Relationship Between Potential Waterway Depth Improvement and River Evolution: A Case Study on the Jingjiang Reach of the Yangtze River in China

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Abstract

Due to the significance of waterway depths in river development, the effect of the evolution of bars and troughs on waterway expansion has always been interesting for river management and water depth conservation. In this study, the aim is to expand the waterway dimensions of the Jingjiang Reach, and it is necessary to determine how river evolution processes relate to its potential for waterway depth improvement and navigation hindrances. Therefore, the sedimentation, hydrological, and terrain data of the Jingjiang Reach from 1950 to 2020 were analyzed to elucidate the aforementioned relationships After the commissioning of the Three Gorges Dam, it was found that the scour of the low flow channel has accounted for 90.95% of all scour in the Jinjiang Reach. Furthermore, its central bars and beaches have shrunken by 9.4% and 24.9%, respectively, and 18.3% as a whole. In view of the bed scour and waterway regulation projects that occurred in the Jingjiang Reach, we investigated the continuity of a 4.5 m × 200 m × 1050 m (depth × width × bend radius) waterway along the Jinjiang Reach, and found that it is navigationally hindered over 5.3% of its length. Furthermore, part of the Jingjiang Reach is an important nature reserve, and there are also many water-related facilities in this area; hence, these conditions inhibit the implementation of waterway deepening projects. As a result, the study findings indicate that there are many challenges with regards to increasing the waterway depths of the Jingjiang Reach.

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Abstract: Due to the significance of waterway depths in river development, the effect of the evolution of bars and troughs on waterway expansion has always been interesting for river management and water depth conservation. In this study, the aim is to expand the waterway dimensions of the Jingjiang Reach, and it is necessary to determine how river evolution processes relate to its potential for waterway depth improvement and navigation hindrances. Therefore, the sedimentation, hydrological, and terrain data of the Jingjiang Reach from 1950 to 2020 were analyzed to elucidate the aforementioned relationships. After the commissioning of the Three Gorges Dam, it was found that the scour of the low flow channel has accounted for 90.95% of all scour in the Jinjiang Reach. Furthermore, its central bars and beaches have shrunken by 9.4% and 24.9%, respectively, and 18.3% as a whole. In view of the bed scour and waterway regulation projects that occurred in the Jingjiang Reach, we investigated the continuity of a 4.5 m × 200 m × 1050 m (depth × width × bend radius) waterway along the Jinjiang Reach, and found that it is navigationally hindered over 5.3% of its length. Furthermore, part of the Jingjiang Reach is an important nature reserve, and there are also many water-related facilities in this area; hence, these conditions inhibit the implementation of waterway deepening projects. As a result, the study findings indicate that there are many challenges with regards to increasing the waterway depths of the Jingjiang Reach.

Keywords：Beach trough evolution; Branching relationship; waterway deepening；Jingjiang Reach；Middle reaches of the Yangtze River

1 Introduction

Inland shipping plays an important role in global transportation and logistics system (Rohács et al., 2007; Willems et al., 2018); thus, the development of riverine shipping is significant for watershed resource utilization. The shipping potential of a river is limited by its carrying capacity, which mainly depends on hydrogeomorphic factors like river depth, width, flow rate, and duration of icing events (Hijdra et al., 2014). Furthermore, due to recent implementation of environmental conservation strategies in waterways, the effects of waterway engineering on river environments cannot be overlooked (Weber et al., 2017). The middle and lower reaches of the Yangtze River are known as the “Golden Waterway” (Cao et al., 2010; Wang et al., 2020a) as they play a central role in the socioeconomic development of the Yangtze

River. As of 2020, the Yangtze River trunk line has a freight volume of 3.06 billion tons per year, which accounts for 78.2% of China's total inland waterway freight transport.

The Jingjiang Reach, which is located at the middle reaches of the Yangtze River, is approximately 60 km away from the Three Gorges Dam (TGD) and has no major tributaries or confluences. Therefore, its hydrologic and sedimentary conditions are directly affected by the operations of the TGD. The runoff flowing through the Jingjiang Reach has not changed significantly over the past 60 years (Chai et al., 2019; Yang et a., 2019; Chai et al., 2020); however, its sediment load has decreased over time due to the implementation of water and soil conservation measures as well as dam construction in its upstream (Yang et al., 2006; Yang et al., 2015a). Ever since the TGD began to hold back water, the downward trend in sediment load has intensified significantly (Hassan et al., 2010; Dai et al., 2018; Li et al., 2018a; Gao et al., 2020; Peng et al., 2020; Tian et al., 2021); this resulted in the Upper Jingjiang Reach (UJR) having the highest rate of scour over the Jingjiang Reach (Dai and Liu, 2013; Xia et al., 2016, 2017; Lyu et al., 2018). Furthermore, the sedimentary regime of the Lower Jingjiang Reach (LJR) changed from 'groove scour with bar deposition' to 'groove and bar scour' (Xu et al., 2011, 2013a, b; Yang et al., 2018). Additionally, there have been many instances of riverbank collapse (Xia et al., 2016; Xia et al., 2017; Zong et al., 2017; Zhou et al., 2017; Deng et al., 2018; Deng et al., 2019; Lyu et al., 2020), shrinking beaches, and central bars (Yang et al., 2015b； Wang et al., 2018; Li et al., 2019) and unstable water diversion ratios (WDR) at the Jingjiang Reach (Wang et al., 2019; Hu et al., 2020; Yang et al., 2021a). The LJR has also showed chute cutoff at its tighter bends (He et al., 2020). These issues have made it challenging to stabilize and improve waterway conditions at the Jingjiang Reach. To address the increased rate of scour in the TGD's downstream reaches since the beginning of its impoundment (Liu et al., 2017; Yang et al., 2017), the Ministries of Water Resources and Transport have implemented systematic river and waterway regulation projects, which have increased the waterway depth of the Yangtze River trunk line from 0.6 to 4.5 m compared to the beginning of the TGD's operational period (Yang et al., 2019). However, at the Jingjiang Reach, river scour has caused the decrease of the dry-season water level per flow rate over time (Sun et al., 2011; Yang et al., 2017; Zhu et al., 2017； Han et al., 2017a); in addition, it has been shown by previous studies that this downward trend is still significant (Fang et al., 2012). Although a number of waterway regulation projects have been implemented at the Shashi Reach, the low beaches of this section are still being scoured. Furthermore, the main and tributary branches of the Taipingkou and Sanbatan central bars alternate with each other (Yang et al., 2021a). Moreover, floods that occurred in 2010, 2016, and 2020 in the middle and lower reaches of the Yangtze River have exacerbated navigation hindrances at the Zhicheng–Dabujie section (Li et al., 2021) and the Shashi Reach (Zhang et al., 2016; Yang et al., 2021a). The ecological effects of a waterway regulation project at the Jingjiang Reach were evaluated using the Analytical Hierarchy Process; it was found that the completion of this project would have a positive effect on the ecological health of the Yangtze River (Li et al., 2017; Li et al., 2018b). Although a number of studies have examined the siltation processes, beach and channel evolution, navigation hindrances, and waterway regulation projects of the Jingjiang Reach, there has not been any investigation of the relationship between waterway projects and potential water depth improvement in this area. To address this issue, we have conducted a study on the relationship between the potential water depth improvement and hydrogeomorphic factors of the Jingjiang Reach. The findings may help to elucidate the potential of the Jingjiang Reach for further waterway development.

To this end, the hydrologic and sedimentation data between 1950 and 2020, and river bed measurements of the Jingjiang Reach between 1975 and 2020 were used to analyze the distribution of scour and deposition in its river bed, channel bars, and beaches on the waterway, and WDRs. In addition, we will study the suitability of the Jingjiang Reach for water depth improvement up to 4.5 m, based on its water levels, beach and central bar morphologies and WDRs.

2 Study area and data

2.1 Study area and hydrologic conditions

The Jingjiang Reach is located at the middle reaches of the Yangtze River (Figure 1a), and it stretches 347.2 km from the Zhicheng hydrological station to Chenglingji. The Jingjiang Reach is divided at Ouchikou into the UJR and LJR, and their lengths are 171.7 km and 175.5 km, respectively. The Jingjiang Reach has a gravelly riverbed from Zhicheng Station to Dabujie, and a sandy riverbed from Dabujie and onwards. From 1950 to 2020, the runoff measurements of the Yichang station did not change in a substantial manner, as the average annual runoff of the 2003–2020 period was only 4.6% lower than that of the 1950–2002 period (Figure 1a). However, the sediment transport rates measured by the Yichang station for the 2003–2020 periods are 92.9% and 91.5% lower than the sediment transport rates of the 1950–2002 and 1986–2002 periods, respectively. In comparison to the average monthly runoffs of the 1991–2002 period, the 2003–2008 and 2009–2020 periods exhibit lower runoff levels in July, August and October, similar runoff levels in June and November, and higher runoffs from December to May (Figure 1b).

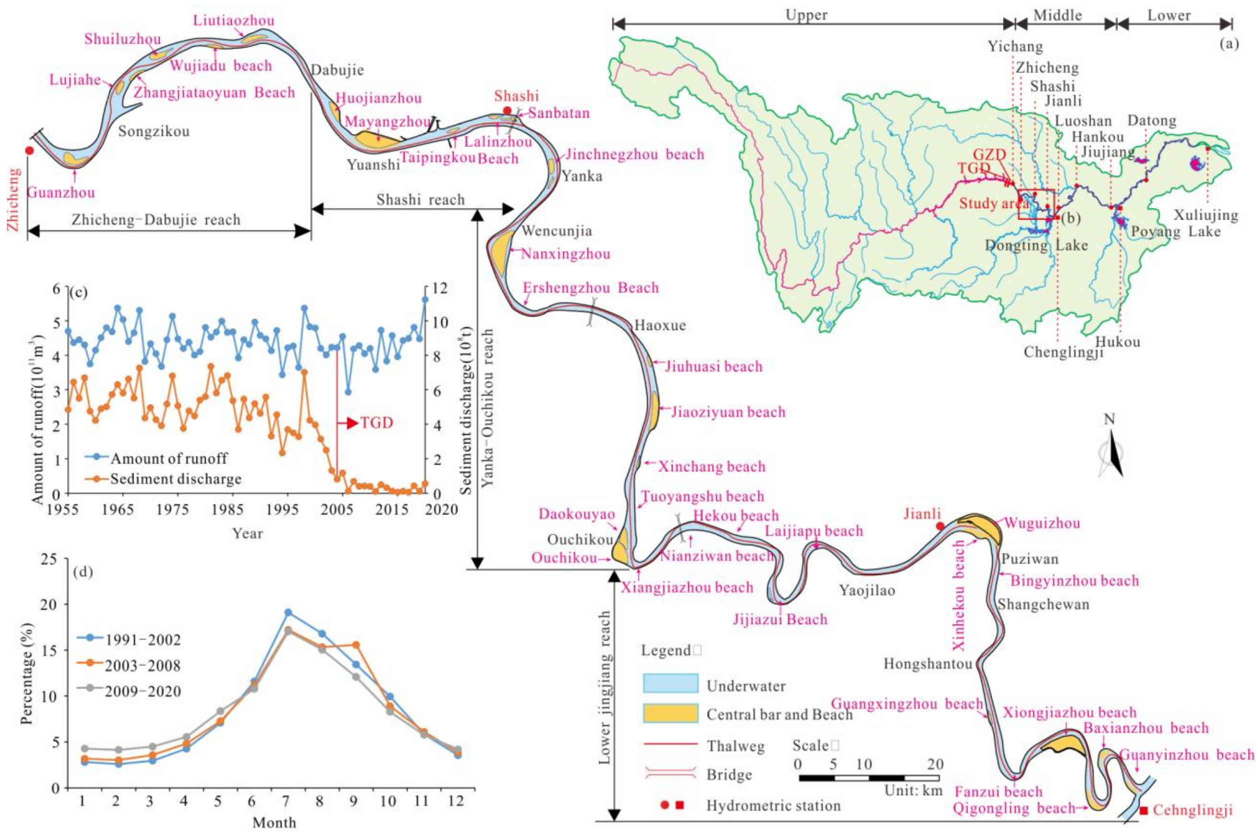

Figure 1. Location and river regime of river reach. (a) Yangtze River Basin; (b) Jingjiang Reach; (c) Annual runoff and sediment; (d)Annual process of Annual runoff and sediment

The Jingjiang Reach includes 33 channels and 33 central bars or beaches (Table 1), including 12 central bars: the Guanzhou central bar (GZCB), Lujiahe central bar (LJHCB), Shuiluzhou central bar (SLZCB), Liutiaozhou central bar (LTZCB), Huojianzhou central bar (HJZCB), Mayangzhou central bar (MYZCB), Taipingkou central bar (TPKCB), Sanbatan central bar (SBTCB), Nanxingzhou central bar (NXZCB), Daokouyao central bar (DKYCB), Ouchikou central bar (OCKCB) and Wuguizhou central bar (WGZCB). From the 21 beaches, 15 are located on straight sections or single bends: the Jincnegzhou beach (JCB), Jiuhuasi beach (JHSB), Jiaoziyuan beach (JZYB), Xinchnag beach (XCB), Tuoyangshu beach (TYSB), Nianziwan beach (NZW), Hekou beach (HKB), Jijiazui beach (JJZB), Laijiapu beach (LJPB), Bingyinzhou beach (BYZB), Guangxingzhou beach (GXZB), Fanzui beach (GZB), Xiongjiazhou beach (XJZB), Qigongling beach (QGLB) and Guanyinzhou beach (GYZB). Additionally, 6 are located on braided reaches, including the Zhangjiataoyuan beach (ZJTYB), Wujiadu beach (WJDB), Lalinzhou beach (LLZB), Yanglinji beach (YLJB), Xiangjiazhou beach (XJZB) and Xinhekou beach (XHKB).

Table 1. Caption

Serial number	Waterway	Length (km)	Beach name	Form	Main branch in dry season	Branch length	Type and position of beaches	
							Type	Position
1	Zhicheng	6.0	/	Straigth	/	/	/	/
2	Guanzhou	10.9	Guanzhou	Branch	Rigth	Left＜Rigth	Central bar	Rigth bank
3	Lujiahe	11.1	Lujiahe	Branch	Rigth	Left >Rigth	Central bar	Rigth bank
4	Zhijiang	10.0	Shuiluzhou	Branch	Rigth	Left＜Rigth	Central bar	Left bank bias
			Zhangjiataoyuan	Bending	/	/	Beach	Rigth bank
5	Liuxiang	5.6	Liutiaozhou	Branch	Rigth	Left>Rigth	Central bar	Left bank bias
6	Jiangkou	7.5	Wujiadu	Straigth	/	/	Beach	Rigth bank
7	Dabujie	11.3	Huojianzhou	Branch	Rigth	Left>Rigth	Central bar	Left bank bias
8	Yuanshi	17.1	Mayangzhou	Branch	Rigth	Left＜Rigth	Central bar	Left bank bias
9	Taipingkou	17.5	Taipingkou	Branch	Rigth	Left=Rigth	Central bar	Midst
			Sanbatan		Rigth	Left＜Rigth	Central bar	Midst
			Lalinzhou		/	/	Beach	Rigth bank
10	Wakouzi	9.1	Jinchnegzhou	Bending	/	/	Beach	Rigth bank
11	Majiazui	12.5	Nanxingzhou	Branch	Rigth	Left＜Rigth	Central bar	Left bank bias
12	Douhudi	9.9	/	Bending	/	/	/	/
13	Majiazhai	9.8	Ershengzhou	Straigth	/	/	Beach	Left bank
14	Haoxue	6.7	/	Bending	/	/	/	/
15	Zhougongdi	10.1	Jiuhuasi	Bending	/	/	Beach	Left bank
			Jiaoziyuan		/	/	Beach	Left bank
16	Tianxingzhou	16.9	Xinchnag	Bending	/	/	Beach	Left bank
17	Ouchikou	7	Tuoyangshu	Branch	/	/	Beach	Left bank
			Daokouyao and Ouchikou		Left branch	Left＜Rigth	Central bar	Rigth bank
18	Shishou	10.0	Xiajiangzhou	Bending	/	/	Beach	Left bank
19	Nianziwan	17.0	Nianziwan	Bending	/	/	Beach	Rigth bank
20	Hekou	5.0	Hekou	Bending	/	/	Beach	Left bank
21	Tiaoguan	16.0	Jijiazui	Bending	/	/	Beach	Left bank
22	Laijiapu	12.0	Liajiapu	Bending	/	/	Beach	Rigth bank
23	Tashiyi	9.0	/	Straigth	/	/	/	/
24	Yaojilao	7.0		Bending				
25	Jianli	9.5	Wuguizhou	Branch	Rigth branch	Left>Rigth	Central bar	Left bank
			Xinhekou		/	/	Beach	Rigth bank
26	Damazhou	10.5	Bingyinzhou	Straigth	/	/	Beach	Left bank
27	Zhuanqiao	9.0	/	Bending	/	/	/	/
28	Tiepu	12.0	Guangxingzhou	Straigth	/	/	Beach	Rigth bank
29	Fanzui	6.5.	Fanzui	Bending	/	/	Beach	Left bank
30	Xiongjiazhou	7.5	Xiongjiazhou	Bending	/	/	Beach	Rigth bank
31	Chibakou	14.0	Qigongling	Bending	/	/	Beach	Left bank
32	Baxianzhou	8.0	Baxianzhou	Bending	/	/	Beach	Left bank
33	Guanyinzhou	10.0	Guanyinzhou	Bending	/	/	Beach	Rigth bank

2.2 Waterway engineering

From 2002 to 2020, a series of waterway regulation projects were implemented at the Jingjiang Reach. This included bank protection works over 50 km of the reach, 71 beach protection belts, 30 spur dikes, and 8 bottom protection belts (Figure 2). Branch and WDR stabilization projects have been implemented at the Zhicheng–Changmenxi section, Shashi Reach and Jianli Reach. The projects for stabilizing beaches and bars have been conducted at the Zhicheng–Jiangkou section, Wakouzi channel, Majiazui channel, Tiaoguan–Lajiapu section, Zhoutian channel, Ouchikou channel, Damazhou channel, Tiepu channel, and Fanzui channel.

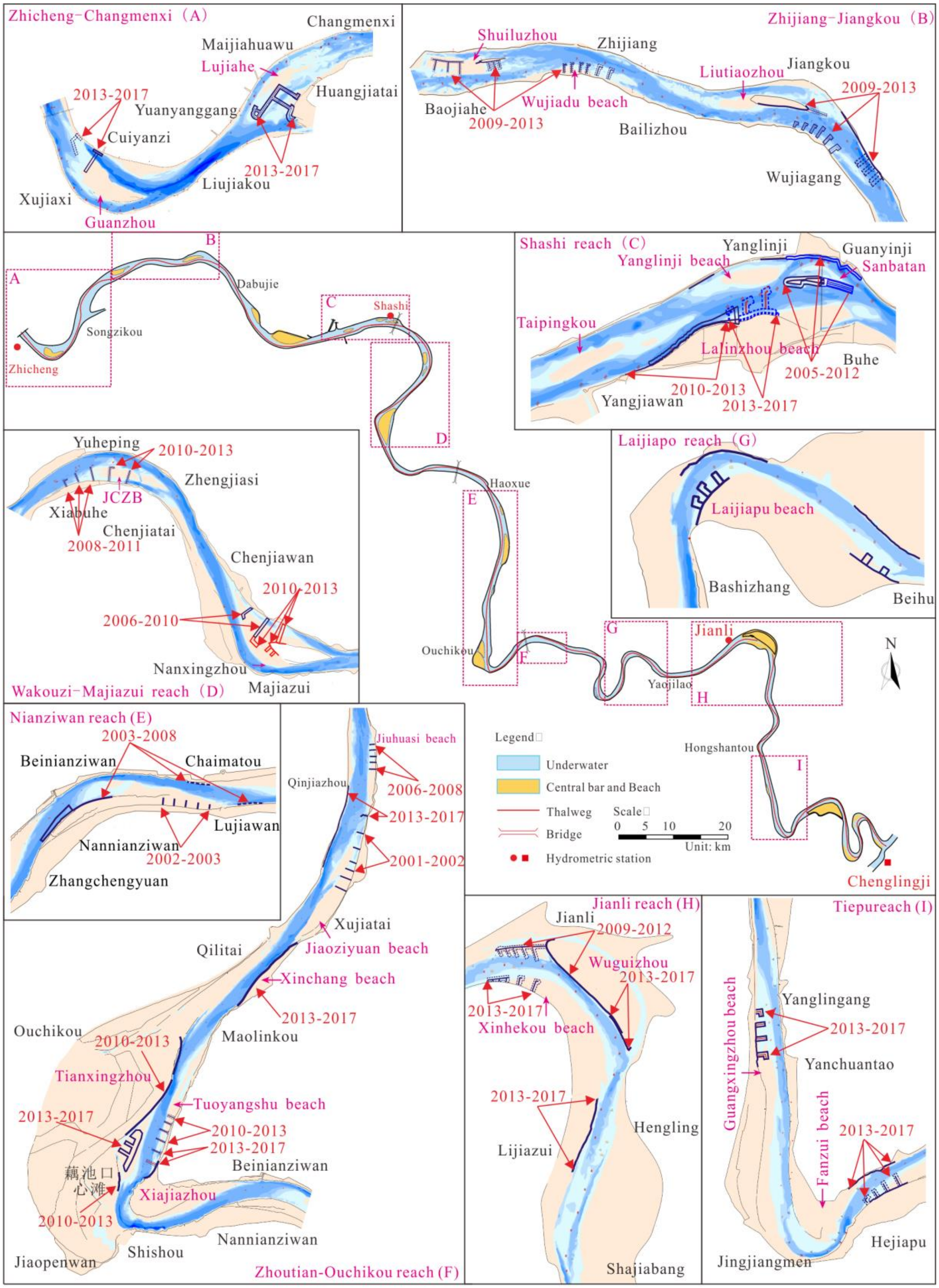

Figure 2. Layout of waterway regulation project

2.3 Data

The runoff and sediment transport rates measured by the Zhiheng, Shashi and Jianli hydrological stations from 1955 to 2020 were collected to analyze changes in the inflow and sedimentary regime of the Jingjiang Reach (Table 2). The river topography data of the Jingjiang reach from October 2002 to October 2020 were collected to enable identification of changes in its distribution of scour and siltation, scour intensity, thalweg, and beach/bar morphologies. The water level data from fixed water level gauges in the Jingjiang Reach during the 2002–2020 period were collected; then, they were combined with changes in channel depth and thalweg, so as to elucidate how the waterway's dimensions changed during this period. The information of waterway regulation structures at the Jingjiang Reach from 2002 to 2020 was also acquired, which relates to the position, type, dimensions, and operational status of these structures; these data were used to analyze how waterway regulation projects affect the bar/beach morphologies and WDRs. These datasets were obtained from the Changjiang Waterway Bureau, Changjiang Water Resources Commission and Changjiang Waterway Bureau Survey Center.

Table 2. Research data and sources

Data type	Period of time	Data characteristics	Data source
Runoff and sediment	1955-2020	Zhicheng, Shashi, and Jianli Hydrographic stations	Changjiang Waterway Bureau, Changjiang Water Resources Commission and Changjiang Waterway Bureau Survey Center
River terrain	2002-2020	Scale1:10000	
Water level	2002-2020	Gauges and Hydrographic stations	
Waterway regulation structure	2002-2020	Type, location and scale	

2.4 Research methodology

2.4.1 Calculation of design water level, waterway dimensions, and WDR

The lowest navigable water level (LNWL) is a term used in water transport engineering that denotes the lowest water level that permits normal navigation by a standard ship or fleet. This is an important parameter in the design of waterways, wharfs, and ports. The Navigation standard of inland waterway (GB50139-2014) specifies that the LNWL should be determined using a synthetic flow-duration curve in reaches that are non-tidal or insignificantly affected by tidal effects. If the water level at some cross-section of the Yangtze trunk waterway's base level is H_0, and the water level corresponding to the 98% navigation guarantee rate (given by the synthetic flow-duration curve) is H_1, the changes in waterway depth may then be characterized as follows (Figure 3a): if $H_1 > H_0$, the LNWL has increased, and if the bed scour or sediment thickness is less than H_1-H_0, the waterway depth has increased. If $H_1 < H_0$, the LNWL has decreased, and if the depth of riverbed sedimentation or scour is less than H_1-H_0, the waterway depth has decreased. The dimensions of a waterway include its water depth (H), width (B), bend radius (R) and navigation clearance height (H_{max}). If the water depth corresponding to the actual LNWL h is less than the target navigation depth H, a break will appear in the depth contour corresponding to H, i.e., a navigation obstacle due to insufficient water depth (Figure 3b). If a location on the waterway has h greater than H (i.e., the depth contour at H is not broken) but a width less than B, this location is then a navigation obstacle caused by insufficient navigable width. Likewise, if R is too small for safe passage, route adjustments will lead to insufficient waterway width and/or depth.

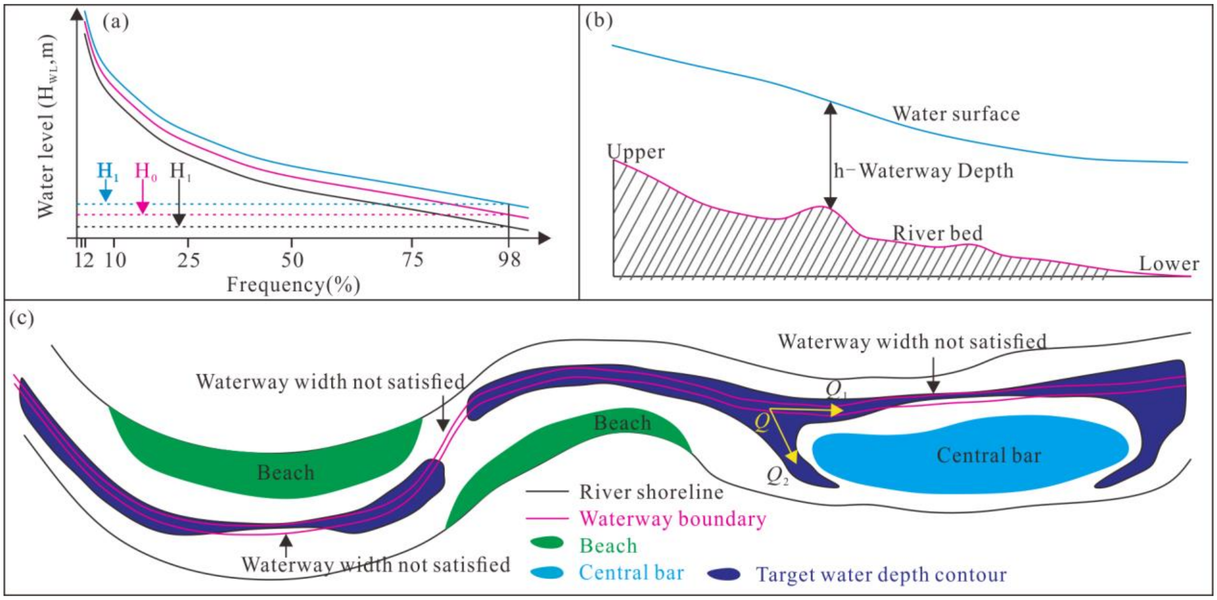

Figure 3. Calculation process of waterway depth and scale. (a) Determination of lowest navigable water level; (b) Waterway water depth calculation process; (c) Calculation of navigation obstruction and WDR.

The calculation of the WDR (Figure 3c) is as follows: firstly, the total inflow of the braided reach Q is obtained by measuring the runoff at the cross-section of its inlet. If the runoff flowing into each branch is Q_i (i = 1, 2, …, n where n is the number of branches), the WDR η_i of each branch is given by:

$$\eta_i = \frac{Q_i}{Q_1 + Q_2 .....Q_n} \times 100\% = \frac{Q_i}{Q} \times 100\%; i = 1, 2, ...n \tag{1}$$

2.4.2 Calculation of riverbed scour and deposition

Here, the low-flow and bankfull channels correspond to flow rates of 5000 m^3/s (Q_1) and 30 000 m^3/s (Q_2) at Yichang Station, and the relationship between water level and flow rate was calculated based on the terrain that was surveyed on October 2002 (Figure 4a, b). The low-flow water level (h_1) and bankfull water level (h_2), i.e., the water levels of the low-flow and bankfull channels, were determined based on the relationship between water level and flow rate in the Jingjiang reach. The low beach is defined as the area between the low-flow channel and bankfull channel.

From topographic cross-sections along the river (Figure 4c) of the upstream and downstream watercourses of the river channels, the cross-sectional areas were calculated according to Eq. (2):

$$A_i = \frac{(h_i + h_{i+1} + \sqrt{h_i h_{i+1}}) \times b_i}{3} \quad i = 0, 1, 2, 3...m \tag{2}$$

where A_i is the cross-sectional area (m^2), h_i and h_{i+1} are the water depths of two consecutive points of a section (m), and b_i is the width at two consecutive points (m).

Using the truncated cone method, the volume of the river channel V_j (Figure 4d) between the upstream and downstream sections at the corresponding water level were calculated according to Eq. (3). Subsequently, the total river channel volume was obtained using Eq. (4):

$$V_j = \frac{(A_j + A_{j+1} + \sqrt{A_j A_{j+1}}) \times L_j}{3} \quad j = 0,1,2,3...n \tag{3}$$

$$V = \sum V_j \tag{4}$$

where V_j is the volume of the channel between adjacent sections (m^3), $A_{i,j}$ and $A_{i,j+1}$ are the areas of adjacent sections (m^2), and L_j is the distance between adjacent sections (m).

After calculating the volumes V_1 and V_2 of the designated river channel over two years and the difference between them (ΔV), the intensity of erosion/deposition (IED) in river channels per unit river length (L) and time (T) can be obtained according to Eq. (5):

$$V_{\text{IED}} = \frac{V_2 - V_1}{\text{L}_{length\ \ river} \times T} \tag{5}$$

where V_{IED} is the erosion and deposition intensity of the unit river length over a certain period ($10^4\ m^3 \cdot km^{-1} \cdot y^{-1}$), T is the length of time (years), and $L_{River\ Length}$ is the river length (km).

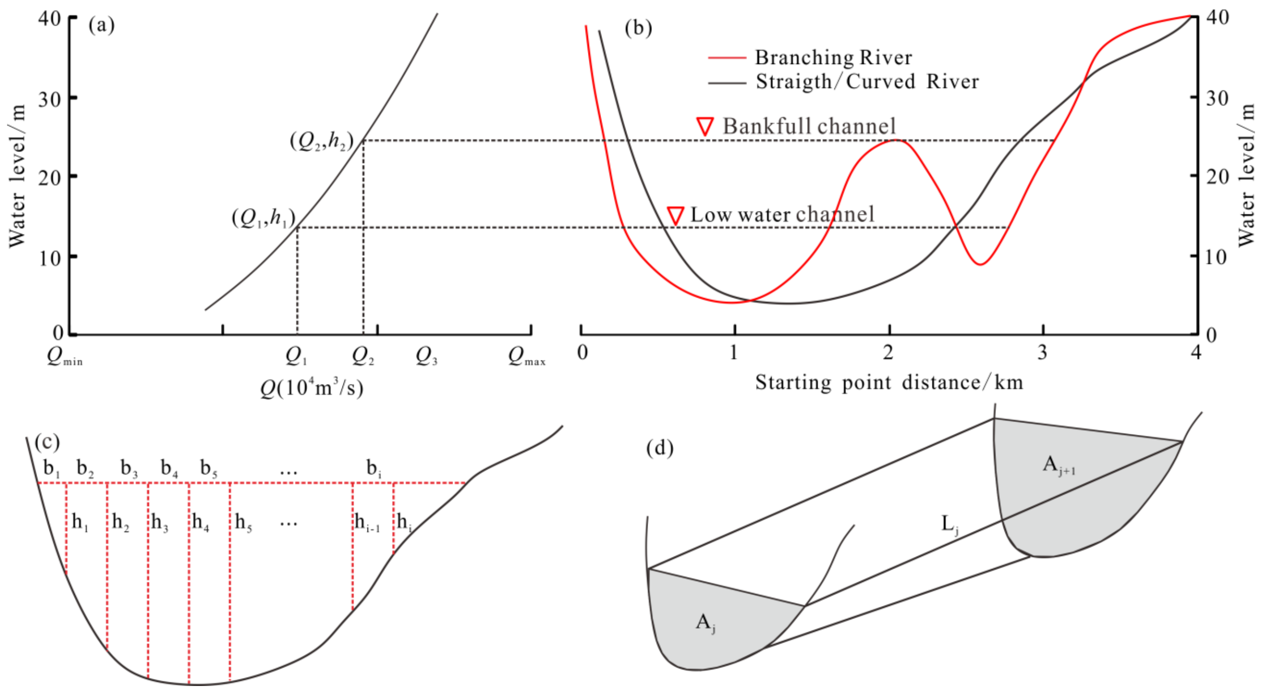

Figure 4. Calculation process of riverbed erosion and deposition. (a) Water level and flow rate; (b) Typical cross section change; (c) Sections area; (d) Channel capacity.

3 Research process

3.1 Relationship between erosion and deposition of water bed and distribution of channel

The cumulative scours of the low-flow channel and bankfull channel from October 1975 to October 2002 are 4.31 × 10^8 and 4.38 × 10^8 m^3 in the UJR, and 0.98 × 10^8 and 1.74 × 10^8 m^3 in the LJR, respectively (Yang et al., 2018, 2019). Therefore, the scour was more intense in the UJR and LJR during this period. In the UJR, most of the scour occurred in the low-flow channel; in the LJR, the channel and beach were both scoured. From October 2002 to October 2020, the cumulative scours of the low-flow and bankfull channels of the Jingjiang Reach are 11.18 × 10^8 and 12.29 × 10^8 m^3, respectively, and the scour in the low-flow channel accounted for 90.95% of the bankfull channel's scour. Therefore, the scour occurred in both the beach and channel (Figure 5a). The cumulative scours of the UJR and LJR accounted for 71.5% and 28.5% of the Jingjiang Reach's total scour in the 1975–2002 period, 41.8% and 58.2% between October 2002 and October 2009, and 69.1% and 30.9% in the October 2009–October 2020 period. Therefore, the scour was significantly more intense in the UJR than the LJR (Figure 5b). Furthermore, during the October 1975–October 2002, October 2009–October 2020, and October 2002–October 2009 periods, the low-flow channel accounted for 98.4%, 90.5%, and 96.4% in the UJR, and 56.3%, 76.7%, and 94.3% of the bankfull channel scour in the LJR, respectively(Figure 5c).

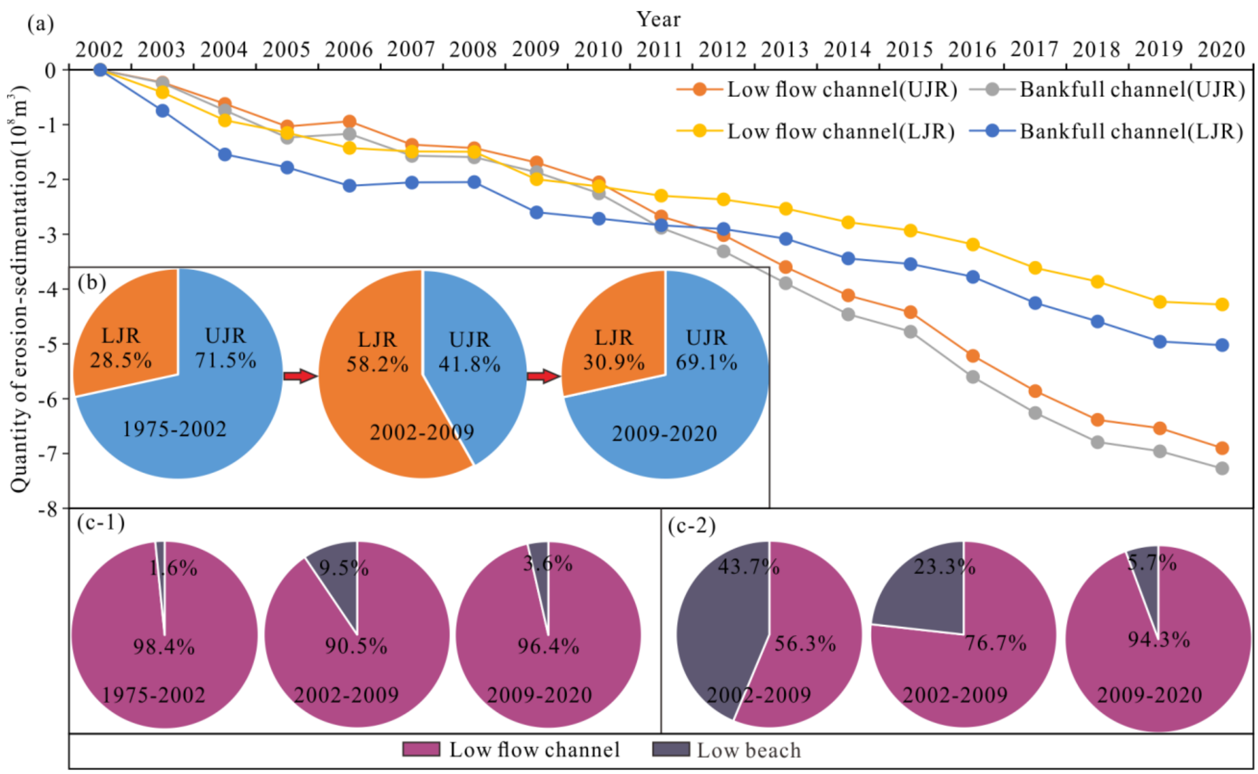

Figure 5. Relationship between erosion and deposition of water bed and disributionof channel. (a) River bed erosion in Jingjiang reach; (b) Proportion of erosion and deposition in bankfull channel; (c-1) UJR, (C-2) LJR.

After comparing the thalwegs of the Jingjiang Reach from October 2020, October 2009, and October 2002 (Figure 6), it was found that the sedimentary regime of the UJR was dominated by scour. The LJR alternated between scour and deposition, even though the scour was dominant. From October 2002 to October 2020, the thalweg of the Jingjiang Reach deepened by 2.97 m on average, with the maximum depth of scour being 20.10 m in the Tiaoguan Reach. Based on the water level corresponding to the 98% navigation guarantee rate and the terrain in October 2020, the LNWL of the UJR was lower than the current navigation base level. The largest decrease in the LNWL (2.01–2.49 m) occurred at the Yuanshi–Majiazui section. In contrast, the LNWL of the LJR was higher than the current navigation base level; at the downstream end of the LJR (Chenglingji), the LNWL increased by 1.79 m.

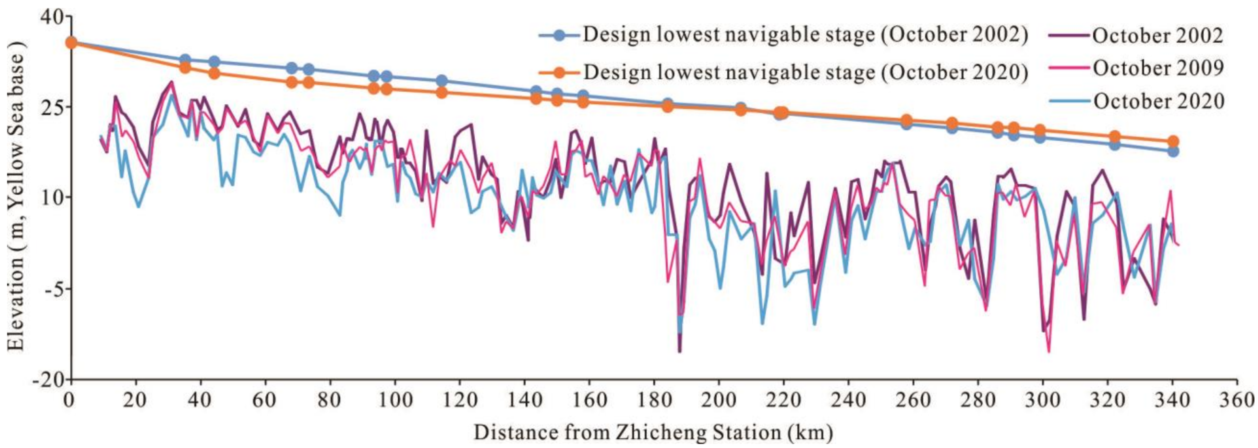

Figure 6. Relationship between thalweg and water level change

3.2 Changes in bar and beach boundaries of the waterway

In comparison to 2002, the area of central bars and beaches has decreased by 18.3% in 2019 (13.9% in the section with the gravelly riverbed, 27.4% in the Shashi Reach, 10.45% in the Yanka–Ouchikou section, and 15.7% in the LJR) (Figure 7, Table 3), with beaches and central bars having shrunk by 24.9% and 9.4%, respectively. The areal changes of beaches and central bars in braided reaches could be divided into four distinct patterns: continuous decrease, increase and then decrease, decrease and then increase, and continuous increase. The central bars and beaches whose areas decreased continuously include the LJHCB, HJZCB, MYZCB, JCB, JZYB, XCB, TYSB, TGB, GXZB, GZB, QGLB, and GYZB. At the HJZCB and MYZCB, waterway regulation projects have not been implemented in these reaches, and their areas are decreasing due to the discharge of clear water. The areas of the LJHCB, JCB, JZYB, XCB, TYSB, Tiaoguan Beach, GXZB, and GZB are still decreasing despite the implementation of waterway regulation projects. Although their beaches and grooves have been stabilized by these projects, they are strongly affected by the discharge of clear water due to their proximity to the dam. As a result, the central bars and low beaches of these areas are still shrinking. The central bars and beaches whose areas initially decreased, and then, increased include the GCZB, ZJTYB, WJDB, SBTCB, OCKCB, XJZB, LJPB, and WGZCB. The areas of these beaches and central bars have increased due to implementation of river training and waterway regulation projects; in other words, their shrinkage was successfully reversed by human engineering. The beaches and central bars whose areas increased, and then, decreased include the LTZCB, SLZCB, TPKCB, and JHSB. These sandy areas became larger after the completion of waterway regulation projects, but their low beaches are still being scoured. Therefore, additional work must be performed to ensure the integrity of these areas in waterway expansion works. The NXZCB is the only central bar whose area has increased continuously; this is due to continuous implementation of waterway regulation projects in the Wakouzi channel, which have succeeded in protecting the integrity of this central bar.

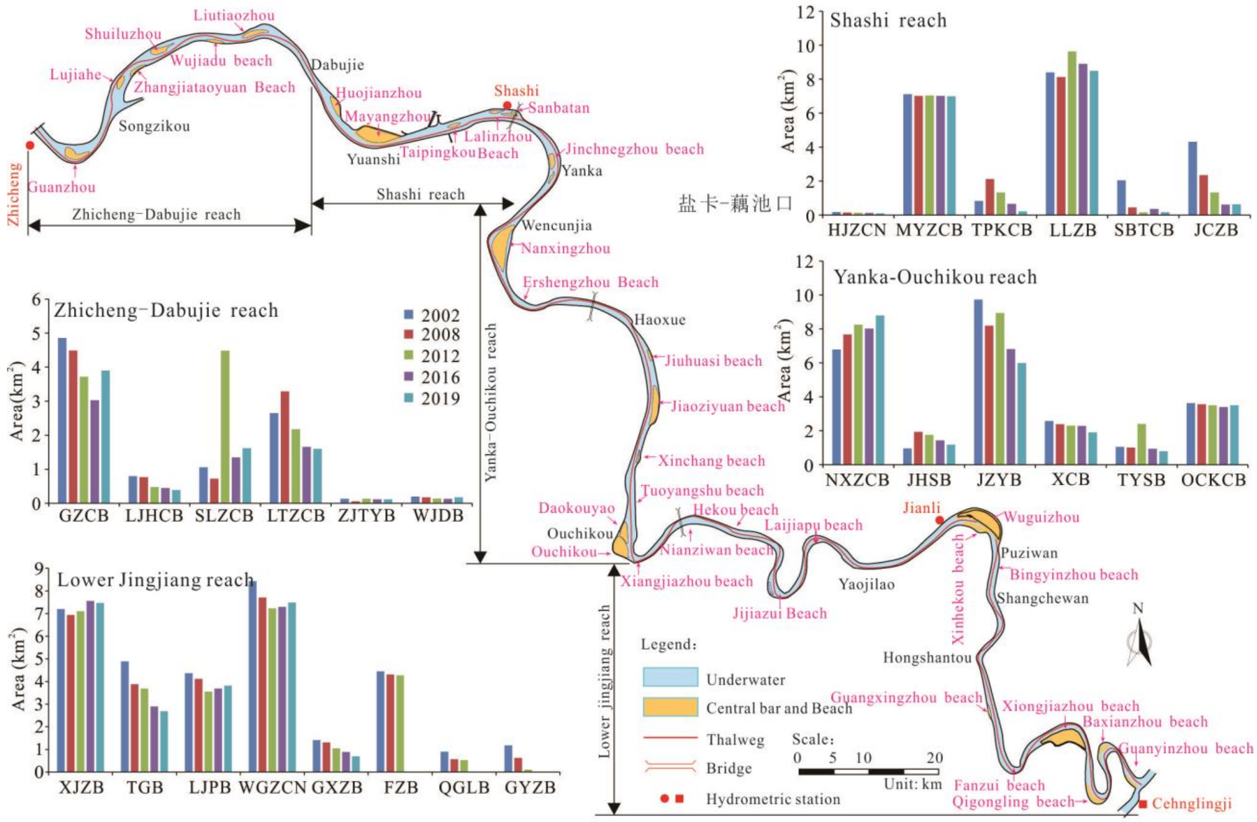

Figure 7. Area of beach and central bar

Table 3. Area of central bar and beach

Year	2002	2008	2012	2016	2019
Central bar (km^2)	38.39	37.96	38.51	33.37	34.79
Beach (km^2)	51.79	46.01	46.97	41.20	38.91
Area of central bar and beach (km^2)	90.18	83.97	85.48	74.57	73.7

3.3 Changes in dry season WDR

The braided reaches of the Jingjiang Reach are located at the GZCB, LJHCB, LTZCB, TPKCB, SBTCB, NXZCB, DKYCB, and WGZCB. The changes in the dry season WDR of these braided reaches are presented in the following list (Figure 8):

(1) GZCB braided reach: From 1984 to 1987, the changes in WDR at the GZCB have been large, as the main and tributary branches have swapped with each other in a few years. The WDRs of this reach did not change significantly from 1987 to 2002, but the WDR of the left branch increased throughout the 2002–2016 period. The WDR per flow rate of the right branch is lower in the 2003–2017 period compared to the 1984–2002 period. After a waterway regulation

project was implemented in the Jingjiang Reach, the 2017 WDR of the left branch increased by 10.1% in 2017 (when the flow rate at Zhicheng was 6404 m^3/s) compared to 2012 (when the flow rate at Zhicheng was 6027 m^3/s).

(2) LJHCB braided reach: The WDR of the left branch decreased throughout the 2003–2014 period, and the WDR per flow rate of the left branch was lower in the 2007–2014 period compared to the 2003–2007 period. After the completion of a waterway regulation project on the Jingjiang Reach, the WDR of the left branch in 2016 (when the flow rate at Zhicheng was 6058 m^3/s) increased by 10.9% compared to the 2014 level (when the flow rate at Zhicheng was 6347 m^3/s).

(3) SLZCB braided reach: The WDR of the right branch has been increasing since 2007; by March 2019, the left branch stopped flowing altogether during the dry season.

(4) LTZCB braided reach: the WDR of the LTZCB did not change significantly during the 2003–2010 period, and the WDR between the left and right branches was 3:7. During the 2011–2014 periods, the WDR of the right branch began to increase, which indicates that the waterway regulation project succeeded in restricting the WDR of the left branch. The bed scour in the left branch was significant from 2014 to 2019, as the WDR of the right branch decreased by approximately 25% during this period.

(5) Shashi Reach: The Shashi Reach has two braided sections, i.e., Taipingkou and Sanbatan. An exchange between the main and tributary branches during the dry season has occurred in both of them. At the Taipingkou braided reach, this process occurred between 2004 and 2006, and ended with the right branch becoming the main branch in 2006. At the Sanbatan braided reach, dry season swapping between the main and tributary branches occurred three times, in the 1978–1980, 1999–2000, and 2010–2011 periods. In terms of WDR per flow rate, the WDR of the left branch in Taipingkou decreased significantly between 2010 and 2017 compared to the 2001–2009 period. In comparison to the 2003–2010 periods, the 2010–2017 WDRs of the right branch of Sanbatan were higher during floods and lower during the dry season.

(6) NXZCB braided reach: The WDRs of this braided reach changed significantly during the 2000–2011 period. From 2000 to 2001, the WDRs of the left and right branches were similar, but in the 2002–2007 periods, the WDR of the right branch increased and then decreased. After the implementation of waterway regulation projects, the WDR of the right branch increased significantly, reaching a point where the left branch was dry during the dry season.

(7) OCKCB braided reach: The WDRs of the OCKCB braided reach were stable until the implementation of a waterway regulation project, which greatly increased the WDR of the left branch (up to almost 100%). The right branch is dry during dry seasons.

(8) WGZCB braided reach: At the WGZCB, two exchanges between the main and tributary branches have occurred since 1970, i.e., in the 1977–1979 and 1990–1993 periods. The WDR of the right branch has been increasing since 1994, and its WDR per flow rate is higher between 2003 and 2017 than in the 1994–2002 periods. This shows that the waterway regulation projects that were implemented after the impoundment of the TGD have been effective in regulating WDR.

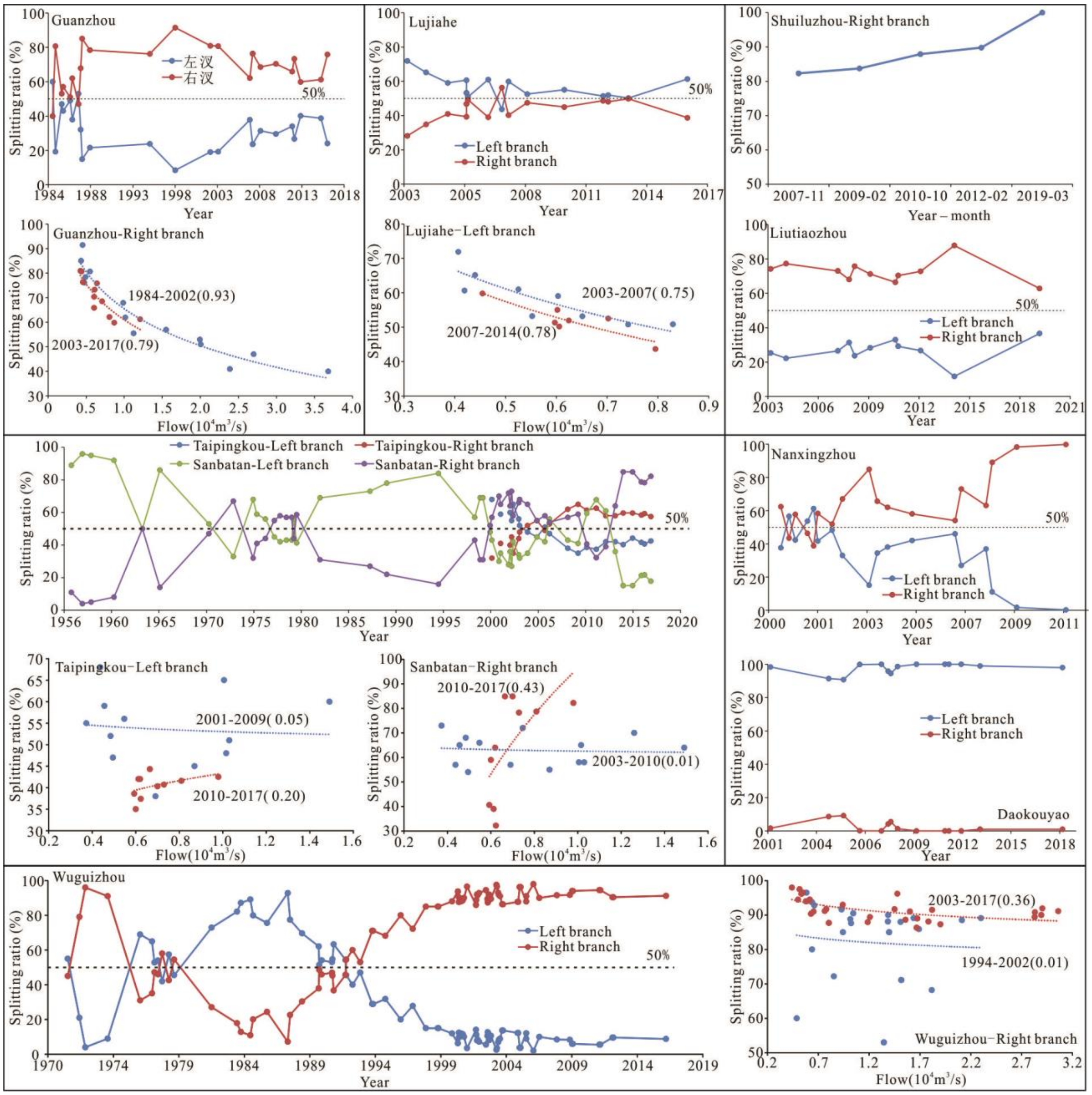

Figure 8. Variation of WDR of main branch in dry season

The time that has elapsed since the commissioning of the TGD may be divided into two periods: the first period begins from the impoundment of the TGD up to the point before waterway regulation projects were implemented, and the second one begins from the completion of the waterway regulation projects and continues to the present day. During the first period, the left branch of the GZCB (2014–2017), right branch of the LJHCB (2003–2014), right branch of the SLZCB (2007–2012), left branch of the LTZCB (2003–2010), right branch of the NXZCB (2004–2007), left branch of the OCKCB (2001–2009), and right branch of the WGZCB (2003–2007) have all seen increases in their WDR. All of these branches have one thing in common, i.e., they are the shorter of the two branches. In the second period, the WDRs of the left branch of the

GZCB (since 2014), right branch of the LJHCB (since 2014), right branch of the SLZCB (since 2012), left branch of the LTZCB (2012–2014), right branch of the NXZCB (since 2007), left branch of the OCKCB (since 2009) and right branch of the WGZCB (since 2007) have all increased. This shows that the waterway regulation projects have succeeded in achieving their goals. The TPKCB and SBTCB braided reaches in the Shashi Reach are straight and slightly curved, respectively, and their evolutionary processes are closely interconnected to those of beaches and bars in their upstream and downstream. Furthermore, they have been affected by numerous human interventions, including waterway regulation projects, construction of the Jingjiang Yangtze River Bridge, and sand mining activities. As a result, the main and tributary branches of these braided reaches frequently interchange with one another, and unlike other braided reaches, the WDR of the shorter branch did not increase after the commissioning of the TGD.

4 Results and discussion

4.1 Requirements analysis for waterway expansion

In 2002, the dimensions of the Jingjiang Reach waterway were 2.9 m × 40 m × 300 m (for the 95% navigation guarantee rate). Due to the implementation of waterway regulation projects, by 2020, the waterway dimensions of the Zhicheng–Changmenxi, Changmenxi–Jingzhou, and Jingzhou–Chenglingji sections were 3.5 m × 100 m × 750 m, 3.5 m × 150 m × 1000 m, and 3.8 m × 150 m × 1000 m, respectively. This allowed the Jingjiang Reach to obtain a 98% navigation guarantee rate all year round (Figure 9). The combined waterway of the Jingjiang Reach has water depths between 3.5 and 3.8 m, which are shallower than those of the upstream TGD reservoir area (4.5 m), downstream Chenglingji–Wuhan (4.2 m) and Wuhan–Anqing (6.0 m) sections. Due to this mismatch in water depths, increasing the water depth of the Jingjiang Reach to 4.5 m will allow the upstream and downstream waterways of the Yangtze to become fully connected; this will significantly improve transportation efficiency in the Yangtze "Golden Waterway".

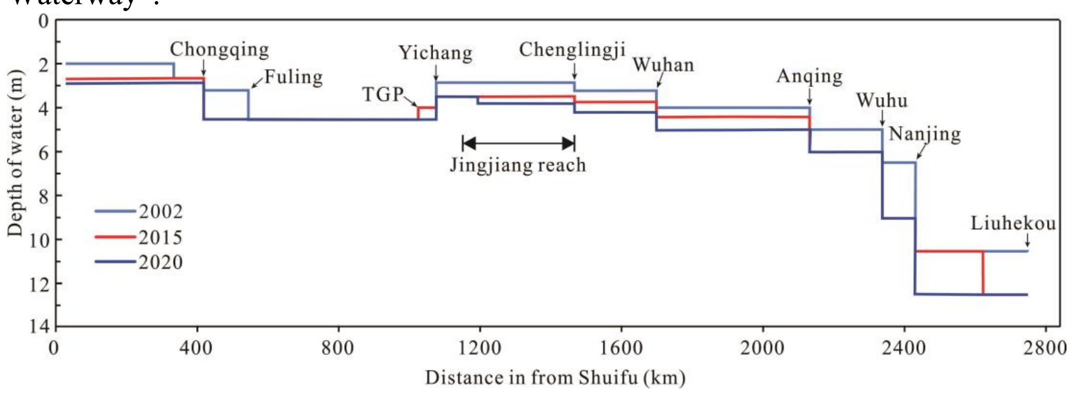

Figure 9. Water depth change of main channel of Yangtze River

4.2 Inspection of waterway conditions

The water depths of the Jingjiang Reach waterway were tallied based on the river topography that was surveyed on October 2020 (Figure 10). Given a waterway width of 200 m, it was found that there are 14 channels with water depths less than 4.5 m in the Jingjiang Reach. This includes the Guanzhou, Lujiahe, Zhijiang, Jiangkou, Dabujie, Yuanshi, Taipingkou, Wakouzi, Zhougongdi, Jianli, Damazhou, Tiepu, Chibakou, and Guanyinzhou channels. The minimum water depths of the 19 remaining channels are all greater than 4.5 m. After drawing a 4.5 m depth contour through the Jingjiang Reach, it was found that there are 13 channels with widths less than 200 m, i.e., the Zhicheng, Guanzhou, Lujiahe, Zhijiang, Jiangkou, Dabujie, Yuanshi, Taipingkou, Wakouzi, Zhougongdi, Jianli, Damazhou, and Guanyinzhou channels. All the other 20 channels have widths greater than 200 m on their 4.5 m depth contours. Given a waterway scale of 4.5 m × 200 m, the Jingjiang Reach is either insufficiently wide or deep in the Guanzhou, Lujiahe, Zhicheng, Jiangkou, Dabujie, Yuanshi, Taipingkou, Wakouzi, Zhougongdi, Jianli, Damazhou, Chibakou, and Guanyinzhou channels. These navigation hindering channels account for 5.3% of the Jingjiang Reach's total length (18.4 km).

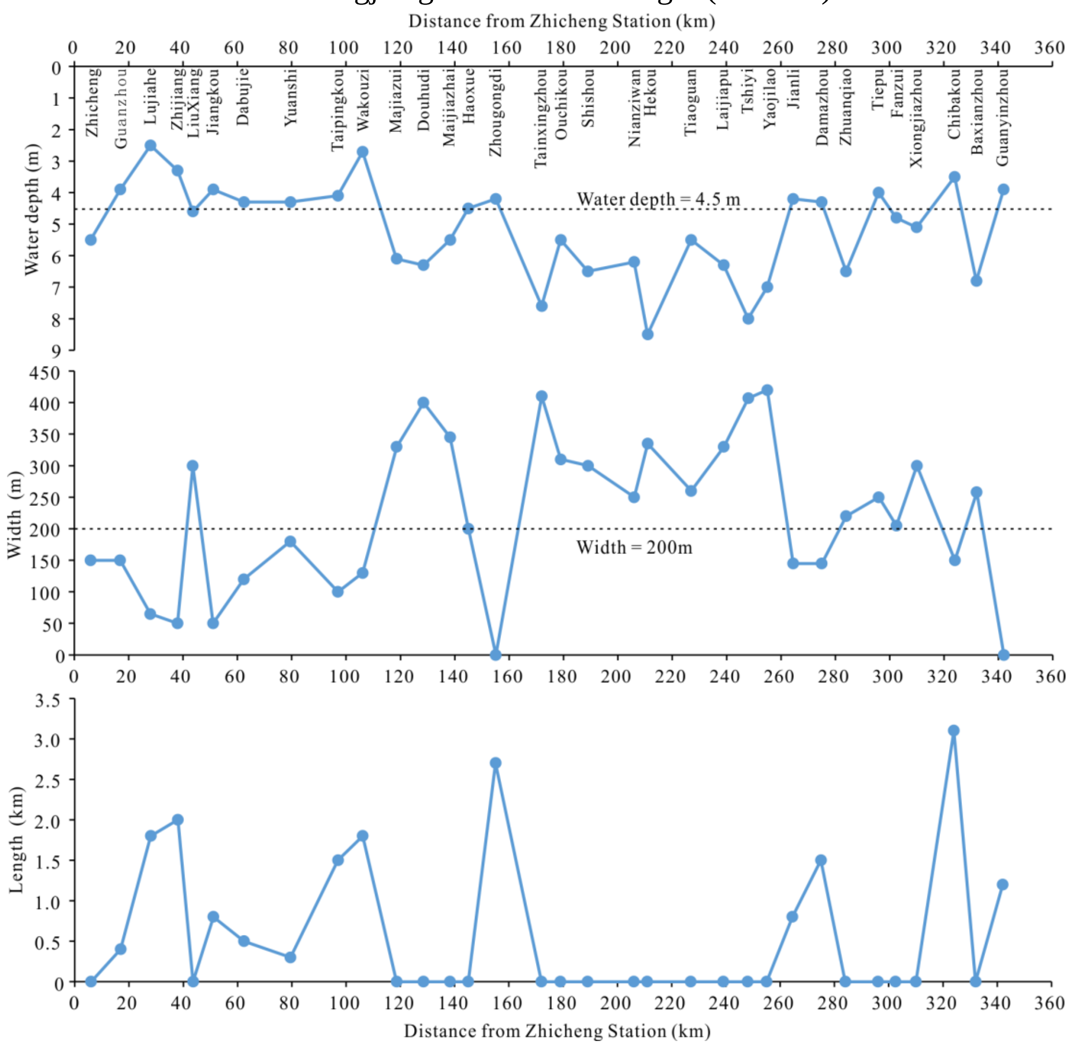

Figure 10. Verification of waterway conditions. (a) Minimum water depth in 200m waterway; (b) Minimum width of 4.5 m water depth line; (c) Length of channel scale less than 4.5 m × 200 m.

4.3 Characteristics of navigation hindrances and their relation to river evolution

4.3.1 Navigation hindrances due to non-uniform decreases in water level

The water levels of the Jingjiang Reach that correspond to a flow rate of 6000 m^3/s at the Yichang Station in the 2003–2020 period are shown in Figures 11a and b. During the 2003–2009 period, the decrease in water level at the fixed water level gauges of the Jingjiang Reach ranged from 0.06 to 0.53 m, with decreases in water level at the Yichang–Zhicheng section and downstream reaches of Zhijiang being greater than those of the Zhicheng–Zhijiang section. The water levels of the Jingjiang Reach decreased between 0.27 and 2.66 m during the 2009–2020 period. The water level decreases were large in the Changmenxi–Shishou section (downstream end of the UJR), but relatively small in the Yichang–Changmenxi section and LJR. The average thalweg depth of the UJR increased by 2.97 m from 2003 to 2020, whereas the corresponding water level decreased by an average of 1.21 m (0.27–2.66 m). Because the average decrease in water level was less than the average increase in thalweg depth, the water depth of the waterway had increased during the 2003–2020 period.

The annual average decrease in water level between 2009 and 2020 compared to the 2003–2009 period was smaller in the Yichang–Zhicheng section, significantly larger in the UJR, and smaller again in the LJR. The 4.5 m depth contour is continuous near the Changmenxi and Caojiahe–Wujiadu areas, but their widths are less than 150 m; in the Lijiadu–Zhangjiataoyuan and Qixingtai areas, there are breaks in the 4.5 m depth contour (Figure 11c). During the 2009–2020 period, the water levels of the Changmenxi–Dabujie section decreased by 2.21 m, but the corresponding deepening of the thalweg was only 1.61 m on average. In other words, the decrease in water level was greater than the deepening of the thalweg; this led to the appearance of a navigation obstacle in the Changmenxi–Dabujie section.

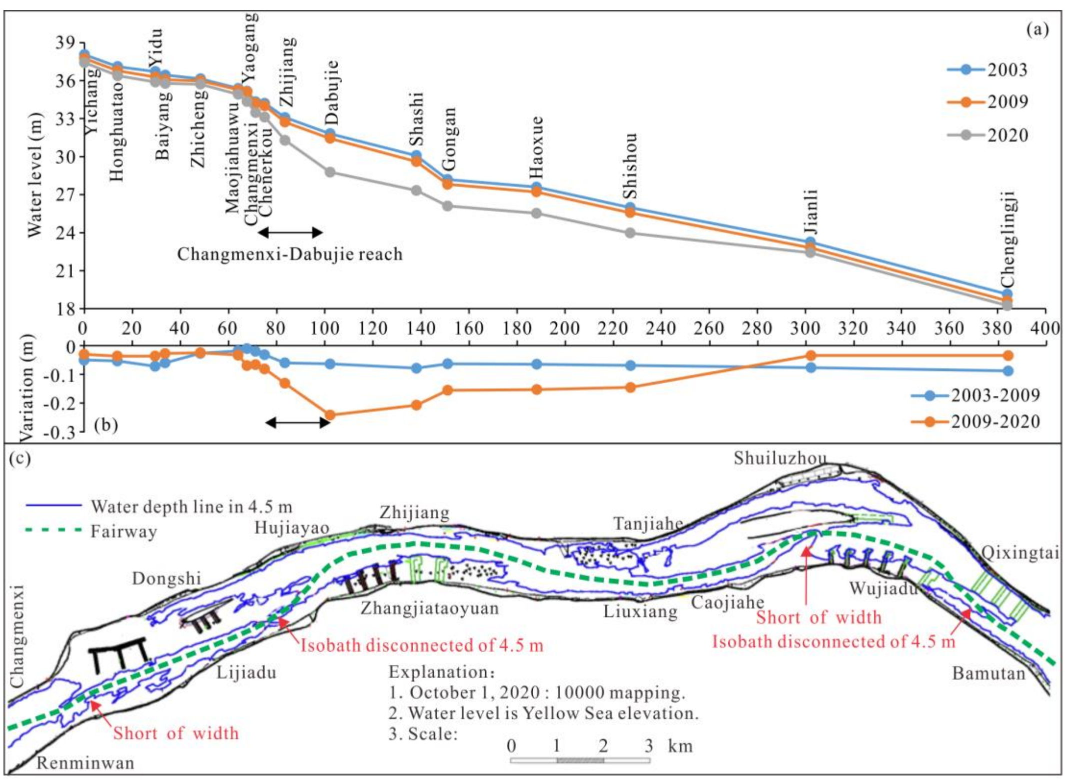

Figure 11. Waterway water depth conditions of sand cobble reach. (a) Water level of Jingjiang reach corresponding to Yichang discharge of 6000 m^3/s; (b) Variation of water level; (c) Waterway conditions of 4.5m depth from Changmenxi-Dabujie reach.

4.3.2 Navigation obstacles due to unstable beach areas in curved sections

The curved sections in the Jingjiang Reach are abrupt bends, like the Tiaoguan–Laijiapu section (22.5 km long) and Yangjianao–Chenglingji section (45.1 km long), which have a curvature of 2.65. The distribution of scour and deposition in these riverbeds from 2002 to 2012 has previously been studied (Zhu et al., 2017). Here, we analyzed the 2012–2020 distribution of scour and deposition in the riverbed (Figure 12), and found that the scour tends to occur on convex banks whereas deposition occurs on concave banks. This trend is consistent with the findings of the study by Zhu et al. (2017). Due to water flow regulation by the reservoir and the consequent redistribution of flow rates in the LJR, the heterogeneity of the hydrodynamic axis actions on the convex and concave banks has increased over time. More specifically, this has greatly extended the duration in which the convex bank is poised within the mainstream compared to the concave bank, which exacerbated erosion in the former (Zhu et al., 2017； Han et al., 2017b). The erosion of the convex bank decreases the bend radius of the waterway, which can make it difficult for ships to safely navigate the bend. Although the 4.5 m depth contour is continuous in the Tiaoguan–Laijiapu section of the Jingjiang Reach, the decrease in its bend radius poses a navigation risk.

The Yangjianao–Chenglingji section consists of four continuous abrupt bends; the Fanzui channel has a bend radius that is too small, whereas the Xiongjiazhou, Chibakou, Baxianzhou, and Guanyinzhou channels contain scattered sections with water depths less than 4.5 m due to outflows from the Dongting Lake (Lai et al., 2013).

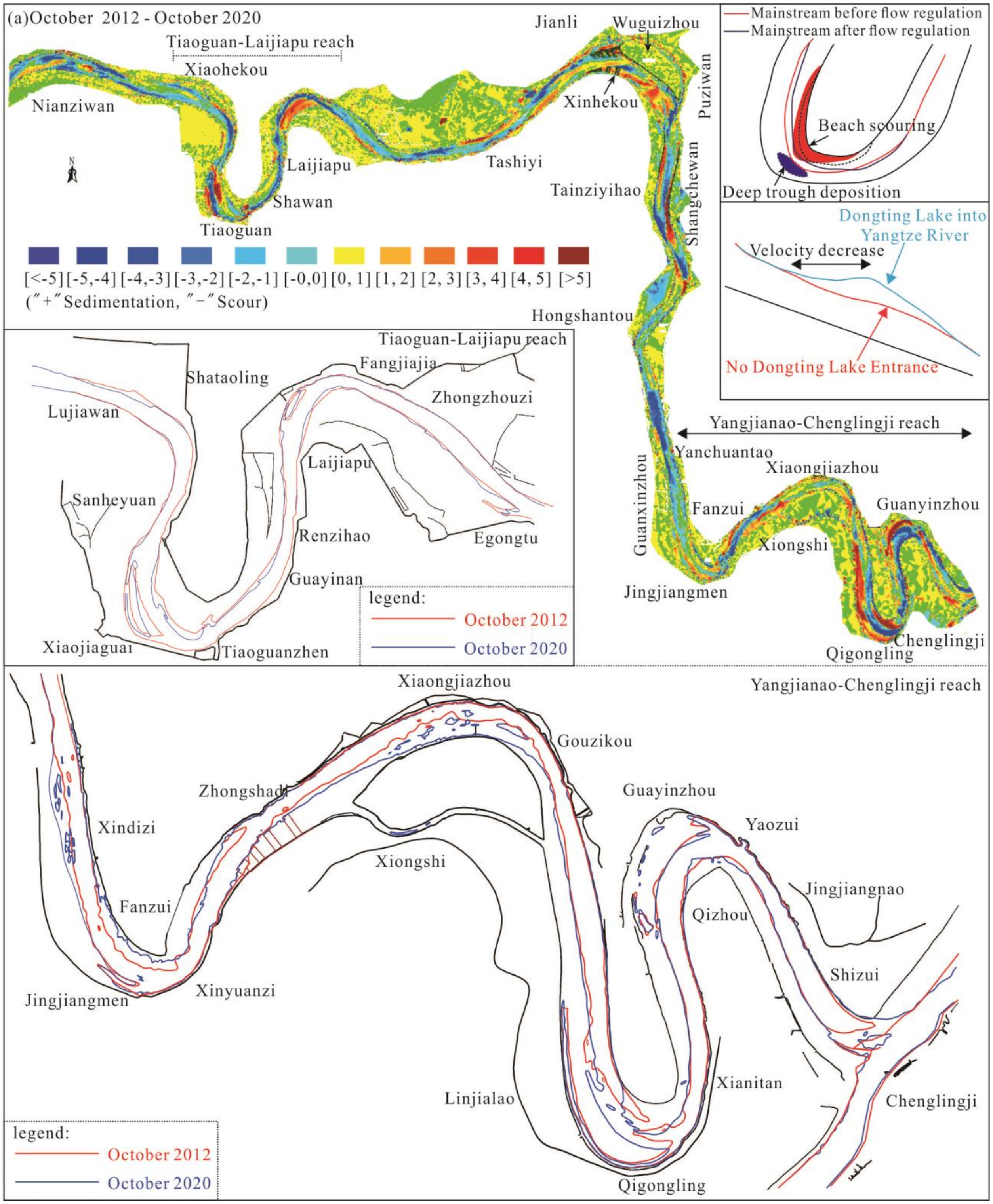

Figure 12. Water depth condition of bend channel. (a) Sediment characteristics of October 2012 - October 2020; (b) Tiaoguan-Laijiapu reach; (c) Yanchuantao-Chenglingji reach; (d) Variation characteristics of beach trough; (e) Influence of confluence ov water lewel of Dongting Lake.

4.3.3 Navigation hindrances due to unstable bars and WDRs in braided reaches

Because the WDR can change with flow rate, the main and tributary branches of a braided reach may either alternate seasonally, or not at all. The braided reaches that alternate seasonally are the Guanzhou, Lujiahe, Taipingkou–Sanbatan, and Wuguizhou reaches, whereas the braided reaches that do not alternate seasonally are the Shuiluzhou, Huojianzhou, Mayangzhou, Nanxingzhou, and Ouchikou reaches. In particular, the Wuguizhou braided reach changed from a seasonally alternating braided reach into a non-alternating reach after the implementation of waterway regulation projects. The navigation hindering characteristics of these braided reaches are described below (Figure 13):

(1) Braided reaches with channels that have no significant beaches, i.e., the Guanzhou, Lujiahe, Shuiluzhou, Liutiaozhou, Huojianzhou, Mayangzhou, Nanxingzhou, and Ouchikou braided reaches. Waterway regulation projects have not been implemented in the Huojianzhou and Mayangzhou reaches because their central and point bars have high elevations and are well preserved; thus, they show only small decreases in the area. Furthermore, the dry season WDRs of their main channels are greater than 80%, and the small amount of scour in their central bars only slightly affects the WDR. The 4.5 m depth contour is also continuous in these reaches. Although the positions of the LTZCB and LJHCB have stabilized after the implementation of waterway regulation works, their areas and dry season main branch have both decreased over time, and the resulting widening of their inlet sections have led to insufficient water depths (< 4.5 m) or channel widths. After the installation of bottom protection structures in the left branch of the GZCB, the area of the central bar has increased; but the dry season WDR of the main branch is still decreasing over time. As a result, the main branch is sometimes insufficiently deep or wide for navigation when the hydrodynamic force at the inlet is weak. The implementation of waterway regulation projects has increased the areas of the OCKCB and NXZCB, and stabilized their dry season WDRs. However, according to the terrain that was surveyed on October 2020, some parts of the 4.5 m depth contour are insufficiently wide for safe navigation at these reaches.

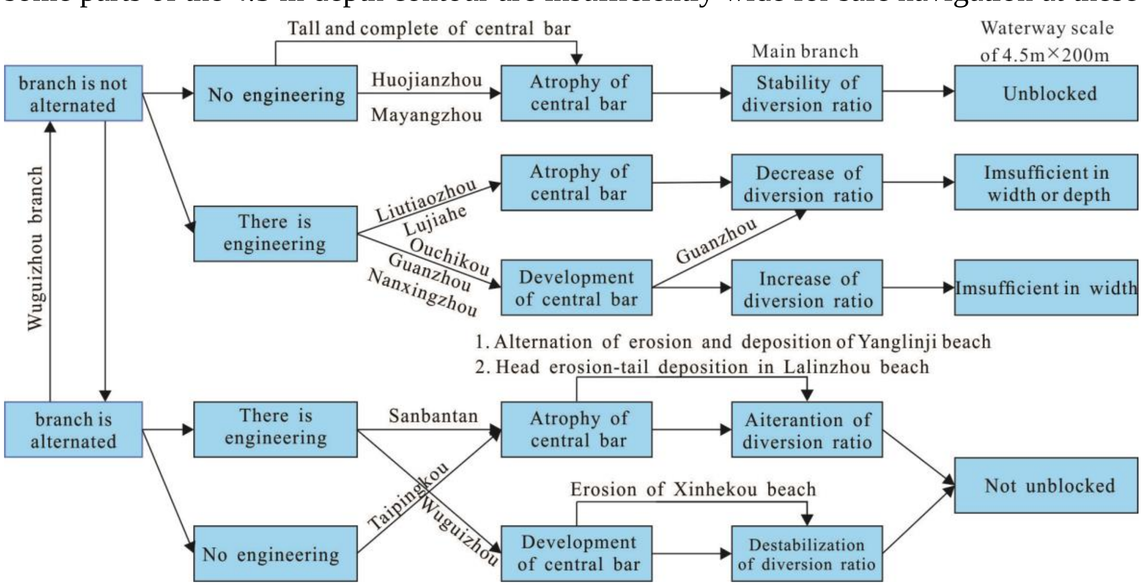

Figure 13. Relationship between beach evolution, WDR, and waterway conditions

(2) Braided reaches with multiple central bars and beaches whose changes are strongly correlated with one another, like the Shashi and Jianli Reaches. The Shashi Reach contains the TPKCB, LLZB, SBTCB, and YLJB (which only appears in specific years), and a number of waterway regulation projects have been carried out in this area, especially at the SBTCB and LLZB (Figure 14). The waterway regulation projects were implemented between 2001 and 2020. During this period, dry season switching between the main and tributary branches occurred at the TPKB and SBTCB. Therefore, waterway regulation projects are directly related to the evolution of central bars and beaches in these reaches. According to the WDRs and bar morphologies of the 2001–2003 period, the southern branch of the TPKCB had a WDR of 41%. Furthermore, 25% of the runoff from the TPKCB's northern branch flowed from a channel sandwiched by the tail of the TPKCB and head of the SBTCB into the southern branch of the SBTCB. Consequently, the southern branch of the SBTCB was the main branch from 2001 to 2003. In the 2004–2006 periods, the scour and deposition occurred at the head and tail of the LLZB, respectively, which increased the WDR of the TPKCB's southern branch. Furthermore, the changes in the morphology of the LLZB caused the flow to swing towards the northern branch of the SBTCB, which induced substantial amounts of scour in the SBTCB. From 2007 to 2013, the scour and deposition at the head and tail of the LLZB continued to progress, and the TPKCB also began to shrink, which increased the average WDR of the TPKCB's southern channel to 59%. During this period, approximately 11% of the runoff flowed via the channel between the tail of the TPKCB and head of the SBTCB into the latter's northern branch; this caused the main and tributary branches to switch around in the dry season for the first time. In the 2014–2018 periods, the weakening in the hydrodynamic force due to previous decreases in the WDR of the TPKCB's northern branch caused the YLJB to grow substantially in the area. The LLZB also shielded the YLJB from erosion, which stabilized the head of the LLZB while allowing deposition to occur at its tail. The expansion of the LLZB and shrinkage of the SBTCB caused the WDR of the SBTCB's southern branch to increase beyond 50%, thus completing another swap between the main and tributary branches. The Jianli Reach, which contains the WGZCB and XHKB, has undergone multiple river training and waterway regulation projects. Because changes in the WGZCB and XHKB are linked to each other, the WDRs of the WGZCB's branches are unstable; this caused the groove of the WGZCB's right branch to overlap with that of the Damazhou channel. The area of overlap between these grooves has water depths less than 4.5 m and an uneven route.

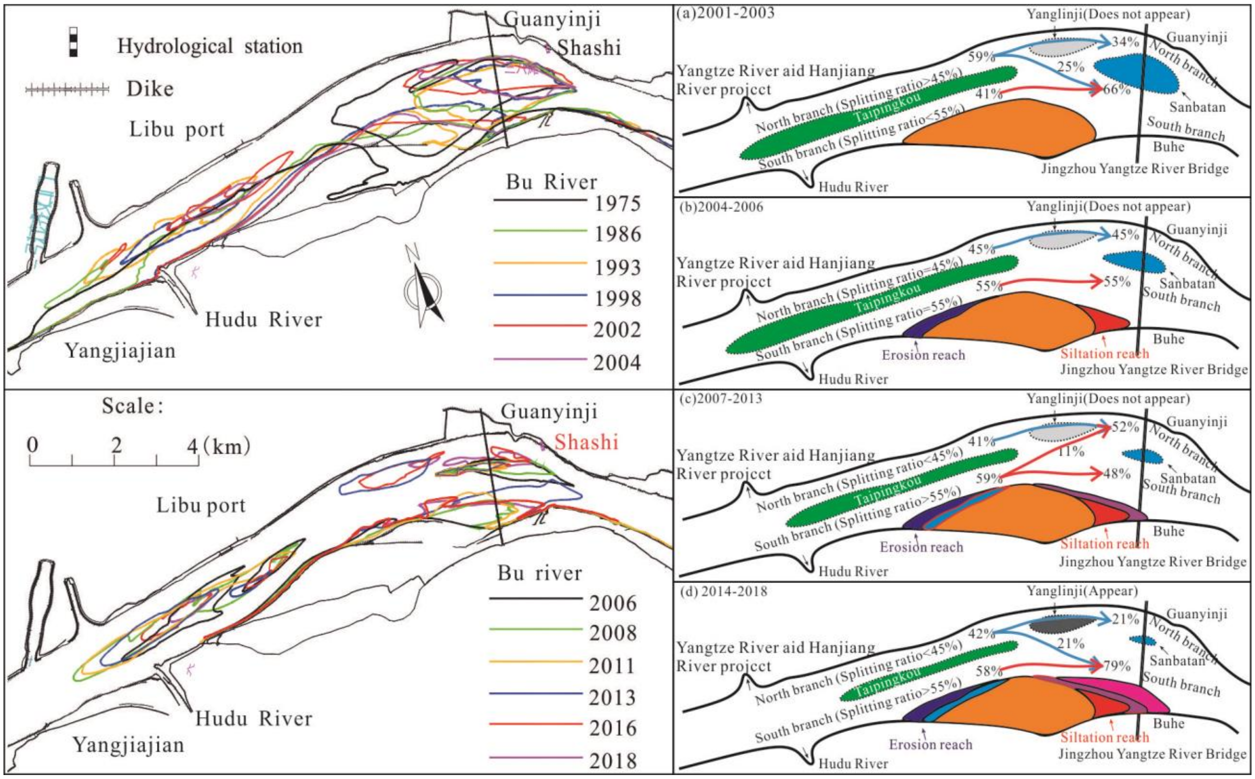

Figure 14. Relationship between beach evolution and branch diversion ratio in Shashi reach

4.4 Relationship between waterway expansion and ecological environment

The development of shipping functions is an important part of watershed resource utilization. However, there is a great deal of uncertainty associated with the use of natural scour alone to deepen waterways, and there is a certain limit regarding the amount of water depth that can be obtained in this way. Waterways often need to be expanded to satisfy growing demand for shipping; this is often performed by constructing reservoirs (Yang et al., 2019) , spur dikes, and canalized rivers (Wan et al., 2014; Wu et al., 2016), and dredging (Ford et al., 2013; Hajdukiewicz et al., 2016; Suedel et al., 2021). The construction of a reservoir will directly increase waterway depths in the reservoir area (Moretto et al., 2014; Smith et al., 2016); moreover, the regulation functions of the reservoir can be used to increase the minimum flow rate during the dry season, thus increasing water level and depth (Chai et al., 2021). Dredging is also a necessary part of waterway regulation, but it often leads to rapid back siltation (Helal et al., 2020). Therefore, maintaining a waterway through dredging can become a very costly process (Ahadi et al., 2018). However, the implementation of waterway regulation projects or dredging works could lead to ecological damage, and its recovery will invoke even greater economic costs (Bernhardt et al., 2005; Szałkiewicz et al., 2018; Logar et al., 2019). In most rivers globally, their systematic development increases significantly the size of their waterways, like the Mississippi River (Yu et al., 2005), Rhine (Quick et al., 2020) and Yangtze River Estuary (Wan et al., 2014; Wu et al., 2016).

The Jingjiang Reach has 124 sluices and drainage outlets (approximately 5.6 km per sluice or outlet), and the Jingzhou Port consists of 16 port areas, which cover 59.01 km of the shore, i.e., 17% of the Jingjiang Reach. There are 4 bridges that span the Jingjiang Reach, which are located at the Zhicheng, Taipingkou, Haoxue, and Nianziwan channels. The frequent exchange of main and tributary branches in the Taipingkou channel is partially a consequence of the construction of the Jingzhou Yangtze River Bridge. There are 36 river-crossing or steam ferries along the Jingjiang Reach, and their density along the coastline is approximately 10.4 km/ferry. It can also be observed that the water-related facilities overlap to some extent on the reach. Because waterway regulation projects must minimize their impact on water-related facilities, this poses difficulties for the implementation of these projects. However, using dredging alone to achieve water depth targets is very costly, and the need for annual maintenance is very significant for navigation safety. Furthermore, the Jingjiang Reach is an important area of activity for the Yangtze Finless Porpoise, and the Tian'ezhou National Nature Reserve is located in this reach as well (Figure 15). The nature reserve covers the Tianxingzhou, Ouchikou, and Nianziwan channels, and the implementation of waterway regulation projects in these areas is highly restricted.

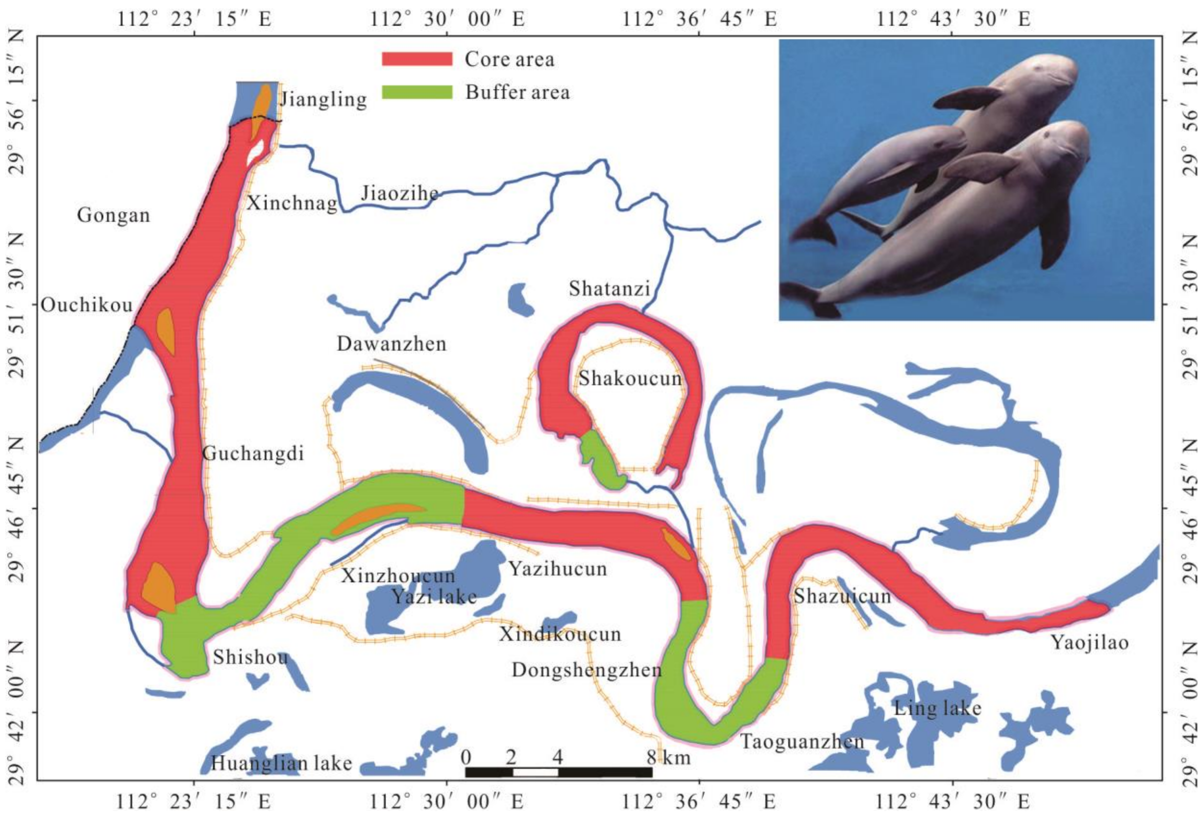

Figure 15. Tianezhoudolphin national nature reserve of Yangtze River in Hubei Province

Waterway regulation projects have been systematically implemented on the Yangtze River trunk line using a variety of environmentally friendly structures, including tetrahedral frames (Wang et al., 2017), dolosse (Cao et al., 2018), W-shaped dams (Huang et al., 2019), “fish tank” bricks (Cao et al., 2018; Wang et al., 2020b), D- and X-shaped rows, and grass-planting and sand-fixing structures (Li et al., 2018c; Fan et al., 2020). Based on long-term observations since 2013, these structures have had a significant positive effect on the ecological environment of the

Yangtze River (Li et al., 2017; Li et al., 2018b). During the planning of waterway regulation projects to increase the Jingjiang Reach's waterway depth to 4.5 m, it is necessary to consider novel waterway regulating structures that are environmentally friendly so that the ecological environment of the Jingjiang Reach will benefit from such projects.

5 Conclusions

In this study, our aim was to expand the waterway dimensions of the Jingjiang Reach. Thus, it was necessary to determine how river evolution processes relate to its potential for waterway depth improvement and navigation hindrances.

Ever since the TGD began to hold back water, the scour in low-flow channel has accounted for 93.1% of the scour in the Jingjiang Reach. This effect is beneficial for increasing waterway dimensions. The total area of central bars and beaches in the Jingjiang Reach has decreased by 18.3%, with the former and latter decreasing by 9.4% and 24.9%, respectively; this effect destabilizes waterway boundaries. If a braided reach has large and intact central bars, the dry season WDRs of their branches tend to be stable. Conversely, if a braided reach has beaches and central bars, the WDRs of their branches are often unstable.

Then, in the section of the UJR with a gravelly riverbed, the decrease in water level is greater than the downcutting of the riverbed; this has caused the waterway to become insufficiently deep. Due to convex bank scouring and concave bank deposition in the curved section, some of the more abrupt bends have a bend radius that is too small, which hinders safe passage through these sections. The shrinkage of beaches and central bars in braided reaches, which are often strongly interconnected, has resulted in unstable dry season WDRs. This has also resulted in swapping between the main and tributary branches during the dry season.

Based on the current terrain of the Jingjiang Reach (which was surveyed in October 2020), the 4.5 m × 200 m × 1050 m waterway of the Jingjiang Reach is navigationally hindered over 5.3% of its length. To improve waterway depth, attention should be drawn to the scour and deposition patterns of the Jingjiang Reach, changes in its central bars and beaches, and the WDR trends of the braided reaches. Although the Jingjiang Reach satisfies all requirements for further water depth improvement, it is necessary to consider the environmental effects of the waterway project.

Acknowledgments

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References

Ahadi, K., Sullivan, K. M., & Mitchell, K. N. (2018). Budgeting maintenance dredging projects under uncertainty to improve the inland waterway network performance. *Transportation Research Part E:*

Logistics and Transportation Review, 119, 63-87. https://doi.org/10.1016/j.tre.2018.08.013.

Bernhardt,E. S., Palmer, M. A., Allan, J. D., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton, S., Dahm, C., Follstad-Shah, J., Galat, D., Gloss, S., Goodwin, P., Hart, D., Hassett, B., Jenkinson, R., Katz, S., Kondolf, G. M., Lake, P. S., Lave, R., Meyer, J. L., O'Donnell, T. K., Pagano, L., Powell, B., &, Sudduth, E. (2005). Synthesizing U.S. River Restoration Efforts. *Science*, 5722(308): 636-637. DOI: 10.1126/science.1109769.

Cao, F. S., Xiao, X., & Wu, P. (2010). Yangtze River: China's golden waterway. *Civil Engineering*, 163(5), 15-18. https://doi.org/10.1680/cien.2010.163.5.15.

Cao, M. X., Shen, X., Huang, Z. B., Luo, H. W., Ying, H. H., & Lin, W. (2018). Techniques of ecological and protection based on deepwater navigation channel project in the Yangtze River below Nanjing. *Port & Waterway Engineering*, (7): 1-9.

Chai, Y. F., Li Y. T., Yang, Y. P., Zhu, B. Y., Li, S. X., & Xu, C. (2019). Influence of Climate Variability and Reservoir Operation on Streamflow in the Yangtze River. *Scientific Reports*, 9: 5060. DOI：10.1038/s41598-019-41583-6.

Chai, Y. F., Yang, Y. P., Deng J. Y., Sun, Z. H., Li, Y. T., & Zhu, L. L. (2020). Evolution characteristics and drivers of the water level at an identical discharge in the Jingjiang reaches of the Yangtze River. *Journal of Geographical Sciences*,30(10): 1633-1648. DOI:10.1007/s11442-020-1804-x.

Dai, Z. J., & Liu, J. T. (2013). Impacts of large dams on downstream fluvial sedimentation: an example of the Three Gorges Dam (TGD) on the Changjiang (Yangtze River). *Journal of Hydrology*, 480(4): 10-18. DOI: 10.1016/j.jhydrol.2012.12.003.

Dai, Z. J., Mei, X. F., Stephen E, & Lou, Y. Y. (2018). Fluvial sediment transfer in the Changjiang (Yangtze) river-estuary depositional system. *Journal of Hydrology*, 566: 719-734. DOI: 10.1016/j.jhydrol.2018. 09.019.

Deng, S. S., Xia, J. Q., Zhou, M. R., Li, J., Zhu, Y. H. (2018). Coupled modeling of bank retreat processes in the Upper Jingjiang Reach, China. *Earth Surface Processes and Landforms*, 43: 2863-2875. DOI: 10.1002/esp.4439.

Deng, S. S., Xia, J. Q., Zhou, M. R., & Lin, F. F. (2019). Coupled modeling of bed deformation and bank erosion in the Jingjiang Reach of the middle Yangtze River. *Journal of Hydrology*, 568: 221-233. DOI: 10.1016/j.jhydrol.2018.10.065.

Fan, Y. J., Yang, Z. H., Zou, M. Z., Li, M., Zhang, Z. Y., Li, D., Liu, J. H., & Liu, Q. (2020). Evaluation of ecological effect of steel wire mesh stone cage revetment in middle and lower reaches of the Yangtze River. *Port & Waterway Engineering*, (1): 129-135. DOI:10.3969/j.ssn.1002-4972.2021.01.023.

Fang, H. W., Han, D., He, G. J., and Chen, M. H. (2012). Flood management selections for the Yangtze River midstream after the Three Gorges Project operation. *Journal of Hydrology*, s 432-433(8): 1-11.

Ford, M. R., Becker, J. M., and Merrifield, M. A. (2013). Reef Flat Wave Processes and Excavation Pits: Observations and Implications for Majuro atoll, Marshall Islands. *Journal of Coastal Research*, 29(3): 545-554. DOI:10.2112/JCOASTRES-D-12-00097.1.

Gao, C., Jin, C. W., Guo, L. C., Lu, J. Y., & Zhou, Y. J. (2020). On the cumulative dam impact in the upper Changjiang River: Streamflow and sediment load changes. *Catena*, 184: 104250. DOI: 10.1016/j. catena.2019.104250.

Hajdukiewicz, H., Wyżga, B., Mikuś, P., Zawiejska, J., and Radecki-Pawlik, A. (2016). Impact of a large flood on Mountain River habitats, channel morphology, and valley infrastructure. *Geomorphology*, 272: 55-67. DOI: 10.1016/j.geomorph.2015.09.003.

Helal, E., Elsersawy, H., Hamed, E., & Abdelhaleem, F. S. (2020). Sustainability of a navigation channel in the Nile River: A case study in Egypt. *River Research and Applications*, 36: 1817-1827. DOI: 10.1002/rra.3717.

Han, J. Q., Sun, Z. H., Li, Y. T., & Yang Y. P. (2017a). Combined effects of multiple large-scale hydraulic engineering on water stages in the middle Yangtze River. *Geomorphology*, 298: 31-40. DOI: 10.1016/j.geomorph.2017.09.034.

Han, J. Q., Zhang, W., Fan, Y. Y., & Yu, M. Q. (2017b). Interacting effects of multiple factors on the morphological evolution of the meandering reaches downstream the Three Gorges Dam. J*ournal of Geographical Sciences*, 27(10): 1268-1278. DOI:10.1007/s11442-017-1434-0.

Hijdra, A., Arts, J., & Woltjer, J. (2014). Do we need to rethink our waterways? Values of ageing waterways in current and future society. *Water Resources Management*, 28: 2599-2613. DOI: 10.1007/s11269-014-0629-8

He, Q. H., Yu, D. Q., Wang, L. C., Li, C. A., Yu, S. C., & Zou, J. (2020). Evolution Process and Characteristics of Lower Jingjiang Paleo-Channel in Recent 400 Years. *Earth Science*, 45(6): 1928-1936. https://doi.org/10.3799/dqkx.2020.015.

Hu, P., Lei, Y. H., Deng, S. Y, Cao, Z. X., Liu, H, H., He, Z. G. (2020). et al. Role of bar-channel interactions in a dominant branch shift: The Taipingkou waterway, Yangtze River, China. *River Research and Applications*, 37(3): 494-508. https://doi.org/10.1002/rra.3761.

Huang, T. J., Lu, Y., Liu, H. X. (2019). Effects of Spur Dikes on Water Flow Diversity and Fish Aggregation. Water, 11(9): 1822. DOI:10.3390/w11091822.

Hassan, M. A., Church, M., Yan, Y., & Slaymaker, O. (2010). Spatial and temporal variation of in‐reach suspended sediment dynamics along the mainstem of Changjiang (Yangtze River), China. *Water Resources Research*, 46(11). https://doi.org/10.1029/2010WR009228.

Juez, C., Garijo, N., Hassan, M. A., & Nadal-Romero, E. (2021). Intraseasonal-to-interannual analysis of discharge and suspended sediment concentration time-series of the Upper Changjiang (Yangtze River). *Water Resources Research*, 57(8). e2020WR029457. DOI:10.1029/2020WR029457

Lai, X. J., Jiang, J. H., Liang, Q. H., Huang, Q. (2013). Large-scale hydrodynamic modeling of the middle Yangtze River Basin with complex river–lake interactions. *Journal of Hydrology*, 492: 228-243. DOI: 10.1016/j.jhydrol.2013.03.049.

Li, S. Z., Yang, Y. P., Zhang, M. J., Sun, Z. H., Zhu, L. L., You, X. Y., & Li, K. Y. (2018a). Coarse and fine sediment transportation patterns and causes downstream of the Three Gorges Dam. *Frontiers of Earth Science*, 12 (4): 750-764. DOI:10.1007/s11707-017-0670-z.

Li, T. H., Ding, Y., Ni, J. R., & Xia, W. (2017). Ecological Waterway Assessment of the Jingjiang River Reach. *Journal of Basic Science and Engineering*, 25(2): 221-234. DOI:10.16058/j.issn.1005-0930. 2017.02.002.

Li, T. H., Ding, Y., & Xia, W. (2018b). An integrated method for waterway health assessment: a case in the Jingjiang reach of the Yangtze River, China. *Physical Geography*, 39(1): 67-83. http://dx.doi.org/10.1080/02723646.2017.1345537.

Li, M. (2018c). Research on the Ecological Shoal Consolidation Methods in River Central Bar Protection: Taking the Implantable Ecological Shoal Consolidation Engineering in Yangtze River Daokouyao Channel

Bar as on Example. *China Rural Water and Hydropower*, (7): 78-83.

Li, D. F., Lu, X. X., Chen, L., & Wasson, R. J. (2019). Downstream geomorphic impact of the Three Gorges Dam: With special reference to the channel bars in the Middle Yangtze River. *Earth Surface Processes and Landforms*, 44: 2660-2670. DOI:10.1002/esp.4691.

Li, M., Hu, C. H., Zhou, C. C., Peng, S. B. (2021). Analysis on the Evolution mechanism of the"steep slope and rapid flow"section of Lujia waterway in the middle reaches of the Yangtze River under new conditions of water and sediment. *Journal of Hydraulic Engineering*, 52(2): 158-168. DOI: 10.13243/j.cnki.slxb.20200418.

Liu, H. H., Yang, S.F., & Cao, M. X. (2017). Advances in “Golden Waterway” Regulation Technologies of the Yangtze River. *Advanced Engineering Sciences*, 49(2): 17-27. DOI: 10.15961/j.jsuese.201700029.

Logar, I., Brouwer, R. & Paillex, A. (2019). Do the societal benefits of river restoration outweigh their costs? A cost-benefit analysis. *Journal of Environmental Management*. 232: 1075-1085. DOI:10.1016/j.jenvman.2018.11.098.

Lyu, Y. W., Zheng, S., Tan, G. M., & Shu, C. W. (2018). Effects of Three Gorges Dam operation on spatial distribution and evolution of channel thalweg in the Yichang-Chenglingji Reach of the Middle Yangtze River, China. *Journal of Hydrology*, 565: 429-442. DOI:10.1016/j.jhydrol.2018.08.042.

Lyu, Y. W., Fagherazzi, S., Zheng, S., Tan, G. M., & Shu, C. W. (2020). Enhanced hysteresis of suspended sediment transport in response to upstream damming: An example of the middle Yangtze River downstream of the Three Gorges Dam. *Earth Surface Processes and Landforms*, 45: 1846-1859.

Moretto, J., Rigon, E., Mao, L., Picco, L., Delai, F., & Lenzi, M. A. (2014). Channel adjustments and island dynamics in the Brenta River (Italy) over the last 30 years. *River Research and Applications*, 30(6): 719-732. DOI:10.1002/rra.2676.

Wan, Y. Y., Gu, F. F., Wu, H. L., & Roelvink, D. (2014). Hydrodynamic evolutions at the Yangtze Estuary from 1998 to 2009. *Applied Ocean Research*, 47(9): 291-302. DOI:10.1016/j.apor.2014.06.009.

Wang, K., Guo, J., Duan, X. B., Chen, D. Q., & Liu, S. P. (2017). Preliminary evaluation on fish-aggregation effects of tetrahedron-like penetrating frame structure in Jingjiang channel regulation project. *Freshwater Fisheries*, 47(4): 97-104. DOI:10.3969/j.issn.1000-6907.2017.04.016.

Wang, J., Dai, Z. J., Mei, X. F. Lou, Y. Y., Wei, W., & Ge, Z. P. (2018). Immediately downstream effects of Three Gorges Dam on channel sandbars morphodynamics between Yichang-Chenglingji Reach of the Changjiang River, China. *Journal of Geographical Sciences*, 28(5): 629-646. DOI: https://doi.org/10.1007/s11442-018-1495-8.

Wang, Y. C., Chen, X. B., Borthwick, A. G. L., Li, T. H., Liu, H. H., Yang, S.F., Zheng, C. M., Xu, J. H., & Ni, J. R. (2020a). Sustainability of global Golden Inland Waterways. *Nature Communications*, 11(1): 1-13. DOI: 10.1038/s41467-020-15354-1.

Wang, D. W., Ma, Y. X., Liu, X. F., & Huang, H. Q. (2019). Meandering-anabranching river channel change in response to flow-sediment regulation: Data analysis and model validation. *Journal of Hydrology*, 79: 124209. DOI:10.1016/j.jhydrol.2019.124209.

Wang, X., Huang, W., Lu, J. T., Luo, H. W., Fan, J., Wang, Q. Q., & Cao, Z. H. (2020b). Ecological protection measures and effects of channel regulation in Jingjiang River section. *China Harbour Engineering*, 40(1): 1-4. DOI:10.7640/zggwjs202001001.

Willems, J. J., Busscher, T., Woltjer, J. & Arts, J. (2018). Co-creating value through renewing waterway networks: a transaction-cost perspective. *Journal of Transport Geography*, 69: 26-35. DOI:10.1016/j. jtrangeo.2018.04.011

Wu, S. H., Cheng, H. Q., Xu, Y. J., Li, J. F, and Zheng, S. W. (2016). Decadal changes in bathymetry of the Yangtze River Estuary: human impacts and potential saltwater intrusion. *Estuarine Coastal & Shelf Science*, 182: 158-169. DOI:10.1016/j.ecss.2016.10.002.

Peng, T., Tan, H., Singh, V. P., Chen, M., Liu, J., Ma, H. B., & Wang, J. B. (2020). Quantitative assessment of drivers of sediment load reduction in the Yangtze River basin, China. *Journal of Hydrology*, 580: 124242. DOI:10.1016/j.jhydrol.2019.124242.

Quick, I., König, F., Baulig, Y., Schriever, S., & Vollmer, S. (2020). Evaluation of depth erosion as a major issue along regulated rivers using the classification tool Valmorph for the case study of the Lower Rhine. *International Journal of River Basin Management*, 18(2): 191-206. https://doi.org/10.1080/15715124.2019.1672699

Suedel, B. C., McQueen, A. D., Wilkens, J. L., Saltus, C.L., Bourne, S. G., Gailani, J. Z., King, J. K., & Corbino, J. M. (2021). Beneficial use of dredged sediment as a sustainable practice for restoring coastal marsh habitat. *Integrated Environmental Assessment and Management*, 1-12. https://doi-org.nuncio.cofc.edu/10.1002/ieam.4501.

Sun, Z. H., Li, Y. T., Ge, H., and Zhu, L. L. (2011). Channel erosion processes of transitional reach from gravel river bed to sand bed in middle Yangtze River. *Journal of Hydraulic Engineering*, 42(7): 789-797. DOI:10.1080/17415993.2010.547197.

Smith, N. D., Morozova, G. S., Marta, P. A., & Gibling, M. R. (2016). Dam-induced and natural channel changes in the Saskatchewan River below the E.B. Campbell Dam, Canada. *Geomorphology*, 269: 186-202. http://dx.doi.org/10.1016/j.geomorph.2016.06.041

Szałkiewicz, E., Jusik, S. & Grygoruk, M. (2018). Status of and Perspectives on River Restoration in Europe: 310 000 EUR per Hectare of Restored River. *Sustainability*, 10, 129-144. DOI:10.20944/preprints201712.0033.v1.

Rohács, J., & Simongáti, G. (2007). The role of inland waterway navigation in a sustainable transport system. *Transport*, 22: 148-153. DOI: 10.1080/16484142.2007.9638117.

Tian, Q, Yang, K. H., Dong, C.M., Yang, S. L., He, Y. J., & Shi, B. W. (2021). Declining Sediment Discharge in the Yangtze River From 1956 to 2017: Spatial and Temporal Changes and Their Causes. *Water Resources Research*, 57(5): e2020WR028645. DOI: 10.1029/2020WR028645.

Xia, J. Q., Deng, S. S., Lu, J. Y., Xu, Q. X., Zong, Q. L., & Tan, G. M. (2016). Dynamic channel adjustments in the Jingjiang Reach of the Middle Yangtze River. *Scientific Reports*, 6: 22802. DOI: 10.1038/srep22802.

Xia, J. Q., Deng, S. S., Zhou, M. R., Lu, J. Y., & Xu, Q. X. (2017). Geomorphic response of the Jingjiang Reach to the Three Gorges Project operation. *Earth Surface Processes and Landforms*, 42(6): 866-876. DO:10.1002/esp.4043.

Xu, Q. X., Yuan, J., Wu, W. J., & Xiao, Y. (2011). Fluvial processes in Middle Yangtze River after impoundment of Three Gorges Project. *Journal of Sediment Research*, 35(2): 38-46. DOI: 10.1002/clc.20818

Xu, Q. X., Zhu, L. L., and Yuan, J. (2013a). Research on water-sediment variation and deposition-erosion in Middle and Lower Yangtze River. *Yangtze River*, 44(23): 16-21. (in Chinese)

Xu, Q. X. (2013b). Study of sediment deposition and erosion patterns in the middle and downstream

Changjiang mainstream after impoundment of TGR. *Journal of Hydroelectric Engineering*, 32(2): 146-154. (in Chinese)

Yang, Z., Wang, H., Saito, Y., Milliman, J. D., Xu, K., & Qiao, S., et al. (2006). Dam impacts on the Changjiang (Yangtze) River sediment discharge to the sea: the past 55 years and after the three gorges dam. *Water Resources Research*, 42(4): W04407. DOI:10.1029/2005WR003970, 2006

Yang, S. L., Xu, K. H., Xu, Milliman, J. D., Yang, H. F., & Wu, C. S. (2015a). Decline of Yangtze River water and sediment discharge: Impact from natural and anthropogenic changes, *Scientific Reports*, 5: 12581. DOI: 10.1038/srep12581

Yang, C., Cai, X.B., Wang, X. L., Yan, R. R., Zhang, T., Zhang, Q., & Lu, X. R. (2015b). Remotely Sensed Trajectory Analysis of Channel Migration in Lower Jingjiang Reach during the Period of 1983-2013. *Remote Sensing*, 7: 16241-16256. https://doi.org/10.3390/rs71215828.

Yang, Y. P., Zhang, M. J., Zhu, L. L., Liu, W. L., Han, J. Q., & Yang, Y. H. (2017). Influence of Large Reservoir Operation on Water-Levels and Flows in Reaches below Dam: Case Study of the Three Gorges Reservoir. *Scientific Reports*, 7, 15640. DOI:10.1038/s41598-017-15677-y.

Yang, Y. P., Zhang, M. J., Sun, Z. H., Han, J. Q., & Wang, J. J. (2018). The relationship between water level change and river channel geometry adjustment in the downstream of the Three Gorges Dam. *Journal of Geographical Sciences*, 28(12): 1975-1993. https://doi.org/10.1007/s11442-018-1575-9.

Yang, Y. P., Zhang, M. J., Liu, W. L., Wang, J. J., & Li, X. X. (2019). Relationship between Waterway Depth and Low-Flow Water Levels in Reaches below the Three Gorges Dam. *Journal of Waterway Port Coastal and Ocean Engineering*, 145(1): 04018032. DOI:10.1061/(ASCE)WW.1943-5460.0000482.

Yang, Y. P., Zheng, J. H., Zhang, M. J., Zhu, L. L., Zhu, Y. D., Wang, J. J., & Zhao, W. Y. (2021a). Sandy riverbed shoal under anthropogenic activities: The sandy reach of the Yangtze River, China. *Journal of Hydrology*, (27): 126861. https://doi.org/10.1016/j.jhydrol.2021.126861.

Yu, T. H. (2005). Essay on the upper Mississippi river and Illinois waterway and US. Grain market. *Texas: Texas A＆M University*, 2005.

Zhang, W., Yuan, J., Han, J. Q., Huang, C. T., Li, M. (2016). Impact of the Three Gorges Dam on sediment deposition and erosion in the middle Yangtze River: a case study of the Shashi Reach. *Hydrology Research*, 47(Z1): 175-186. DOI:10.2166/nh.2016.092.

Zong, Q. L., Xia, J. Q., Zhou, M. R., Deng, S. S., & Zhang, Y. (2017). Modelling of the retreat process of composite riverbank in the Jingjiang Reach using the improved BSTEM. *Hydrological Processes*, 31: 4669-4681. https://doi.org/10.1002/hyp.11387.

Zhou, M. R., Xia, J. Q., Lu, J. Y., Deng, S. S., & Lin, F. F. (2017). Morphological adjustments in a meandering reach of the middle Yangtze River caused by severe human activities. *Geomorphology*, 285: 325-332. DOI:10.1016/j.geomorph.2017.02.022.

Zhu, L. L., Yang, X., & Xu, Q. X. (2017). Response of low water level change to bed erosion and the operation of Three Gorges Reservoir in Upper Jingjiang reach. *Acta Geographica Sinica*, 72(7): 1184-1194. DOI: 10.11821/dlxb201707005.

Zhu, L. L., Xu, Q. X., & Xiong, M. (2017). Fluvial processes of meandering channels in the Lower Jingjiang River reach after the impoundment of Three Gorges Reservoir. *Advances in Water Science*, 28(2): 193-202. DOI:10.14042/j.cnki.32.1309.2017.02.004.