (%)	Accumulative sedimentation (Mt)
2003	208.1	84.1	124.0	60	124.0
2004	166.0	64.0	102.0	61	226.0
2005	254.0	103.0	151.0	59	377.0
2006	102.0	8.8	93.2	91	470.2
2007	220.5	51.0	169.5	77	639.7
2008	217.8	32.2	185.6	85	825.3
2009	183.0	36.0	147.0	80	972.3
2010	228.8	32.8	196.0	86	1168.3
2011	101.6	6.9	94.7	93	1263.0
2012	219.0	45.3	173.7	79	1436.7
2013	126.8	32.8	94.0	74	1530.7
2014	55.4	10.5	44.9	81	1575.6
2015	32.0	4.2	27.8	87	1603.4
2016	42.2	7.6	34.6	82	1638.0
2017	34.4	3.3	31.1	90	1669.1

The TGD is thus far the largest dam in the CR, and its impact on sediment delivery is tremendous because of its massive storage capacity. Since the pilot phase of its operation in 2003 and as of 2017, the TGD has amassed a total of 1669.1 Mt of sediment (Table 4). As the incoming sediment flux has decreased to a new low after the construction of the big new dams in the upper mainstem, the reservoir sedimentation rate in the TGD has reduced to 34.6 Mt yr^{-1} in the period of 2014–2017, and the outflux of sediment load from the dam decreased accordingly (Table 4). Note that the TGD has a net sediment storage capacity of 22.9 km^3 (51% of its total storage capacity). In other words, the TGD is able to accommodate 29,757 Mt of sediments (considering a bulk density of 1.3 t m^{-3}). This implies that, with the mean incoming flux in 2014–2017, it will take approximately 800 years for the TGD to be filled before it can flush a significant amount of sediment downstream through the pre-installed sand sluices in the dam. This suggests that the TGD's impact on sediment load will persist for centuries.

Furthermore, we use the RSCI to quantify the cumulative dam impact on the sediment load. As the total storage capacity had reached approximately 169 km^3 by the end of 2017, the data showed significant decrease trends in SSC both in the mainstem and the major tributaries (Fig. 12). We also noted that the SSC variations behaved differently with changes of RSCI in different tributaries. For instance, when the RSCI was < 4%, the decline in SSC with an increase of RSCI was mild. However, the SSC decreased sharply and its variability became smaller with an increasing RSCI > 4%. We observed the rapid decline of SSC with increasing RSCI when the RSCI reached approximately 4%,

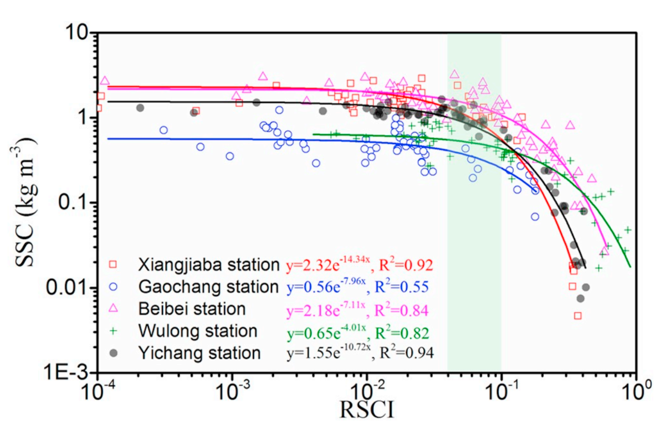

Fig. 12. Variations in suspended sediment concentration (on the $\log_{10}$ scale) with changes of RSCI in the main stem and the major tributaries of the uCR. The lines indicate the exponential fitting curves.

particularly at Xiangjiaba, Beibei and Yichang (Fig. 12). This identified RSCI threshold indicates that the sediment load at the outlet of the uCR will persist at the low level in the near future, considering the huge cumulative impact of the dams. We estimate that the sediment load at Yichang will further decrease to approximately 1.6 Mt yr^{-1} (corresponding to a SSC of ~0.004 kg m^{-3}) after the completion of all the dams across the river (when the RSCI reaches 55%) in the uCR. Overall, these evidences suggest that it is not only the effect of the TGD, but also the cumulative impact of the dams that will profoundly modulate the river discharge and sediment load in the uCR for the centuries to come.

4.3. Causes of changes in suspended sediment size

The grain sizes of the suspended sediment play a pivotal role in its transport behavior, as well as the transport of adherent nutrients and contaminants, especially for fine sediment. It is crucial for water quality management and has implications for study of reservoir sedimentation, harbor siltation, geomorphological evolution, and ecosystem management (Xu, 2007; Guo et al., 2017; Yang et al., 2018).

The decrease of suspended sediment grain sizes in the mainstem and major tributaries in the uCR could be attributed to three factors: the trapping of relatively coarse sediment in the reservoirs, soil and water conservation measures, and precipitation changes over the region (Xu, 2007; Yang et al., 2018). Coarse sediments were rapidly deposited in the reservoirs, and only the fine sediments were flushed downstream, leading to a fining trend of the sediment downstream of the dams (Yang et al., 2014; Tan et al., 2016). A similar decreasing trend of suspended sediment size has also been observed in Huanghe (Yellow River) after dam construction, i.e., a decrease in D_{50} by 20% from approximately 20 μm in 1950–1999 to approximately 16 μm in 2000–2006 after the operation of Xiaolangdi Dam in 1999 (Wang et al., 2010).

Channel erosion and sediment pick-up in the river downstream of the dam may mitigate the fining trend of the suspended sediment, but it may take a long time and may depend on the availability of fine sediment on the riverbed. The riverbed sediment in the uCR mainstem and almost all the tributaries are generally composed of sand and gravel, with a D_{50} in the range of approximately 30–100 mm (Xu, 2007; Yang et al., 2018). It means that there is limited fine sediment on the bed for suspension transport in the uCR. Soil conservation measures and decreasing precipitation may also explain the decreasing sediment size through reduced erosion and sediment yield, and trapping of relatively coarse sediment in the mountainous terrains (Xu, 2007).

The mean D_{50} at Beibei, Wulong, and Yichang exhibited increasing trends, > 40% in 2010s when compared with those in 2000s, from 6.4 to 9.8 μm, 6.2 to 10.8 μm, and 5.3 to 8.0 μm, respectively. The increase trends may be ascribed to the operation mode of the reservoirs and the resuspension of relatively coarse bed sediment. Further surveys and studies are needed to identify the causes of this increase trend and its impacts.

4.4. Implications of the changes

The delicate balance between river flow and sediment load was disturbed, and it has induced significant hydro-morphodynamic changes (Zhao et al., 2017). Since approximately 85% of the CR's sediment load to the sea was derived from the upper basin, a drastic sediment load reduction at Yichang resulted in severe sediment starvation in the downstream river. The middle-lower mainstem of the CR downstream of Yichang has shifted from a depositional state to an erosional state after the impoundment of TGD in 2003 (Yang et al., 2007; Xu and Milliman, 2009; Han et al., 2017). Severe bed scour and bank erosion have been detected along the downstream river, even 1500 km downstream of the TGD. Besides bed scour, bank erosion and collapse also occurred widely. According to the reports of CWRC (2003–2017), there have been ~920 bank collapses along the mainstem of the middle-lower CR, with a cumulative bank collapse length reaching approximately 693 km.

The hydro-morphological changes threaten the dikes and levees that protect the low-lying middle-lower basin from flooding, and also other waterfront infrastructure such as bridges and piers. Due to the combined effect of bed erosion and seasonal river discharge reduction, the river stage has apparently decreased in the middle-lower mainstem under the same river discharge (Han et al., 2017; Guo et al., 2018). This river stage drop affects channel navigation, water sources supply, and riparian ecosystem. Moreover, as the sediment produced in the uCR were largely entrapped by the man-made reservoirs, the quantity of sediment delivered to the delta has also decreased by ~74% (Guo et al., 2019), and this reduction will cause delta erosion, loss of saltmarsh and habitat, and possibly increased risk of coastal flooding risk in the long-term, when considering the persisting and cumulative dam impact. Overall, the decreased sediment load and a regime shift to sediment deficiency exert substantial influence on the natural dynamic behavior and service functions of the river system, and it needs a new management vision to discover a way to maintain the stability and safety of river channels.

Drastic reduction in sediment load has a fundamental environmental impact as well. The mainstem of the upper river changes from being muddy to be clear as a result of substantial SSC decrease, and it will affect the light and oxygen level in the water column. Moreover, the suspended sediment in the CR are mainly composed of fine-grained particles with a median diameter of < 63 μm (see Fig. 10), and they are not transported as individual particles but in the form of aggregates, i.e., flocs (Li et al., 2014; Guo et al., 2017). Flocs have a larger settling velocity than individual particles and are composed of both inorganic and organic matter (Guo et al., 2017). The aggregated flocs become significant carriers of nutrients and contaminants. This explains the highly positive correlation between phosphorus content and sediment concentration (Zhou et al., 2013). As the sediment load decreased profoundly, a 77% reduction in the total phosphorous content and an 84% reduction in particulate phosphorus load in the CR downstream of the TGD since 2003 has been observed compared with the average value in 1950–1990 (Zhou et al., 2013). Similar reductions in the content and flux of silica and carbon have also been detected (Ran et al., 2016). These changes tend to have profound impact on the aquatic ecosystem and the land-to-ocean biogeochemical cycle by altering nutrient concentrations and ratios (Gong et al., 2006). The impact of sediment load reduction on the transport and cycling of nutrients and contaminants in the river continuum is a new challenge needing future research and management perspectives.

5. Conclusions

We examined dam construction and its impact on the streamflow, sediment load, and sediment composition in the uCR based on a long time-series data from 1950s to 2017. The impact of climate change and human interference were quantified by applying the double mass curve method, and the role of dams was emphasized and evaluated. We found that the streamflow in the uCR has not shown any significant decreasing trend over the 60 year time scale, but exhibited a reduction regime in the very recent years. The sediment load has decreased progressively in statistically significant trends ($p < 0.05$). The sediment load at the outlet of the uCR basin has decreased from 519.8 Mt yr^{-1} in the 1950s to 17.1 Mt yr^{-1} in the 2010s, indicating a reduction of 97%. At the same time, the median diameters of the suspended sediment at Yichang showed a general decreasing trend, i.e., from approximately 17 μm in the 1960s to 8 μm in the recent years.

The sediment rating curves and the double mass curves revealed three significant change points of sediment load in 1990, 2003, and 2014. The first two change points were ascribed to the soil and water conservation and dam construction in the tributaries, and the TGD, respectively. The change point in 2014 was attributed to the newly built large dams in the Jinsha River and Jialing River. These dams substantially increased the total reservoir storage capacity, and played a crucial role in trapping sediment and reducing downstream sediment load. We find that an increasing RSCI (> 4%) will cause a sharp SSC and sediment load decline, indicating the substantial cumulative impact of the dams. The sediment load at Yichang is predicted to be 1.6 Mt yr^{-1} after the construction of all the dams in the mainstem of the uCR. This low sediment load regime is highly likely to persist in the coming centuries. The low sediment load regime has invoked downstream channel degradation, delta erosion, and associated changes of nutrient and contaminant transport, which merit future research and attention of the concerned authorities.

Acknowledgements

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