Journal of
Water & Climate Change

Journal of Water and Climate Change Vol 13 No 4, 1936 doi: 10.2166/wcc.2022.428

Analysis of the evolution pattern and causes of downstream gigantic hydraulic projects

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ABSTRACT

The Jingjiang reach, located in the middle Yangtze River, downstream of the Three Gorges Reservoir (TGR), is a typical curved reach. After TGR impoundment, the evolution behaviors of the Jingjiang reach changed, mainly because one or more original factors, including geological conditions, existing projects, bending radius, upper reaches' regimes, and incoming water and sediment changed. In this paper, these influencing factors were investigated by using the measured data and the mathematical models that were proposed by the authors in a previous paper, and consequently, the evolution laws of the curved reach were analyzed. The results showed that the existing river nodes reduced the influence of the upstream river regime on the evolution of curve reaches and also slowed the speed of convex bank scouring and concave bank depositing. Constructed projects could reduce sediment transport intensity from the concave bank to the convex bank. The decrease in incoming sediment after TGR impoundment was beneficial to convex bank scouring. The increase in median water period duration was favorable for convex bank scouring and concave bank depositing. Both convex bank and concave bank were scoured when the incoming sediment concentration decreased sharply. The sediment concentration of suspended load would stabilize near the saturation point, and the riverbed would be scoured when there is sediment concentration under the saturation point, while the riverbed would be deposited when the sediment concentration reaches the saturation point.

Key words: curved reach, evolution laws, incoming water and sediment condition, saturation point

HIGHLIGHTS

- Systematic analysis of channel changes downstream of the Three Gorges Reservoir.
- The mechanism of upstream water flow change is introduced to analyze the downstream channel change.
- Considering the impact of human activities on the giant reservoir.
- Targeted analysis of longer river sections.
- The results obtained from the study are useful for the management of water resources.

1. INTRODUCTION

The Three Gorges Reservoir (TGR), the construction of which started in December 1994 and which was impounded to the normal water level (above the sea level of 175 m) in October 2010, is the largest water conservation project in human history (Han *et al.* 2017; Yang *et al.* 2018) and provides comprehensive benefits, including flood control, hydropower, shipping and water supply (Yang *et al.* 2018). After TGR impoundment, the water and sediment conditions and evolution laws of the downstream reaches have changed (Jia *et al.* 2013) and this has affected navigation in these reaches.

The Jingjiang reach is the nearest curved reach (CR) downstream TGR and it is one of the most complicated CRs because it consists of 16 local CRs (Jiang *et al.* 2010), namely, the Guanzhou CR, Jiangkou CR, Yuanshi CR, Shashi CR, Maijiazhai CR, Haoxue CR, Ouchikou CR, Nianziwan CR, Tiaoguan CR, Laijiapu CR, Jianli CR, Zhuanqiao CR, Fanzui CR, Xiongjiazhou CR, Qigongling CR and Guanyingzhou CR.

Under natural conditions in a CR, the main stream will pass along the river bank during a low water period, while going downstream directly during a high water period. In the long term, the concave bank will be scoured, while the convex bank will be deposited (Liu *et al.* 2018). The Jingjiang CR mainly followed the evolution disciplines of concave bank scouring and convex bank depositing (Yu 2006; Jia *et al.* 2010; Lu *et al.* 2011). A comparison of the measured data from 2003 to 2016 and those from 1980 to 2002 showed that the total flow remained almost unchanged, while the sediment discharge downstream TGR decreased by more than 80% (Chen *et al.* 2010; Xu *et al.* 2011; Jia *et al.* 2016). In recent years, however, researchers have observed that concave banks have begun to deposit, while some convex banks have begun to scour, which present an opposite discipline to the one before TGR impoundment (Xu *et al.* 2011; Jia *et al.* 2016).

However, the evolution behaviors of meandering reaches located downstream of gigantic hydraulic projects are sensitive to incoming water and sediment conditions (Frascati & Lanzoni 2009; Grenfell *et al.* 2012; Jia *et al.* 2016). Similarly, the evolution behaviors of the Jingjiang reach have changed because TGR changed the water and sediment conditions (Jiang *et al.* 2010; Yang *et al.* 2015). Actually, the evolution behaviors are affected by many factors, including the channel boundary conditions, the adjacent river regimes and the incoming water and sediment conditions (He *et al.* 2011; Zhou *et al.* 2013). Rahman and Chakrabarty (2020) proposed a one-dimensional numerical model for sediment transport in an alluvial river, while Li *et al.* (2020) used a three-dimensional numerical model to simulate the flow regime and sediment transport in the Detroit River.

The literature indicates that some changes have occurred in the meandering evolution of the Jingjiang reach, and some influencing factors have been studied. However, the disciplines of meandering evolution should be macroscopically summarized. Therefore, prototype observation, model and other means should be used to analyze all possible factors affecting the riverbed evolution, clarify the main factors affecting the evolution of curved reaches, and then reveal the evolution law of the curved reach.

In this work, the effects of the CR on evolution behaviors , including river nodes, bending radius, incoming water process, sediment transport intensity and sediment composition, are studied based on measured data and mathematical models. The evolution pattern and causes of downstream gigantic hydraulic projects have been revealed. The results have been well used for studying Jingjiang waterway regulation Phase I and Phase II projects. They could also be used for other waterway regulation projects downstream of gigantic hydraulic projects.

2. STUDY AREA AND BOUNDARY CONDITIONS

2.1. Study area

The previous paper (Liu *et al.* 2018) has studied that the evolution behaviors of the Jingjiang reach can be divided into two types. In Type-A, before TGR impoundment, the concave bank was scoured, while the convex bank was deposited; after the impoundment, the reverse happened, namely, the concave bank was deposited, while the convex bank was scoured. In Type-B, before the impoundment, the convex bank was scoured and even became a cutting bend; after the impoundment, the convex bank would be further scoured and was more likely to be a cutting bend.

The Jingjiang reach, in the middle Yangtze River, downstream the TGR, from Zhicheng to Chenglingji, with a total length of 347.2 km, consists of 16 local CRs (Jiang *et al.* 2010; Xia 2016), as shown in Figure 1. In this work, five CRs with minimum curvature, namely, the Tiaoguan CR, Laijiapu CR, Xiongjiazhou CR, Qigongling CR and Guanyinzhou CR, are selected to analyze the evolution mechanism of the CR by mathematical models. A 2D and a 3D numerical model, considering the unbalanced water and sediment transportation properties, were proposed and verified by the measured data in the previous paper. In this study, these models will be used to analyze the flow line, bottom velocity, shear stress, circulation intensity and relative intensity of circulation, in order to reveal the evolution mechanism of CRs.

The navigation channel charts of the five CRs were investigated from 1992 to 2012 (10 years before TGR impoundment and 10 years after TGR impoundment). Taking the Tiaoguan CR as an example, the water depth was marked as independent points with 150- m intervals and a 1:10,000 scale, as shown in Figure 2. The vertical error limit of the water depth (H) was 0.2 m for $H \leq 20$ m and 0.01*H for $H > 20$ m. The reference datum used in the charts was the navigational datum of the middle Yangtze River. The values of water discharge and sediment discharge were provided by the hydrologic stations, and the types and proportions of riverbed components were provided by the Chang Jiang Waterway Bureau (CJWB) (Zheng *et al.* 2018).

2.2. Geological conditions

The river regime stability is affected by the riverbed components distinctly. The Jingjiang reach riverbed is mainly deposited by medium and fine sand (Dade 2000; Wang 2009). Therefore, the riverbed is vulnerable to be scoured (Yang *et al.* 2011; Yuan *et al.* 2012; Lai *et al.* 2017). Ouchikou is a critical point of the geological component of the riverbed. Before the Ouchikou point, the bed consists of gravels and soil, and the gravels are glued by the soil in the substrate, leading to good erosion resistibility. Thus, the river regime before Ouchikou is relatively stable. After the Ouchikou point, the bed mainly consists of sand and soil, and the median particle size is only 0.18 mm, making the CRs after Ouchikou vulnerable to change (Jia *et al.* 2013). Hence, under natural conditions and under the effect of bend circulation, the concave banks would be scoured, while the convex banks would be deposited.

2.3. Existing projects

The evolution behaviors are obviously affected by the existing projects (Harmar *et al.* 2005; Anthony 2015; Wang 2015; Zhou *et al.* 2017). Many projects have been built in the Jingjiang reach to handle problems like flood control and navigation, including dyke projects, bank-protection projects and waterway regulation projects. Dyke projects are distributed on both sides of the river. On the left side are the left Jingjiang dyke (182.35 km), Jianli main dyke (92.34 km) and lower Balizhou dyke (37.37 km). On the right side are the Jingnan main dyke (189.32 km) and Yueyang main dyke (163 km). Bank-protection projects include the lower Balizhou bank-protection project (15.58 km), Jingjiang bank-protection project (86.97 km), Jinnan main dyke bank-protection project (55.82 km), Jianli main dyke bank-protection project (39.06 km) and Yueyang main dyke bank-protection project (42.76 km). Waterway regulation projects include Tiaoguan, Laijiapu, Qigongling and an other 23 waterway regulation projects, as shown in Figure 1.

These projects have obviously prevented a collapse of the concave bank by reducing the sediment transport volume from concave bank to convex bank under the effect of bend circulation and by reducing the degree of concave bank scouring and convex bank depositing.

2.4. Bending radius

The bending radii of the CRs were calculated by the trial circle method (Fan *et al.* 2017), and each radius is listed in Table 1. The results show that the evolution type of the CRs is not linked to its bending radius. For instance, the bending radii of both the Shishou CR and the Qigongling CR are 910 m, but the evolution types of the Shishou CR and Qigongling CR are Type-A

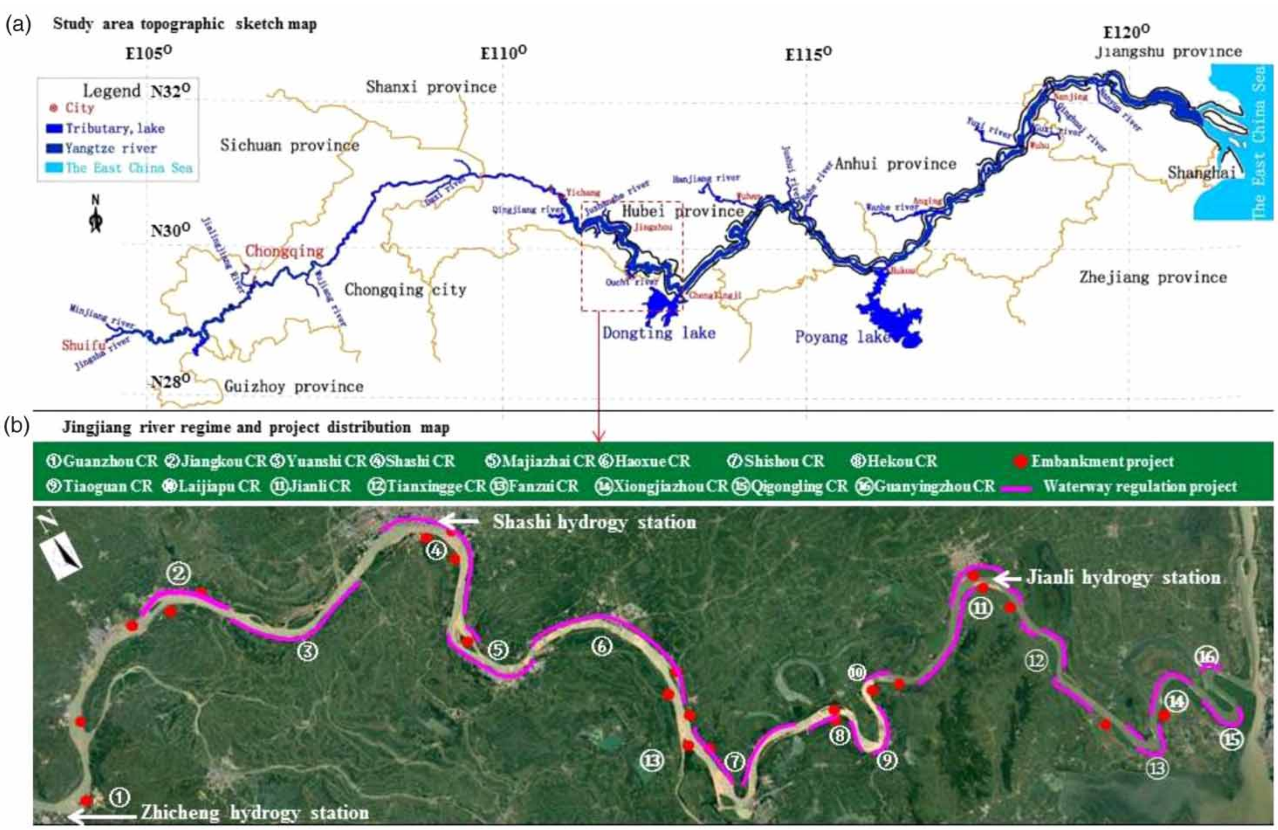

Figure 1 | Jingjiang CR distribution and engineering drawing.

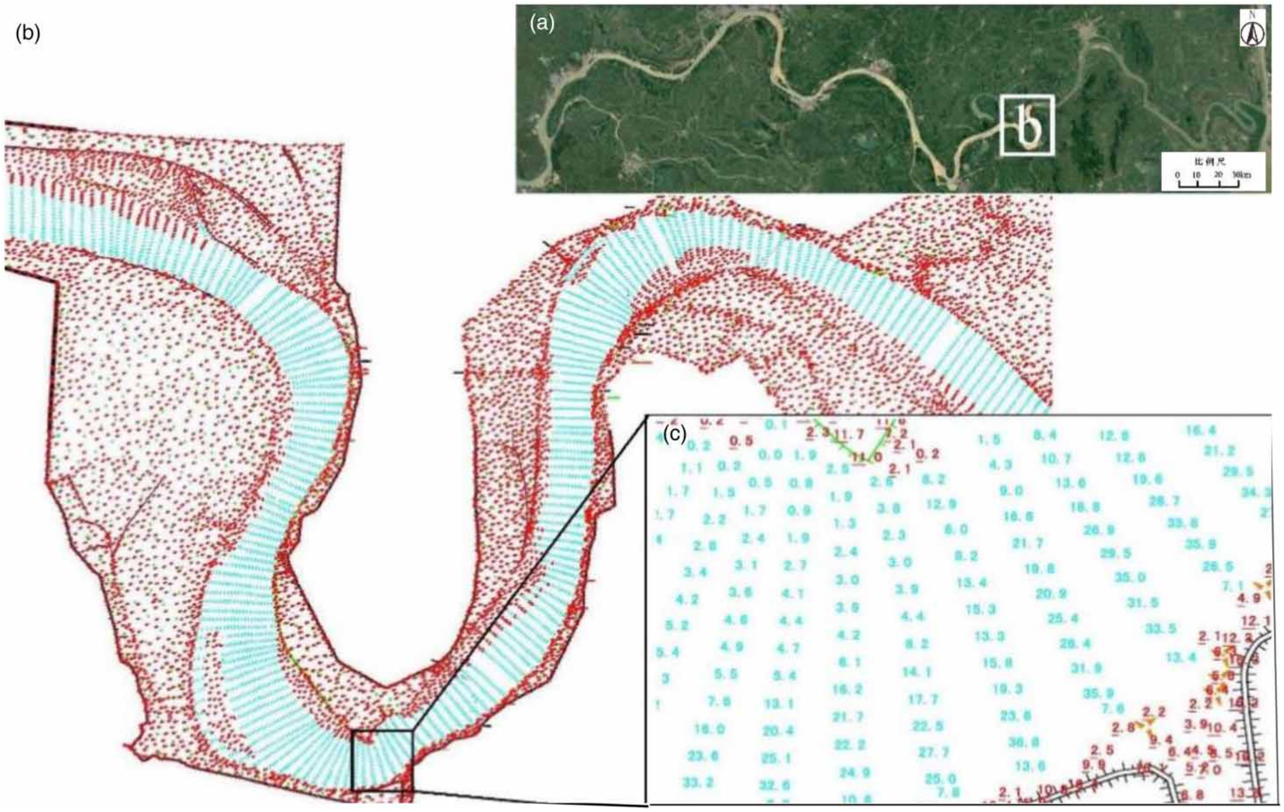

Figure 2 | Digitized water depth point charts of the Tiaoguan CR.

and Type-B, respectively. Furthermore, the bending radii of the Shashi CR and Jianli CR are similar but much bigger than those of the Shishou CR, and the evolution types of the Shashi CR and Jianli CR are Type-B and Type-A, respectively. Thus, the bending radius has no obvious effect on CR evolution.

3. UPPER REACHES' REGIMES

3.1. Influence of nodes

River node is an important factor affecting river bed evolution. The river nodes of the Yangtze River are mainly divided into two types: one is natural rock projecting over the water, and the other is an artificial project. The nodes could reduce the influence of upstream river regime change on this CR. For example, the evolution behavior of the Hekou CR entrance should be affected by the thalweg swing in the upper waterway; in fact, the thalweg of the Hekou CR entrance became stable from the year 2002 to 2012 (Figure 3(a)). This is mainly because the artificial project has reduced the water erosion

Table 1 | Bending radius of CRs

Reach name	Bending radius (m)	Evolution type	Reach name	Bending radius (m)	Evolution type
Guanzhou CR	2,164	A	Tiaoguan CR	1,170	A
Jiangkou	2,350	A	Laijiapu CR	1,400	A
Yuanshi	2,410	A	Jianli CR	2,400	A
Shashi CR	2,608	B	Tianxingge	1,692	A
Majiazhai CR	2,820	B	Fanzhui CR	830	A
Haoxue	12,800	A	Xiongjiazhou CR	1,950	A
Shishou CR	910	A	Qigongling CR	910	B
Hekou CR	1,620	A	Guanyinzhou CR	1,320	A

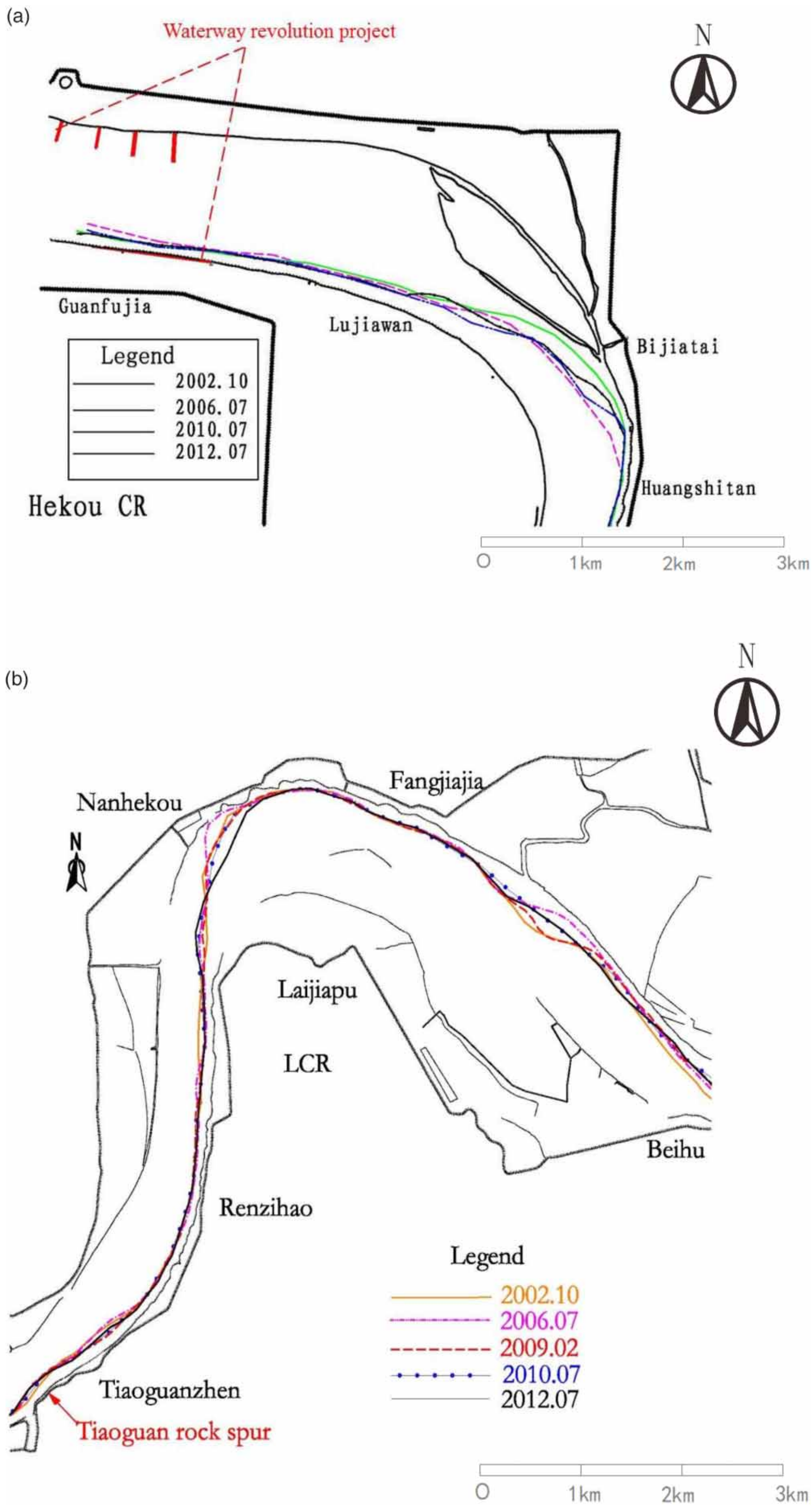

Figure 3 | Thalweg change. (a) Hekou CR and (b) Laijiapu CR.

effect of the Hekou CR; hence, the speed of convex bank scouring and concave bank depositing has slowed down. Moreover, because of the water resistance effect of the Tiaoguan natural rock project and manmade revetment project in the upper Laijiapu waterway, the flow became stable after the Tiaoguan rock spur, forming a long straight reach (Figure 3(b)). Thus, river nodes could reduce the speed of convex bank scouring and concave bank depositing in CRs.

3.2. Influence of river branch

The main river is interspersed with confluence branches and distributary branches. Dongting Lake, the largest distributary branch of the Jingjiang reach, is located 15 km downstream of the Qigongling CR, between the Jianli hydraulic station (HS) and Chenglingji HS. Be affected by the lake, water level-flow relation in the Jianli hydrological station is scattered and unordered, as shown in Figure 4. After TGR impoundment, from the year 2003 to 2005, the flow ratio of the Chenglingji and Jianli stations reduced from 73 to 60%. At year 2012, the flow ratio increased to 71%. Figure 4 shows that the change in the trend of the flow ratio is either linear or monotonous and that the river branch is not the key reason for convex bank scouring in CRs.

4. DISCUSSION OF THE EFFECTS OF WATER VOLUME

4.1. Analysis of measured data

Incoming water condition has a great influence on convex bank evolution (Yang *et al.* 2017). According to the flow process, the water discharge (Q) in the Jingjiang reach can be divided into seven degrades, namely, river trough discharge ($Q = 6{,}500\ m^3/s$), waterway regulation discharge ($Q = 7{,}580\ m^3/s$), beach submerged discharge ($Q = 9{,}500\ m^3/s$), average discharge ($Q = 15{,}000\ m^3/s$), bankfull discharge ($Q = 25{,}000\ m^3/s$), beach submerged discharge ($Q = 30{,}000\ m^3/s$) and flood discharge ($Q = 45{,}000\ m^3/s$). When $Q < 9{,}500\ m^3/s$, the river is in the dry season; when $9{,}500 \leq Q < 30{,}000\ m^3/s$, the river is in the median water period; when $Q \geq 30{,}000\ m^3/s$, the river is in the drought season. Figure 5 gives the

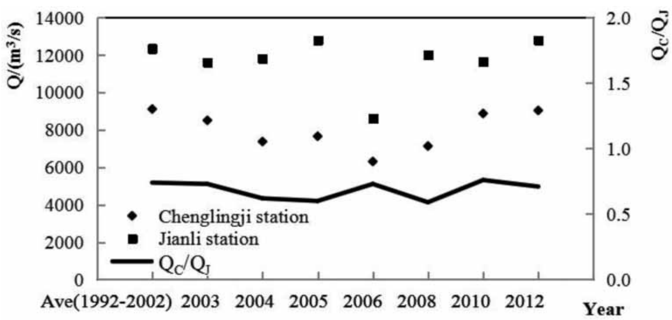

Figure 4 | Flow rate change in the Chenglingji and Jianli stations after TGR impoundment.

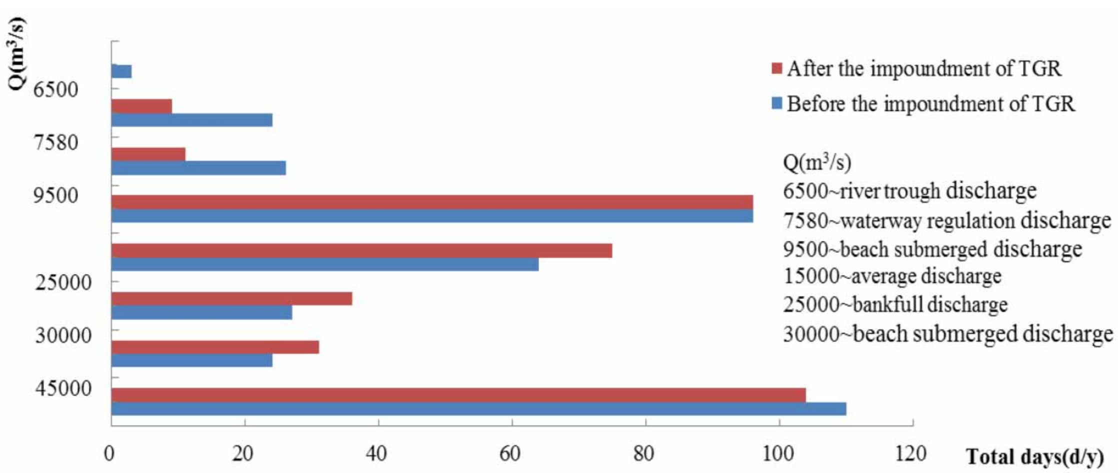

Figure 5 | Flow rate duration of the Jianli hydrological station.

statistical data of the average water discharge per day of the Jianli HS, which is located in the middle of the Jingjiang reach. After TGR operation, the flow duration in the median water period has increased and the flow recession process after the flood season has shortened. The total number of days of the median water period of the Jianli HS was about 185 before TGR impoundment, but it increased to 205 after TGR impoundment. In the flow recession process after the flood season, from bankfull discharge to average discharge, the total days decreased from 37 before TGR impoundment to 15 after TGR impoundment.

Generally, for a sandy reach, high discharge is favorable for channel depositing, while middle and low discharge is favorable for channel scouring (Jiang *et al.* 2010; Zhang *et al.* 2017). Hence, after TGR impoundment, a reduction in the high discharge duration and an increase in the middle discharge duration are favorable for convex bank scouring in CRs.

4.2. Numerical model computation and analysis

4.2.1. Mainstream of CR

The bending radius of the water main flow can be calculated by Zhang's equation (Zhang *et al.* 1984), as shown in the following equation:

$$R_0 = 0.053R\left(\frac{Q^2}{gA}\right)^{0.348} \tag{1}$$

where R_0 is the bending radius of the water main flow (m); R is the bending radius of the river (m); Q is the water discharge (m^3/s); A is the cross-section area of the river (m^2) and g is the gravitational acceleration (m^2/s).

From Equation (1), it can be noted that the bending radius of the main flow is proportional to the water discharge, and if the incoming water discharge increases gradually, the bending radius of the main flow would increase, forcing the river to change from a curve to a line. Consequently, during the flow rising period, the main flow would be biased in favor of the convex bank and scour the convex bank; whereas during the flow recession process, the main flow would be biased against the convex bank and deposit the concave bank.

The setup and verification method of the numerical model were provided by the previous paper (Liu *et al.* 2018), and then the model was used to analyze the change disciplines of the mainstream line, the flow velocity and the shear stress of the river. The measured topographic data of February 2012 were chosen as the original boundary condition of the 2D numerical model.

Figure 6 shows the change in the mainstream line of the Tiaoguan CR, Laijiapu CR and Qigongling CR, respectively. When the water discharge was under 6,500 m^3/s, the mainstream line kept close to the concave bank; when the water discharge increased to 15,000 m^3/s, the mainstream line began to move away from the concave hank; when the water charge increased to 25,000 m^3/s, the mainstream line of the Tiaoguan CR, Laijiapu CR and Qigongling CR moved away 280, 320 and 600 m, respectively. When the water discharge went up to 45,000 m^3/s, the mainstream line almost approached the convex bank. That is to say, a heavier water discharge would bring about a higher scouring to the convex bank.

4.2.2. Flow velocity

The bottom flow velocity, shear stress and circulation intensity can be calculated by using the 3D numerical model. Figure 7 shows the flow velocity distribution at the bottom of the Tiaoguan CR, Laijiapu CR and Qigongling CR, respectively. Each figure has a legend, with the deeper red color denoting a higher flow velocity. The water flowing at the river bottom will have a great influence on the sediment of the riverbed. Particularly, the riverbed components of the Jingjiang reach are mainly composed of fine sand, making it easy to be scoured. It can be clearly seen that when the water discharge increased from 6,500 to 25,000 m^3/s, the highest flow velocity increased from about 1.5 to about 3.0 m/s. Furthermore, when the water discharge got heavier, the highest flow velocity got closer to the convex bank. That is to say, a heavier water discharge would bring about a higher scouring to the convex bank.

Three testing points at the same cross-section in the CRs, Tiaoguan CR (T_1, T_2 and T_3), Laijiapu CR (L_1, L_2 and L_3) and Qigongling CR (C_1, C_2 and C_3), were chosen to clarify the change in different discharges (Figure 7). The values of flow velocity and shear stress at each testing point are listed in Table 2. Taking the results of the Tiaoguan CR for instance, when the water discharge was 6,500 m^3/s, the flow velocities at points T_1, T_2 and T_3 were 0.85, 0.89 and 1.28 m/s, respectively, resulting in $V(T_1) < V(T_2) < V(T_3)$; when the water discharge was 15,000 m^3/s, the flow velocity resulted in $V(T_3)<$

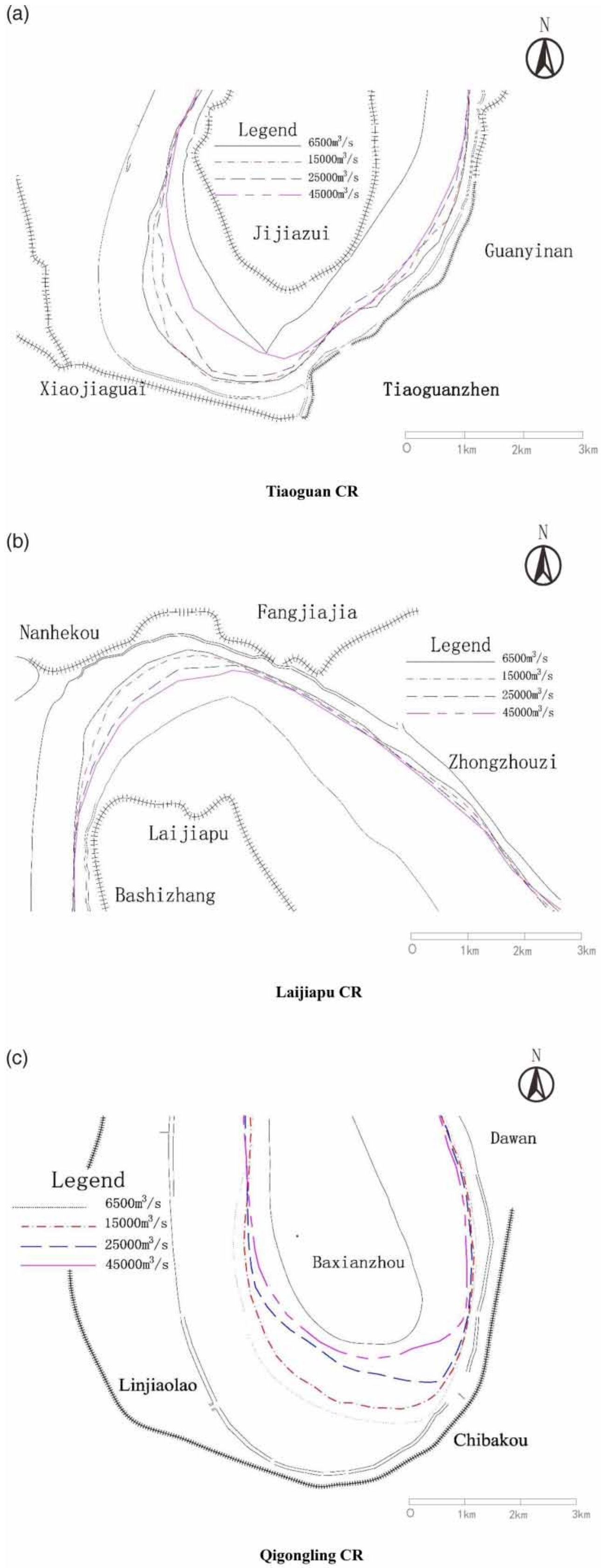

Figure 6 | Mainstream line changes in CRs. (a) Tiaoguan CR, (b) Laijiapu CR and (c) Qigongling CR.

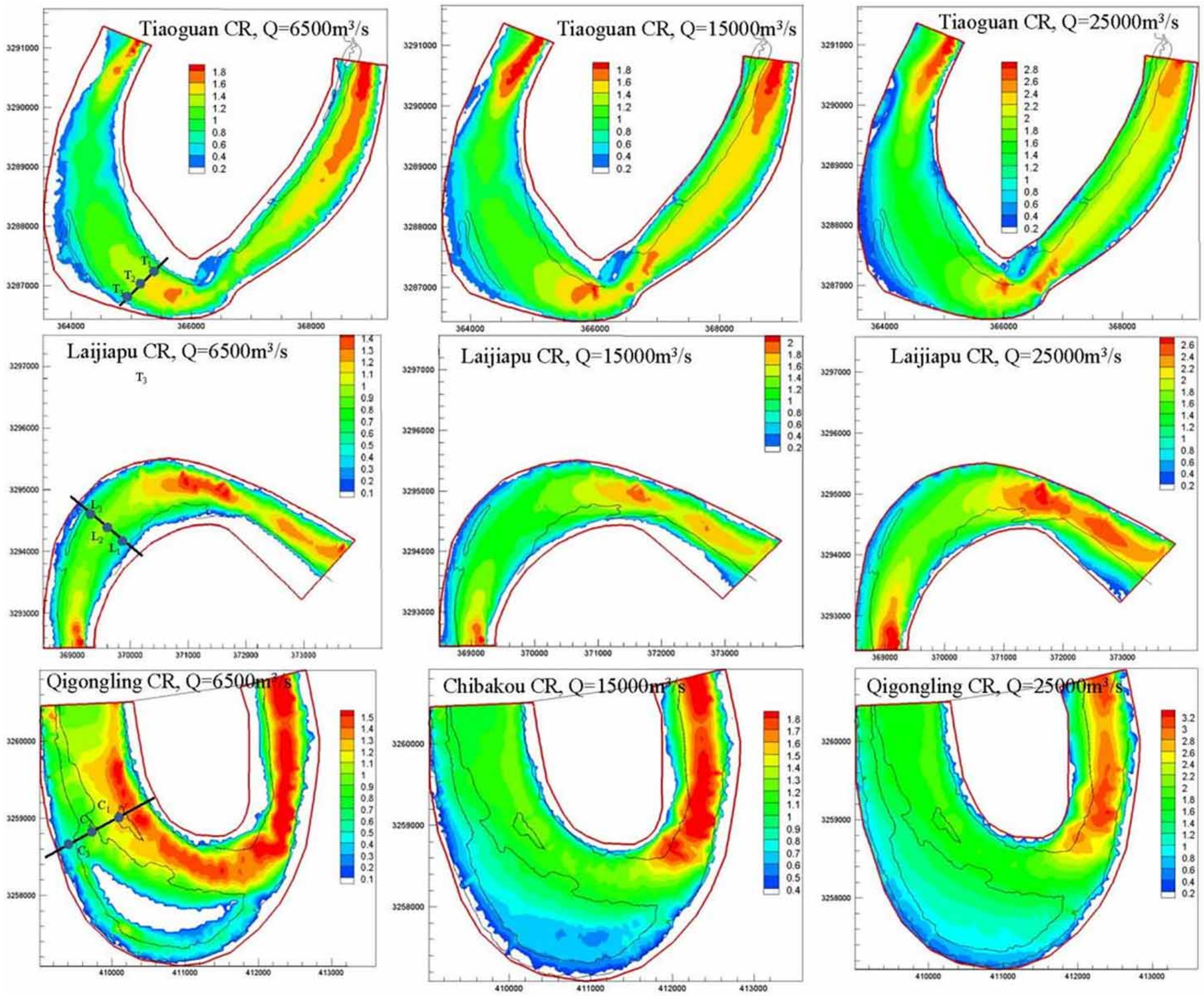

Figure 7 | Bottom velocity distribution in CRs.

Table 2 | Flow velocity and shear stress variations at different flow levels in typical CRs

		6,500 m³/s			**15,000 m³/s**			**25,000 m³/s**			**45,000 m³/s**		
CR	**Point**	***V***	τ	***C***	***V***	τ	***C***	***V***	τ	***C***	***V***	τ	***C***
Tiaoguan CR	T_1	0.85	2.1	0.48	1.17	4.5	0.52	1.67	10.2	0.64	1.51	6.6	0.51
	T_2	0.89	4.5	0.49	1.20	5.9	0.53	1.65	9.9	0.58	1.48	6.2	0.52
	T_3	1.28	2.7	0.15	1.00	3.0	0.16	1.34	5.0	0.17	0.89	1.9	0.10
Laijiapu CR	L_1	0.35	0. 9	0.19	0.57	3.5	0.26	1.27	9.1	0.33	0.86	3.2	0.23
	L_2	0.40	1.8	0.37	0.85	4.5	0.48	0.94	7.9	0.57	0.73	3.0	0.40
	L_3	0.59	0.5	0.24	0.52	1.4	0.28	0.43	2.3	0.28	0.45	0.8	0.22
Qigongling CR	C_1	0.71	3.2	0.37	0.74	5.3	0.40	1.19	11.0	0.57	1.03	2.2	0.64
	C_2	0.60	2.7	0.45	0.80	5.4	0.55	1.13	7.1	0.78	0.89	5.4	0.94
	C_3	0.41	0.3	0.17	0.67	0.7	0.20	0.72	1.2	0.32	0.56	2.4	0.34

V, bottom flow velocity, m/s; τ, shear stress, 10^{-4} Pa; *C*, circulation intensity; C_d, relative circulation intensity.

$V(T_1) < V(T_2)$, and when the water discharge was 25,000 m^3/s, the flow velocity resulted in $V(T_3) < V(T_2) < V(T_1)$. The changes in the Laijiapu CR and Qigongling CR were similar to the change in the Tiaoguan CR. That is to say, when the water discharge increased, the main flow was biased toward the convex bank.

4.2.3. Shear stress

Figure 8 shows the shear stress distribution at the bottom of the Tiaoguan CR, Laijiapu CR and Qigongling CR, respectively, and the calculation results are listed in Table 2. When the water discharge of the Tiaoguan CR was 6,500 m^3/s, the shear stress resulted in $\tau(T_1) < \tau(T_3) < \tau(T_2)$; when the water discharge was 15,000 m^3/s, the shear stress resulted in $\tau(T_3) < \tau(T_1) < \tau(T_2)$ and when the water discharge was 25,000 m^3/s, the shear stress resulted in $\tau(T_3) < \tau(T_2) < \tau(T_1)$. That is to say, the distance between main flow and convex bank would decrease with the increase in the water discharge. The changes in the Laijiapu CR and Qigongling CR were similar to the change in the Tiaoguan CR.

4.2.4. Bend circulation intensity

The bend circulations in CRs are caused by the centrifugal force. It affects the sediment transport capacity in the transverse direction. It carries sediment from the concave bank to the convex bank, resulting in concave bank scouring and convex bank depositing. The values of circulation intensity at the river bottom are listed in Table 2. Basically, for the Tiaoguan CR, the

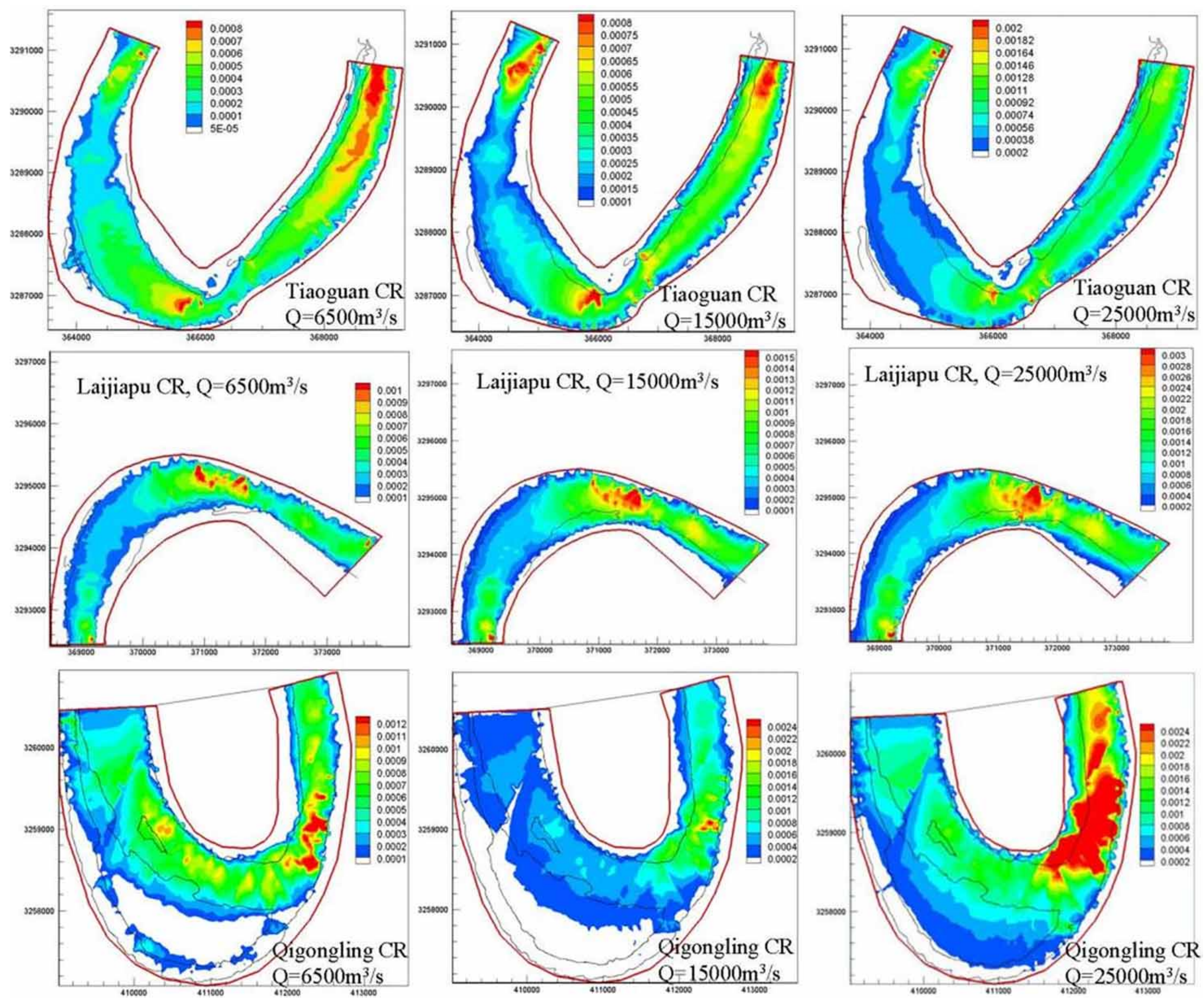

Figure 8 | Bottom shear stress distribution in CRs.

bend circulation intensity increased with the water discharge increasing from 6,500 to 25,000 m^3/s, but it decreased with water discharge decreasing from 25,000 to 45,000 m^3/s. During the dry and flood periods; that is when $Q < 9{,}500$ and $Q \geq 25{,}000$ m^3/s, the water conditions were conducive for the transverse sediment transport, resulting in concave bank scouring and convex beach depositing. During the median water period, that is when $9{,}500 \leq Q < 25{,}000$ m^3/s, the conditions were favorable for concave bank depositing and convex bank scouring. Circulation intensity changes in the Laijiapu CR and Qigongling CR are similar to that of the Tiaoguan CR. From Section 3.1, it can be noted that with the increase in the median water period duration, the water conditions became favorable for concave bank depositing and convex bank scouring.

From the above analysis, it can be concluded that after the TGR impoundment, in the dry period, the evolution behaviors, including the main stream, are near the concave bank; the bend circulation intensity is high; the flow velocity and shear stress in the concave bank are higher than those in the convex bank. These behaviors are conducive for concave bank scouring and convex bank depositing. During median water and flood periods, current with a relatively high velocity and shear stress overflows the beach and this could scour the beach. The sharp increase in the overflow area leads to a decrease in the flow velocity and shear stress on the beach surface. This weakens the scouring of the beach, and even accelerates its depositing. From Section 3.1, it can be noted that with the increase in the median water period duration, the water conditions became conducive for concave bank depositing and convex bank scouring.

5. DISCUSSION OF SEDIMENT IMPACT

5.1. Total sediment concentration

Figure 9 gives the statistical data of water discharge and sediment discharge from the year 2002 to 2012, provided by the Jianli HS. After TGR impoundment, the average water discharge per year almost remained steady, but the sediment discharge per year kept decreasing gradually. The sediment carrying capacity was restored until saturation in the downstream reaches. This caused generally scouring in the downstream reaches. Furthermore, this result is confirmed by relevant conclusions of previous researchers (Dai & Liu 2013; Yang *et al.* 2016).

5.2. Fine sand reduction

Before TGR impoundment, the fine sand, whose particle size was smaller than 0.125 mm, was the main source for convex bank deposition. After TGR impoundment, the fine sand concentration dropped sharply and water scouring capacity increased. Figure 10(a) displays the geological location of the CRs and the HSs. Figure 10(b) shows the suspended load of different sands from the year 2002 to 2012. Taking the Shashi HS as an example, the average fine sand discharge of suspended load ($d \leq 0.125$ mm) was about 3.9×10^8 *t* at year 2002, but it sharply dropped to about 1.1×10^8 *t* at year 2003, declining by nearly 70%. The records of the Jianli HS were similar to those of Shashi HS; the suspended load of fine sand decreased from 3.3×10^8 *t* (at year 2002) to 1.1×10^8 *t* (at year 2003). Therefore, there was not enough fine sand to deposit the beach. Conversely, the incoming clearer water would wash away some fine sand from the beach, bank and bed, which would result in beach scouring, especially convex beach scouring. Figure 10(c) illustrates that the bed was scoured by the incoming water. From the year 2001 to year 2010, the median particle size of the bed load gradually increased not only in

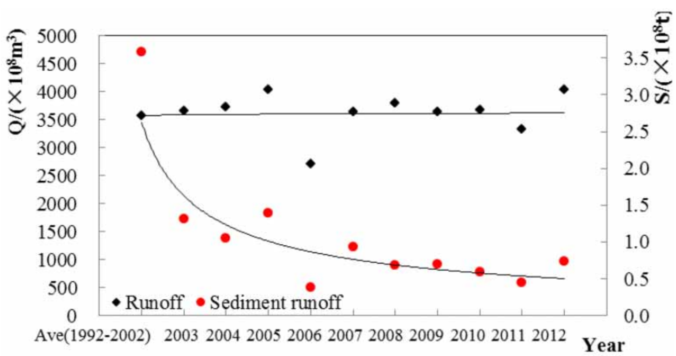

Figure 9 | Flow and sediment concentration chart.

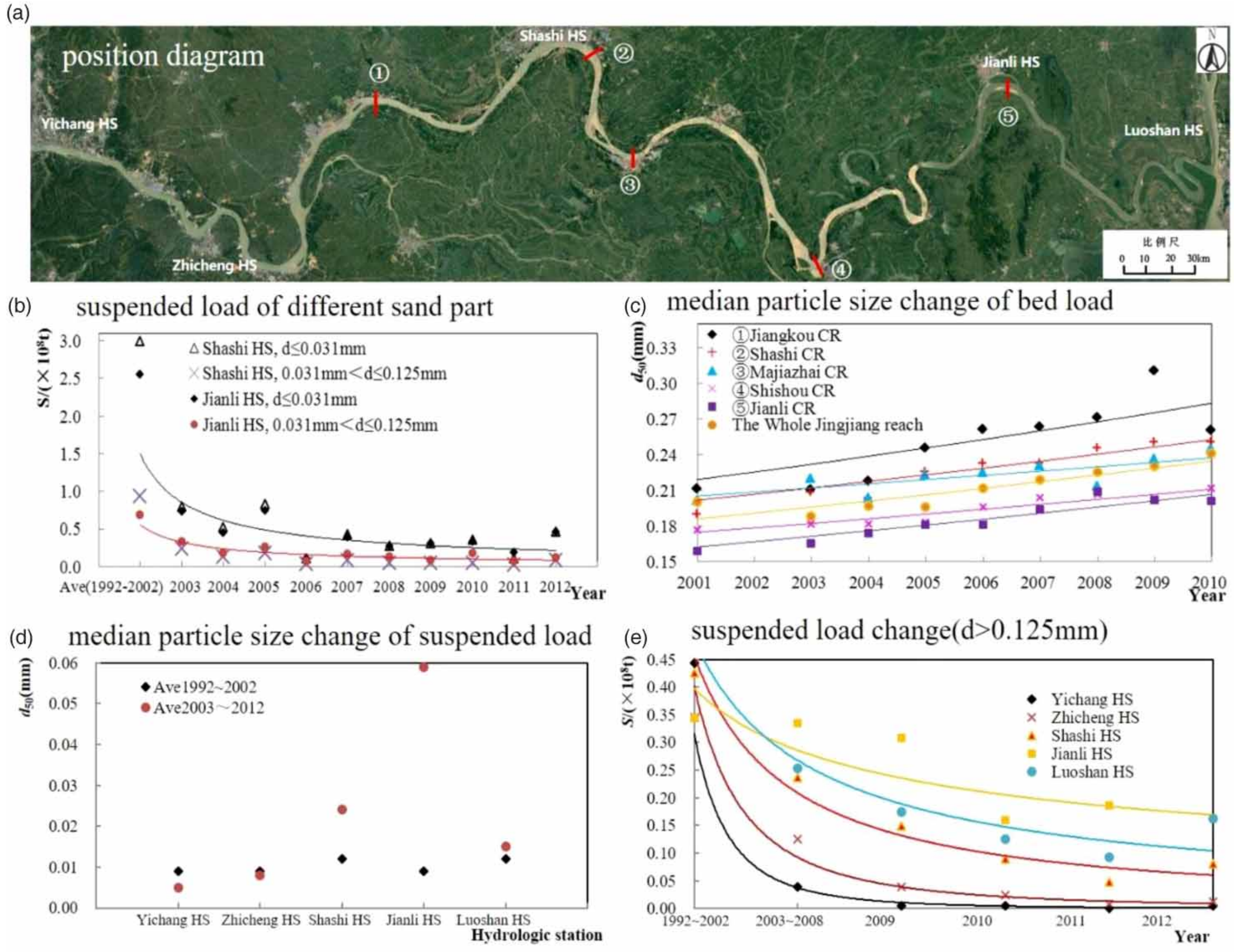

Figure 10 | Sediment transport and median particle size change chart.

the chosen five CRs, but also in the whole Jingjiang reach. This was because the incoming water washed away some fine sand and left coarse sand, and hence the median particle size of the bed increased.

5.3. Sediment exchange between suspended load and riverbed

Figure 10(d) shows the median particle size of the suspended load in each hydrologic station, as the TGR reserved most of the coarse sand, and the median particle size of suspended load declined in the Yichang HS and Zhicheng HS. This made the mainly sand supplement from the riverbed as coarse-grained sediment and also made the median particle size of suspended load increase gradually in the downstream Shashi HS, Jiangli HS and Luoshan HS. For the coarse sediment ($d > 0.125$ mm) of suspended load, the suspended load increased from the Yichang HS to Jianli HS, reached the peak in the Jianli HS, and then decreased from the Jianli HS to Luoshan HS. This indicates that in the Jianli HS, the suspended load restored to saturation. Figure 10(e) shows that the peak is in the Jianli HS from the year 2003 to 2009, then it moves downstream, and the suspended load in the Jianli HS has not restored to saturation after the year 2009.

For reaches where the sediment gradation of suspended load had restored to saturation, concave bank depositing and convex beach scouring were obvious. If its sediment gradation had not restored to saturation, convex beach scouring would be enhanced.

Take the Qigongling CR and Laijiapu CR as examples. For the Laijiapu CR, the reach is located above the Jianli HS, and the suspended load has not restored to saturation. From the year 2003 to year 2014, the convex beach scoured 80 m per year on average, with the scouring being continuous and of high intensity. For the Qigongling CR, located above the Jianli HS, before the year 2010, the sediment gradation of suspended load could restore to saturation. After 2010, the peak moved downstream, and bed sediment transport in the Jianli HS decreased obviously. This accelerated convex beach scouring. In the years 2007–2009, the convex beach scoured only 50 m per year on average and concave bank deposited continuously. In the years 2010–2012, convex beach scoured increased to 90 m, and even the concave bank started scouring.

6. CONCLUSIONS

In this work, the effect of CRs on evolution behaviors , including river nodes, bending radius, incoming water process, sediment transport intensity and sediment composition, is studied. The evolution pattern and causes of downstream gigantic hydraulic projects are also studied:

(1) River node would reduce the speed of convex beach scouring and concave bank depositing in CRs. The bending radius has little effect on CR evolution. Sediment transport intensity from concave bank to convex bank would be reduced directly by constructed projects. Reduction in incoming sediment is beneficial to convex bank scouring.
(2) After GPR impoundment, during the dry period, flow velocity and shear stress in the concave bank are higher than those in the convex bank, which is conducive for concave bank scouring and convex bank depositing. In the median water period and flood period, current with a relatively high velocity and shear stress overflowing the beach could possibly scour the beach. The sharp increase in the overflow area leads to a decrease in flow velocity and shear stress on the beach surface. This weakens the scouring of the convex beach, and even accelerates its depositing. With the increase in median water period duration, the conditions became conducive for convex beach scouring and concave bank depositing.
(3) Fine sediment in suspended load is the main source for convex beach depositing. However, this has decreased by about 70%, in turn, decreasing the depositing volume in the concave beach. The convex beach is still scoured obviously after impoundment.
(4) The coarse sand of suspended load restores to saturation at the critical point. After this point, median particle size decreases gradually. For reaches where sediment gradation of suspended load has restored to saturation, concave bank depositing and convex beach scouring are obvious. If its sediment gradation has not restored to saturation, concave bank depositing and convex beach scouring would continue, but concave bank depositing would be weakened and convex beach scouring would be enhanced.

ETHICAL APPROVAL

The experimental protocol was established according to the ethical guidelines of the Helsinki Declaration and was approved by the Human Ethics Committee of Wuhan University. Written informed consent was obtained from individual or guardian participants.

CONSENT TO PUBLISH

The author confirms that the work described has not been published before; that it is not under consideration for publication elsewhere; that its publication has been approved by all co-authors, if any; that its publication has been approved by the responsible authorities at the institution where the work is carried out. The author agrees to publication in the Journal indicated below and also to publication of the article in English. The copyright to the English-language article is transferred to Springer effective if and when the article is accepted for publication.

AUTHOR CONTRIBUTIONS

This research was done at Wuhan University with strong support from the Yangtze River Waterway Bureau. We have given guidance and help to the collection of sediments in our experiment. L.L. was responsible for the whole research work, including the experimental work and the analysis of the results. W.L. designed the main content framework of the manuscript and assisted in the analysis of the experimental results. L.Z. assisted in the preparation and operation of the experiment. B.M. mainly assisted in the in-depth analysis of experimental data and the collation of results.

FUNDING

This study is supported by the State Key Laboratory of Eco-hydraulics in Northwest Arid Region, Xi'an University of Technology (Grant No. 2018KFKT-7), the National Natural Science Foundation of China (Grant No. 52109099), the Fundamental

Research Funds for the Central Universities (Grant No. 2042020kf0004) and the National Natural Science Foundation of China (Grant No. 52079094).

COMPETING INTEREST

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

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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First received 19 November 2021; accepted in revised form 10 February 2022. Available online 28 February 2022