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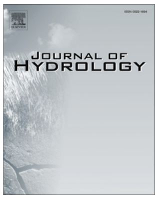

Research papers

How have the river discharges and sediment loads changed in the Changjiang River basin downstream of the Three Gorges Dam?

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ABSTRACT

Streamflow and sediment loads undergo remarkable changes in worldwide rivers in response to climatic changes and human interferences. Understanding their variability and the causes is of vital importance regarding river management. With respect to the Changjiang River (CJR), one of the largest river systems on earth, we provide a comprehensive overview of its hydrological regime changes by analyzing long time series of river discharges and sediment loads data at multiple gauge stations in the basin downstream of Three Gorges Dam (TGD). We find profound river discharge reduction during flood peaks and in the wet-to-dry transition period, and slightly increased discharges in the dry season. Sediment loads have reduced progressively since 1980s owing to sediment yield reduction and dams in the upper basin, with notably accelerated reduction since the start of TGD operation in 2003. Channel degradation occurs in downstream river, leading to considerable river stage drop. Lowered river stages have caused a 'draining effect' on lakes by fostering lake outflows following TGD impoundments. The altered river–lake interplay hastens low water occurrence inside the lakes which can worsen the drought given shrinking lake sizes in long-term. Moreover, lake sedimentation has decreased since 2002 with less sediment trapped in and more sediment flushed out of the lakes. These hydrological changes have broad impacts on river flood and drought occurrences, water security, fluvial ecosystem, and delta safety.

1. Introduction

River and sediment discharges in worldwide large rivers are subject to significant changes (dominantly reduction) because of climate changes and increasing human activities (Walling and Fang, 2003; Syvitski et al., 2005). Global climate changes induce accelerated hydrosphere circulation, resulting in increased frequency of extreme events (e.g., droughts and floods) and possibly evoking hydrological and ecological influences at a broader scale (Xu and Singh, 2004; IPCC, 2013; WMO, 2016). Arnell and Gosling (2013) had modeled and projected that climate changes will cause significant changes in hydrological behavior by 2050, e.g., streamflow increase for nearly half of the global land surface and decrease over the other 36% of the land surface. Regional variability is still high because of the uncertainties in the climate models and the non-linear regional responses to global changes (Arnell and Gosling, 2013; Nakaegawa et al., 2013). Regional case studies can provide perspectives for interpretation of hydrological and climatic changes at global scale.

Human activities in terms of dam constructions, water consumption, and land use changes exert increasing influences on basin-scale hydrological regimes (Nilsson et al., 2005; Syvitski et al., 2005). Dams are built worldwide to control river floods and store water for irrigation and power generation. On the other hand, dams can significantly alter hydrological, geomorphological, and ecological processes in fluvial systems (Milliman, 1997; Brandt, 2000; Walling and Fang, 2003; Graf, 2006). For instance, at basin scales, dam operation regulates river discharge hydrograph by changing the timing, magnitude and frequency of low and high flows, and disrupts sediment delivery, e.g., the Aswan Dam in the Nile River (Woodward et al., 2007) and the Hoover Dam in the Colorado River (Graf, 2006). At continent scales, large artificial reservoirs are able to alter regional climate regarding changes in precipitation and surface evaporation etc., particularly in the semi-arid regions (Degu et al., 2011). Moreover, increasing global water storage by man-made reservoirs has reduced water volume reaching oceans, potentially slowing down global sea-level rise by 30 mm in the past half century (Chao et al., 2008).

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River flow regulation and irrigation at global scales also increase evapotranspiration and water consumption (Jaramillo and Destouni, 2015). These evidences demonstrate remarkable regional to global effects of water usage and hydrological regime changes, which merit specific examinations.

The Changjiang River (CJR, also called Yangtze River) basin in China is such a system undergoing significant hydrological changes under the influences of both climatic changes and human interferences. Regional climatic changes include changing intensity and behavior of the Asian monsoon (Xu et al., 2011a), while human activities include increasing water consumption by a booming population, more hydropower dams and water transfers etc. A number of reports have been devoted to examining changes of precipitation, temperature, river and sediment discharges in the CJR basin. Yang et al. (2004, 2006), Gao et al. (2013), Wei et al. (2013), and Chen et al. (2001b, 2016) etc. had examined river discharge changes and reported no significant decrease or increase changes at the half century time scale. Yang et al. (2004, 2006, 2011, 2018), Wang et al. (2007b, 2008), Hu et al. (2009), and Xu et al. (2009) etc. had documented radical sediment load reductions due to the TGD. Li et al. (2013a, 2016), Dai and Lu (2013), Xu et al. (2013a), and Zheng (2016) discussed comprehensive impacts of the TGD on the river and sediment discharges and associated ecological, environmental and socio-economic influences. These studies provide useful insights on the hydrological regime changes. On the other hand, we find that there is inconsistency remained to the author's knowledge. For instance, Yang et al. (2006), Hu et al. (2009) and Zhao et al. (2017) documented no apparent decrease or increase trend of the annual streamflow at Yichang and Datong (data range 1953–2013), whereas Jiang et al. (2007) detected a weak decrease trend at Yichang and a weak increase trend at Datong (data range 1961–2005). The different interpretations maybe caused by inconsistent data range and/or different analysis methods at different significance levels. In addition, most previous studies interpreted inter-annual changes of streamflow and sediment loads while the seasonal changes were insufficiently examined. Therefore, there is still a demand to clarify hydrological changes by rigorous trend analysis of datasets at annual and seasonal time scales.

Additionally, low water conditions (low river discharges and low river stages) frequently occurred in the middle-lower CJR basin downstream of TGD in the recent decade. For instance, nearly the lowest or the second lowest river stages at a 50–150 year time scale were recorded downstream of Cuntan (Fig. 1) in the summer of 2006 (Dai et al., 2011). Regional low water occurred successively in 2006, 2009, 2011, and 2013 in the Dongting and Poyang lakes (Fig. 1; Li et al., 2012). This is controversial to that the TGD discharges more water in the dry seasons which is expected to relieve low water occurrence. Big floods still occurred in the downstream basin after the TGD was constructed, rising doubt on the effectiveness of the TGD in mitigating flooding risk. There are increasing debates on TGD's negative influences on the downstream basin regarding water resources security, and drought and flood hazard, and fluvial ecosystems. The TGD has been put into operation for 14 years since 2003 and a rigorous assessment of its impacts on the river discharge and sediment delivery processes is needed for integrated river management.

In this work we review a wide range of publications, collect a long time series of river discharges and sediment loads data at multiple gauge stations in the basin downstream of the TGD, and examine them rigorously by trend analysis methods. We will clarify the TGD's role in the hydrological changes and elaborate consequent impacts in the river system. In the end we identify knowledge gaps in our present understandings. The rest of this paper is organized as follows. Section 2 briefly introduces the CJR basin, data source, and methods. Section 3 presents the operation of the TGD. Section 4 addresses changes with respect to hydrometeorology, river and sediment discharges at both seasonal and annual time scales, and Section 5 discusses causes and implications of the changes with a focus on the river–lake interactions. The last section formulates conclusions and briefs knowledge gaps.

2. Setting, data, and method

2.1. The Changjiang River basin

The CJR, stretching west-eastward in the middle China, is one of the world longest rivers of great ecological and socio-economic importance. It has a mainstem length of ~6,300,000 m, a basin area of ~1900 billion m^2 (19.5% of China's land area), an annual streamflow of 903.4 billion m^3 (37% of China's total streamflow) and an annual sediment load of 414 million tons (between 1950 and 2005 at Datong) (Yang et al., 2006; Wang et al., 2007b). The CJR is home to ~480 million people, indicating its critical role on socio-economic development (Chen et al., 2001b; Xu et al., 2008).

The CJR basin is geographically divided into the upper, middle, and lower sub-basins, and the delta regions with divisions at Yichang, Jiujiang, and Datong, respectively, based on landscape (Fig. 1). The upper basin has a high relief and is mountainous and the main sediment source region, while the middle-lower basin consists of vast fluvial flood plains and its mainstream channel is a conduit conveying sediment to the sea. The TGD is about 40 km upstream of Yichang. Upstream of the TGD, Cuntan is the main gauge station where the TGD inflows are monitored. Another new dam, the Xiangjiaba Dam, which has a flood control capacity of 0.9 billion m^3 and is ~408 km upstream of Cuntan, was constructed and put into operation since 2012. Downstream of the TGD, Yichang, Shashi, Jianli, Luoshan, Hankou, Jiujiang, and Datong are the major gauge stations along the mainstream in the downward direction (Fig. 1). The annually mean river discharges are 10,870, 13,620, 28,400 m^3/s at Cuntan, Yichang and Datong, respectively.

A number of big tributaries scatter in the CJR basin, such as the Wu River, the Han River, and the Dongting Lake and Poyang Lake systems (Fig. 1). The Dongting Lake receives flows from four secondary tributaries and conjuncts the CJR mainstream at Chenglingji. In addition, there are three inlets diverting mainstream water and sediment into the Dongting Lake in the wet seasons (Fig. 1). The Poyang Lake has five secondary tributaries and conjuncts the CJR mainstream at Hukou. Reverse flows, i.e., flows from the CJR mainstream to the Poyang Lake, can happen at Hukou occasionally in the wet seasons. The water and sediment exchanges between the lakes and mainstream play a profound role in buffering hydrological changes.

The CJR basin has a basin-wide mean annual precipitation of ~1100 mm and the precipitation exhibits strong spatiotemporal variations owing to Asian monsoon (Wang et al., 2012). The mean annual precipitation is 270–500 mm in the upper basin and 1,600–1900 mm in the middle-lower basin (Gemmer et al., 2008). Temporally, rainfall concentrates in the wet seasons between May and September and as a result a major portion of streamflow (~75%) and sediment loads (~85%) are discharged in the wet seasons (Chen et al., 2001b). Spatially, the prime rainy season is between May and October in the upper CJR basin, one-to-two month lagging the rainy season in the middle-lower basin, i.e., between March and August (Jiang et al., 2007; Guo et al., 2011). Extreme floods or droughts are likely to happen if wet or dry climate occurs occasionally in the same season between the upper and middle-lower basins, such as the big river floods in the summer of 1954 and 1998 (Zong and Chen, 2000) and the severe droughts in the

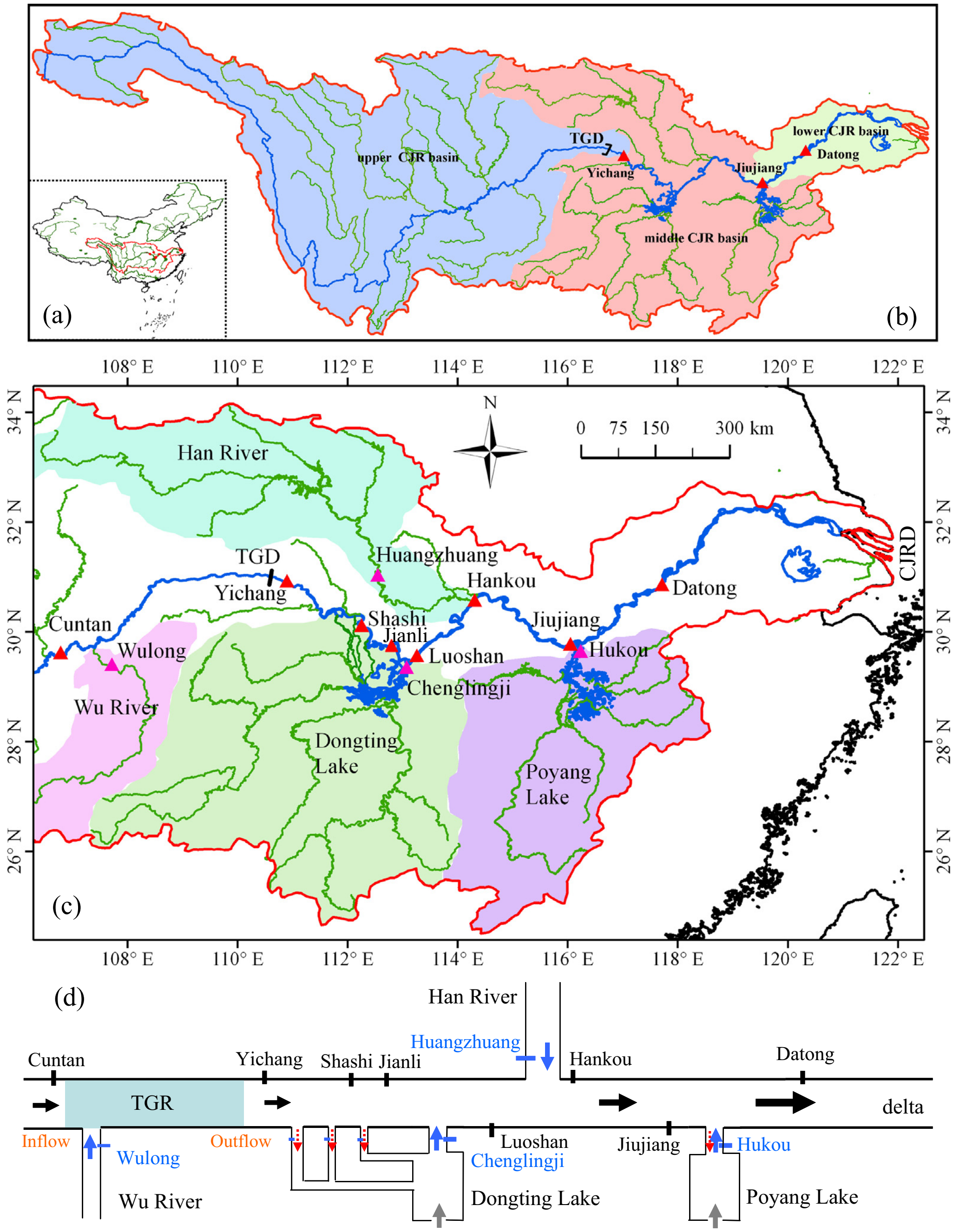

Fig. 1. Sketch maps of (A) the location of the CJR basin in China, (B) the CJR basin as a whole, (C) the middle and lower CJR basin with major tributaries and the gauge stations, and (D) a cartoon showing the relative position of the tributaries and gauge stations. The TGD and TGR mean the Three Gorges Dam and the Three Gorges Reservoir, respectively. The CJRD refers to the Changjiang River delta.

autumn of 2006 (Dai et al., 2011). The highest flood peak discharges ever recorded are 105,000 m^3/s at Yichang (in 1870) and 92,600 m^3/s at Datong (in 1954). Catastrophic floods impose huge risks on the densely populated flood plains downstream of Yichang and there was an idea of constructing the TGD to control big floods many decades ago.

2.2. Data

We collect hydro-meteorological data including air temperature, precipitation, daily river discharges and water levels, monthly and yearly streamflow and sediment loads at multiple stations along the mainstream downward Cuntan and at the mouths of the tributaries and lakes (Fig. 1). Air temperature and precipitation data are collected from publications (NCC, 2011; Sang et al., 2012; Wang et al., 2012; Zhang et al., 2014). Daily river discharges and water levels (http://xxfb.hydroinfo.gov.cn) and the inflow and outflow of the TGD (http://www.ctgpc.com.cn) are obtained from official websites. The monthly and yearly streamflow and sediment loads are from government bulletins, e.g., CWRM (2006, 2016). The annual streamflow and sediment loads data date back to 1950s and the daily river discharges and water levels date back to 1980s. Annually mean river discharges, annually minimum and maximum monthly river discharges are also collected at

Yichang (1878–1986), Hankou (1865–1986), and Datong (1948–1986), from a global river discharge data base (http://www.compositerunoff.sr.unh.edu/) (Fekete et al., 2002). Preliminary analysis suggest that the data from the global data base are consistent with the officially published data in the overlap period (1950–1986), with a mean deviation <1%. Note that the annually minimum monthly discharge is not the same as the minimum 30-day averaged discharge. The river discharge and sediment loads differences between the inflow (that at Cuntan plus Wulong) and outflow (that at Yichang) of the TGD are used to indicate its regulation effects. The streamflow differences between the inflow and outflow during TGD's impounding periods are taken as the amount of water stored by the reservoir when assuming limited water loss to evaporation and groundwater etc. Only surface flow is taken into account while groundwater and its exchange with surface water and evaporation are not analyzed in this work as a first approximate.

Sediment loads are represented by suspended sediment transport while bed load is excluded in this study. It is because bed load transport accounts for a small proportion (<5%) of the total load transport. At Cuntan, for instance, the annual bed load is 0.1–0.6 million tons prior 2000 and is <0.1 million tons afterward (Fang and Dong, 2011). The bed load transport flux is much smaller compared to suspended load downstream of Yichang (Chen et al., 2010). It is technically difficult to monitor bed load transport accurately in fluvial sandy environments and data in that sense is scarce.

2.3. Trend analysis methods

We first apply change-point analysis (Taylor, 2000) to the normalized discharge anomaly to test non-linear trend (e.g., monotonic non-linear, plateau, through, peak, rapid changes). The cumulative function S, whose values S_i are defined as: $S_i = S_{i-1} + (\overline{X} - X_i)$ while X_i, i = 1, 2…N, is the time series of normalized anomaly and $\overline{X}$ is the mean value. A potential change point is detected when a change in the direction of the S function occurs, whose interval of occurrence is defined by the parameter $S_{diff} = \max(S) - \min(S)$. Statistical significance of the identified change points is verified by using a bootstrapping technique at a 5% significance level (Castino et al., 2016). It is achieved by randomly resampling (to remove any potential change point) M times ($M > 10^3$, in this analysis 10^4) and the statistics for the parameter S_{diff} is generated. The level of significance is given by the percentage of bootstrap cycles for which the synthetic S_{diff} parameter is greater than the observed one. Once a primary, statistically significant change point is obtained, the same procedure is applied to the sub-time series of the X variable before and after the change point, to search for secondary change points. This iterative procedure is applied as long as statistically significant change points are detected (Castino et al., 2016). Preliminary tests show that the change-point timing is independent of the normalization reference period thus the mean value in the interval of 1950–1985 (considering that the mid-1980s is a visual changing point of annual streamflow and sediment load at most stations, see Section 4 for details) is used in this study if not specified in particular. Note that the detected change points may not locate at an exact year but around some year when the changes are not sharp.

We then apply linear regression analysis to the normalized anomaly of streamflow and sediment loads to detect linear trends and change rates on both sides of the change points. Student's *t* test and Mann-Kendall (MK) test at 5% significance level are used to determine the statistical significance of the linear trend (Mann, 1945; Kendall, 1975). Details of the linear trend analysis methods can be found in literatures thus are not repeated here.

3. TGD operation

In this section we provide a brief overview of TGD operation and its effects on river discharge hydrograph. The TGD was constructed from 1993 to 2009. With a dam height of 185 m (above mean sea level) and a dam length of 2335 m, the TGD forms a reservoir stretching about 600,000 m between the dam site and Cuntan (Fig. 1) and with a surface area of 1084 million m^2 (which was 452 million m^2 under no TGD situation), a total storage capacity of 39.3 billion m^3, and a flood control capacity of 22.15 billion m^3 at a high pool level of 175 m. The flood control capacity is ~5% of the annual streamflow at Yichang, i.e., annually 451.0 billion m^3 between 1950 and 2005. The TGD has generated a hydropower output of averagely 88.2 billion kilowatt hours per year in the past 14 years. Flood control, power generation, and promoting irrigation and navigation are its essential functions.

The TGD operation follows a scheme by storing and flushing water seasonally. Rising water level ahead the dam (WLAD) suggests larger inflow than outflow and TGD impoundments while falling WLAD indicates larger outflow than inflow and water release (Figs. 2 and S1). Specifically, the WLAD maintains at a low level of 145 m between June and September (the wet season), sustaining the flood control volume available for occasional river floods forming in the upper basin with a peak discharge >55,000 m^3/s (Zheng, 2016). Since early October when the wet season ends, the TGD will reduce outflow and store water for hydropower generation until the WLAD reaches 175 m. The WLAD will stay at 175 m until January after which the WLAD drops gradually until June when the wet season begins. Overall the TGD operation reflects a flood-control scheme which is designed to control river floods and to store water for hydropower generation (Zheng, 2016). Regarding reservoir sedimentation management, the TGD operation reflects a strategy of 'storing clear water (in the dry season with a high pool level) and releasing muddy water (in the wet seasons with a low pool level)'. Even though reservoir sedimentation is still huge in its early stage of lifespan because of a large reservoir size (see Section 5.3).

The realistic TGD operations follow the abovementioned scheme other than that the starting time of its impoundments is 1–2 months earlier than October (Fig. 2). Specifically, the TGD started to store water the first time in May of 2003 and the WLAD was raised from 67 to 135 m. In the second phase of its pilot operation, the WLAD was raised from 135 to 156 m in October of 2006. In the third phase, the WLAD was raised from 145 to 172 m in 2008. Given concerns of the safety of the dam and the influences on the downstream basin, the WLAD did not reach 175 m until 2010 the first time (Fig. 2). Since then the TGD is put into normal operation with a seasonally and regularly raised and dropped pool

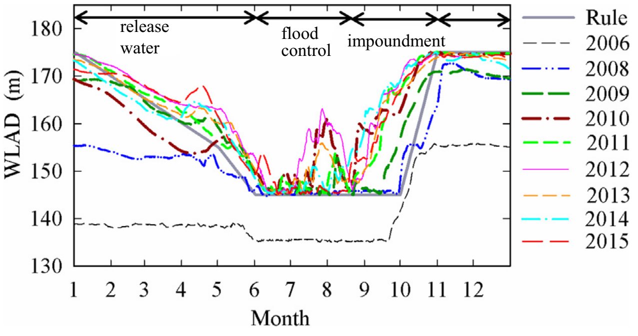

Fig. 2. Yearly variations of water level ahead the dam (WLAD) in comparison with the designed operation scheme.

level. So far we see that TGD impoundments in autumn last for a period of 37–90 days (Table 1).

We compare TGD's inflow and outflow hydrographs to quantify its impacts on river discharges. It shows that the peak river discharges of the outflow are up to 20,000 m^3/s smaller in a short period of days to weeks, reflecting TGD's capability in mitigating big floods (see Fig. S2 in the Appendix). The outflow during the impounding periods in autumn is averagely reduced by 2790–5880 m^3/s (Table 1). By adding the stored water to the actually measured streamflow at Yichang and Datong during the impounding periods, we estimate that the mean streamflow is reduced by 11–32% and 7–20%, respectively. By contrast, the outflow is averagely 2000 m^3/s larger than the inflow in the dry months between January and May (see Fig. S2). Overall the TGD modulates river discharge hydrograph by reducing flood peak discharges and river discharges during the impounding periods, and slightly increasing river discharges in the dry seasons.

4. Results

4.1. Hydro-meteorological changes

This section describes hydro-meteorological changes in terms of air temperature, precipitation, and evapotranspiration. The nation-wide daily maximum temperature is increasing in China since 1980s owing to changes in the Asian monsoon, indicating a warm trend (Kuang et al., 2014). In the CJR basin, the basin-wide mean air temperature decreases slightly between 1950 and 1985, followed by a fast increase trend indicating climatic warming as well (Figs. 3A and S3A; Chen et al., 2001a; Sang et al., 2012). Linear trend analysis reveals an increase rate of 0.45 °C per decade between 1985 and 2010 for the CJR basin as a whole (Figs. 3A and S3A).

The precipitation exhibits large spatial and temporal variations in the CJR basin (Wang et al., 2012; Zhang et al., 2014; Chen et al., 2016). The basin-averaged precipitation shows a significant decrease trend between 1950 and 2015 ($p < 0.02$), i.e., a decrease rate of ~13 mm per decade (Figs. 3B and S3B). Similar decrease at decadal time scales occurs in the upper CJR basin particularly in the interval of 1950–1970 while the afterward decrease trend is non-significant. Seasonally, summer precipitation displays an increase trend while autumn precipitation decreases significantly particularly since the mid-1980s (Becker et al., 2006). In contrast, a significant decrease of summer precipitation occurs in the upper CJR basin (Jiang et al., 2007; Gemmer et al., 2008; Deng et al., 2013). The basin-wide precipitation becomes more concentrated in time, i.e., increased precipitation intensity in short durations (Becker et al., 2006; Zhang et al., 2014).

Regarding evaporation, both annual reference evapotranspiration and pan evaporation show a significant decrease trend between 1960 and 2007, which is ascribed to decreasing net total radiation and wind speed (Xu et al., 2006; Wang et al., 2011). The decrease in evapotranspiration is more significant in summer and in the middle-lower basin (Wang et al., 2007a, 2011). In the middle-lower CJR basin, the annual reference evapotranspiration also decreases significantly between 1960 and early-1990s mainly due to declined net radiation, followed by an afterward slight increase which is ascribed to reduced relative humidity in the air (Xing et al., 2016).

As an evaporation source, the large reservoir formed by TGD potentially has impacts on regional climate considering its surface cooling effects and reduced radiative heating. The impacts diminish fast with distance away from the reservoir and so far measurable but non-significant air temperature decrease is detected in the regions surrounding the reservoir (Miller et al., 2005; Wu et al., 2012). Data and modeling results suggest that the reservoir's impact on basin-scale climate is overall limited (NCC, 2011; Wu et al., 2012). Further monitor and in-depth examination is needed to clarify the degree to which the large reservoirs formed by TGD and other new big dams in the upper CJR basin can affect regional and sub-basin climate.

When looking forward into the future, Sun et al. (2013) modeled that the temperature will increase and the annual rainfall will decrease in the upper CJR basin in the 21st century, as a result of climatic warming. Nakaegawa et al. (2013) predicted that the streamflow of the CJR basin may increase in the wet seasons between May and August if considering climate change impacts only. Considering the uncertainties in the model projections (Birkinshaw et al., 2017) and the land use changes in the future, it remains an open question how the basin-scale hydro-meteorology will change in response to climate changes and human activities.

4.2. River discharge changes

4.2.1. Annual streamflow changes

The annual streamflow exhibits only slight decrease trends along the mainstream downward TGD. At Cuntan, a non-significant change point ($p < 0.11$) is detected in 1968 based on data between 1940 and 2015 (Figs. 4A and S4A). The change points detected in 1954 and 1968, however, are significant ($p < 0.02$) at Yichang (Figs. 4B and S4A). There are no significant directional changes prior 1954 but an afterward decrease trend by a rate of 4.8 billion m^3 per decade between 1955 and 2015. Over century, the annual streamflow decreases from averagely 455.8 billion m^3 in 1878–1954 to 402.6 billion m^3 in 2003–2015 at Yichang, indicating a reduction by 11.7%. At Hankou, the annual streamflow decreases from averagely 750.2 billion m^3 in 1865–1954 to 696.7 billion m^3 in 1955–2015, but the change point detected in 1954 is non-significant ($p < 0.21$) (Figs. 4C and S4B). Similarly, the

Table 1
TGD impoundments in the recent years and their impacts on reducing river discharges.

Year	Impounding period	Stored water (km^3)	Mean discharge reduction (m^3/s)	Streamflow at Yichang (km^3)	Streamflow at Datong (km^3)
2003	24 May-10 Jun	10.0	6430	10.78	56.04
2006	21 Sep-27 Oct	11.1	3470	30.52	50.15
2008	28 Sep-04 Nov	19.3	5880	40.25	82.78
2009	15 Sep-30 Oct	17.7	4440	40.56	70.69
2010	22 Aug-26 Oct	21.0	3800	103.7	204.5
2011	20 Aug-30 Oct	21.8	3550	67.45	135.9
2012	21 Aug-30 Oct	21.7	3540	112.7	214.5
2013	27 Aug-13 Nov	20.9	3100	73.8	140.9
2014	02 Aug-31 Oct	21.7	2790	182.5	282.7
2015	17 Aug-01 Nov	21.4	3260	114.4	183.2
2016	08 Sep-02 Nov	21.5	4430	50.7	98.6

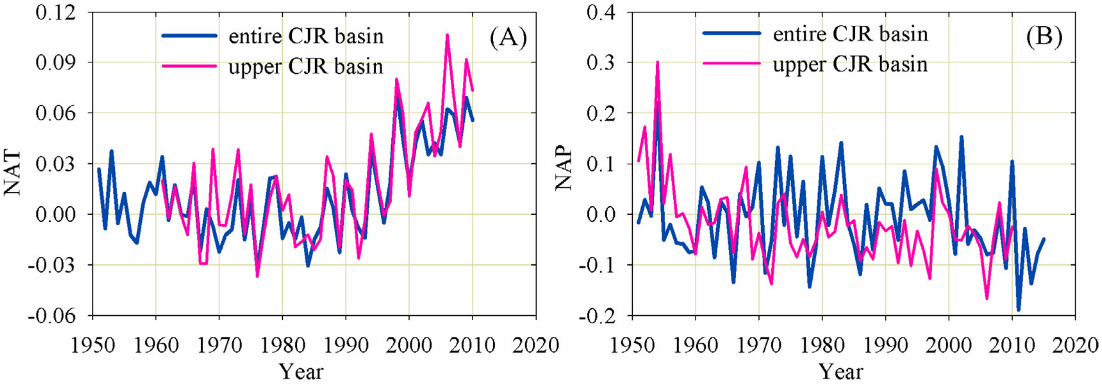

Fig. 3. Variations of the normalized anomaly of (A) annual temperature (NAT) and (B) annual precipitation (NAP) averaged in the upper CJR basin and in the entire basin as a whole.

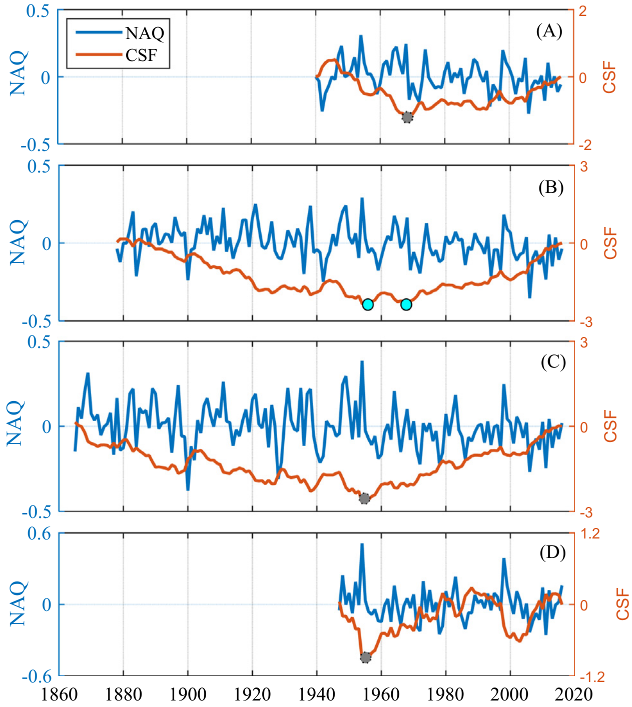

Fig. 4. The normalized anomaly of the annual streamflow (NAQ) and associated cumulative functions (CSF) at (A) Cuntan (1940–2015), (B) Yichang (1878–2015), (C) Hankou (1865–2015), and (D) Datong (1947–2015). The dots indicate the detected change points.

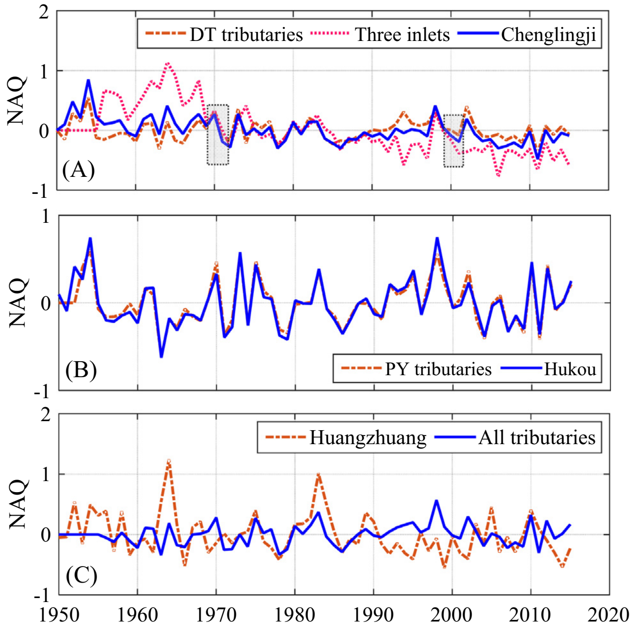

Fig. 5. The normalized anomaly of the annual streamflow (NAQ) (A) of the Dongting (DT) Lake tributaries, at three inlets, and at Chenglingji, (B) of the Poyang (PY) Lake tributaries and at Hukou, and (C) at Huangzhuang and the total of the three tributaries between 1950 and 2015.

change point in 1954 is non-significant at Datong though the data length is shorter (Figs. 4D and S4C). The change point in the early 2000s is non-significant at both Yichang and Datong ($p < 0.18$), suggesting limited impacts of the TGD on the annual streamflow. In the interval of 1955–2015, the decrease trends of the annual streamflow are significant at Cuntan ($p < 0.01$) and Yichang ($p < 0.02$), whereas it is non-significant at Hankou ($p < 0.08$, 0.6 billion m^3 per decade) and Datong ($p < 0.14$, 6.9 billion m^3 per decade).

More temporal streamflow changes are detected in the tributaries based on data between 1950 and 2015. In the Dongting Lake system, the total streamflow of the three inlets exhibits significant decrease change points in the late 1960s ($p < 0.01$) and early 2000s ($p < 0.05$) (Figs. 5A and S5A). Specifically, it decreases from 134.2 billion m^3 in 1956–1968 to 48.6 billion m^3 in 2001–2015, a reduction by 64%. With no directional changes of the total streamflow of the four tributaries, the streamflow at Chenglingji has decreased significantly between 1950 and 1970 ($p < 0.003$), followed by a non-significant decrease trend until 2015, i.e., from 338.3 billion m^3 in 1951–1968 to 241.3 billion m^3 in 2001–2015. No significant change points are detected on the time series of annual streamflow at Huangzhuang, Hukou, and Poyang Lake tributaries (Fig. 5B and C). The total streamflow of the Poyang Lake tributaries and that at Hukou exhibits consistent temporal variations (Figs. 5B and S5B). Linear trend analyses suggest significant streamflow decrease trends at Chenglingji ($p < 0.0001$), three inlets ($p < 0.0001$), and Huangzhuang ($p < 0.03$) in 1950–2015, while the decrease trends for Dongting Lake tributaries ($p < 0.81$) and the increasing trends at Hukou ($p < 0.60$) and Poyang Lake tributaries ($p < 0.66$) are non-significant. In all, the total streamflow of the Dongting Lake, the Han River, and Poyang Lake, represented by the summed streamflow at Chenglingji, Huangzhuang, and Hukou minus that at three inlets, exhibits a non-significant increase trend ($p < 0.27$) (Figs. 5C and S5C).

4.2.2. Seasonal river discharge changes

River discharge may change remarkably at intra-annual time scales when the annual streamflow remains unchanged. The annually minimum monthly discharges (not necessarily in the same month in different years) increase substantially in the recent decades. The minimum monthly discharges are slightly smaller in 1940–2000 compared to 1880–1940 at Yichang (Figs. 6A and S6A). A significant change point is present at both Cuntan and Yichang in 1999. The abrupt increase at Yichang since 2007 is ascribed to TGD operation while the abrupt increase at Cuntan since 2012 is caused by Xiangjiaba Dam. Specifically, the annually minimum monthly discharges have increased by up to ~3000 m^3/s at Yichang, while the differences between Cuntan and Yichang increase sharply from averagely ~800 m^3/s (1940–1999) to ~1900 m^3/s (2007–2015). It suggests that the TGD flushes nearly ~2000 m^3/s more water downstream in the driest months.

The annually minimum monthly discharge starts to increase since 1900s at Hankou, and the afterward increase rate becomes larger with a significant change point in 1954 ($p < 0.001$) (Fig. S6B). Similar increase is observed at Datong since the late 1950s (Figs. 6A and S6C), i.e., an increase from averagely 9260 m^3/s (1960–1980) to 12,000 m^3/s (2007–2015). The changes since 2007 are less noticeable at both Hankou and Datong compared to Yichang, suggesting downward dissipated changes.

The annually maximum monthly discharge exhibits more spatial and temporal changes. It changes limitedly at Cuntan since 1960 whereas a stepwise reduction in late 1950s and a linear reduction trend since 1980s are detected at Yichang (Figs. 6B and S7A). The maximum monthly discharges are averagely ~3400 m^3/s smaller at Yichang in 2001–2015 compared to 1955–2000. They are slightly smaller in the decades since 2000 compared to the prior decades at Hankou and Datong (Figs. S7B and S7C). Higher streamflow in the 1990s affects the trend detection at Hankou and Datong, and it is too early to conclude whether the decrease trend since 2000 is significant.

The mean river discharges in October exhibit decrease trends. The October river discharges decrease slightly since 1980 at Cuntan (Figs. 6C and S8A). The decrease trend is at a faster rate at Yichang than Cuntan in the decades since 1980 and the October river discharges become smaller at Yichang since 2006, implying

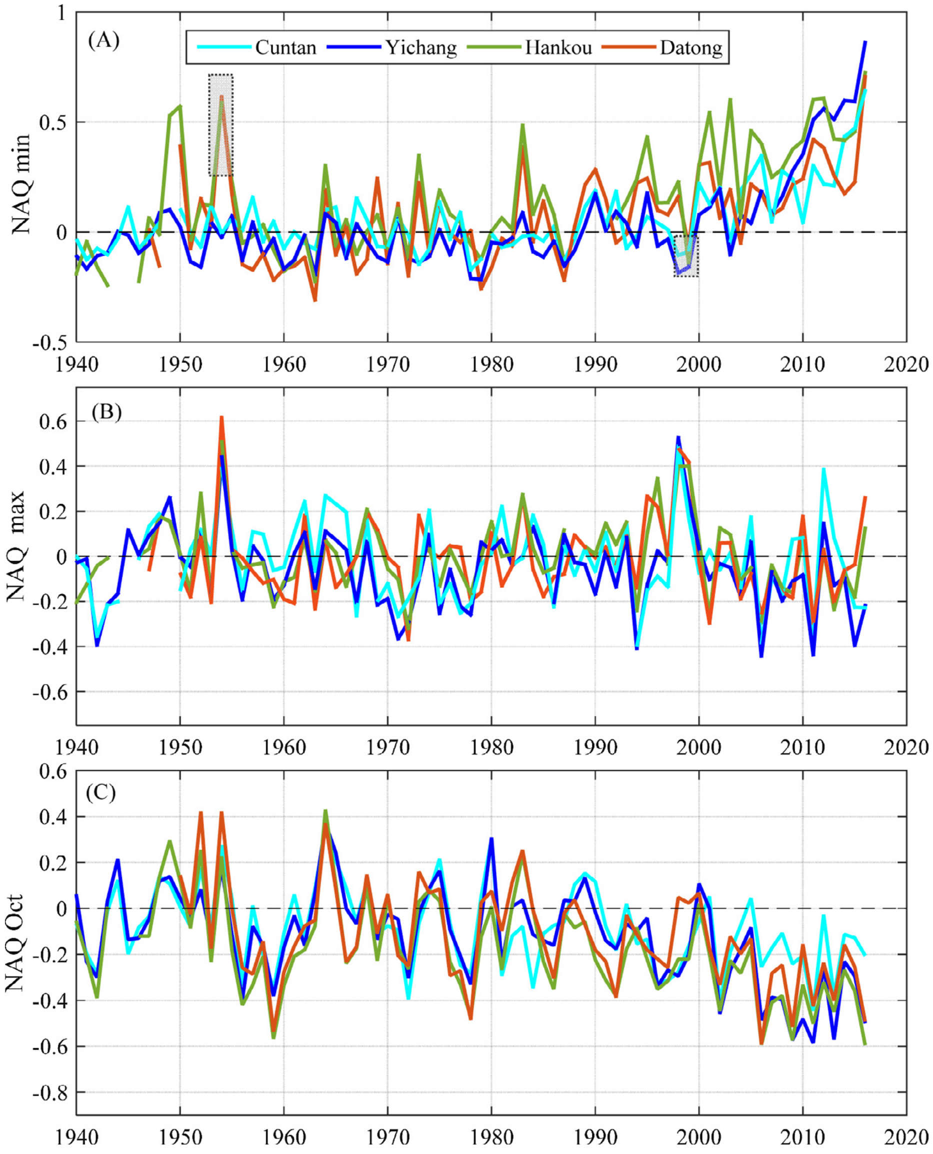

Fig. 6. The normalized anomaly (NAQ) of (A) annually minimum monthly, (B) annually maximum monthly discharge, (C) monthly river discharge in October at Cuntan, Yichang, and Datong in the periods of 1960–2015. The normalization reference period is chosen as the period prior 1960.

the impacts of TGD impoundments in autumn. Specifically it declines from 19,800 m^3/s in 1890–1954 to 11,000 m^3/s in 2006–2015 at Yichang. Similarly, the October river discharges reduce significantly since 1960s at both Hankou and Datong (Figs. S8B and S8C), e.g., from 33,600 m^3/s in 1960–1980 to 23,800 m^3/s in 2006–2015 at Datong.

We further estimate the probability distributions of daily river discharges at Cuntan, Yichang, and Datong to infer seasonal changes. Notably we find that the probability of both extremely low and high river discharges has decreased while that of medium river discharges (e.g., river discharges in the range of 10,000–25,000 m^3/s at Datong) has increased at all three stations (Fig. 7A). The river discharge at the 50th percentile reduces accordingly (Fig. 7B). The mean river discharge hydrographs show that the low river discharges in the dry seasons slightly increase while the high river discharges in the wet seasons decrease profoundly (see Fig. S9). The river discharge reduction is much more significant at Yichang and Datong than Cuntan between August and October, again demonstrating the impacts of TGD impoundments. Overall, these results suggest that the river discharge hydrograph of TGD inflow is ever changing and the TGD operation modulates it at a seasonal time scale.

4.3. Changes of sediment loads

4.3.1. Sediment loads changes along the mainstream

The sediment loads in the CJR basin exhibit radical decreases at the decadal time scales, particularly since 1980s. Significant change points are detected in the early 1990s ($p < 0.004$) and early 2000s ($p < 0.012$) at both Cuntan (plus Wulong to represent sediment influx of TGD) and Yichang (Figs. 8A and S10). The sediment loads variations display consistent behavior between Cuntan and Yichang in the decades prior 2002, though it is slightly larger at Yichang. Since 2003, the sediment loads become smaller at Yichang and the differences between Cuntan and Yichang become larger, reflecting sediment trapping effects of the TGD. Specifically, the summed sediment loads at Cuntan and Wulong have not changed very much between 1950 and mid-1980s (annually 487.6 ± 231.9 million tons), but decreased to 164.4 ± 131.3 million tons in 2003–2015, indicating a reduction by 66%. Immediately downstream of the TGD, the sediment loads are 527.2 ± 221.4 and 40.4 ± 69.6 million tons in 1950–1985 and 2003–2015, respectively, at Yichang, indicating a reduction by 92%. The dramatic reduction reflects combined effects of a source reduction upstream of Cuntan and TGD sedimentation. In all these changes suggest that the sediment loads have reduced progressively since the mid-1980s and the TGD accelerates the reduction since 2003 at a remarkable rate.

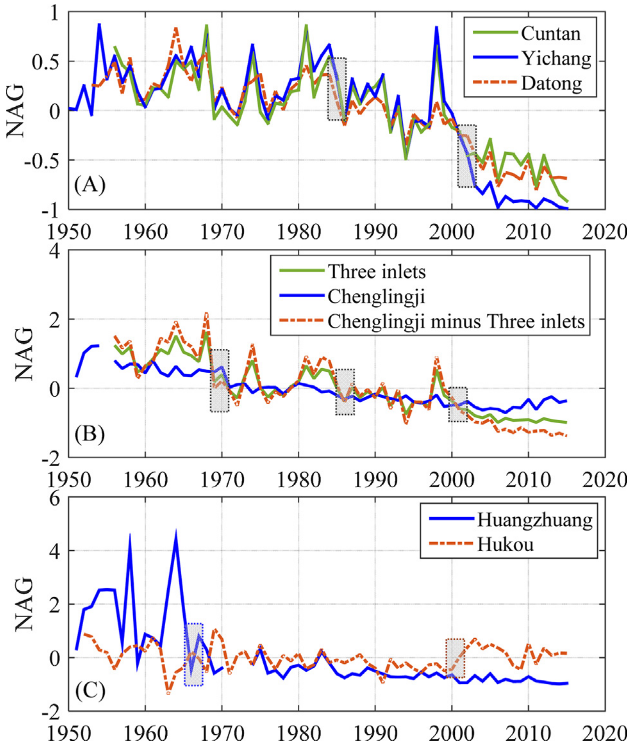

Fig. 8. The normalized anomaly of sediment loads (NAG) (A) at Cuntan (plus Wulong), Yichang, and Datong, (B) at three inlets, Chenglingji, and that at Chenglingji minus at three inlets, and (C) at Huangzhuang and Hukou. The shade bars indicate change points.

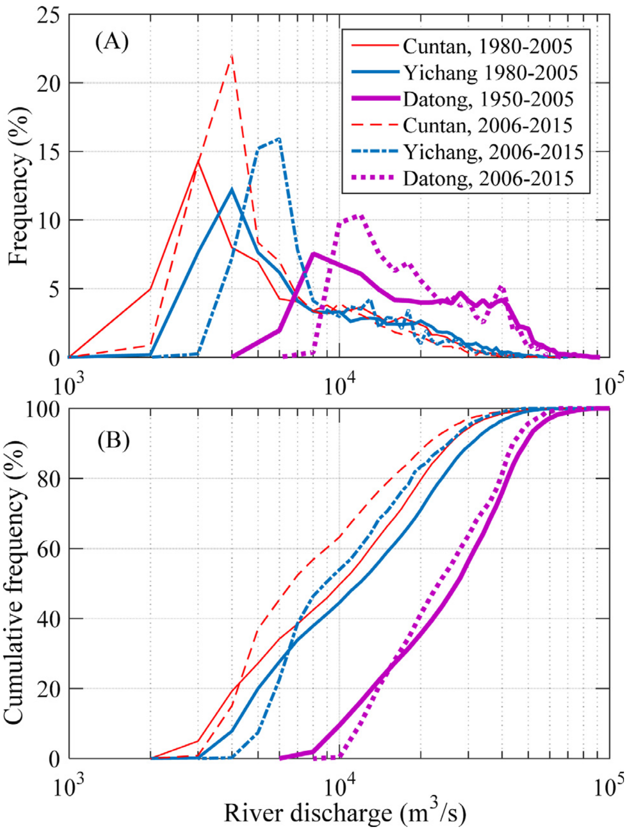

Fig. 7. (A) the frequency distribution, and (B) the cumulative frequency distribution of the daily river discharges at Cuntan, Yichang, and Datong in two periods.

The sediment loads downstream of Yichang follow the reduction trend but at a smaller rate. At Hankou (not shown), the sediment loads have decreased from 431.3 ± 167.8 (1953–1985) to 105.9 ± 68.1 million tons (2003–2015), suggesting a reduction by 75%. Further downstream, at Datong, it decreases from annually 470.4 ± 207.6 million tons in 1951–1985 to 138.7 ± 77.3 million tons in 2003–2015, suggesting a reduction by 70%. Over time, four statistically significant change points are detected in the late 1960s ($p < 0.04$), mid-1980s ($p < 0.05$), early 1990s ($p < 0.02$), and early 2000s ($p < 0.001$) at Datong. More variability at Datong than Yichang is ascribed to superimposed changes occurred in the upper and middle-lower CJR basins (see Section 5.3). In the near future decades, the annual sediment loads at Yichang are highly likely to remain at a low level (<10 million tons) considering ongoing dam constructions in the upper basin (Fig. S10). With sediment compensation from tributaries and bed erosion (see Section 5.3), the sediment loads at Hankou and Datong seem to have reached a decadal stable state, i.e., annually averaged ∼88.2 and ∼126.1

million tons, respectively, in 2006–2016. It is reasonably expected that the sediment loads will not restore to a mean value larger than that in future at Hankou and Datong, and further reduction may occur considering diminished river erosion downstream of TGD.

4.3.2. Sediment loads changes in the main tributaries

The sediment loads of the main tributaries in the middle CJR basin have reduced profoundly as well. The total sediment loads of the four tributaries of the Dongting Lake system exhibit non-significant changes between 1950 and the mid-1980s (except the extreme peak in 1954) but decrease abruptly in the mid-1980s, followed by a slow decrease trend until nowadays (Figs. 8B and S11A). The annual sediment loads are 35.2 ± 23.5, 17.8 ± 11.4, and 8.0 ± 4.5 million tons in the interval of 1953–1984, 1985–2005, and 2006–2015, respectively. At the three inlets, the sediment loads display three significant change points in the late 1960s, mid-1980s, and early 2000s. It decreases from averagely 200.2 ± 59.4 million tons in 1956–1968 to 118.2 ± 59.5, 64.7 ± 87.6, and 6.5 ± 6.8 million tons in 1969–1984, 1985–2005, and 2006–2015, respectively. Accordingly, significant change points of sediment loads reduction are detected in the early 1970s ($p < 0.001$), early 1980 ($p < 0.008$), and mid-2000 s ($p < 0.001$) at Chenglingji (Figs. 8B and S11A). The sediment loads have decreased from averagely 62.5 ± 22.5 million tons in 1951–1970 to 22.1 ± 7.5 million tons in 2008–2015. Note that slightly more sediment is flushed out of the Dongting Lake at Chenglingji in 2008–2015 compared to the previous decade (Fig. S11A).

The sediment balance between the mainstream and the Dongting Lake is reversed around 2006. The CJR mainstream diverted more sediment to the lake via the three inlets than its gain from the lake via Chenglingji prior 2006 (Fig. S11A). The imbalance diminished over time due to more dramatic sediment loads reduction at the three inlets. Specifically, the CJR mainstream annually lost a net of 136.3 ± 56.1 and 48.1 ± 72.1 million tons of sediment to the Dongting Lake in 1956–1966 and 1990–2000, respectively. In the recent decade since 2006, the CJR mainstream has an annual sediment surplus of 16.1 ± 7.7 million tons regarding its exchange with the lake (Fig. S11B). With respect to the Dongting Lake, lake sedimentation and sediment surplus occurs prior 2006 because of more sediment sources (from lake tributaries and three inlets) than loss (at Chenglingji) but it shifts to afterward lake erosion because of more sediment loss than the total sediment supply.

Similar changes are observed in the Poyang Lake system. The total sediment loads from five tributaries of the Poyang Lake show no directional changes between the mid-1950s and mid-1980s but a significant decrease trend ($p < 0.001$) between the late 1970s and late 2000s (Fig. S11C). It is averagely 16.2 ± 12.4 million tons in 1956–1984 and 6.0 ± 6.9 millions in 2001–2015. The sediment loads at Hukou have decreased gradually between 1970 and 2000 and displayed an abrupt increase in 2001 ($p < 0.007$) (Figs. 8C and S11C). The mean sediment loads are 14.1 ± 8.3, 6.2 ± 5.6, and 12.2 ± 6.6 million tons in the decades of 1952–1962, 1990–2000, and 2001–2015, respectively. As a result, the Poyang Lake receives less sediment supply from its tributaries comparing to its loss to the mainstream at Hukou since 2000, suggesting a shift from lake sedimentation to erosion as well.

The sediment loads of the Han River show two significant change points, i.e., in the late 1960s ($p < 0.04$) and late 1980s ($p < 0.02$) (Figs. 8C and S11D). The mean sediment loads are 119.4 ± 112.6 million tons in 1951–1964 but reduce sharply after the closure of the Danjiangkou Dam in the upper Han River in 1965, and decline further to a relatively small quantity in the recent decade, i.e., averagely 5.8 ± 11.3 million tons in 2001–2015.

The total sediment loads of the three main tributaries undergo dramatic decreases and exhibit strong temporal changes. From a sediment budget point of view, the CJR mainstream loses more sediment to the Dongting Lake than its total gain from the two lakes and the Han River prior 2001 (other than the extreme years) (Fig. S11D). The late 1960s is featured by maximal net loss due to dramatically reduced sediment loads from the Han River. The CJR mainstream attains a net sediment surplus in the recent decade since 2002, which is mainly because of reduced sediment loss via the three inlets and increased sediment loads at both lake mouths, i.e., Chenglingji and Hukou. The net sediment surplus is ~30.5 million tons per year in the interval of 2003–2015.

4.3.3. Seasonal changes of sediment loads

Sediment loads also change profoundly at seasonal time scales. Basically >85% of annual sediment loads are discharged between May and October in the middle-lower CJR river, because of higher precipitation and associated higher river discharge and higher sediment yield in the wet seasons (Fig. 9). The sediment loads in the wet seasons, however, have decreased enormously in the recent decade since 2003 while the reduction in the dry seasons is less measurable. Specifically, the sediment loads in the wet season are 456.5 ± 425.3 (96% of annual total) and 364.7 ± 361.7 millions tons (87% of annual total) at Yichang and Datong, respectively, in the interval of 1950–2002. They decrease to 43.2 ± 113.7 (98% of annual total) and 111.1 ± 112.6 million tons (80% of annual total) in 2003–2015, respectively (Fig. 9). TGD sedimentation is the main reason of the dramatic reduction in the wet seasons (see discussion in Section 5.3).

4.3.4. Sediment rating curves

The sediment rating curves imply changes out of phase between the streamflow and sediment loads. We see that the lower CRJ mainstream, i.e., at Datong, is overall much less sediment-loaded compared to Yichang and Cuntan (Fig. 10A). Over time, it becomes increasingly less sediment-loaded at all three stations in the mainstream due to strikingly reduced sediment loads. In the tributaries, the Han River and the three inlets are characterized by a higher sediment loading rate while the outflows of the Dongting and Poyang lakes are much less sediment-loaded. The annual sediment loads of the Han River and at the three inlets have decreased significantly considering streamflow reduction at a smaller rate, while the changes at Chenglingji and Hukou are comparatively less apparent because sedimentation and/or erosion inside the lakes have buffering impacts on sediment flux at the lake mouths. In all, these changes suggest that the CJR downstream of the TGD becomes much less sediment-loaded in the decades since the mid-1980s due to more remarkable reduction of sediment loads compared to streamflow.

5. Discussion

5.1. Sensitivity to data range in inferring long-term changes

The length of a data series has considerable impacts on interpretation of hydrological changes. For instance, the significant change point of the annual streamflow at Yichang and Hankou in 1954 is detected based on data in 1865–2015 which is however not revealed by datasets in 1950–2015 (see Fig. 4B). Linear trend analysis of the streamflow at Datong shows a slight but non-significant decrease trend based on data in 1950–2015 whereas it exhibits a non-significant increase trend in 1955–2015. The later is more reasonable given a significant change point in 1954. The extreme values, e.g., much higher streamflow in 1954 and the late 1990s, influence the trend analysis results too.

The sediment loads changes at Datong provide another example of the sensitivity to data range. The time series of annual sediment loads at Datong do not show an apparent decrease or increase

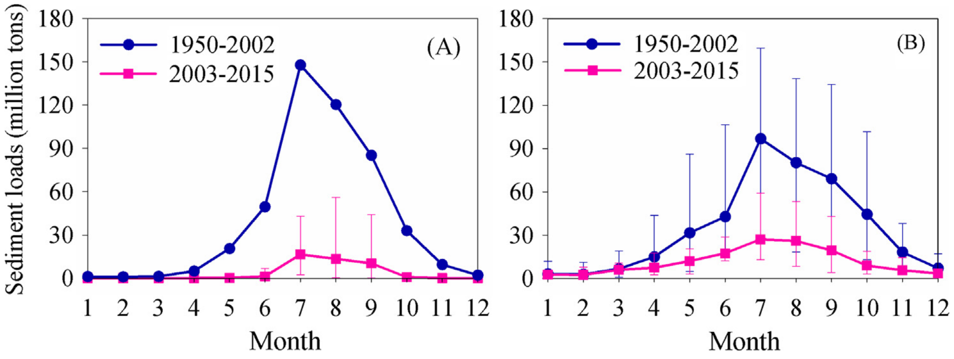

Fig. 9. Intra-annual variations of monthly sediment loads at (A) Yichang and (B) Datong in the periods of 1950–2002 and 2003–2015. Only the mean values of monthly sediment discharges at Yichang are collected between 1950 and 2002 thus the variation range is not shown.

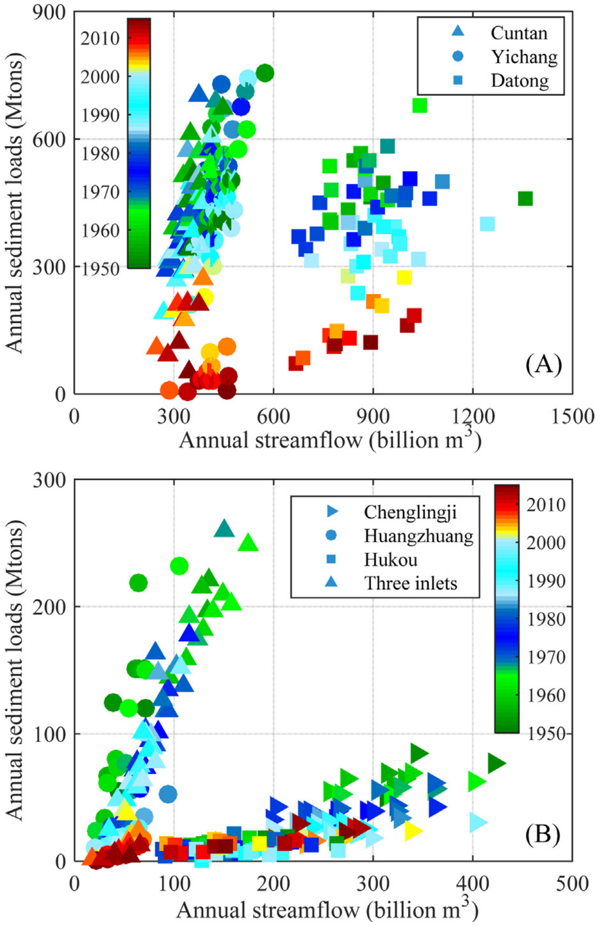

Fig. 10. The sediment rating curves (A) at Cuntan, Yichang, and Datong, and (B) at Chenglingji, Huangzhuang, Hukou, and three inlets based on yearly streamflow and sediment loads.

trend between 1950 and 1970, but a decrease trend is detected between the early 1960s and late 1990s, as well as a much faster decrease trend between 1980 and 2015 (see Figs. 8A and S10). These evidences explain why inconsistent interpretation was obtained by using data of different length in previous studies.

5.2. River–lake interplay and its hydrological impacts

The interactions between the CJR mainstream and the two lakes in terms of water and sediment exchanges play an essential role on the hydrological regime downstream of the TGD (Hu et al., 2007; Guo et al., 2011; Ou et al., 2012). Diversion of water and sediment from the mainstream to the Dongting Lake via the three inlets is only observed in the wet seasons when river stages in mainstream are higher than the bed level at the inlets. The diverted amount of water and sediment has reduced significantly because of lowered river stage in the mainstream and sedimentation in the inlet channels. The former is partly caused by bed erosion due to sediment starvation at the year-to-decade time scale and by decreased river discharges at the seasonal time scale. With non-significant change of total streamflow from the lake tributaries, the streamflow reduction at three inlets explains 89% of streamflow reduction at Chenglingji in 2002–2015 compared to 1951–1968 (see Section 4.2).

Interactions between mainstream and Poyang Lake have changed considerably as well. The Poyang Lake discharges water and sediment towards the mainstream and the mainstream has a 'backwater effect' on the lake outflows most of the time in a year course (Guo et al., 2011). Reverse flow happens in the wet seasons between July and September when the CJR is at a river stage higher than that in the Poyang Lake. River stage differences occur because of earlier start and ending of the rainy season in the middle-lower basin than that in the upper CJR basin as mentioned in Section 2.1. The magnitude and frequency of the reverse flow at Hukou however have decreased profoundly even vanished in the recent decade (Guo et al., 2011; Zhang et al., 2012b,c). In the mean time the annual streamflow at Hukou has changed little between 1950 and 2015 (see Fig. S5B). It is because the reverse flow is overall limited compared to the total streamflow of the lake tributaries while the later exhibits no directional changes.

The river–lake interactions are inherently controlled by river stages in the vicinity of river–lake conjunctions. There are highly linear correlationships between the river stages in the mainstream and at the lake mouth, such as that between Luoshan and Chenglingji and that between Jiujiang and Hukou (see Fig. S12). It implies that water level falling in the mainstream will induce synchronized water level drops at the lake mouth, thus lowering the 'backwater effect' (Guo et al., 2011; Mei et al., 2016). River stages along the mainstream fall because of seasonal river discharge decreases and channel degradation (Xu et al., 2011b; Dai and Liu, 2013). Channel degradation is evidenced by river bank erosion and bed scour (Xia et al., 2016) and by changed river discharge-river stage rating curves. River stages are falling under the same river discharge at Yichang and Shashi, particularly under low and medium river discharges (see Fig. S13). For instance, the river stage under a river discharge of 10,000 m^3/s drops from ~43.8 m in 1960, to ~42.7 m in 1990, ~42.1 in 2005, and ~41.3 m in 2015 at Yichang. Falling river stages in the mainstream cause consequent water level drop at the lake mouths, enlarging the water level gradients in the river–lake vicinity (Dai et al., 2015). The enlarged water level gradients foster faster lake outflow, which is in particular significant in the wet-to-dry transition season following TGD impoundments (see Fig. S14). It creates a 'draining effect' on the lake outflow, resulting in decreased water storage inside the lakes and lowered lake stage. The slightly increased river discharges along the mainstream in the dry seasons by the TGD may reinforce the backwater effects on the lake outflow but it is not able to restore water storage inside the lakes. As a consequence, low water occurrence is advanced in time, e.g., by ~20 days in the Dongting Lake (Fig. 11). Moreover, there are non-significant decreasing trends of precipitation (Zhang et al., 2011) and reference evapotranspiration (Ye et al., 2014) in autumn in the Poyang Lake basin. These changes augment the low water regime and can cause severe droughts in the dry seasons.

Lake size shrinkage in long-term further endangers water resources security in the lakes. The annually mean water levels at Chenglingji have increased between 1960s and 1990s but underwent a switch to decline since 2000s (Duan et al., 2012). Similarly, the mean water levels at Hukou and Xingzi, a stage station 38 km more inside the Poyang Lake compared to Hukou, have increased between 1960 and 2000 and switched to an afterward decline (Mei et al., 2016; Zhou et al., 2016). It is estimated that one meter water level drop will induce a surface area reduction and water storage volume shrinking by approximately 200–440 million m^2 and 1.3–1.9 billion m^3, respectively, in the Dongting Lake according to the water level-lake area and water level-storage volume curves (Ding and Li, 2011). The yearly-averaged surface area of the Dongting Lake has decreased from 4350 km^2 in 1949 to 2518 km^2 in 1998 and 1837 km^2 in 2006 (Chen et al., 2001a; Feng et al., 2013; Zhao et al., 2013). The surface area of the Poyang Lake has decreased from 5160 km^2 in 1954 to 3860 km^2 in 1992 at a water level of 22 m at Hukou (Min, 2000). In fact the water level at Hukou rarely exceeds 22 m in the recent decade when the yearly-averaged lake area is only 1740 ± 520 km^2 (Feng et al., 2012). Lake sedimentation and extensive reclamation of the low-lying lands are the main causes of the lake shrinkage. On the other hand, extensive sand mining inside the lakes (Lai et al., 2014) and a sediment balance shift from lake sedimentation to erosion (see Section 4.3) may slow down the shrink trend to some degree. Anyhow reduced lake area and storage volume at a decadal time scale implies degenerated function of the lakes in buffering intra-annual river discharge changes along the mainstream.

Lake size reduction, seasonal river discharge decline and associated draining effects enhance low water occurrence and severity inside the lakes. Given that it is dry season following TGD impoundments, hastened and persistent low water conditions impair water security and riparian ecosystem in the lakes. The wetlands in the Dongting Lake and Poyang Lake, as valuable habitats for fishes and migratory birds in the eastern Asia, are exposed for longer time, particularly in the dry seasons between October and March (Xu et al., 2013b; Sun et al., 2012; Mei et al., 2016). In October 2006 and May 2011, for instance, the wet surface area of the Poyang Lake is estimated by merely ~50 km^2 due to persistent low water level (Zhang et al., 2012b; Feng et al., 2013). As a result, it causes enormous growth of pioneer species such as poplar and over-reproduction of *Microtus fortis* etc., endangering lake ecosystem as valuable natural reserves (Chang et al., 2010; Sun et al., 2012; Xu et al., 2013b). To protect the lakes from drying, measures such as constructing sluices at the lake mouths to control lake outflow are under debating (Wang et al., 2015). But it remains insufficiently known how such a sluice will change the river–lake interactions further and has impacts on sediment imbalance, flooding risk, and lake water quality etc., and integrated research work is needed to sort out nature-based solutions.

The river–lake interplay also plays an important role in mitigating flood risk in the middle-lower CJR basin. The TGD can proactively reduce outflow when its inflow is >55,000 m^3/s, thus protecting the downstream basin, particularly the reaches between

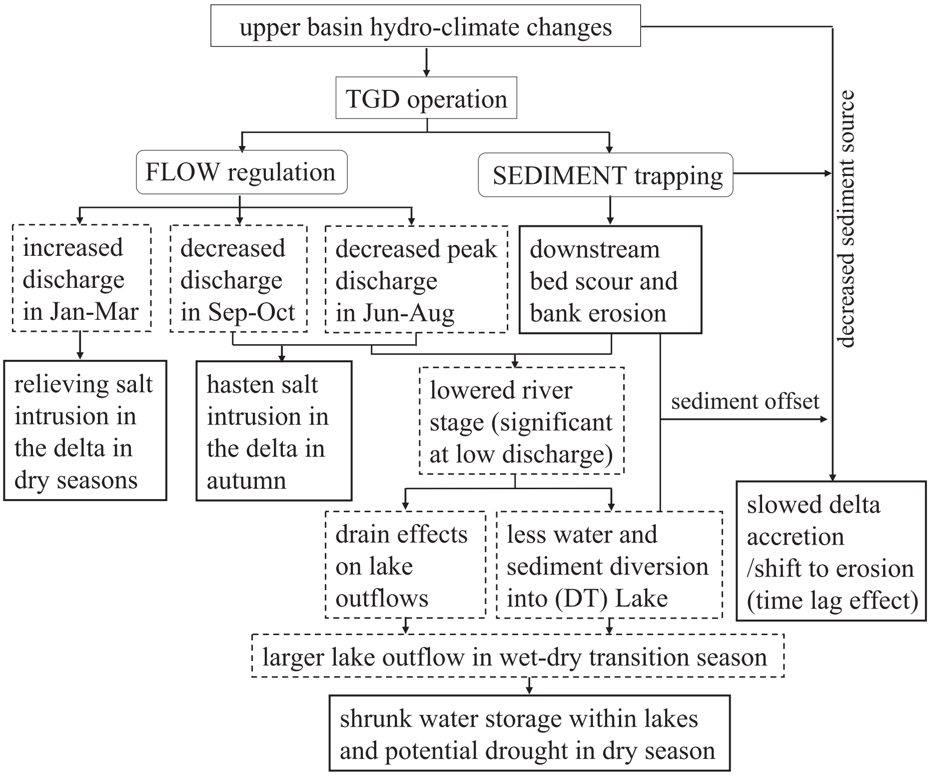

Fig. 11. Flow charts of the hydrological regime changes and the consequences downstream of the TGD in the CJR basin.

Yichang and Luoshan, from big floods formed in the upper basin. For instance, the inflow of TGD was as large as 70,000 m^3/s in July of 2010 and 2012 while the outflow was reduced to <50,000 m^3/s (see Fig. S2). In addition, the TGD can reactively reduce outflow when the downstream basin encounters floods, thus lowering mainstream river stage and providing beneficial conditions for downstream floods flushing. By that the TGD is able to prevent occurrence of 1/100 probability disastrous floods as that in 1954 and 1998 in the downstream basin. Even though the TGD can not regulate regional river floods within the lake systems caused by local strong rain storms. The effects of TGD in mitigating basin-scale big floods need to be evaluated in long-term and shall not be underestimated and overestimated.

The above discussion suggests that it is not only the magnitude of river discharge but also its frequency, timing, duration, and rate of change that matters in basin-scale hydrological processes. As the TGD may be obligated to keep the pool level as high, as early, and as long as possible for more hydropower generation by advancing impoundment and slowing flushing (Li et al., 2013b), integrated management considering flood control, power generation, outflow reduction, and resultant influences on the downstream basin is of pivotal importance. The successive droughts occurred in recent years remind that low water management is also badly needed other than flood risk mitigation.

5.3. Causes of the hydrological changes

5.3.1. Causes of streamflow changes

Natural hydro-meteorological changes and human activities are generally two main forces driving hydrological changes at river basin scales. We see that the basin-wide air temperature has increased since the mid-1980s (Chen et al., 2001a; Sang et al., 2012), and precipitation has decreased since 1950s and evaporation rate is decreasing since 1960s (Wang et al., 2011). At century time scales, the actual evapotranspiration and the ratio of actual evapotranspiration to precipitation has increased in 1955–2008 compared to 1901–1954 in the CJR basin, i.e., by 30 mm per year and 0.06 per year, respectively (Jaramillo and Destouni, 2015), which may explain the detected change point in 1954 and the afterward streamflow reduction (see Figs. 4 and S4). There are attempts to isolate the impacts of natural climate changes and human interferences on the streamflow variations. For instance, there is a well established correlationship between basin-wide averaged precipitation and streamflow at Datong, suggesting a dominant role of precipitation on streamflow changes (Yang et al., 2005; Jiang et al., 2007; Zhao et al., 2017). Similarly, Wang et al. (2013) inferred that rainfall variations may explain 29% of streamflow changes in the CJR basin between 1970 and 2008. Note that there is large variability in the relationship between precipitation and streamflow, thus consideration of both precipitation and evapotranspiration is necessary to isolate meteorological controls on streamflow changes.

Human interferences play an increasingly significant role in modulating the hydrological regime. Annual water consumption (consumptive use of water resources for agriculture and industry and domestic purposes) has increased from 15 to 90 billion m^3 between 1949 and 2000 due to booming economy and population within the CJR basin (MWR, 1997–2005; Xu et al., 2007). The ongoing South-to-North water transfer project withdraws annually 18.3 billion m^3 of surface water out of the CJR basin to the north China since 2014 and the total diversion capacity will be 44.8 billion m^3 per year after completion of the project in the near future (OSNWDPCC, 2016). The number of hydropower dams has increased exponentially since 1950s, reaching >50,000 nowadays (Yang et al., 2011). The total reservoir storage capacity has increased markedly, reaching 200 billion m^3 by 2003 (Yang et al., 2004) with 55.69 billion m^3 in the upper basin by 2005 (Wei et al., 2011). The dams recently constructed and under constructions in the upper basin are not yet included. Increasing water consumption and water withdrawal causes net reduction of streamflow while the dams mainly modulate the timing and magnitude of river discharges. We see that the seasonal streamflow changes are more profound compared to the inter-annual changes, and human activities are ascribed to be the main cause of that.

5.3.2. Causes of sediment loads changes

Sediment loads changes are very much influenced by human activities. Rainfall variations affect sediment yield through surface erosion (sediment source) while the later is also influenced by human-related land use changes. Sediment loads reduction is much more profound than streamflow changes (see Fig. 10), suggesting that sediment transport is source-limited instead of transport-limited. It was reported that the land surface area subject to hydraulic erosion nearly doubled between 1950 and 2001 over the entire CJR basin, i.e., from 364 to 707 billion m^2 (Yang et al., 2004), suggesting possibly increasing sediment yield. On the other hand, implementation of anti-deforestation measures in the upper CJR basin since 1980s reduces the area and intensity of surface erosion (Yang et al., 2006; Hu et al., 2009). Forest coverage rate is estimated by an increase from 33.8% to 56.2% in the upper basin by 2005 (Wei et al., 2011). Analysis of satellite images in 1980s and 2010, however, shows only marginally increased forest area and residential land area and decreased irrigated land and dry farmland areas within the CJR basin, and the change rates are overall small (<4%) (Zhao et al., 2017). These studies are somehow inconsistent though reduced sediment yield in the upper basin due to land use changes is widely recognized as one of the main causes of sediment loads reduction at Cuntan since the mid-1980s (Yang et al., 2006, 2011; Wang et al., 2007b; Hu et al., 2009).

Reservoir sedimentation is another main reason of sediment loads reduction (Yang et al., 2006; Wang et al., 2007b). Yang et al. (2006) suggested that reservoirs were responsible for 66% of sediment loads reduction at Cuntan and Yichang since the mid-1980s. Downstream of Cuntan, the TGD retains annually 125.7 million tons sediment between 2003 and 2015, which is averagely 76% of its sediment influx (Table 2). A major portion of the reservoir sedimentation (>95%) occurs in the wet seasons (Xu and Milliman, 2009; CWRM, 2006, 2016), explaining pronounced sediment loads reduction in the wet seasons (see Fig. 9). By adding the sediment trapped by the TGD to the measured sediment loads at Yichang and Datong, we see that the linear reduction trend dating back to the early 1980s and mid-1960s at the two stations, respectively, continues until nowadays (see Fig. S10). We also estimate that the sediment loads reduction at Yichang and Datong in the period of 2003–2015 would be 76% and 49% smaller, respectively, if there is no TGD (see Table 2 and Fig. S10). The newly constructed big dams in the upper mainstream, e.g., the Xiangjiaba Dam, have caused additional substantial sediment loads decrease at Cuntan since 2012. It will slow down TGD sedimentation and in the mean time further reduce sediment loads downstream of TGD (Table 2).

Other human activities having impacts on sediment loads include river regulation, lake sedimentation, and sand mining and associated river morphological changes. The sharp reduction of sediment loads at the three inlets in the late-1960s was ascribed to river regulations in the Jing River (the meander river between Yichang and Luoshan), i.e., meander cutoff and river length reduction (Chen et al., 2010). Sand mining (i.e., sediment extraction from the river bed) in the CJR mainstream is overall limited (Dai and Liu, 2013), but intensive sand mining within the Poyang Lake (Lai et al., 2014), by stirring the lake bed and enhancing suspension transport, causes notably increased sediment loads at Hukou (see Fig. S11C). The Dongting Lake changes from a sediment sink to a source

Table 2
Annual sediment inflows and outflows (million tons) of the TGD and the sediment loads at Datong. Data are from CWRM (2006, 2016).

Year/ Period	TGR In*	TGR Out**	TGR sedimentation	Datong
1956–2002	448.7	488.7	-40.0	424.5
2003	220.4	84.0	136.4	206.0
2004	183.8	63.7	120.1	147.0
2005	274.4	103.0	171.4	216.0
2006	112.4	8.9	103.5	84.8
2007	220.4	50.9	169.5	138.0
2008	216.9	32.2	184.7	130.0
2009	174.4	36.0	138.4	111.0
2010	216.6	32.8	183.8	185.0
2011	93.1	6.9	86.2	71.8
2012	219.0	45.3	173.7	161.0
2013	126.8	32.8	94.0	117.0
2014	55.4	10.5	44.9	120.0
2015	32.0	4.2	27.8	116.0
2016	42.2	8.8	33.4	152.0
2003–2015	165.0	39.3	125.7	138.7

regarding sediment exchange with the CJR mainstream since 2000 (see Fig. S11A). Smaller sediment loads at Datong compared to the summed sediment loads at Yichang and that from the three main tributaries suggest river aggradations in 1978–2001 (see Figs. S10 and S11). There is a switch from river deposition to erosion since 2002 which is evidenced by morphological survey (Li et al., 2009; CWRM, 2016). For instance, an erosion of 1001.3 million m^3 is observed along the river between Yichang and Luoshan (a river length of 408 km) between October 2002 and October 2015 (CWRM, 2016), and the erosion volume is ~201.1 million m^3 in the river between Luoshan and Hankou (a river length of 251 km) between November 2003 and November 2015 (CWRM, 2016). Considering a bulk density of 1.05 tons per m^3, the sediment erosion rate is ~105.2 million tons per year in the river segment between Yichang and Hankou. It suggests that river erosion in the mainstream and the sediment source from main tributaries contribute ~70% and ~20% of sediment loads at Datong, respectively, in 2003–2015. It is these sediment sources that mitigating sediment loads reduction at Hankou and Datong compared to Yichang (see Figs. 8 and S10).

So far we see that the TGD's impacts on the hydrological regime are not confined to river discharge regulation and sediment trapping but also include indirect influences in terms of reinforcing downstream river erosion and altering river–lake interplay (Fig. 11). The TGD's impacts on river discharges are more profound at seasonal time scales while its impacts on sediment loads reduction are more pronounced at annual to decadal time scales. Overall we see that climatic changes and human activities in the upper basin have caused remarkable river discharge and sediment loads changes, and the TGD exerts additional modification on that and causes subsequent changes in the downstream river while along-river buffering dissipate the changes in the downward direction.

5.4. Implications of the hydrological changes

The changed hydrological regime has broad impacts and consequences on the river morphology and ecosystem and other relevant river functions. The CJR downstream of Yichang is a 'golden waterway' regarding its importance on water transportation. Its navigation channel depth is threatened by the seasonally lowered river stages. The suspended sediment concentrations have reduced from 0.467 ± 0.539 kg/m^3 under the pre-TGD condition to 0.070 ± 0.108 kg/m^3 under the post-TGD condition at Yichang (Xiao and Duan, 2011), which can have profound impacts on the aquatic ecosystem given increased water transparency and light penetration. Downstream channel degradation in terms of bed scour and bank erosion and collapse threatens the safety of the dikes and other flood defense structures (Li et al., 2009; Xia et al., 2016). As a result of bed erosion, bed sediment is coarsening, i.e., changes from coarse sand (~mm) before 2003 to gravel and pebble (~cm) in 2008 at Yichang (Luo et al., 2012; Yang et al., 2018), which will stimulate downward development of bed scour until a new river morphological equilibrium state is reached in long-term (decades to a century). The altered river–lake interplay and shrinking lakes will lower flood resilience in the middle-lower CJR basin due to decreased lake storage capacity (Li et al., 2009; Fang et al., 2012), and increase drought occurrence probability and impair lake ecosystem. Moreover, dramatically declined sediment loads are accompanied by reduced nutrient loading because the suspended sediments are composed of dominantly fine material (e.g., median size of ~10 μm at Datong) and are transported in the form of aggregated flocs (Guo and He, 2011). For instance, there is a 77% reduction of total phosphorous and an 83% reduction of particulate phosphorous annually (Zhou et al., 2013) and also a substantial decrease of silica flux (Ran et al., 2016). These changes would have impacts on the biogeochemical cycling in the river-estuary-coastal ocean continuum (Zhang et al., 2015). These issues deserve attention from both research and management point of view.

The changed river and sediment discharges impose a threat on the delta with respect to salt intrusion and delta erosion. River discharge provides a critical force in inhibiting salt intrusion driven by marine tides and waves in the delta region. Landward salt intrusion affects freshwater intake in the CJR delta in the dry seasons when the river discharge at Datong is <15,000 m^3/s, threatening freshwater supply to millions of people in Shanghai (Luo and Shen, 1994). Modeling studies have showed that TGD impoundments in autumn tend to advance the timing and enhance the intensity of salt intrusion while larger river discharges in the dry seasons may relieve salt intrusion to some degree (Qiu and Zhu, 2013). In addition, water withdrawal along the river downstream of Datong is considerable and will further reduce the river discharge in counteracting salt intrusion (Zhang et al., 2012a). The altered river discharge hydrograph is highly likely to hasten the onset of and induce more landward saltwater intrusion in the CJR delta in the wet-to-dry transition seasons. Regulating lake outflow by constructing sluices at the lake mouths may worsen this situation. Maintaining a river discharge at Datong larger than a minimum threshold (e.g., 12,000 m^3/s) through optimized dam operation can help to reduce the salt intrusion risk.

Delta erosion and salt marshes loss is a global concern and also a big issue in the CJR delta. Yang et al. (2011) had reported a shift from accretion to erosion around the sub-merged CJR delta (the study area is selective and small compared to the entire CJR delta) in the recent decade and ascribed it to reduced sediment supply.

On the other hand, the CJR delta as whole has not shown directional erosion in the period of 1958–2010 (Luan et al., 2016; Zhao et al., 2018). So far it is widely known that the deposition rate in the CJR delta has decreased measurably in the recent decade though overwhelming erosion has not emerged, which can be ascribed to a time lag effect between deltaic morphological response and sediment supply reduction. It is reasonably expected that the sediment loads at Datong will remain low in the coming decades to century, thus delta erosion is somehow inevitable in long term. Delta safety and ecosystem is at high risk considering sediment loads reduction, sea-level rise and land subsidence. Research work to figure out the effects of sediment redistribution within the delta in causing a time lag of large scale deltaic morphological adaptation is needed.

6. Conclusions

In this work we collect and examine a long time series of river discharges and sediment loads data in the CJR basin downstream of the TGD and elaborate the hydrological regime changes at seasonal, annual and decadal time scales. The causes and implications of those changes are discussed and the role of the TGD is evaluated.

The annual streamflow changes are non-significant downstream of TGD other than a significant change point in 1954. Streamflow changes are more remarkable at seasonal time scales, such as decreased flood peak and autumn discharges and increased dry season discharges. The hydro-climate changes occurred in the upper basin and the regulation effects of TGD together explain the seasonal changes.

Sediment loads have decreased progressively in the CJR basin. The decrease trend dates back to the mid-1980s and the TGD accelerates the decrease since 2003. The sediment loads immediately below TGD have decreased by 92% in 2003–2015 compared to 1950–1985 at Yichang. The TGD is responsible for 76% and 49% of the sediment loads reduction at Yichang and Datong, respectively. As a result, subsequent bed scour and bank erosion occur in the downstream river. The eroded sediment, together with the sediment loads from the tributaries, mitigates sediment reduction in the down river direction.

The altered river–lake interplay in response to channel degradation and seasonal river discharge reduction is highly responsible for low stages in the lakes. Substantial river stage falling downstream of the TGD and enlarged water level gradients in the vicinities of river–lake conjunctions induce a ‘draining effect’ fostering faster lake outflow following TGD impoundments. It results in lower stage and reduced lake water storage which threatens water resources security and riparian ecosystem in the lakes.

The hydrological changes have a wide scope of influences and consequences on water security, flooding and drought risk management, and delta safety. More big dams are under construction along the mainstream upward TGD and they will further regulate the river discharge and sediment delivery processes. We identify knowledge gaps in research, including: (1) there lacks of in-depth analysis of climatic and hydrological changes and their coherent behavior at different time and space scales, in particular regarding the role of nature and human activities (e.g., land use changes, big hydropower dams, water transfer and consumption) on streamflow changes based on analysis of precipitation, evapotranspiration, and streamflow data together; (2) insufficient understanding of the climatic impacts of the series of large reservoirs including the TGD and the others under construction in the upper basin; (3) integrated water resources management and flooding and drought hazard management when considering both surface water and groundwater, gross water storage changes, optimized hydropower dam operations, and fluvial ecosystem restoration opportunity etc., and last but not least (4) study of basin-scale hydrological and geomorphologic changes and ecosystem evolution given a doctrine switch from ‘economical development first’ to ‘environment protection and ecosystem conservation first’. Coping with these issues will need comprehensive management strategies by taking the entire river basin into consideration regarding water, sediment, and associated resources, ecology, and safety.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jhydrol.2018.03.035.

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