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Key Points:

- The record-breaking 2016 ENSO event drove the heaviest rainfall over the Changjiang basin since 1950 but generated only the seventh largest flood since 1950 due to the effects of the TGD
- Bed and bank erosion induced by the TGD has caused a steeper rate of rise and increased flood peaks for high flow discharges at Datong
- Morphological adjustments downstream of large dams may inhibit their full potential to mitigate extreme flood risk

Supporting Information:

- Supporting Information S1

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Modulation of Extreme Flood Levels by Impoundment Significantly Offset by Floodplain Loss Downstream of the Three Gorges Dam

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Abstract River flooding—the world's most significant natural hazard—is likely to increase under anthropogenic climate change. Most large rivers have been regulated by damming, but the extent to which these impoundments can mitigate extreme flooding remains uncertain. Here the catastrophic 2016 flood on the Changjiang River is first analyzed to assess the effects of both the Changjiang's reservoir cascade and the Three Gorges Dam (TGD), the world's largest hydraulic engineering project on downstream flood discharge and water levels. We show that the Changjiang's reservoir cascade impounded over 30.0×10^3 m^3/s of flow at the peak of the flood on 25 July 2016, preventing the occurrence of what would otherwise have been the second largest flood ever recorded in the reach downstream of the TGD. Half of this flood water storage was retained by the TGD alone, meaning that impoundment by the TGD reduced peak water levels at the Datong hydrometric station (on 25 July) by 1.47 m, compared to pre-TGD conditions. However, downstream morphological changes, in particular, extensive erosion of the natural floodplain, offset this reduction in water level by 0.22 m, so that the full beneficial impact of floodwater retention by the TGD was not fully realized. Our results highlight how morphological adjustments downstream of large dams may inhibit their full potential to mitigate extreme flood risk.

Plain Language Summary The role of damming in modulating flood risk in large rivers and the issue of how flood risk changes is attracting considerable interest. We develop the first study to address how the cascade of reservoirs behaves under extreme flood conditions in terms of the interplay between the positive effects of impoundment versus the impacts of downstream morphological changes. Our findings are highly significant to those dealing with the theory (hydrology, physics, and geosciences), application (hydrology, geomorphology, ecology, biology, and geochemistry) and implications (social science, policy, and environmental management) of flood risk in the world's large rivers in the context of rapid climate warming and extensive dam regulations.

1. Introduction

The history of human development is coupled closely with the need to protect civilizations from the adverse effects of flooding. However, there is evidence of an increasing global risk of damaging flooding (Pall et al., 2011). Notable recent catastrophic flood events include the widespread flooding of Bangladesh in 1998 (Chowdhury, 2000), the record-breaking floods in Central Europe in 2002 (Becker & Grünewald, 2003), the historic spring 2011 flood of the Mississippi River (Falcini et al., 2012), and the extraordinary flash flood in Canada in 2013 (Wake, 2013). The El Niño/Southern Oscillation (ENSO) is probably the best known driver of extreme floods at the global scale (Ward et al., 2010). For example, the occurrence of flooding in the Amazon (Aalto et al., 2003), Nile (Wang & Eltahir, 1997), and Mekong Rivers (Darby et al., 2016; Räsänen & Kummu, 2013) have all been linked to ENSO episodes. The extreme ENSO event of 2015–2016 was unprecedented since the start of the instrumental record in 1870 (Barnard et al., 2017), both in terms of its strength and its duration, triggering severe drought in Ethiopia, along with intense rainstorms in Abu Dhabi, California, and Argentina. In China, the event caused large-scale precipitation anomalies and deadly floods, resulting in direct economic losses of U.S.$ 24 billion within the Changjiang River basin alone (Xu, 2016): the Earth's fifth most expensive weather-related natural disaster outside of the United States since 1980 (Masters & Henson, 2016). Despite

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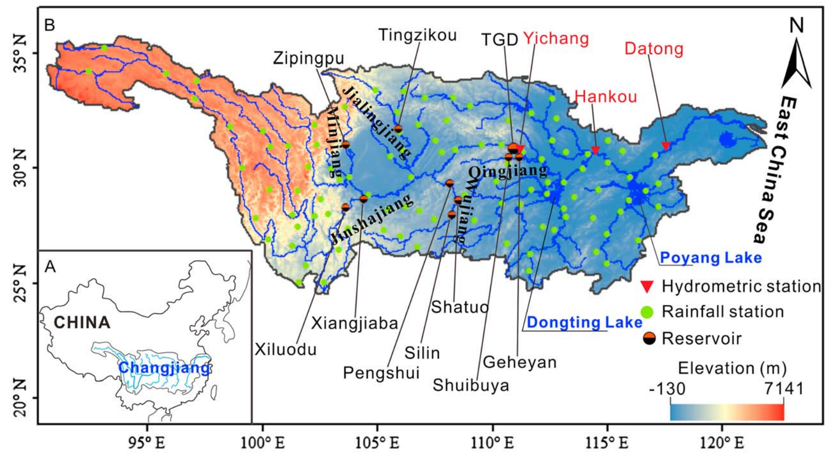

Figure 1. The hydrometeorological gauging network of the Changjiang River catchment showing: (a) the Changjiang River's location in relation to China; (b) the Changjiang River basin. The diagram highlights the locations of major reservoirs, including the Three Gorges Dam (TGD), as well as locations of the three main hydrometric gauging stations on the Changjiang River downstream of the TGD.

these profound impacts, there has not yet been a comprehensive analysis of the response of the Changjiang River to the record-breaking 2016 ENSO-driven flood event.

Several major infrastructural investments have been made in attempts to mitigate the adverse impacts of the increasing frequency and intensity of global flooding. Since the 1930s, over 45,000 large dams have been established globally, with flood control frequently being cited as either their main or secondary purpose (World Commission on Dams (WCD), 2000). The Changjiang River is in this respect not unusual in that it operates an extensive dam cascade, albeit the Three Gorges Dam (TGD) is exceptional in being the world's largest hydraulic engineering structure. In these circumstances, important questions are raised concerning the actual effects of damming on flood regulation, in particular, during the extreme flood events that pose the greatest risk to society. Yet, notwithstanding their increasing frequency, the relative rarity of large floods means that to date there has been very little research on the flood control performance of dams during extreme events (Allamano et al., 2009; Hamlet & Lettenmaier, 2007).

Addressing this knowledge gap is even more important when it is considered that undesirable downstream channel changes associated with dams have also become apparent (Petts & Gurnell, 2005). For example, the large-scale trapping of sediment behind dams has been linked to the loss of floodplains downstream (Pinter & Heine, 2005) which, by reducing the potential for storage of floodwater, has been shown to potentially amplify the flood hazard (Hughes, 1980; Opperman et al., 2009; Pinter, 2005). Furthermore, although channel erosion typically occurs immediately downstream of dams, such erosion may itself lead to increased sediment supply to reaches farther downstream, thus reducing channel conveyance capacity and promoting increased flooding (Stover & Montgomery, 2001). These, and other, potentially adverse morphological impacts of dams on flooding have not yet been well documented under extreme conditions.

Previous studies have shown that, as a result of the TGD trapping sediment, significant erosion has occurred in the reaches downstream of the TGD since its closure in 2003 (Luan et al., 2016; Mei et al., 2018; Yang et al., 2007). The extent of the morphological adjustment is sufficiently great to potentially affect flow conveyance in the reach downstream of the dam, but the relationship between these morphological adjustments and flood risk has not yet been evaluated. Here we utilize the unique opportunity presented by the extreme 2016 ENSO event to develop the first study that addresses how the Changjiang River's cascade of reservoirs (Figure 1), including the iconic TGD, perform under an exceptional flood. Specifically, for these extreme conditions, we examine the interplay between the effects (with respect to flood levels) of impoundment versus the impacts of downstream morphological changes induced by the TGD.

2. Methods

In this section we first provide brief contextual information regarding the global and regional significance of the Changjiang River before outlining some specific characteristics of the extreme 2016 ENSO-driven flood event (section 2.1). We then go on to describe how a flow routing model was set up and used to estimate the behavior of the 2016 flood event. Specifically, the hypothetical scenarios without the TGD and the rest of the Changjiang's reservoir cascade are compared with the observed flood to quantify how impoundment by the dams alters extreme flood discharges (section 2.2). Finally, we outline the methods used to quantify how changes in channel and floodplain morphology in the reach downstream of the TGD have, since the TGD's construction, led to shifts in the relationship (the so-called stage-discharge rating curve) between flow discharge and water level (section 2.3). In all cases we focus on the hydrometric station at Datong, the most downstream gauging station along the Changjiang River (Figure 1). Full details of the methodological approach are provided in the supporting information (Holland, 1992; Khan, 1993; Mohan, 1997). In summary, the approach outlined above seeks to identify the trade-off between the beneficial impacts of runoff impoundment by the TGD's reservoir on flood levels (via flow routing modeling) versus the adverse impacts of dam-induced morphological changes on water levels (via analysis of stage-discharge rating shifts).

2.1. The Changjiang River and the 2016 ENSO-Driven Flood

As one of the world's great rivers the Changjiang is of great regional, and indeed global, significance as the 6,300-km-long river contributes 17.6% of the Chinese freshwater wetland area. Along with the Mississippi (Graf, 1999), the Amazon (Nazareno & Lovejoy, 2011), the Mekong (Darby et al., 2016), and other rivers, the Changjiang may also be considered as a hot spot of hydrologic engineering structures. Over 45,000 reservoirs with a total storage of 220 billion m^3 have been constructed within the Changjiang River catchment, including the iconic TGD (Yang et al., 2009). Since its completion in 2003, the TGD has successfully prevented flooding during most normal flood seasons (Dai et al., 2008). However, until 2016, the TGD had not previously experienced an extreme runoff event, so the 2016 flood provides the first opportunity to evaluate how the dam's flood control function performs under exceptional conditions.

The Changjiang River basin typically experiences large floods in July and August during or following ENSO events (Shankman et al., 2006). Extreme daily discharges as observed at Datong coincide well with years with a strong global ENSO signal, as was the case with the 1983, 1998, and 2016 floods (supporting information Figure S4). It is worth noting that the 2016 flood generated the heaviest rainfall observed over the Changjiang region (950 mm of cumulative rainfall) since 1950 (supporting information Figure S5). However, the resultant flood peak discharge (70,100 m^3/s) and water level, while still extreme (as defined by their exceedance of the 90th percentile threshold), were nevertheless only the seventh and sixth largest since 1950, respectively (Table S3), indicating that the 2016 rainfall runoff dynamics differ from those in pre-TGD conditions.

2.2. Change in Flood Dynamics Due To Impoundment of Flow by Reservoirs

To isolate the effectiveness of the Chiangjiang's reservoir cascade, including the TGD, in reducing the flow discharge of the 2016 flood, we developed a Muskingum flow routing model. Note that the flow routing model was initially set up and calibrated using the flows actually observed during the 2016 flood event at each of the three (Yichang, Hankou, and Datong) main hydrometric stations downstream of the TGD, in concert with data representing the storage and release of flows observed at each reservoir (see the supporting information for full details). The data presented in the supporting information (Figure S3) indicates that the calibrated flow routing model replicates successfully the observed 2016 flood hydrographs at these three hydrometric stations. We therefore applied the model to generate simulated flows for two further (hypothetical) scenarios. The first scenario represents a case in which flood water is routed through the Changjiang in the absence of storage associated with all major reservoirs in the dam cascade, whereas the second scenario excludes only the TGD (see supporting information Table S2 for an overview of the major dams included in the analysis; the locations of these dams are indicated in Figure 1).

By comparing the model-simulated flows for the two scenarios versus the observed flow during the 2016 flood, we isolated the effects on water discharge of dam impoundment by (i) all dams in the Changjiang's cascade and (ii) the TGD only. We then estimated the corresponding variations in water level for each scenario via application of stage-discharge rating curves derived from observations of flow discharge and water level. The supporting information provides details of the data sources and curve-fitting technique used to generate these stage-discharge rating curves, but we emphasize here that we used two distinct ratings: one for the pre-TGD period (using observations for the period 2000–2002) and the other for the post-TGD period (using observations for the period 2012–2014).

2.3. Estimation of Shifts in Flood Levels Due To Morphological Change

In this study we quantified morphological changes (see section 3.3 for details) through comparison of bathymetric data sets obtained in the vicinity of the Datong hydrometric station. These data were digitized from maps provided by the Changjiang Waterway Bureau, the body responsible for river mapping, with the map data ranging from scales of 1:40,000 (2008) to 1:80,000 (2013). The underpinning bathymetric surveys were all conducted during the dry season. The bathymetric maps were transferred into depth points relative to Beijing 54 coordinates and calibrated into the "Wusong Datum" using ArcGIS. Thereafter, data from each survey were gridded by the Kriging scheme at 20 × 20 m resolution to produce digital elevation models (DEMs) (Dai et al., 2016). Previous studies have shown that the morphological adjustments observed at Datong are part of a phase of erosion that extends throughout the reach downstream of the TGD and which have been induced as a result of sediment trapping by the dam (Luan et al., 2016; Mei et al., 2018; Yang et al., 2007). The timing and reach-wide nature of these adjustments (supporting information Figure S6), which extend even to the estuarine delta front, means that the observed morphological adjustments at Datong can confidently be attributed to the impacts of the TGD, as opposed to reflecting local adjustments.

Morphological changes along the Changjiang River are likely to lead to altered flood levels. Specifically, TGD-induced changes in channel capacity and floodplain extent cause further modifications in both the hydraulic conveyance at a specific channel cross section and (for the extreme floods that are the focus of this study) the downstream attenuation of the flood wave, the latter via the change in floodplain storage during overbank flows. These morphologically induced changes in flood characteristics are, therefore, reflected in shifts in the relationships between water level and flow discharge at individual hydrometric stations. To identify changes in flood water levels arising from TGD-induced morphological changes, and following Pinter and Heine (2005), we employed the same stage-discharge rating curves as developed in section 2.2 for the periods before and after the construction of the TGD. As noted above, we used flow discharge and water level data for the periods 2000–2002 and 2012–2014 to represent these pre-TGD and post-TGD scenarios, respectively. Water level variations arising from morphological changes within the study reach between the pre-TGD period (2000–2002) and the 2016 flood event were then estimated for any given flow discharge, simply by differencing the water levels obtained from the location-specific rating curves for the pre-TGD and post-TGD scenarios (the procedure is illustrated in the schematic supporting information Figure S1).

3. Results and Discussion

3.1. Comparison of the 2016 Flood With Selected Floods From the Pre-TGD Era

We initially compare the observed 2016 flood characteristics with the 1954 and 1998 flood events. These two floods offer a useful baseline as they represent the top two largest floods in the Changjiang River's history before the construction of the TGD (Table S3). The hydrographs for the 1954 and 1998 floods are relatively flat during the high flow period, whereas the 2016 flood changes more rapidly. For example, at Datong, the water level in 2016 reached its peak level of 15.64 m within a period of only one week from 1 to 8 July, retaining this high value for around 4 days, before falling back to its original value within the next month (Figure 2a). In contrast, during both the 1954 and 1998 floods, high water levels were maintained for over 2 weeks and also took more than 2 weeks to reach their peak values (Figures 2c and 2d) while the rainfall for both events was less than that for 2016 in both amount and duration. The rapid hydrological response of the 2016 event is also evident in the steep gradients of the rising and falling limbs of the water level curve (Figure 2e), with Datong's daily rate of rise and fall of water level in 2016 being, respectively, 0.51 m/day and −0.10 m/day, both of which are greater than those during the 1954 (0.06 m/dat and −0.04 m/day) and 1998 (0.12 m/day and −0.08 m/day) events. The observable difference between the 2016 flood and the two previous events is also evident in their stage-discharge rating curves. Both the 1954 and 1998 flood events exhibit a typical counterclockwise hysteresis loop (Figure 2f) owing to the influence of flood and backwater fluctuations (Petersen-Øverleir, 2006). Thus, during the rising stage of these two flood events water level

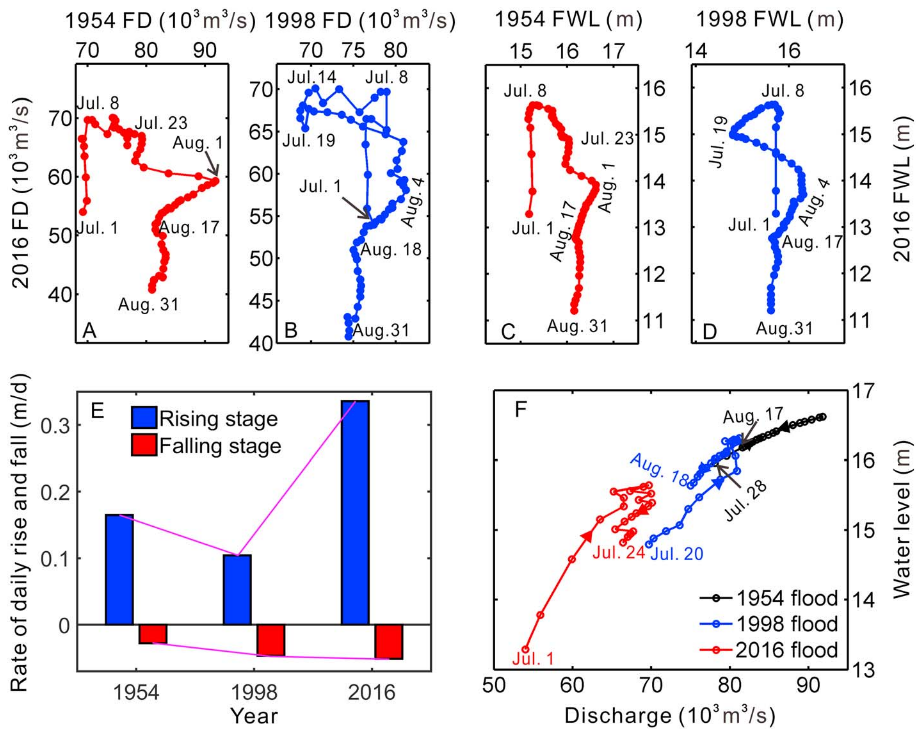

Figure 2. Comparison of flood characteristics observed at the Datong hydrometric station. (a, b) Daily flood discharge (FD); (c, d) daily water level (FWL) for the 2016 versus the 1954 and 1998 floods; (e) rate of daily rise and fall of water level during the 1954, 1998, and 2016 floods; and (f) loop-rating curves of the daily water level versus water discharge for the 1954,1998, and 2016 flood events.

increases with discharge, but during the falling limb, water levels remain at a high stage. In contrast, the rating curve for the 2016 flood exhibits a positive (clockwise) loop, with water level running ahead of discharge (Figure 2f), implying that there is only a weak hysteresis effect during the 2016 flood.

3.2. Effects of Reservoir Storage on the 2016 Flood Event

In section 2.2 we employed a Muskingum flood routing analysis to identify the extent to which the 2016 flood was affected by impoundment of storm runoff by the upstream reservoirs. Specifically, we compared simulated flood behavior for two (one removing all upstream dams, the other just the TGD) hypothetical scenarios with the observed characteristics of the 2016 flood (Figure 3a). It is evident from Figure 3a that the simulated flood "without reservoirs" differs significantly from the actual 2016 flood in terms of both the magnitude and timing of the flood peak. Without reservoirs the onset of the peak daily discharge moves from 14 July (actual flood) to 25 July ("all dams" scenario), with the maximum daily discharges on these dates changing from 7.01×10^4 m^3/s to 8.79×10^4 m^3/s, respectively. These altered discharges lead to corresponding increases in daily water levels (as computed from the stage-discharge ratings developed in section 2.2) from 15.39 m to 17.44 m. On 25 July, the TGD and the rest of the upstream reservoirs are shown to store as much as 1.45×10^4 m^3/s and 1.56×10^4 m^3/s, respectively, of runoff, which together impound over 34% of the discharge passing through Datong (supporting information Figure S2; note that the TGD reservoir was operated relatively normally, even during the 2016 event, as illustrated by supporting information Figure S7).

To put these results into context, it may be noted that had all of the water stored within the cascade during the 2016 event been returned to the river, the second largest flood in the historical record would have occurred in terms of flood discharge, peaking on 25 July. Indeed, if "only" the water stored behind the TGD had been released, the 2016 flood would still have had a peak discharge (at Datong) of 8.47×10^4 m^3/s (on 6 July), which would also have placed it second in terms of peak discharge behind only the 1954 flood (Figure 3a and Table S3), with the corresponding water peak water levels rising from 15.39 m (actual 2016

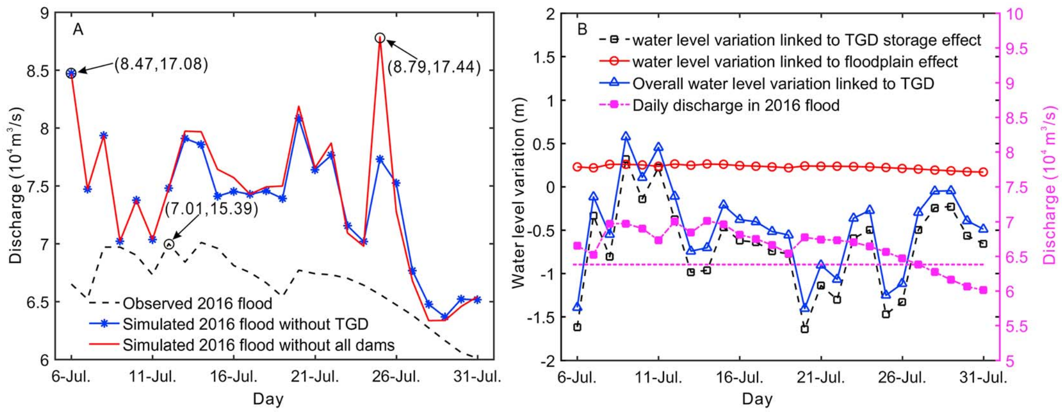

Figure 3. (a) Simulated and observed (black lines) flow hydrographs for the 2016 flood event at the Datong hydrometric station. The simulated flows are for scenarios without reservoirs, with the red line highlighting the scenario without flow storage in all of the Changjiang reservoirs and the blue line depicting the scenario without flow storage behind the Three Gorges Dam (TGD) only; (b) comparison of the flow discharge variation over time (solid pink line) for the 2016 flood for the hydrometric station at Datong. The blue line indicates the overall change (positive values denoting that the TGD increases water levels, negative values indicating that the TGD modulates water levels downward) in water level computed herein and arising from the combined (flow impoundment and downstream morphological adjustment) effects of the TGD. This overall change in water level is decomposed into the change of water level arising from impoundment by the TGD (black line) and the change in water level arising from downstream adjustments of channel morphology (red line). The horizontal pink dashed line indicates the flow discharge required to trigger the flood alarm level.

flood) to 17.08 m ("without TGD" scenario), meaning that the TGD, through storage of runoff, is estimated to have modulated peak flood levels downward by 1.69 m.

3.3. Effects of Dam-Induced Morphological Variations on the 2016 Flood Event

In section 3.2 the beneficial effects of the Changjiang reservoirs in reducing flood discharge and water levels, via impoundment of floodwaters that would otherwise be released downstream, are clearly demonstrated. However, a second potential modulating effect that the Changjiang cascade may have on downstream flood risk, which has been neglected in prior studies, arises from dam-induced variations in channel capacity and floodplain storage. To address this issue we follow the methodology outlined in section 2.3 to quantify changes in extreme flood risk arising from morphological adjustments downstream of the TGD.

Since the construction of the TGD, trapping of sediment within its reservoir has led to a significant decline in the downstream transmission of sediment. Indeed, the sediment load from the Changjiang River to the East China Sea is now only 150 Mt/year (2003–2012; Dai et al., 2014), which is approximately 30% of the pre-TGD level (1956–2002; Yang et al., 2014). This low sediment load means that the river downstream of the TGD is now sediment starved, and serious channel bed incision on the scale of hundreds of kilometers has been experienced there (Dai & Liu, 2013; Lai et al., 2017). For example, data derived from morphological change analysis (Figures 4a and 4c) show that at Datong the average water depth increased by 13% from 7.71 m in 2008 to 8.72 m in 2013. Meanwhile, bank erosion has also accelerated, presumably in response to the channel overdeepening such that the floodplain extent and therefore volume of sediment stored there also decreased by 63% (from 13.86×10^6 m^3 to 5.17×10^6 m^3) during the same period.

An increase in channel capacity arising from channel scour should, in principle, increase flow conveyance and therefore act to reduce flood levels, at least for moderate flows with water levels below the floodplain elevation. Figure 4d shows that the postdam channel enlargement does indeed result in reduced flood levels at Datong, for flow discharges below the bankfull level of 10.06 m. The increase in channel capacity is significant enough to offset the effects of the postdam decrease in mean flow velocity, which is evident across the full range of observed flows (Figure 4b). Such a decrease in flow velocity would be expected to increase water levels for a given discharge in the absence of any change in channel capacity, but the observed velocity decrease (for flow below bankfull) is itself a response (to maintain flow continuity) to the post-TGD channel erosion (channel enlargement).

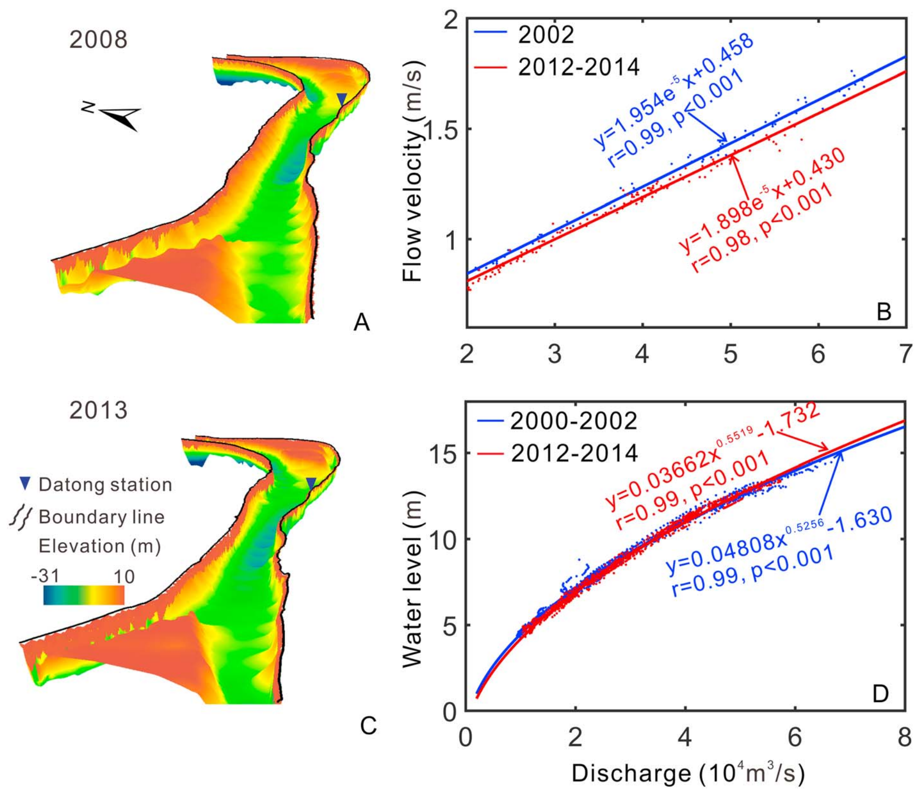

Figure 4. Channel erosion along the Changjiang River around the Datong hydrometric station as detected from bathymetric maps between (a) 2008 and (c) 2013; (b) relationship between cross-sectional average flow velocity and flow discharge in the pre-TGD (2002) and post-TGD (2003–2013) periods; (d) relationship between daily discharge and water level during the pre-TGD (2000–2002) and post-TGD (2012–2014) periods. Note that the flow velocity data, discharge, and water level data used here were provided by the Changjiang Water Resources Commission, China.

However, Figure 4d also reveals that there is a crossover point in the response such that at higher flow discharges (the transition being at $Q \approx 42{,}200\ m^3/s$, which is just above the bankfull condition) there is an upward shift in water levels for a given discharge in the post-TGD period. The adverse impacts on water levels are amplified (i.e., the divergence between the red and blue rating curves on Figure 4d increases) as the extremity of flooding increases: for a flow discharge of $6.0 \times 10^4\ m^3/s$ the post-TGD increase in flood level is 0.17 m and is even more prominent as the flow discharge increases still further (Figure 4d). For instance, during the actual peak of the 2016 flood (on 14 July), morphological changes induced a water level rise of 0.26 m (Figure 3b). Increased extreme flood levels associated with postdam morphological response have also been recorded on other regulated rivers like the Upper Missouri (Pinter & Heine, 2005) and may be linked to the substantial loss of floodplain, which provides a geomorphic mechanism for the exacerbation of extreme flooding (Opperman et al., 2009). In the case of the Changjiang River at Datong the extensive postdam loss of floodplain in the reach downstream of the TGD results in a considerable loss of overbank storage (Hughes, 1980) and a reduced attenuation of the flood wave as it travels from the TGD, causing a steeper rate of rise and increased flood peaks for high flow discharges at Datong (Figure 4d**)**. Combined with the decrease in mean flow velocity at this station (Figure 4b), it is evident that the flood levels for high flow discharges are elevated significantly as a consequence of post-TGD morphological adjustments (Figure 3b).

3.4. Implications

The relatively large magnitude (15% of the change in peak water level due to flood water storage) of the effect of recent, rapid, floodplain loss in offsetting the otherwise positive influence of the TGD's storage capacity in modulating extreme water levels is a cause for concern. First, raised water levels during extreme floods carry a disproportionately high additional damage burden: For example, in July 2016 the morphological adjustments caused water levels at Datong to be elevated above the alarm level for two additional days

(Figure 3b). Moreover, floodplain loss is ongoing, meaning that the impact of morphological change on flood levels will very likely continue to increase further over time. Furthermore, the additional risk of extreme flooding arising from this morphological effect is compounded because the TGD's storage capacity is itself declining as a result of sediment trapping behind the dam, progressively reducing the TGD's ability to attenuate high flow discharges. Therefore, there is a risk that downstream of the TGD water levels linked to extreme floods similar to the 2016 event will become higher in the future and as a result, the relative significance of the morphological effect will increase over time, even as such extreme events are likely to become more common.

4. Conclusion

This study shows that flood risk prediction on the Changjiang and other similar, large, and heavily regulated rivers demands a fully integrated approach that accounts for both hydrological and morphological responses to damming. The key points to emerge from our modeling and analysis of hydrological observations made during the exceptional 2016 flood event are as follows:

1. The historical strongest 2016 ENSO generated the heaviest ever recorded rainfall within the Changjiang River basin. However, the associated flood event, although exceptional, was not the largest ever recorded.
2. Instead, the large storage capacity of the full upstream cascade of reservoirs successfully retained over 3.0×10^4 m^3/s of flood water at the peak of the flood on 25 July 2016, thereby preventing the occurrence of what would otherwise have been the second largest recorded flood on the Changjiang.
3. Approximately 50% (1.45×10^4 m^3/s) of the total flood storage was contributed by the TGD alone, which for the extreme 2016 event is estimated to have reduced peak water levels at Datong by 1.47 m on 25 July, in comparison with pre-TGD conditions.
4. However, the adverse morphological impacts of the TGD, namely, loss of floodplain storage by erosion, offset the full beneficial impact of floodwater retention by increasing peak water levels at Datong by around 0.22 m, such that the net reduction in peak water level induced by the TGD was 1.25 m (on 25 July), not the 1.47 m reduction linked to the impoundment effect alone.

As discussed in section 3.4 the relative magnitude of this morphological effect on peak water levels is likely to progressively increase in the future because the adverse morphological adjustment is ongoing and because the storage capacity in the reservoir is being reduced by rapid sedimentation. The Changjiang River is similar to other large rivers that are intensively regulated by large dams. As many new large dams are either under construction or planned on large water courses throughout the world, our study provides a warning that full risk assessments are needed to more holistically determine whether dams are a blessing or a curse in terms of their downstream flood control (Milliman, 1997). The need for such risk assessments is pressing given that anthropogenic warming will very likely trigger more frequent extreme floods worldwide (IPCC, 2013).

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