

Analysis of Riverbed Evolution of the Waigaoqiao Branch Channel of the Yangtze Estuary in Flood Period Under New Water and Sediment Conditions

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To cite this article:

Dai Wenyuan. Analysis of Riverbed Evolution of the Waigaoqiao Branch Channel of the Yangtze Estuary in Flood Period Under New Water and Sediment Conditions. *American Journal of Water Science and Engineering*. Vol. 7, No. 2, 2021, pp. 48-56.

doi: 10.11648/j.ajwse.20210702.13

Received: April 27, 2021; **Accepted:** May 8, 2021; **Published:** May 21, 2021

Abstract: With the change of sediment conditions in the Yangtze River Estuary, the river regime evolution pattern has entered a new stage. The overall trend has changed from siltation to erosion, and the impact of the evolution trend of overall river regime on local river regime needs to be further studied. Based on the hydrological and topographic data of flood season in 2020, this paper analyzes the riverbed change of Waigaoqiao branch channel during flood period under new water and sediment conditions. The river bed evolution law and causes of scouring and silting are analyzed statistically. Result shows that the water depth of branch channel decreases with the influence of channel dredging and river regime change in South Harbour under new water and sediment condition. During the flood period of 2020, the Waigaoqiao branch channel generally presents a continuous silting situation, mainly located in the front of Waigaoqiao Wharf (phase IV). The increase of sediment concentration caused by the flood and the scouring of shoal along the upstream of the branch channel are the main reasons for the silting of the branch channel. Based on the actual needs of waterway operation and maintenance, this paper puts forward relevant countermeasures and suggestions according to the analysis results.

Keywords: New Water and Sediment Conditions, Flood, Yangtze River Estuary, Waigaoqiao Branch Channel, Riverbed Evolution

1. Introduction

The Shanghai Waigaoqiao Branch Channel is located on the south bank of the South Port of the Yangtze River Estuary and adjacent to the Yuanyuansha precautionary area. It is recognized as a vital part of the Waigaoqiao Channel and the connecting water area between the front of the wharf in the Waigaoqiao Port Area and the deep-water channel. In addition, it can primarily satisfy the berthing and unberthing needs of ships in the Waigaoqiao port area and the up and down navigation requirements of small and medium-sized ships in the main channel. Moreover, there is a relatively large flow of ships and frequent arrivals and departures of ships at the wharf [1]. The variations in the river bed and the safety of the water depth are of essential significance for ensuring the navigation safety of the coastal port channel and the main channel of the South Port.

Due to the changes of river regime in Nangang around 2005, amount of sand passed through the northern channel, which not only caused the process silting from the upstream to the downstream, but also intensified the backsilting in the middle section [2-5]. As the amount of the incoming sediment in the Yangtze River Basin has been decreasing, the evolution of the Yangtze River Estuary is undergoing a significant change [6]. The succession model has ushered in a novel stage, which is being transformed from a trend of overall silting over the years to a trend of overall erosion. However, the respective region of the estuary exhibits different erosion and deposition characteristics. The river section above the sandbar at the estuary and the front edge of the underwater delta have been scouring, and the sandbar water area remains slowly silting up [7]. Over the past few years, as river regime adjustments have been gradually transmitted downstream, the deep trough of the Nangang section above the sandbar has been scouring and

cutting downward. Besides, the evolution of the areas on both sides of the deep groove reveal different characteristics. Moreover, the response of local river regime variations to the overall river regime evolution has displayed a certain spatial difference [8]. After a series of waterway regulation and river regulation projects have been conducted [9], the river bed boundary of the Yangtze River estuary and the overall river regime have been primarily stabilized. Nevertheless, the erosion and cutting of local sand bodies (e.g., the Xinliu River Sand and Shabao, Ruifeng Sand in the Nangang River section) still more significantly impact the Nangang Channel and the port area. In particular, the vicinity of the Waigaoqiao branch channel is significantly impacted by the overall river regime variations in Nangang and the sediment that has been discharged from the upstream beach, and some variations may irreversibly affect the future river bed evolution and the channel maintenance [10, 11]. Besides, the effect of river basin floods on river bed changes is of critical significance [12]. The 2020 flood season displayed the largest flood peak since the impoundment of the Three Gorges Reservoir, with the Datong flow of $84800 \text{ m}^3/\text{s}$, which is nearly twice the normal flow in the flood season. Given on the recent variations in the Nangang river regime, an analysis is conducted on the variations in the water depth conditions of the Waigaoqiao branch channel in the flood period under the novel water and sediment conditions and the effect of the overall river regime of the Nangang reach. Thus, this study is critical to ensure the

navigation safety of the existing waterways and the stable operation of the Waigaoqiao Port area, or research the dynamics of water and sediment under the new river regime.

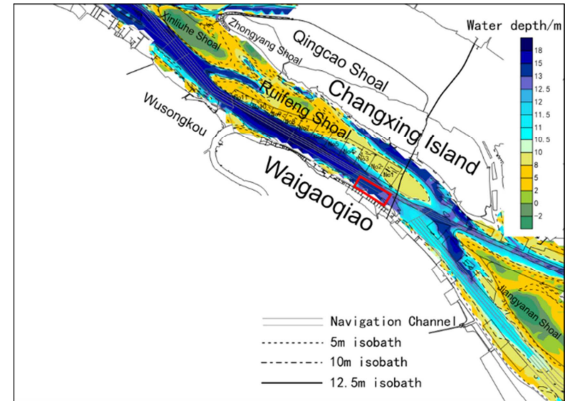


Figure 1. Schematic diagram of the location of the Waigaoqiao branch channel.

2. Incoming Water and Sand Conditions and the 2020 Flood Process

Since the 1950s, the annual average runoff of the Datong Station has been 895.9 billion m^3 , with relatively stable variations.

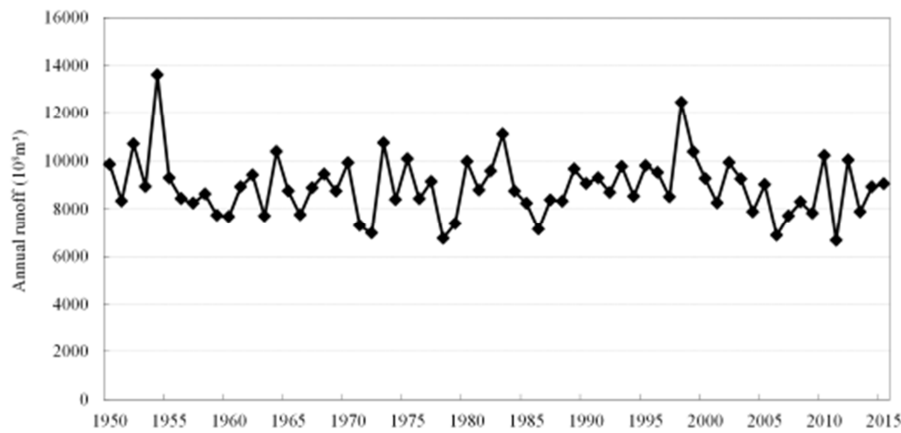


Figure 2. Annual runoff process of Yangtze River at Datong Station (1950~2019).

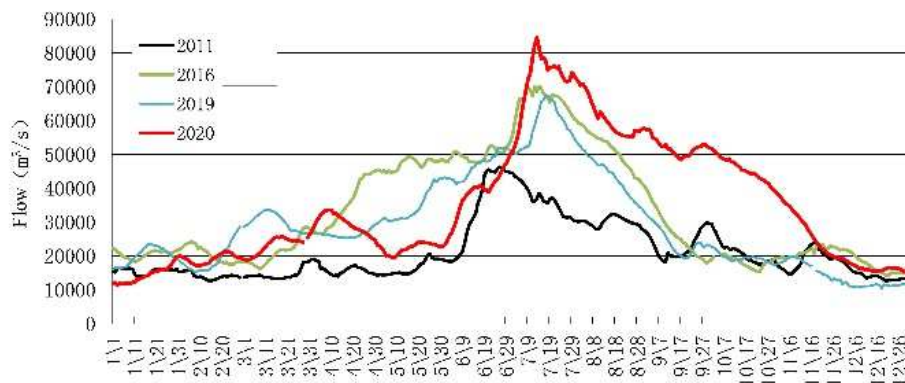


Figure 3. Datong flow process.

After a major flood in 2020, the Datong flow was peaked in July, and the Datong flow after July increased overall as compared with previous years. In May 2020, the average monthly Datong flow was approximately $20000\text{m}^3/\text{s}$; the peak value was $84800\text{m}^3/\text{s}$ in July 2020, with the average monthly flow of $71000\text{m}^3/\text{s}$; the flow in September remained at a relatively high value of nearly $52000\text{m}^3/\text{s}$ as compared with previous years.

From 1951 to 2019, the annual sediment transport at the

Datong Station decreased [13]. To be specific, the average annual sediment transport from 1951 to 1985, from 1986 to 2002, and from 2003 to 2019 reached 470 million tons, 340 million tons and 134 million tons, respectively. During the flood and dry seasons, the sediment transport in the Yangtze River estuary is different. The sediment transport takes up nearly 78.5% and 21.5% of the year in the flood season and dry season, respectively.

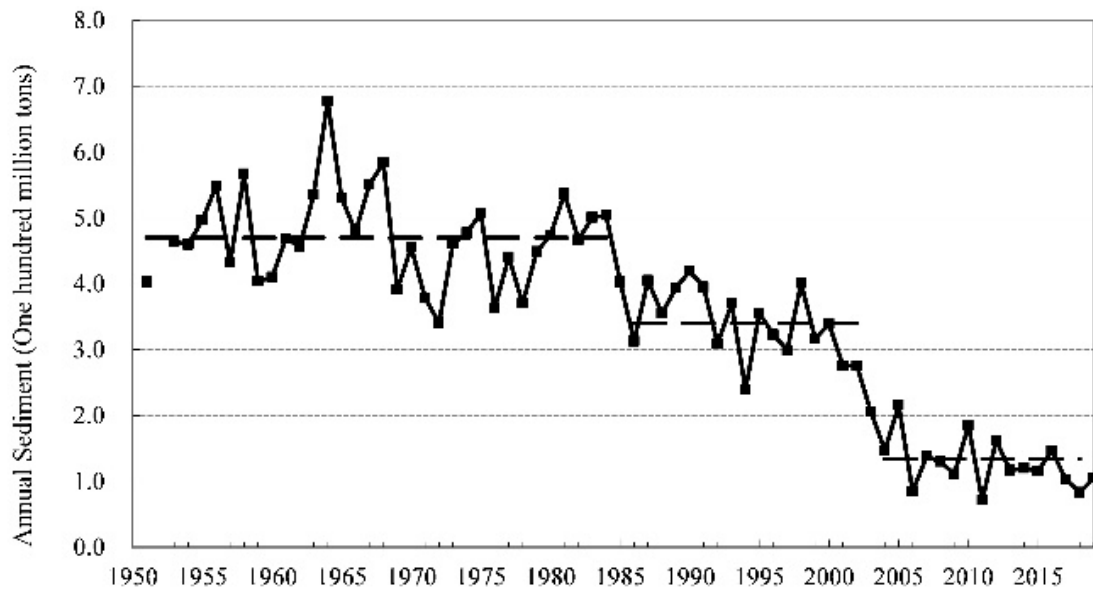


Figure 4. The change process of annual sediment transport at Datong Station (1951–2019).

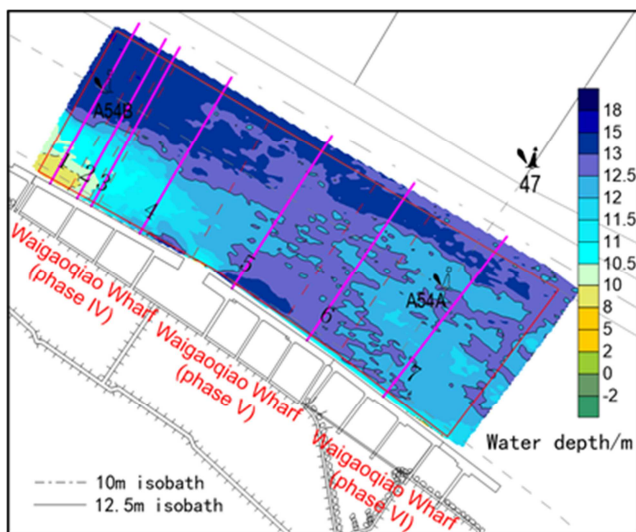


Figure 5. Water depth of the study area in Sept. 2020.

3. Analysis of Recent Evolution

1) Current status of the river

The waters north of the A54A-A54B light-floating line in the branch channels of Waigaoqiao Phases IV~VI is connected with the deep-water channel, and the water depth is great, which is basically 13~14m. The

Waigaoqiao Coastal Channel is the water area on the south side of the light-floating line, and the water depth is relatively shallow, generally shallower than 12.5m. It is also characterized by the low water depth in the upstream and the downstream, as well as the high water depth in the middle section. To be specific, the water depth at the front of Waigaoqiao Phase IV decreases significantly from north to south.

The design bottom elevation of the branch channel of Waigaoqiao Phases IV~VI undergoes the stepped arrangement, increasing from -10.0m to -11.5m from top to bottom, and then reducing to -10.5m. For the simple presentation, the maintenance dredging areas are numbered as 1~7 from top to bottom (Figure 1).

2) The law of river regime changes over the years

Given the water depth data of the fixed section of Nangang over the past years (the section illustrated in Figure 1), since 2009, the branch channel in the port area of Waigaoqiao Phases IV~VI has achieved the basically unchanged section shape, and the water depth has progressively increased. Recently, the increase rate has declined and tended to be stabilized [14]. To be specific, the section A8 refers to the water area in front of the upper wharf of Waigaoqiao Phase IV; the water depth exhibited by the section decreases from north to south; the coastal waters exhibit the relatively small water depth on the south side; the water depth patterns of

other sections are relatively stable.

From November 2009 to November 2010, the deep-water channel significantly had been deepened by 1.5~2m. Since then, the water depth has basically remained below 12.5m. From November 2010 to November 2014, the water depth

of the branch channel had increased significantly by 1.5~2m. Afterward, the water depth was relatively stable on the north side of the light-floating line, and the water depth on the south side slightly increased, marking a depth of about 1m.

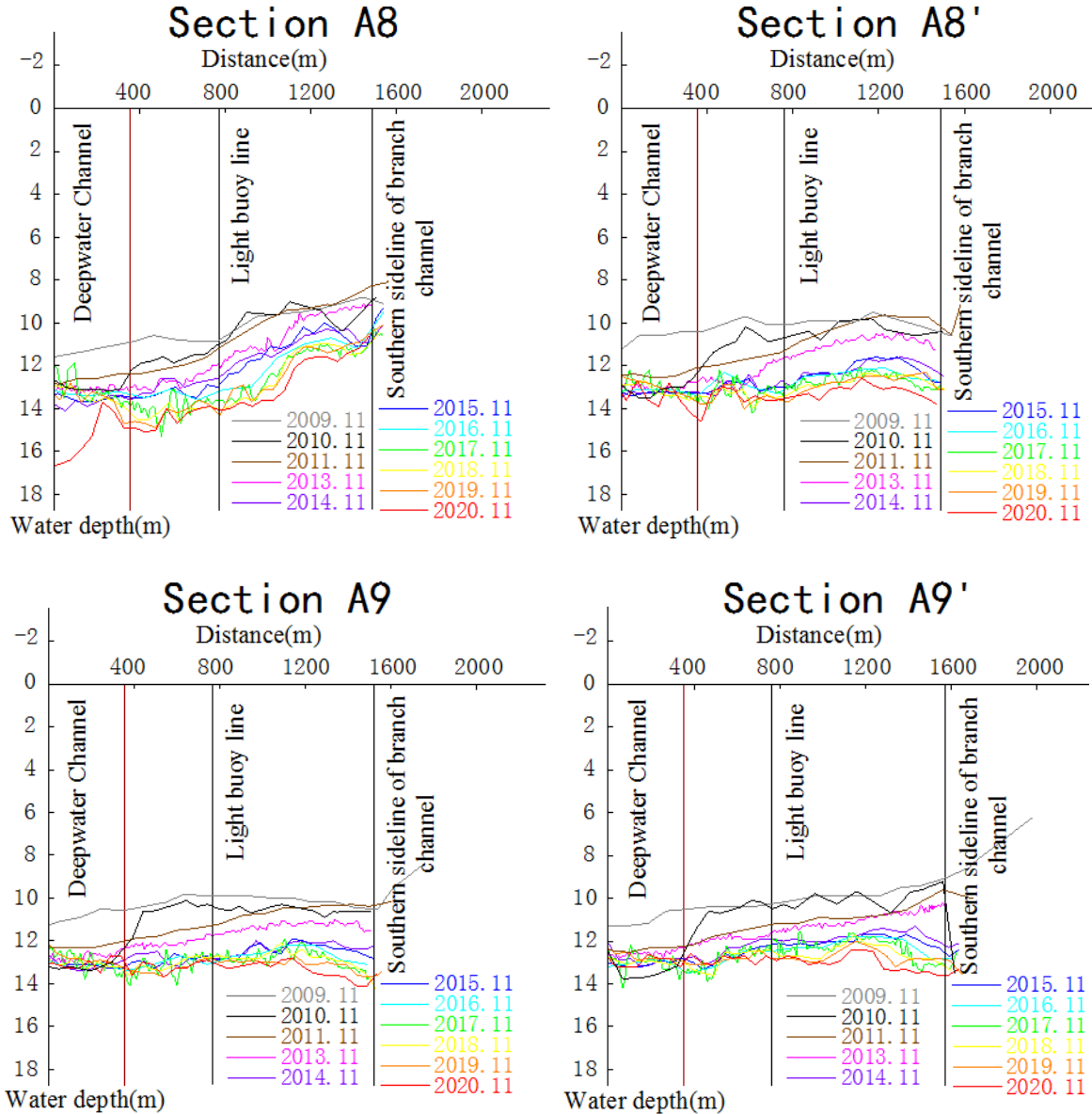


Figure 6. Water depth variations of typical sections at Waigaoqiao Phases IV~VI.

3) The law of river regime variations during the flood

Given the analysis on the topographical data in the major flooding period from May to September 2020, the branch channel of Waigaoqiao Phases IV~VI was continuously silted (Figure 7), which achieved an overall net siltation volume of 1.33 million m^3 . The section morphology of the respective dredging area did not significantly change, and the water depth decreased to a certain extent. The average water depth in the light-floating line in the dredging area decreased by nearly 0.5m. Figure 5 and Figure 8 respectively present the layout of

the dredging area and section and the typical section.

The near-shore siltation was largely concentrated in the front of the upper wharf of Waigaoqiao Phase IV; the siltation amplitude nearly reached 0.5~0.8m, and the riverbed close to the deep-water channel north of the light-buoy line achieved the overall siltation amplitude about 0.5m. From May to July, the downstream wharf of Waigaoqiao Phase IV and the vicinity of the A54B light buoy were being alternately scoured and silted, with an amplitude of 0.2~0.5 m.

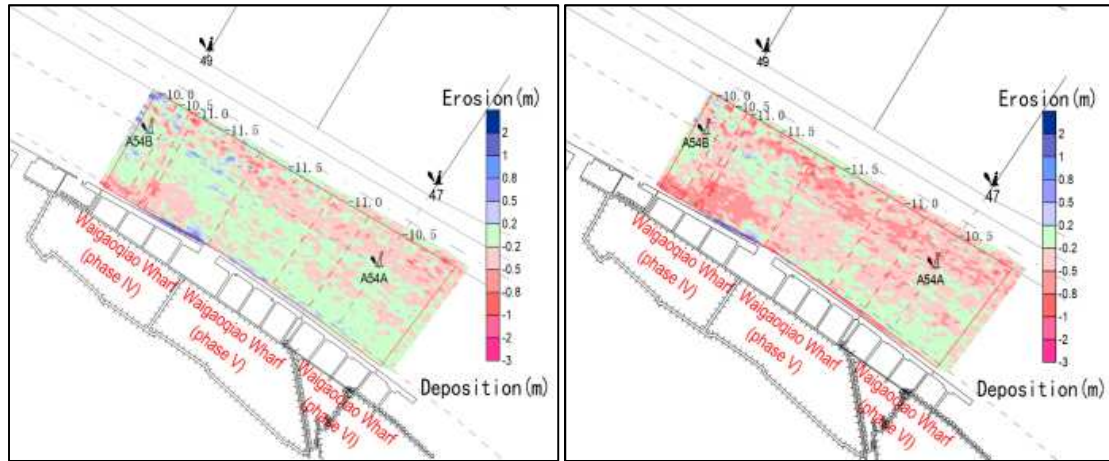


Figure 7. Water depth scour and siltation variations of Waigaoqiao Phases IV~VI.

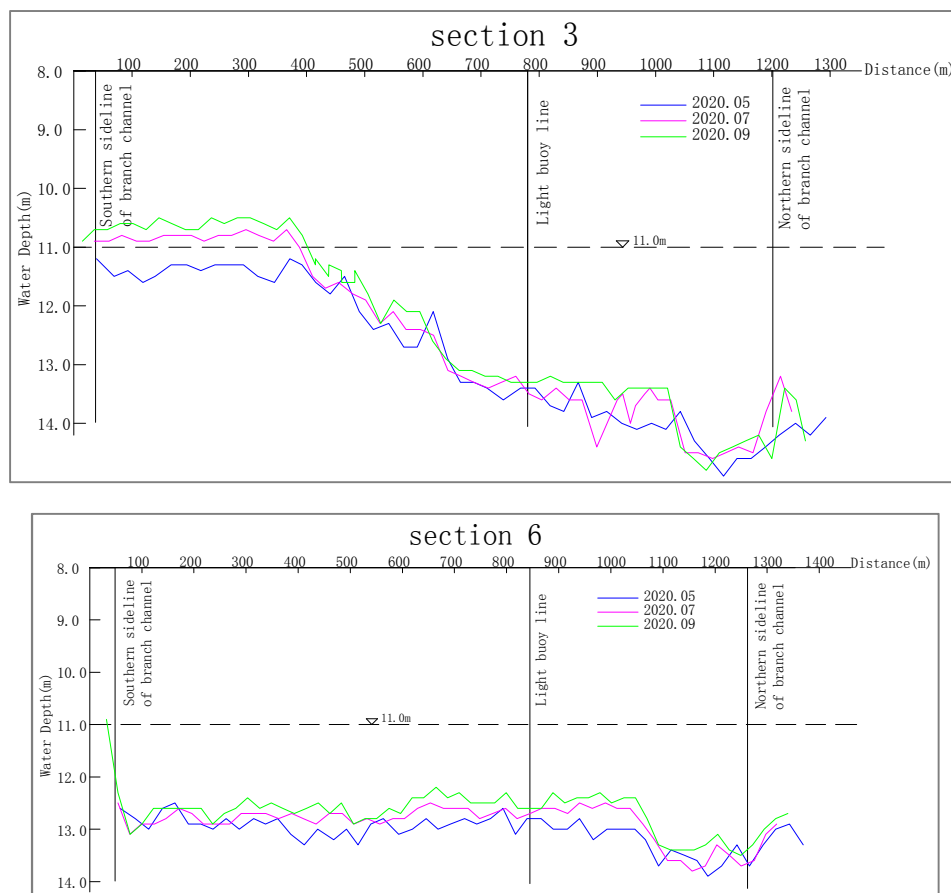


Figure 8. Water depth changes of the typical sections in 2020 (sections 3 and 6).

Under the new water and sediment conditions in the Yangtze River estuary, the overall erosion and deposition of the Waigaoqiao branch channel in the previous flood seasons was relatively balanced or undergoing a slight scouring process. From April to September 2018, the total scouring of the branch channel was 300,000 m³, and that from April to August 2019 reached 20,000 m³. Under the new water and sand conditions, the branch channel was significantly silted during the 2020 flood, and the siltation amount reached 1.33 million m³.

4) Shallow area analysis

With the normal operation of the wharf ensured, the bottom elevation of the stepped channel has been designed for the Waigaoqiao branch channel by complying with the characteristics of the water depth at the front of the wharf and years of dredging experience, as an attempt to decrease the amount of dredging and save the cost of channel maintenance. However, some areas remain, in which the water depth cannot satisfy the design requirements of the channel.

The Waigaoqiao branch channel was maintained and dredged at the end of February 2020. In May 2020, the water depth in the respective area was basically meet the channel

design requirements. When the channel was continuously silted during the flood season in 2020, the shallow spot rates of the areas 1~4 from July to September all exceeded 10%. For the distribution of shallow areas, the shallow areas of the channel were mainly distributed in front of Waigaoqiao Phase IV. For the change in the rate of shallow spots, the area of the shallow area in front of the Waigaoqiao Phase IV Wharf significantly was broadened from May to July. From July to September, under the high upstream flow, there was no erosion in the shallow area, and the rate of shallow spots still increased slightly.

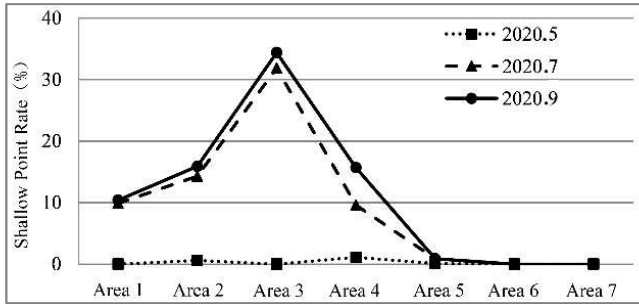


Figure 9. Changes of the shallow point rate of each subarea.

4. Analysis of the Causes of Erosion and Siltation

1) Changes in incoming water and sand conditions

The average sand content of the flood season in recent years overall decreased, as revealed by the statistics of the NG0 station on the fixed vertical line of Nangang (located on the north side of the lower section of the Nangang channel). The average sand content in the flood season from 2014 to 2020 was nearly 0.2kg/m^3 , about 60% less than that before 2008. Since the amount of sediment coming from the upper reaches of the Yangtze River declines, Nangang has been slightly scouring over the past few years, and the major changes in scouring and silting remain with the development of the channeling and the erosion and discharge of sand bodies. Under the new water and sand conditions, the overall water depth of the branch channel has increased and turns out to be increasingly stable, which helps maintain the water depth of the channel.

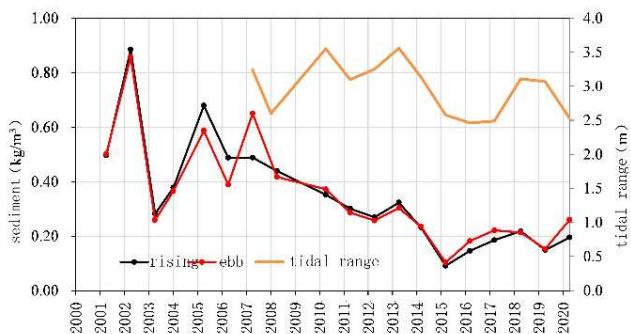


Figure 10. Changes in average sand content of Nangang during the flood season from 2001 to 2020.

During the flood of July 2020, the large runoff and relatively high sediment content in the Yangtze River estuary area led to the considerable sediment transport in the water body. This was one of the reasons for the siltation of the branch channel in the 2020 flood season. Besides, the flood period is strong, making it easy to form erosion. In the absence of late sediment replenishment, the local sand body exhibits a higher instability, and the sediment is discharged from the upstream beach, thereby causing the instability of the branch channel riverbed.

2) Adjustment of Nangang Beach and Trough Shape

Under new water and sediment conditions, the level of sediment concentration in Nangang waters has decreased overall over the past few years. In particular, the overall pattern of the Nangang beach trough has remained stable after 2012, the main trough has been converted into an erosion trend, and the deep trough has been widened. On the whole, the Changxing Waterway exhibited a scour situation. The sand tail of the upper sand body of Ruifeng Sand was eroded, and the ebb channel was developed and cut the upper sand body of Ruifeng Sand, thereby causing the south of the upper sand body to scour along the beach surface. The discharged sediment has formed a siltation zone in its downstream, thereby making the Wusongkou anchorage on the north side of the lower section of the Nangang main trough silt. As impacted by the siltation of shallow sand bodies 10m on the north side, the depth of the lower section of the Nangang main trough underwent a southward shift. Shenhong swayed to the south of Waigaoqiao Phase IV~VI wharf waters, and the Waigaoqiao branch channel was scoured.

On the whole, under the new water and sand conditions, Nangang has a stable overall river regime pattern. The volume of the 0m river channel increases, and the deep channel is in a state of erosion. The sand body on the north side of the lower section of the main trough is silted, while the deep part moves southward. All the mentioned conditions underpin the stability of the water depth of the Waigaoqiao branch channel on the south bank.

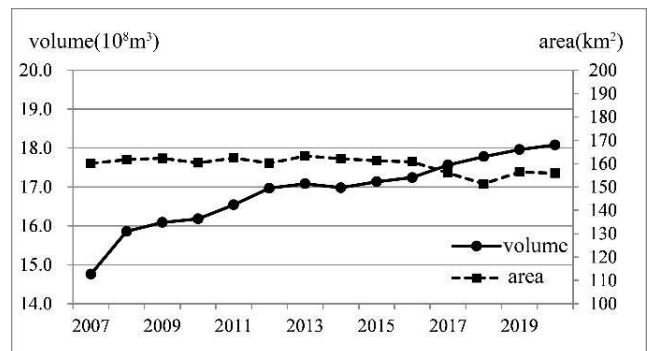


Figure 11. Volume change of the 0m river channel in Nangang.

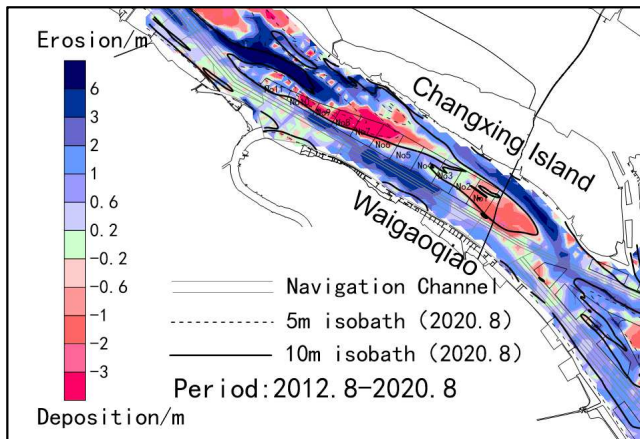


Figure 12. Topographic erosion and deposition map of Nangang (2012.8-2020.8).

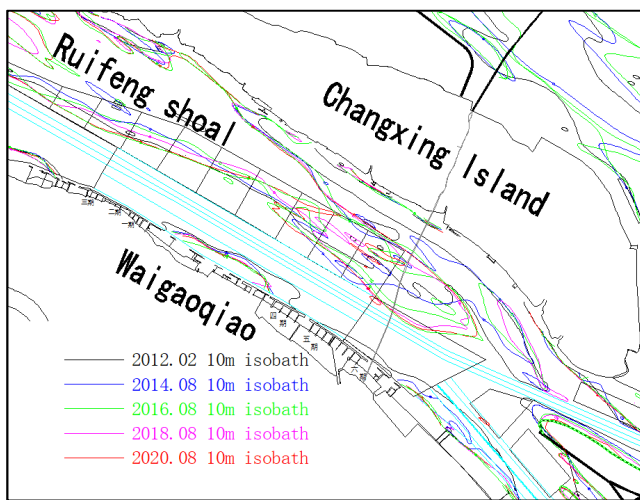


Figure 13. Change of 10m isobath of Nangang (2012.8-2020.8).

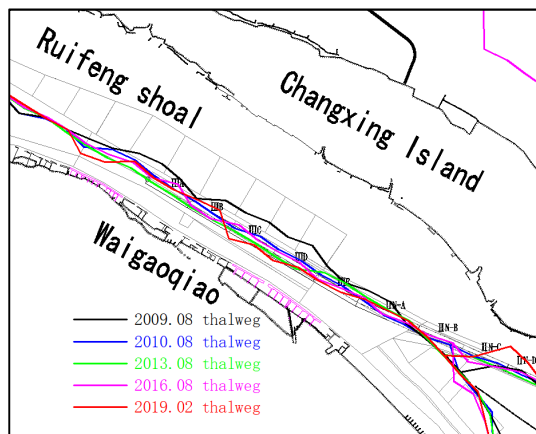


Figure 14. Changes of Nangang Shenhong Line.

According to the flow field during the rapid ups and downs of the Nangang flood season, Nangang's ebb tide exhibits the overall flow rate greater than the rising tide, and the overall flow direction is relatively smooth and consistent during the ebb tide. The upstream beach of Waigaoqiao Phase IV~VI Branch Channel is scoured by the ebb tide and then affected by the diverting current at high tide. Accordingly, the flow

rate decreases, and the sediment falls and causes the siltation. Thus, the front of Waigaoqiao Phase IV Wharf has constantly exhibited a silting state.

From May to August 2020, the upstream beach of Waigaoqiao Phase IV~VI pier was scoured and then narrowed, and the 10m isobath slightly retreated. The scouring of the upstream beach caused the sediment to be discharged, and silt fell in the maintenance dredging area of the downstream branch channel, especially in the front of Waigaoqiao Phase IV Wharf. The siltation range was between 0.2 and 0.6m.

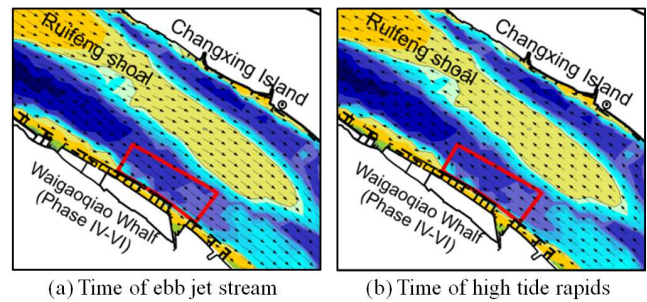


Figure 15. Flow field diagram at the peak of high tide during the flood season.

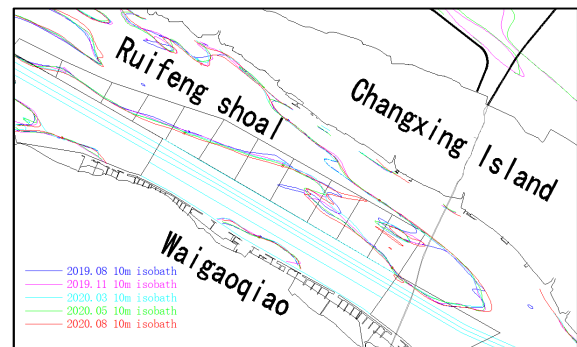


Figure 16. Change of 10m isobath of Nangang (2019.8-2020.8).

3) Dredging maintenance

The deep-water channel is located on the north side of the branch channel. During the maintenance dredging, the bottom soil has been disturbed, and the sand content in the nearby waters has increased, thereby causing the branch channel of Waigaoqiao Phases IV~VI to be silted [15].

The Waigaoqiao branch channel has been continuously maintained and dredged annually since the initiation of the infrastructure dredging project in 2010. Except for the emergency maintenance dredging in 2014, the amount of maintenance dredging decreased. From February 2016 to February 2020, the overall dredging volume for two maintenance dredging in the four years from February 2016 to February 2020 reached 100,000 cubic meters. As impacted by new water and sediment conditions in the upper reaches and human intervention in maintaining dredging, the water depth in this area has been relatively stable over the past few years. There was no channel for dredging during the major floods from May to September 2020. As indicated from the surveying map, the channel tended to be silted. In October

2020, the maintenance and dredging of the branch channel took up 200,000 cubic meters. It is therefore demonstrated that at this stage, especially in the environment of specific water and sand conditions, this area still requires regular terrain monitoring and maintenance dredging to meet the ship's berthing and navigation requirements.

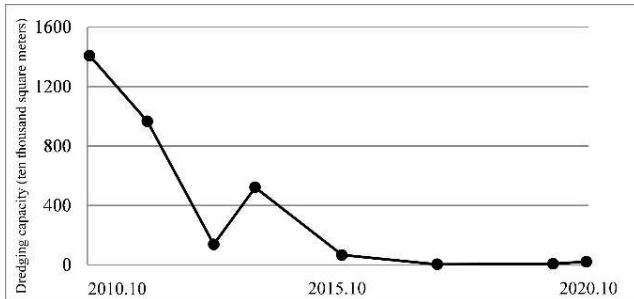


Figure 17. The amount of dredging of the branch channel of Waigaoqiao Phases IV~VI over the years.

5. Waterway Operation and Maintenance Needs Analysis and Countermeasures and Suggestions

1) Status of operation and maintenance of branch waterways

From the perspective of the Nangang shipping structure, the construction of the Waigaoqiao branch channel can comply with the berthing and unberthing requirements of large container ships at Waigaoqiao Wharf and ensure the normal and efficient operation of the terminal. Moreover, small ships can be diverted into the main channel, and the pressure on the deep-water channel can be reduced. The operation of the Waigaoqiao branch channel boosts the development of the Yangtze River Estuary shipping. From the perspective of the Nangang River regime, under the effect of new water and sand conditions and the implementation of a series of comprehensive treatment projects in recent years, the water depth conditions of the Waigaoqiao branch channel have been constantly stabilized with the progressive improvement and stabilization of the river regime of the Nangang deep channel. Accordingly, the requirements of the design water depth of the channel can be basically met. Thus, the construction of the Waigaoqiao branch channel is reasonable.

However, the branch channel is affected by the diverting flow pattern at high tide, the hydrodynamic force is insufficient, and the sedimentation has caused the shallow water depth in the front of Waigaoqiao Phase IV Wharf and a shallow area that hinders navigations. The mentioned situations were aggravated during the flood.

2) Response measures and suggestions

(1) Maintain water depth monitoring and channel dredging

As indicated from the changes in the water depth of the channel and the comparison of the dredging volume over the past years, the channel water is significantly impacted by the dredging. The branch channel may be blocked by the siltation

in the absence of the man-made interference (e.g., maintenance and dredging). Thus, it is necessary to continuously stress the changes in the water depth and topography of the area, strengthen topographic monitoring, and perform dredging maintenance-related works promptly.

(2) Properly extend the maintenance cycle and strengthen monitoring under special water and sand conditions

Under the new water and sand conditions and by maintaining the existing river regime pattern in Nangang, the maintenance period of this water area can be appropriately extended to down-regulate the maintenance cost. Besides, water depth monitoring is required to be optimized in the presence of floods, as an attempt to avoid obstructing navigations and affecting port productions.

(3) Continue to pay attention to changes in the pattern of Nangang river regime

The Waigaoqiao branch channel is located on the south bank of the lower reaches of Nangang, which is affected by changes in the upstream river regime. The south side of the upper sand body of Ruifeng Sand has been recently eroded by channeling gullies, sand tails have been scoured, and an independent sand body has been cut out on the south side of the upper sand body of Ruifeng Sand. As impacted by the activity of independent sand bodies, the silt released under the current Nangang scouring environment may be increasingly eroded, causing temporary siltation in the lower section of Nangang. In the long term, it is necessary to continuously stress the changes in the overall river regime in Nangang, especially the effect of changes in the river core sand bodies (e.g., Ruifengsha) on the outer Gaoqiao branch channel. If necessary, it is suggested to work with relevant departments to take certain rectification measures on Ruifengsha and stabilize the local river regime of Nangang and the water depth of the Waigaoqiao branch channel.

6. Conclusions and Prospects

1) Under the new water and sand conditions, the overall river regime pattern of Nangang turns out to be stable, the overall volume of the river channel has increased, and the deep channel exhibits a state of scouring. The sand tails of the upper sand body of Ruifeng Sand are eroded, and the ebb channel develops and cuts the upper sand body of Ruifeng Sand. The discharged silt is deposited on the north side of the lower section of the main trough, which causes local deep swells to move southward. Under the overall scoured river pattern of the main channel of Nangang and the effect of channel dredging, the water depth of the branch channel of the Waigaoqiao Phase IV~VI port area has progressively increased since 2009, and the increase rate has declined in recent years.

2) During the 2020 flood, the Yangtze River estuary area had a large runoff and a high sand content. The scouring of the upstream beach of the Waigaoqiao branch channel caused the sediment to leak. The dredging area in the downstream branch channel has been maintained, especially in the front of Waigaoqiao Phase IV Wharf. During such a period, the

Waigaoqiao Phase IV~VI branch channel was continuously silted, with a total net siltation volume of 1.33 million m³. The average water depth of each section has decreased to a certain extent.

3) Under the new water and sand conditions and by maintaining the existing river regime pattern in Nangang, the maintenance period of this water area can be appropriately extended to down-regulate the maintenance cost. However, at this stage, especially under certain water and sand conditions, regular terrain monitoring and maintenance dredging are necessary for this area to meet ship berthing and navigation requirements. In the long run, it is recommended to stress the overall river regime changes in Nangang, especially the effect of the changes in the sand bodies of the river core (e.g., Ruifengsha) on the outer Gaoqiao branch channel.

The analysis of riverbed evolution of Waigaoqiao branch channel in Changjiang Estuary can bring about significant direct economic benefits as well as many comprehensive social benefits. Analysis of riverbed evolution can not only promote water purification, but also create new habitats for aquatic animals. The analysis of riverbed evolution can reduce the energy consumption during ship transportation, promote energy conservation, emission reduction and green economic development. Therefore, the observation record of riverbed evolution of Waigaoqiao in the Yangtze Estuary should be kept in the next step, so as to promote the Yangtze River to drive the better development of surrounding economy.

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