Mega dam-induced riverbed erosion substantially lowers the water surface elevation of the Changjiang River during the dry season

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Abstract

By regulating the seasonal flow discharge, dams are frequently used to augment downstream flow discharges and water surface elevations in dry season periods. However, dams also typically generate severe bed incision in their downstream reaches, which while not reducing the volume of flow passing through the channel, can nevertheless reduce water surface elevations. Such reductions in water surface elevations can make it more difficult to access available water in the river in instances where they drop substantially below the levels of water intake structures. Here we evaluate the extent to which dam-induced incision downstream of the Three Gorges Dam (TGD) contributes to falling water surface elevations during the 2019 dry season (December to February), which was a period characterized by extremely low water surface elevations along the mid-lower reaches of the Changjiang River. Our results indicate that the 2019 dry season exhibited the second lowest water surface elevation ever recorded in the middle Changjiang even though the flow discharge was actually larger than in previous dry seasons. The 2019 event was found to be characterized by a sharp fall of water surface elevation, caused by TGD-induced downstream channel narrowing and bed incision. Thus, while TGD releases did augment flows during the 2019 dry season, channel degradation resulted in a substantial net lowering of water surface elevations. Consequently, the overall impact of the TGD on dry season water surface elevations was to aggravate (not mitigate) low water surface elevations experienced along the Changjiang River. Our study has relevance for other major dam-altered rivers that experience extreme low water surface elevations in dry periods.

Keywords: low water surface elevation; dam regulation; riverbed erosion; Changjiang River; Three Gorges Dam

1. Introduction

Humans have long used reservoirs as a tool to control the seasonal behaviors of river discharge (Best, 2019). By storing water during high flow periods and releasing it during low flow periods, dams can potentially help with flood protection in wet months and maintain basic water requirements in dry periods (Graf, 2006; Milliman and Farnsworth, 2011; Cui et al., 2020). However, despite making major contributions to human development through such flow management, dams also trap large proportions of the river's sediment discharge, which in turn can trigger sediment starvation and disrupt the natural geomorphological evolution of the channel downstream (Syvitski et al, 2005; Dunn et al., 2019; Dethier, et al., 2022). As the numbers of dams have proliferated across the world, particularly large dams, it is important to understand the trade-offs between their negative and beneficial effects (Best and Darby, 2020; Grill et al., 2019).

To date, around 50,000 large dams (large dams are defined as those over 15 meters in height or which have a storage capacity greater than 3 million m^3) have been built (these dams are not always constructed with the sole purpose of regulating flows) and river flows are now heavily regulated on more than half of the world's large rivers (Grill et al., 2019). Such a high degree of flow regulation can significantly change the morphologic stability of the river system, specifically, the stability of a river system in the form of morphological approaches, e.g. channel forms, channel dimensions, channel substrates, channel pattern, bank profile, et al. (Rinaldi et al., 2013; Li et al., 2020; Gao et al., 2021). Morphological changes do not affect the volume of water flowing through the river's channel, but they can considerably lower the river bed and in turn the water surface elevation. As a result, such geomorphological responses can disrupt the normal relationship between flow discharge and water surface elevation (Lu and Chua, 2021). Reductions in the water surface elevation, particularly if they fall below the level of water intake structures, have the potential to generate severe adverse consequences, notably by limiting access to the in-channel water supply (Choat et al., 2012; Mishra et al., 2015; Schwalm et al., 2017). For instance, waterworks shut-down accident has been frequently reported along the mid-lower Changjiang River basin in dry season over the recent years because of continuous water surface elevation declining at their fixed water source intake points, which arise serious conflicts of water supply and demand. Therefore, there is an urgent need to understand how water surface elevations respond to channel changes induced by dam construction, to enable more effective water resources management and hydraulic engineering planning in an era when so many rivers are impacted by large dams.

The Changjiang River has been regulated by the Three Gorges Dam (TGD), the world's largest hydraulic structure since its completion in 2003. However, episodes of extreme low water surface elevations (i.e., periods when the water surface elevation drops below the 10th percentile threshold of daily dry season water surface elevations during 2000-2019) have occurred in 2006, 2007 and 2019 along the mid-lower Changjiang Reach (Fig. 1C-D). Note that for these events in 2006 and 2007 these low water surface elevations occurred concurrently with extreme low flow discharges. However, in 2019 extreme low water surface elevations were experienced even under a relatively normal flow discharge scenario. Particularly in 2019, these occurrences of low water surface elevations during the dry season periods have led to growing concerns about their impacts on the viability of navigation and, especially, the ability of the existing water supply infrastructure to access the available river flow. The impacts of the TGD on low water surface elevations have, therefore, become a focus of international concern and some previous studies have been undertaken with the aim of detecting the possible influence of the TGD on dry season water levels and flow discharges (Dai et al., 2008; Lu et al., 2011; Webber et al., 2015; Barnett et al., 2015). Few studies to date, however, have detected the mechanisms responsible for the observed periods of low water surface elevation, in part due to the complicated basin structure of the mid-lower Changjiang River.

It is obvious that TGD directly affects downstream flows through the effect of water releases from the dam. However, a potentially important, previously overlooked, factor concerns the indirect impacts that changes in channel morphology (notably, the bed incision that is typically triggered in river reaches downstream of dams) may have on water surface elevations (Mei et al., 2018; Cochrane et al., 2014). In this study, we undertake a detailed analysis of the processes affecting extreme low water surface elevations in the Changjiang River downstream of the TGD during the 2019 dry season, when low water surface elevation occurred simultaneously with augmented flow discharge. We employ a combination of empirical data analysis and model simulation to: 1) identify the hydrological characteristics of dry season flows in the post-TGD period; 2) isolate the drivers of extreme low water surface elevations downstream of the TGD; and 3) quantify and separate out the different factors contributing to low water surface elevations along the mid-lower Changjiang. The insights provided by our study represent an important reference point for understanding the impacts on dry season flows and water surface elevations along major dam-regulated rivers.

2. Study area

As one of the world's largest river systems, the Changjiang River flows from west to east for 6300 km, draining an area of 1.8 million km^2 (Fig. 1A). The river is geographically divided into three sub-basins with the upper, middle, and lower reaches being defined by the locations of Yichang, Hankou, and Datong, respectively (Xu et al., 2006, Fig. 1B). The upper, middle, and lower watersheds contribute around 50%, 30% and 20% of the total discharge to the estuary and cover 55%, 38% and 7% of the total drainage area, respectively (Mei et al., 2015). Heavily influenced by the monsoon circulation, precipitation over the Changjiang catchment is highly seasonal (Chen et al., 2016). Specifically, high flow discharges occur during the wet months of June-August, with an average daily discharge of 34900 m^3/s at Hankou, while low flow discharges occur during the dry months of December, January and February at a mean daily discharge of 11200 m^3/s (Fig. S1). It is the dry season flows within the mid-lower Changjiang River that are the focus of this study.

With a total of over 50,000 dams with a combined storage of 200 billion m^3 within its upstream catchment, including the iconic TGD (Yang et al., 2011), Changjiang River represents an excellent case study for this work. Located close to the Yichang station (Fig. 1B), the TGD itself has a storage capacity of 39.3 billion m^3. Although representing only about 5.7% of the mean annual flow at Hankou, a number of studies have shown that this is sufficient modify the seasonal characteristics of the downstream river regime (Dai et al., 2008; Yang et al., 2015). For example, compared with the pre-TGD period (2000-2002), water discharge at Hankou during the post-TGD period (2003-2019) has decreased by 5.8% in the flood season while increasing by 3.0% in the dry season (Fig. S1).

3. Materials and Methods

3.1 Data collection

The datasets employed in this study were collected from multiple sources for a detailed analysis of the 2019 low water surface elevation episodes that occurred along the mid-lower Changjiang. These datasets include: a) daily water level (i.e. water surface elevation) and flow discharge data for the dry season (December to February) at Hankou and Datong were obtained for the period 2000-2020 from the Changjiang Water Resources Commission (CWRC, www.cjw.gov.cn); b) daily precipitation and daily evaporation data during 2000-2020 for the same dry season period were collected for 104 weather stations from the National Meteorological Information Center of China (http://cdc.cma.gov.cn, the locations of these meteorological stations are indicated on Fig. 1B); c) cross section information from 2002 to 2017 at Hankou and Datong were obtained from CWRC; d) bathymetric maps around Datong and Hankou (these maps were based on bathymetric surveys dating from 2012 and 2017) were collected from the Changjiang Waterway Bureau. Dual-frequency echo-sounder was used for depth measurements for the cross section and bathymetric maps, with a vertical error of 0. 1 m. GPS by Trimble was used for positioning, with an error of 1 m. All surveys were carried out between early May and early June, prior to peak discharge, and completed before August. The data density for cross section and bathymetric survey was ~70 survey points per km and ~20 survey points per km^2, respectively. Such data density made bathymetric changes greater than 0.1 m are acceptable in this study. Data for the period 2000-2020 were divided into two sets representing the period before and after the 2003 construction of the Three Gorges Dam (TGD).

3.2 Methods

3.2.1 Streamflow simulation using the GR5J rainfall-runoff model

The GR model family (i.e., GR3J, GR4J, GR5J and GR6J) is a series of well-developed daily lumped empirical rainfall-runoff models that have been widely applied in different hydroclimatic conditions globally with good performance (Edijatno et al., 1999; Perrin et al., 2003; Cornelissen et al., 2013). Of the GR model family, the GR5J is characterized by a track-record of successful performance in low-flow simulations while avoiding performance losses when representing high flows. The GR5J model employs a set of 5 discrete equations with a total of 5 calibratable parameters (Pushpalatha et al., 2011; Althoff et al., 2022), namely: X_1, the maximum capacity of the production store (mm); X_2, the groundwater exchange coefficient (mm); X_3, the one day ahead maximum capacity of the routing store (mm); X_4, the time base of the unit hydrograph (day), and; X_5, a dimensionless threshold parameter that allows a change in the direction of the groundwater exchange (-). A summary of the model with daily time series of precipitation and potential evapotranspiration as inputs is given as follows (Fig. 2):

Determination of net precipitation and evapotranspiration

Let P and E be precipitation and potential evapotranspiration, respectively. Here, E is a climatic average over several years. All water quantities are expressed in mm. The net precipitaion P_n and net evapotranspiration E_n can then be determined by subtracting E from P:

$$\text{If } P \geq E, \text{then } P_n = P - E \text{ and } E_n = 0 \tag{1a}$$

$$\text{Otherwise } P_n = 0 \text{ and } E_n = E - P \tag{1b}$$

Capacity of the production store (X_1)

The next operation is via a production store (soil moisture accounting store). Let S be the reservoir storage. Depending on the value of S, fluxes into (P_s) and out of (E_s) the reservoir occur when P_n and E_n are positive, respectively, thus:

$$P_s = \frac{X_1\left(1-\left(\frac{S}{X_1}\right)^2\right)\tanh\left(\frac{P_n}{X_1}\right)}{1+\frac{S}{X_1}\tanh\left(\frac{P_n}{X_1}\right)} \tag{2}$$

$$E_s = \frac{S\left(2-\frac{S}{X_1}\right)\tanh\left(\frac{E_n}{X_1}\right)}{1+\left(1-\frac{S}{X_1}\right)\tanh\left(\frac{E_n}{X_1}\right)} \tag{3}$$

The water content in the production store is then updated using:

$$S = S - E_s + P_s \tag{4}$$

A percolation leakage P_{erc} from the production store is defined as:

$$P_{erc} = S(1-(1+(\frac{4}{9}\frac{S}{X_1})^4)^{-1/4}) \quad (5)$$

P_{erc} is always lower than S, the reservoir content then becomes:

$$S = S - P_{erc} \quad (6)$$

Linear routing with unit hydrographs

The total water that reaches the routing function (P_{erc}+(P_n-P_s)) is divided into two parts. The first part, amounting to 90% of (P_{erc}+(P_n-P_s)), is transformed by a unit-hydrograph derived from an *S*-curve whose expression is the function of SH1 depending on paremeter X_4:

$$j \leq 0 \quad SH1(j) = 0 \quad (7a)$$

$$0 < j < X_4 \quad SH1(j) = (\frac{j}{X_4})^{5/2} \quad (7b)$$

$$j \geq X_4 \quad SH1(j) = 1 \quad (7c)$$

The second part, amounting to 10% of (P_{erc}+(P_n-P_s)), is transformed by a second unit-hydrograph derived from the *S*-curve whose expression is the function of SH2 depending on the same parameter X_4 as SH1:

$$j \leq 0 \quad SH2(j) = 0 \quad (8a)$$

$$0 < j \leq X_4 \quad SH2(j) = \frac{1}{2}(\frac{j}{X_4})^{5/2} \quad (8b)$$

$$X_4 < j < 2X_4 \quad SH2(j) = 1 - \frac{1}{2}(2 - \frac{j}{X_4})^{5/2} \quad (8c)$$

$$j > 2X_4 \quad SH2(j) = 1 \quad (8d)$$

Catchment water exchange

The first part of the total water volume is input to a reservoir with storage of R, which is subjected to exchanges of water (F) that depend on the reservoir capacity at the end of the previous time step and the value of the parameters X_2 and X_5:

$$F = X_2(\frac{R}{X_3} - x_5) \quad (9)$$

where X_2 is a water exchange coefficient. When X_2 is positive, F is an output from R; otherwise F is an input to R. X_5 is a dimensionless threshold parameter that allows a change in the direction of the groundwater exchange.

Let R^* be the sum of the previous value of R, F and the output from the SH1 derived unit-hydtograph. If the result is negative, R^* is 0. The reservoir R then yields a flow rate Q_r, depending on R^* and X_3:

$$Q_r = R^*(1-(1+(\frac{R^*}{X_3})^4)^{-1/4}) \quad (10)$$

The value of R at the end of the time step is obtained by subtracting Q_r.

Total streamflow

F is also added to the SH2 derived unit hydrograph, and results in a flux Q_d. The final output streamflow of the model is thus given as the sum of Q_r and Q_d.

The model is calibrated and validated based on comparisons of model simulated and observed daily streamflow. Full details of the model calibration, validation, and simulation procedure along the mid-lower Changjiang are provided in the supporting information (Fig. S2). We use the GR5J model to generate the natural streamflow that should flow as the outcome of the rainfall-evaporation budget without any interference from human activities (Althoff et al., 2022). Thus, for a basin dominated by a mega-dam, like the Changjiang River, the regulating effects of the dam on the downstream discharge can be quantified by comparing the stream flow predictions from GR5J with the corresponding observations.

3.2.2 Sensitivity calculation of daily water surface elevation in response to water discharge variation

To assess the sensitivity of water surface elevation to discharge variation, the slope of the loop-rating curve of daily water surface elevation versus water discharge (i.e., the water surface elevation variation in response to a unit decrease in flow discharge) is calculated (Fig. 3). Taking the hydrological event in the figure as an example, the rising flow stage exhibits a larger slope, indicating a higher sensitivity to discharge variations. This calculation can be repeated for different hydrological events to compare their sensitivities to discharge variations and further assess their potential risks.

3.2.3 Water surface elevation-discharge rating curves

In this study, water surface elevation-flow discharge rating curves were constructed to quantify associations between daily flow discharges and water surface elevations in the dry season period along the mid-lower Changjiang River for the periods before and after the construction of TGD. These rating curves were developed using power functions of the form:

$$Q = aW^b \tag{11}$$

where W and Q are, respectively, the water surface elevation and flow discharge for each hydrological station, and a and b are empirical parameters, which were obtained by fitting the observed flow discharge and water surface elevation data using a nonlinear least-square power-law solver. We constructed rating curves for both the pre- and post-TGD periods at Hankou and Datong stations. In this way, water surface elevations corresponding to any flow discharge were able to be predicted from the flow discharge models, for use in the analysis described below.

3.2.4 Quantification the impacts of dam-induced flow regulation versus channel degradation on downstream water surface elevations

TGD regulation increases downstream water surface elevations in the dry season through water releases, but potentially also reduces the water surface elevation as a result of channel bed incision in the reaches downstream of the dam. To isolate each of these two effects, water surface elevations for different scenarios were calculated by first using the streamflow simulation model GR5J to compute the flow discharge before employing the water surface elevation-discharge rating curves to determine the corresponding water surface elevations. The model simulation scenarios employed were as follows:

- For scenario (1) water surface elevations corresponding to the GR5J simulated stream flows under post-dam rainfall and potential evapotranspiration were predicted using the pre-TGD rating curve, to show the natural scenario without human interference;
- For scenario (2) water surface elevations corresponding to the post-dam observed streamflow were predicted using the pre-TGD rating curve, to consider the influence of dam releases only. Thus, the impact of dam-induced flow regulation on downstream water surface elevations can then be quantified by computing the difference in water surface elevations (for a given flow discharge) between Scenarios 1 and 2.
- For scenario (3) the observed water surface elevation in the post-TGD period covers the effects of both water release and channel morphological variations, the effect of altered morphology on water surface elevation can therefore be estimated by comparing the post-dam observed water surface elevation with the water surface elevation of scenario 2.

3.2.5 Bathymetric change analysis

The bathymetric data were firstly transformed into depth points relative to Beijing 54 coordinates and calibrated into 1985 National Height Datum using ArcGIS. Subsequently, Kriging interpolation was used to generate a series of Digital Elevation Models (DEMs) with 5×5 m grid resolutions (van der Wal et al., 2002; Lentz and Hapke, 2011). Bathymetric changes were then obtained by differencing adjacent (in time) DEMs.

4. Results

4.1 Hydrological behaviors during the dry season

Compared with the pre-TGD period (2000-2002), mean daily flow discharge in the dry season during the post-TGD period has increased from 1.09×10^4 m^3/s to 1.12×10^4 m^3/s during 2003-2018 and 1.24×10^4 m^3/s during 2019 at Hankou (Fig. 4A). In contrast, and notwithstanding the increased flow discharge, dry season daily water surface elevation in this same middle reach exhibit a markedly different response, declining by an average of around 0.67 m between the periods 2000-2002 to 2003-2018, with a further decrease of 0.2 m in 2019 (Fig. 4B). Indeed, on 20th December 2019, Hankou experienced its second lowest water surface elevation (13.52 m) recorded since 2000, following closely behind the record low of 13.50 m observed in 2013. This is despite the 2013 event being associated with a much smaller flow discharge of 9180 m^3/s, compared to the 10100 m^3/s recorded in 2019.

Further downstream, in the lower Changjiang at Datong, the response of the river is characterized by a decline in both dry season flow discharge and water surface elevation in the post-dam versus pre-dam periods (Fig. 4C-D). Specifically, the dry season mean daily flow discharge decreased slightly, from 1.50×10^4 m^3/s during 2000-2002 to 1.45×10^4 m^3/s during 2003-2018, while mean daily water surface elevation declined from 5.86 m during 2000-2002 to 5.54 m during 2003-2018 (Fig. 4C-D).

4.2 Water surface elevation-discharge relations during the dry season

The changing relationships between dry season water surface elevation and flow discharge at Hankou and Datong are shown in Fig. 5 A, C. It is evident that water surface elevation (for a given flow discharge) during the post-TGD period have declined substantially, compared to the pre-TGD period. The constructed rating curves at both gauging stations exhibit obvious downward shifts following the construction of the TGD, with the curve for the year 2019 lying at the bottom, indicating a significant decrease in dry season water surface elevations for the same discharge scenario (Fig. 5 B, D). For the dry season, when mean daily flow discharges at Hankou and Datong during 2000-2019 were 11200 m^3/s and 14700 m^3/s, respectively (Fig. S1), the corresponding water surface elevations exhibit reductions of 1.64 m and 0.27 m, respectively in 2019 (Fig. 5 B, D).

4.3 Hydrological characteristics of the 2019 dry season flows

Detailed water surface elevation-discharge rating curves along the mid-lower Changjiang indicate the dynamic behavior of the 2019 dry season flows (Fig. 6). Specifically, it is evident that the water surface elevation-discharge curve during the 2019 dry season exhibits a counterclockwise hysteresis loop at Hankou (Fig. 6A), whereby water surface elevation falls with flow discharge during the falling stage, but runs ahead of the flow discharge during the rising limb. In contrast, a clockwise loop is evident in the rating curve at Datong (Fig. 6C), where water surface elevation remains low even after the flow discharge begins to rise. The sensitivity of water surface elevation to flow discharge variation is also further analyzed (Fig. S3-4). During the falling stage, Hankou and Datong respectively exhibit sensitivities of 0.00075 $m/(m^3/s)$ and 0.0018 $m/(m^3/s)$ (Fig. 6 B, D). These sensitivities are slightly lower during the rising stage, when they attain values of 0.00068 $m/(m^3/s)$ at Hankou and 0.0012 $m/(m^3/s)$ at Datong. When the six most severe episodes of low water surface elevations since 2000 are compared, it is found that the 2019 event is characterized by a much steeper falling limb than any of the other five years (Fig. 6 B, D), indicating that in 2019 there is a much larger drop in water surface elevation in response to a unit decrease in flow discharge.

5. Discussion

Compared with the pre-TGD scenario, post-TGD water surface elevations along the mid-lower Changjiang River drop substantially for a given flow discharge in the dry season, this drop being particularly marked during the 2019 dry season (Fig. 4-5). In this section we identify the potential factors driving this decline in dry season water surface elevation, isolating the potential impacts of climate change, in-channel morphological variations, and changes in the way in which operation of the TGD affects downstream water surface elevations.

5.1 Precipitation-evaporation budget along the mid-lower Changjiang

Dominated by the seasonal monsoon climate, precipitation and evaporation play a prominent role in controlling stream flows along the Changjiang River, together accounting for 89% of the variance in annual discharge (Chen et al., 2014; Mei et al., 2015). Over the study period of 2000-2019, both mean daily precipitation and mean daily evaporation in the dry season exhibit slight variations along the mid-lower Changjiang (Fig. 7 A-B). When calculating the net water gain (by subtracting evaporation from precipitation), it is found that neither the middle nor lower reach experience any substantial variations in this period. Note that the net water gains evident in the year 2019 ranks 4th and 5th highest in this study period for the middle and lower reach, respectively. Such a high net water gain cannot explain the severe low water surface elevations experienced in the 2019 dry season, suggesting that other factors were responsible.

5.2 Morphological variations along the mid-lower Changjiang

Morphological variations along the mid-lower Changjiang may be detected by comparing the bathymetric maps and surveyed cross-section morphology across different years. During the period of 2012-2017, the overall pattern of morphological changes along the middle and lower Changjiang River are complex, but dominated by incision (Fig. 8A, C). Hankou experiences the most significant scour around a zone located 1850 m from the left bank, where the bed elevation dropped from 5.68 m in 2002 to 3.27 m in 2009, and further declining to 0.84 m in 2017, indicating a total incision of 4.84 m (Fig. 8B). Datong also experiences intense downcutting, in this instance focused on a zone located around 1530 m from the left bank, where the bed level elevation decreased sharply from -9.46 m in 2002 to -13.53 m in 2009, and then to -15.61 m in 2017, giving an overall incision of 6.15 m (Fig. 8D). This large-scale channel incision means that water surface elevations over the mid-lower Changjiang will also exhibit significant declines even if flow discharge remains unchanged.

Besides, both the bathymetric map and cross section morphology analyses suggest that there is an obvious lateral sediment transfer from the channel bed to adjacent channel-marginal shoals, with most sediment depositing in the shoal just under the extreme low water surface elevation (the 10th percentile threshold of daily water surface elevation during the 2000-2019 dry seasons, Fig. 8B, D), and consequently, the lateral gradient of the channel enlarges substantially (Fig. 8E). The left channel gradient, in detail, increases from 0.008 in 2002 to 0.011 in 2017 at Hankou and from 0.012 in 2002 to 0.015 in 2017 at Datong as the shape of channel cross section shifts from trapezoid to triangular. The narrowing of the channel and increase of river bed gradient indicates water surface elevation is much more sensitive to discharge variation once it drops below the extreme low water surface elevation, which can well explain the sharp fall and rise of the water surface elevation along the mid-lower Changjiang during the 2019 dry season (Fig. 6).

5.3 Quantifying the impacts of the Three Gorges Dam on low water surface elevations

Dam regulation is a prominent factor in altering downstream water surface elevations, through the combined effects of the dam controlling the flow discharge and (as discussed in Section 5.2) sediment trapping resulting in altered river morphology (Mei et al., 2018; Mezger et al., 2021). It is important to quantify these changes separately and in combination in order to fully understand the impacts of the TGD on the 2019 dry season water surface elevations.

Here we reconstruct the 2019 dry season flows via GR5J streamflow simulation, which generate the natural streamflow as the outcome of the rain-evaporation budget only without considering the influences of human activities, like TGD regulation (Fig. 9A-B). It is evident that the simulated water discharges along the mid-lower Changjiang for this scenario are less in comparison with the observations from the post-TGD period, with flows in the middle and lower reaches declining by 1100 m^3/s and 800 m^3/s, respectively, on average. Using the rating curves for the period 2000-2002, this allows dry season water surface elevations under the unregulated versus regulated flow scenarios to be calculated (Fig. 9 C-D). From this analysis the effect of flow regulation is to *increase* water surface elevations at Hankou and Datong by 0.67 m and 0.13 m, respectively, implying that TGD-influenced augmentation of downstream dry season flow could attenuate the low water surface elevations that would otherwise be induced during the dry season.

However, when the morphological effects caused by dam regulation are also considered, mean water surface elevations at Hankou and Datong decrease by 0.97 and 0.06 m, respectively, compared with the natural scenario. This means that the water surface elevation reductions generated by dam-induced channel downcutting are as high as 1.63 m at Hankou and 0.19 m at Datong. This reduction in water surface elevations is sufficiently large to mean that, dam-induced bed degradation directly leads to the occurrence of the extreme low water surface elevations observed during the 2019 dry season, compounding the natural low water surface elevations that occur in this period.

5.4 Risk from low water surface elevation induced by dam-based channel degradation

While making an important contribution to flood control and drought relief over the river basin by regulating downstream flows (Gernaat et al., 2017; Hogeboom et al., 2018), dams also destroy river connectivity, trigger downstream ecosystem degradation and drive delta subsidence (Kareiva, 2012; Grill et al., 2019). As the largest hydraulic engineering in the world, TGD processes comprehensive benefits in harnessing and developing of the Changjiang River, like power generation, navigation improvement and flood control. However, at the same time, TGD induced downstream morphological variations, which may weaken its broad advantages to a certain extent. Recent analysis has even demonstrated that dam-induced floodplain loss may lessen the flood buffering capabilities of dam impoundment (Mei et al., 2018). This study also suggests that, far from reducing extreme low water surface elevations in dry season, the channel response to the TGD has in fact aggravated extreme low water surface elevations, even while the dam operation augments dry season flow discharges.

Such artificial low water surface elevations following dam construction poses a range of threats that normal low flows do not, for instance by increasing the risk of ships grounding and slope failure (Piton and Recking, 2017). Furthermore, great rivers, like Changjiang support large populations, large-scale industry and agriculture (Best, 2019). The sudden reduction of water surface elevations may reduce access to available water, lower the groundwater table, and decrease the connectivity between a river and its floodplains, which, in turn, may result in several adverse consequences to agriculture and industrial productivity and even endanger domestic water supplies (Juracek et al., 2015; Kondolf et al., 2018). Besides, there are many lacustrine wetland systems connecting to the river that favor vegetaion growth and migrating bird habitats (Webb & Leake, 2006; Mei et al., 2016). Lowering river water surface elevations can threaten natural lake-river interactions and generate early and prolonged lake droughts, which directly affects the survival of aquatic plant and birds and ultimately leads to a loss of habitat biodiversity (Cochrane et al., 2014; Dai et al., 2021).

6. Conclusions

Dams have long been used as an important way of regulating dry season flows to avoid the risk of low flows. However, frequent low water surface elevations have been reported recently in areas with dam protection. Taking the mid-lower Changjiang River as an example, this study has provided a comprehensive evaluation of the impacts of the TGD on the downstream water surface elevations during the dry season. The main findings drawn from this study can be summarized as follows:

1) The middle reach of the Changjiang River experienced the second lowest water surface elevations observed in the last two decades during the 2019 dry season, despite the flow discharges in the impacted reaches being higher than those experienced in previous dry seasons.
2) Lateral sediment transfer from the river bed to adjacent shoal flats following TGD regulation has transformed the channel cross-section from a trapezoid to triangular shape, which increases the sensitivity of the water surface elevation to flow discharge variations.
3) Water surface elevation reductions generated by TGD-induced channel downcutting are as high as 1.63 m at Hankou, which directly led to the occurrence of the extreme low water surface elevations observed during the 2019 dry season.

Acknowledgments

This study was jointly supported by the Joint Key Funds of National Natural Science Foundation of China (U2040202), National Science Foundation of China (42076174) and International Science and Technology Cooperation Foundation Projects of Shanghai (19230742700). We are indebted to Jie Wang, Chuqi Long and Xinyao Zhang for their exceptional graphical skills that were essential in preparing the figures. We gratefully acknowledge Professor B. Finlayson at the University of Melbourne and the anonymous reviewer for their constructive comments that helped greatly to improve the previous manuscript.

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Figures and Captions

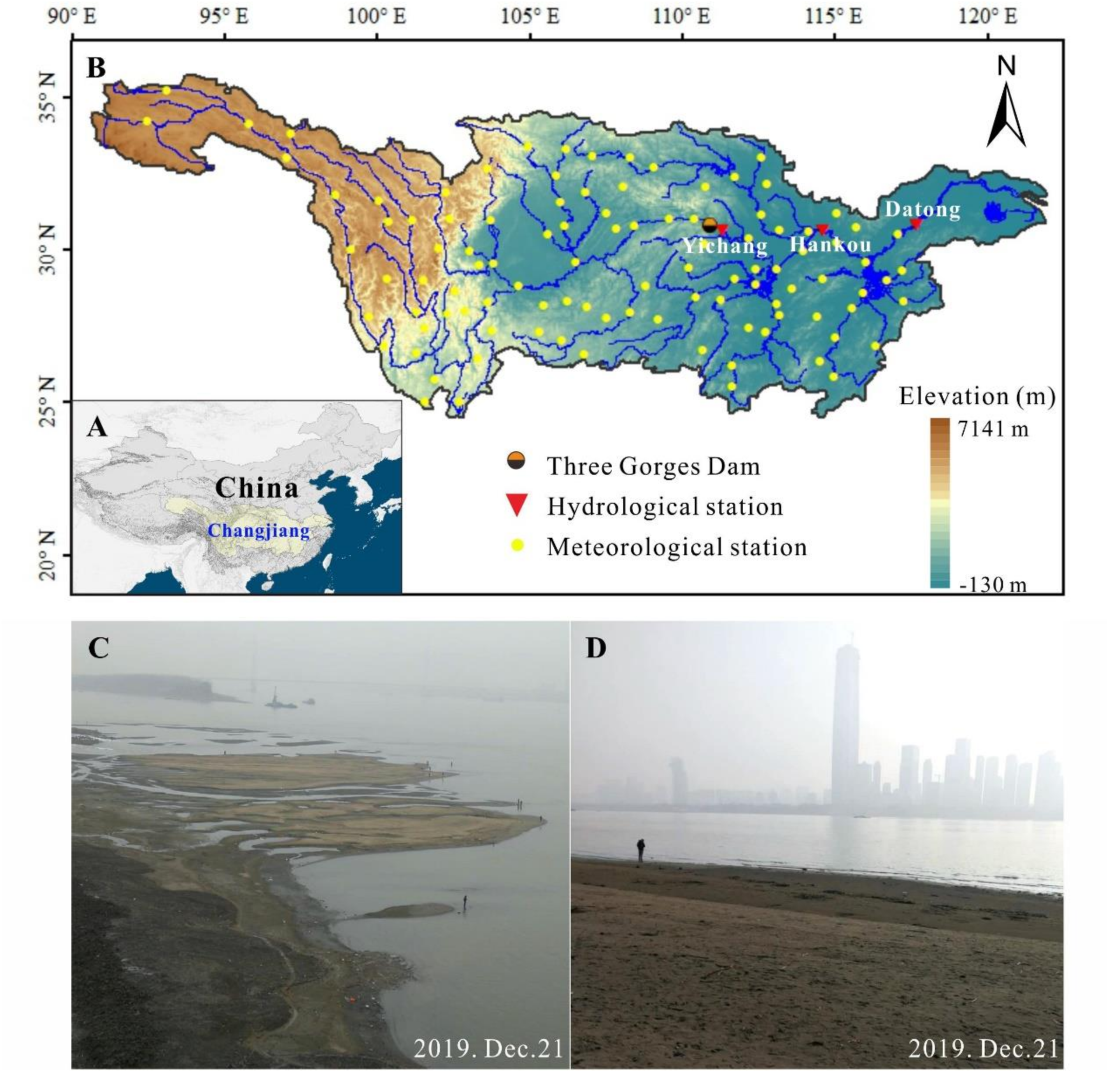

Fig. 1 Map of the study region. A) Location of the Chanjiang River in relation to China, B) DEM of the Changjiang River basin also showing the location of major hydrological and meteorological stations. Photographs of C) the river bed and D) banks of the Changjiang River around Hankou on 21 December 2019, when the water surface elevation was 40% lower than the past 20-year average, while the flow discharge changed only slightly in the same period.

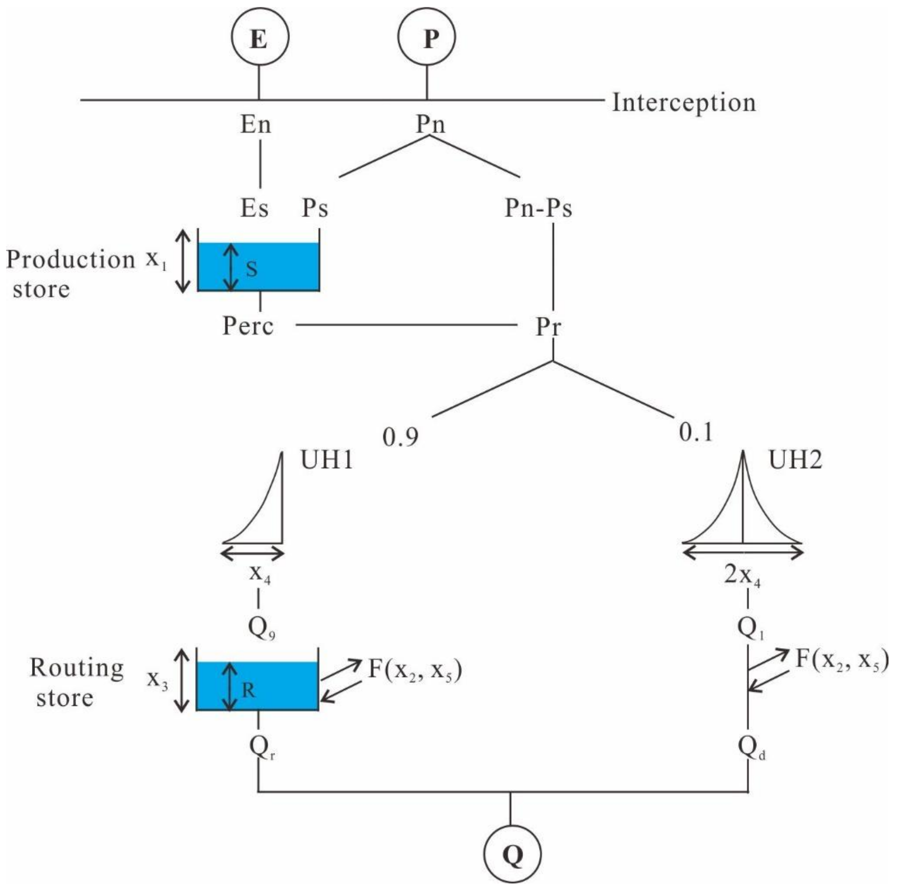

Fig. 2 A schematic diagram showing the GR5J rainfall-runoff model (from Pushpalatha et al., 2011).

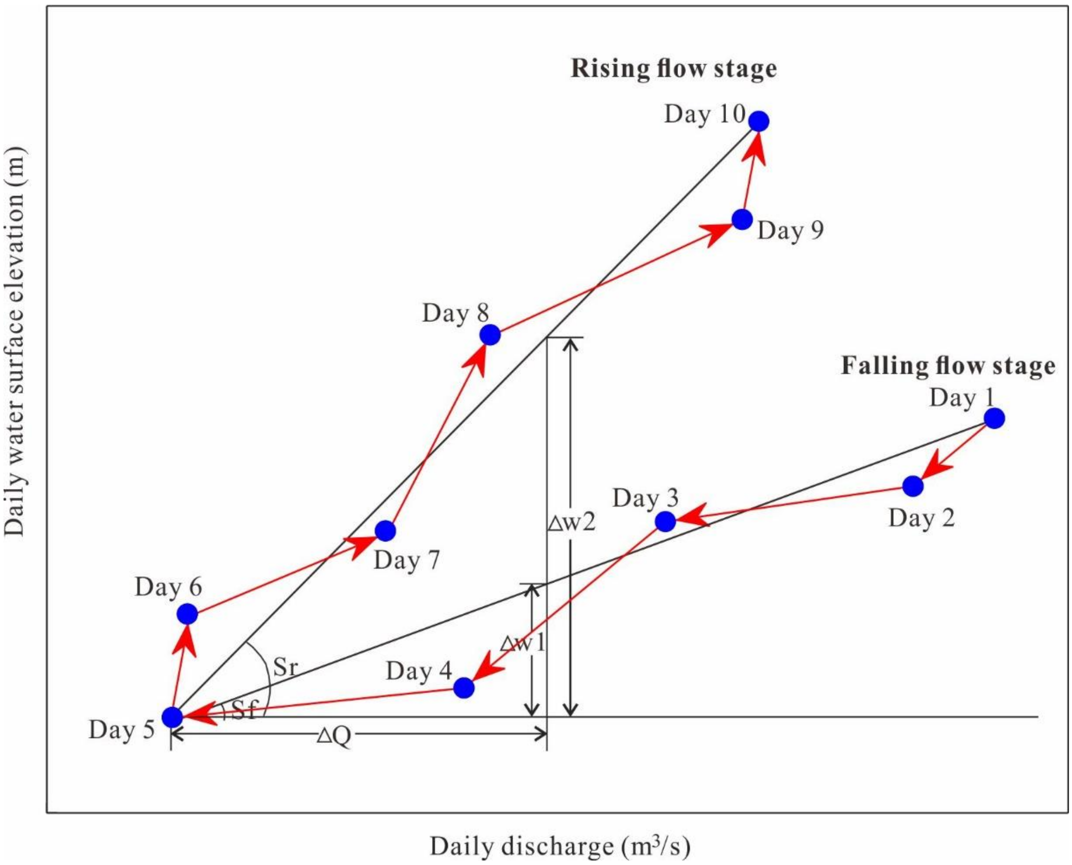

Fig. 3 Diagram showing daily water surface elevation versus flow discharge during the falling and rising flow stages of defined hydrological events and the significance of the curve slope.

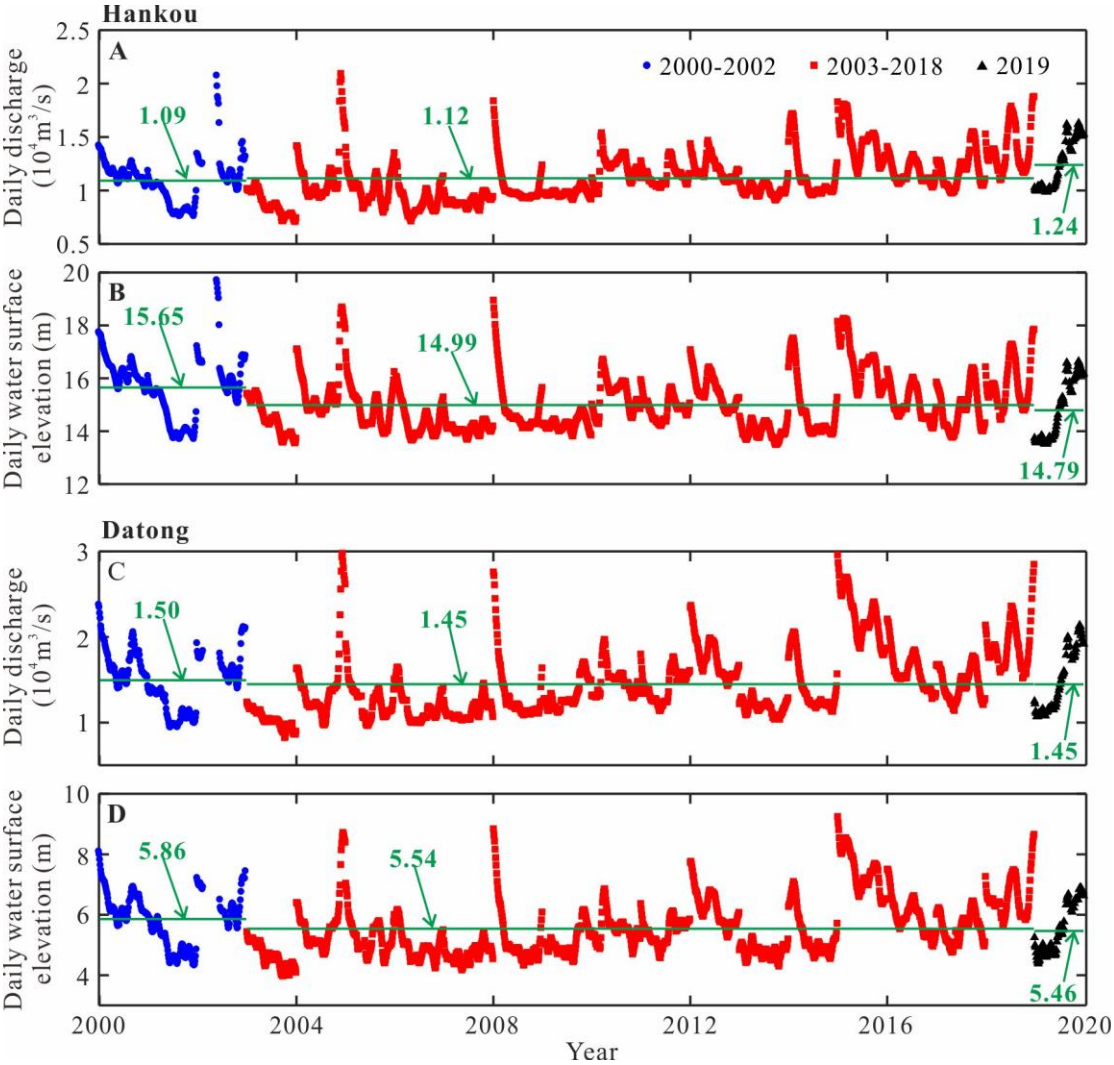

Fig. 4 Observed dry season daily flow discharge and water surface elevation at selected Changjiang River gauging stations, with the green lines showing the dry season mean values: A-B) Hankou, and C-D) Datong.

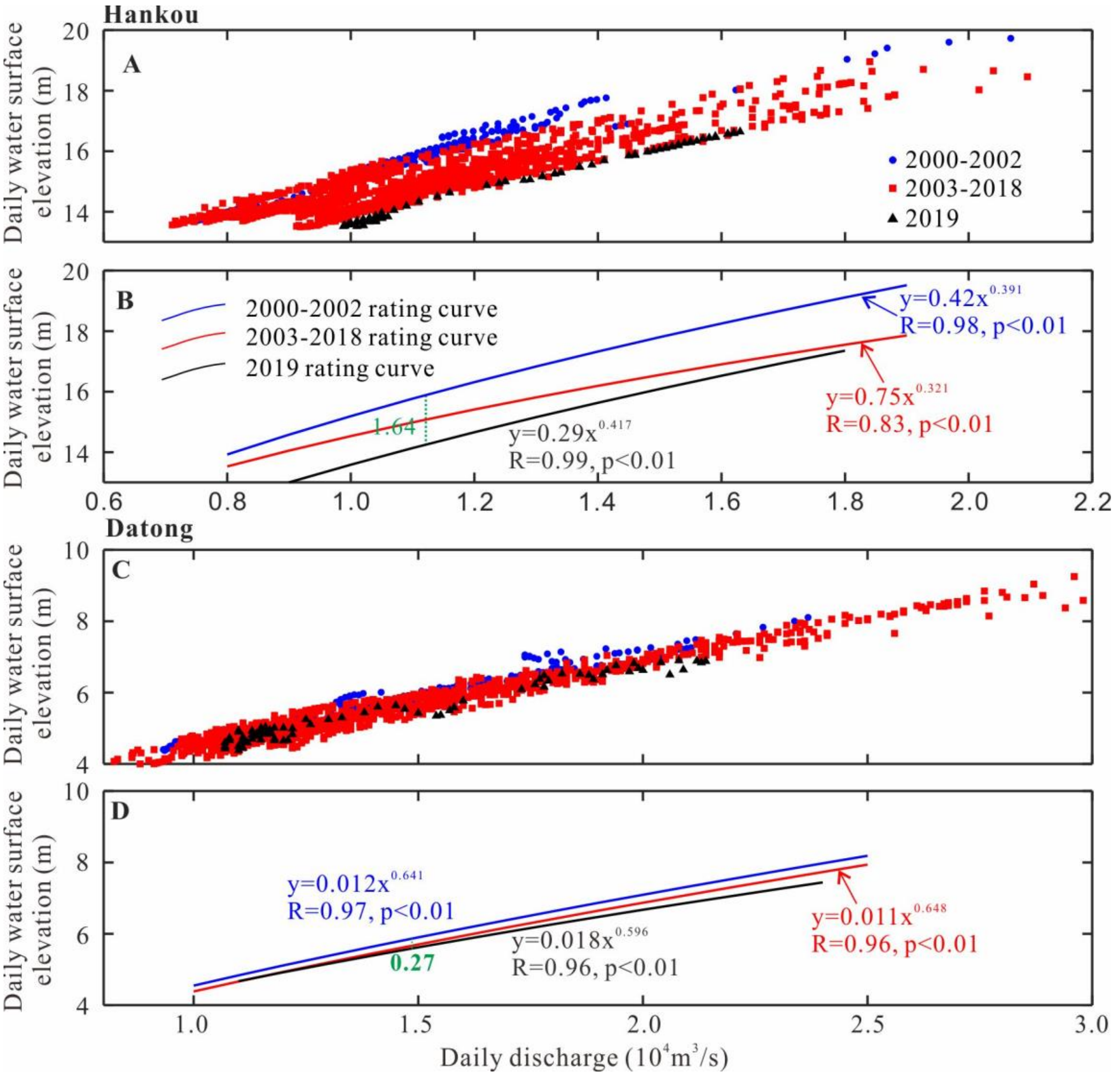

Fig. 5 Relationships between observed dry season water surface elevation and daily flow discharge for the periods 2000-2002 (pre-Three Gorges Dam), 2003-2018 and 2019 (both of these being post-TGD scenarios) and the associated 'best fit' rating curves at A-B) Hankou and C-D) Datong. The green dotted line indicates water surface elevation reduction following TGD regulation for the scenario of mean daily discharge in the dry season.

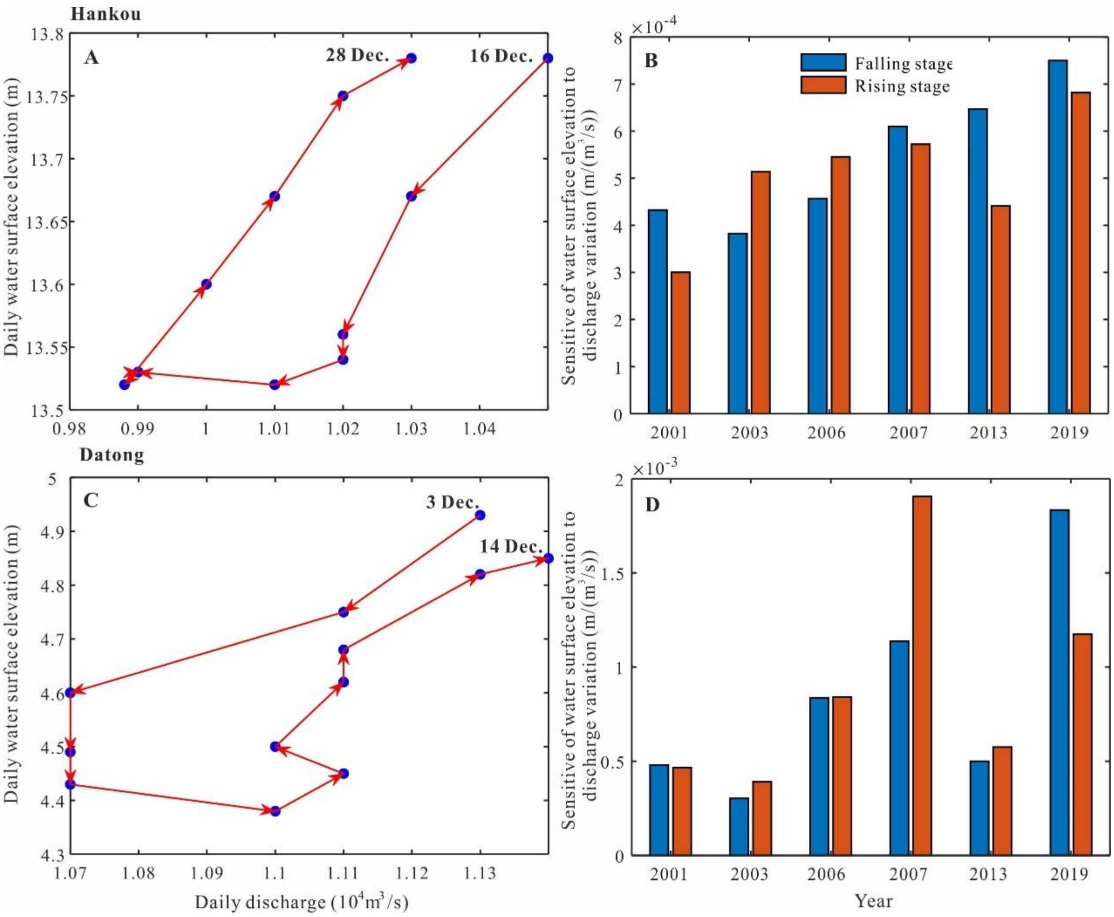

Fig. 6 Loop-rating curves of daily water surface elevation versus flow discharge for the 2019 Changjiang River dry season episodes at A) Hankou and C) Datong stations. A comparison of the sensitivities of water surface elevations to discharge variations for the 2019 and five other dry season episodes is also shown for B) Hankou and D) Datong.

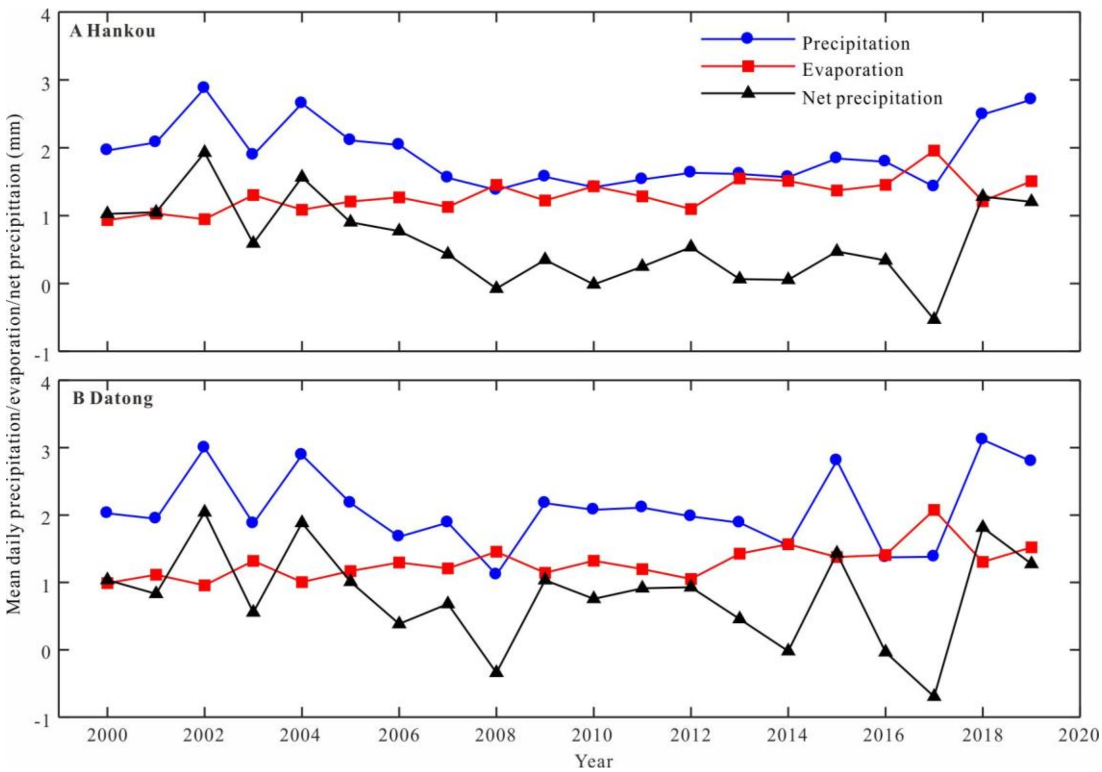

Fig. 7 Time series of mean daily precipitation, mean daily evaporation and mean net daily precipitation over the A) middle and B) lower Changjiang catchment during the dry season.

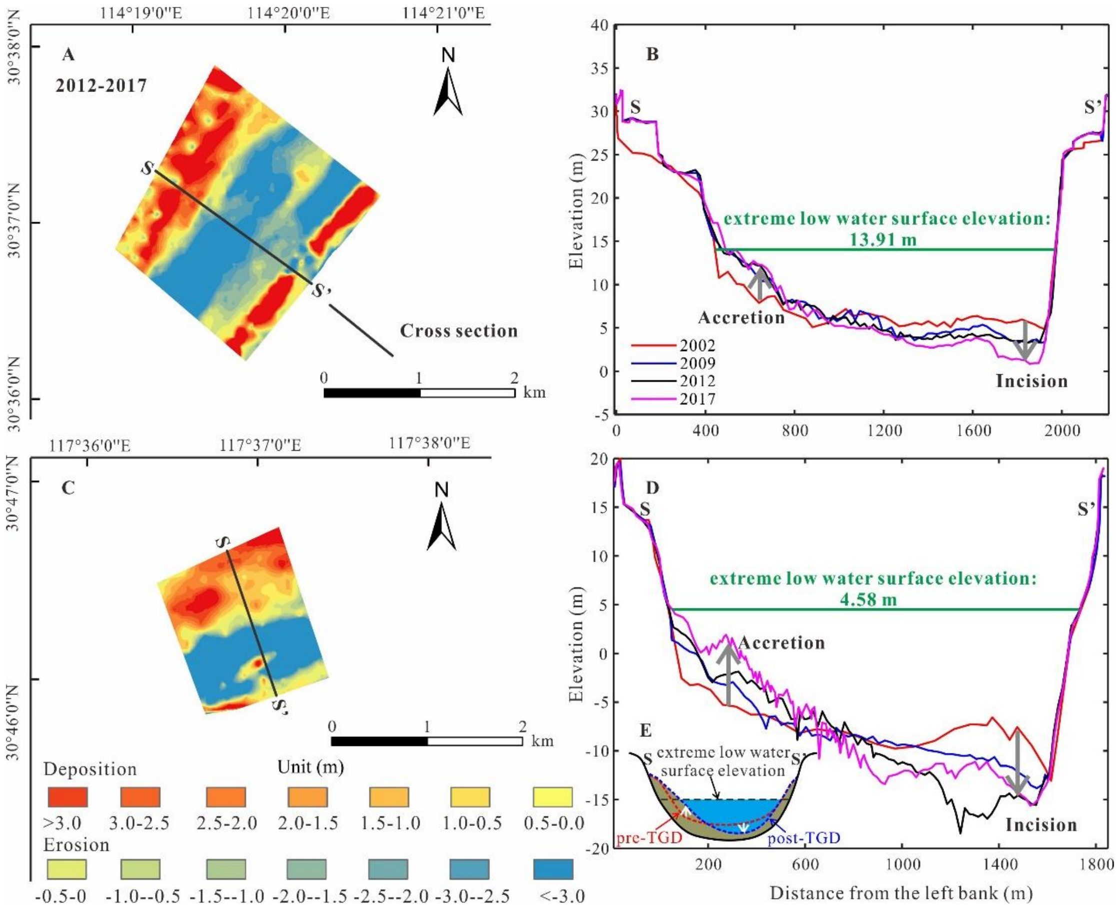

Fig. 8 Morphological change as detected from bathymetric maps and cross section changes at A-B) Hankou and C-D) Datong, and E) diagram showing the transition in channel morphology from a trapezoid to triangular shaped cross-section in the period following the Three Gorges Dam regulation.

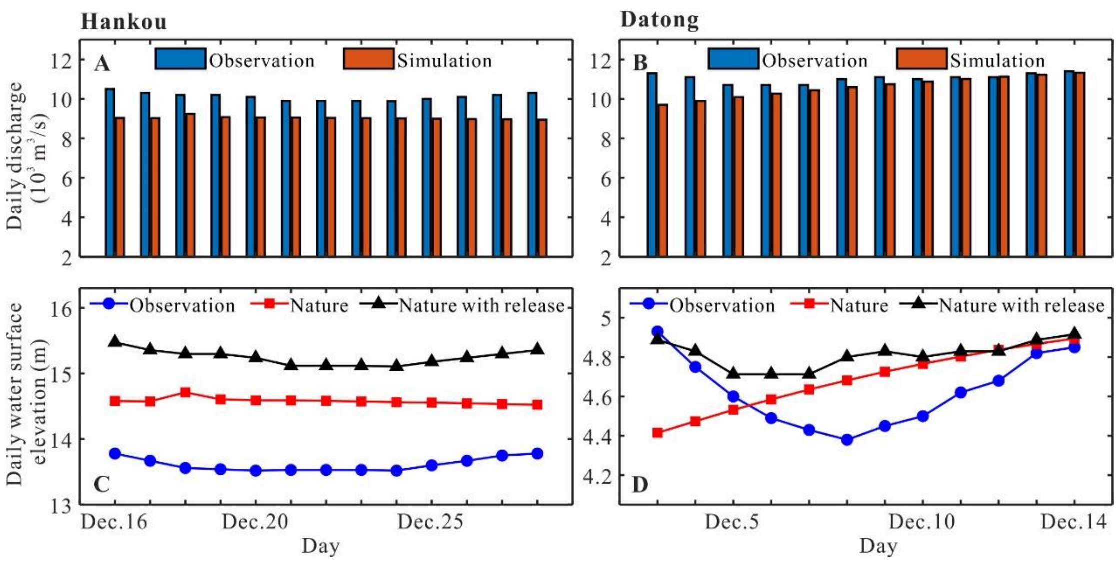

Fig. 9 Simulated and observed daily flow discharge at A) Hankou, B) Datong and daily water surface elevation at C) Hankou, D) Datong during the 2019 dry season.