A historical review of sediment export–import shift in the North Branch of Changjiang Estuary

Guo, Leicheng; Xie, Weiming; Xu, Fan; Wang, Xianye; Zhu, Chunyan; Meng, Yi; Zhang, Weiguo; He, Qing

DOI
10.1002/esp.5084

Publication date
2021

Document Version
Accepted author manuscript

Published in
Earth Surface Processes and Landforms

Citation (APA)
Guo, L., Xie, W., Xu, F., Wang, X., Zhu, C., Meng, Y., Zhang, W., & He, Q. (2021). A historical review of sediment export–import shift in the North Branch of Changjiang Estuary. *Earth Surface Processes and Landforms*, *47*(1), 5-16. https://doi.org/10.1002/esp.5084

A historical review of sediment export-import shift in the North Branch of Changjiang Estuary

Leicheng Guo [a, *], Weiming Xie [a], Fan Xu [a], Xianye Wang [a], Chunyan Zhu [a, b], Yi Meng [a], Weiguo Zhang [a], Qing He [a]

[a] State Key Lab of Estuarine and Coastal Research, East China Normal University, Shanghai 200241, China

[b] Civil Engineering and Geosciences faculty, Delft University of Technology, PO Box 5048, Delft 2600 GA, the Netherlands

[*] Corresponding author, E-mail: lcguo@sklec.ecnu.edu.cn

Abstract

Net sediment transport is predominantly seaward in fluvial-dominated estuaries worldwide. However, a distributary branch in the Changjiang Estuary, the North Branch, undergoes net landward sediment transport, which leads to severe channel aggradation. Its controlling mechanism and the role of human activities remain insufficiently understood, although such knowledge is necessary for better management and restoration opportunities. In this study we revisit the centennial hydro-morphodynamic evolution of the North Branch based on historical maps, field data, and satellite images and provide a synthesis of the regime change from ebb to flood dominance. The North Branch was once a major river and ebb-dominant distributary channel. within which alternative meandering channels and sand bars developed. Deposition of river-borne sediment leads to infilling of the branch, while tidal flat embankment reduces the bankfull width and modifies the channel configuration, resulting in a profound decline in the sub-tidal flow partition rate. The North Branch then becomes tide-dominant with an occurrence of tidal bores and elongated sand ridges. Once tidal dominance is established, extensive tidal flat reclamation enhances the funnel-shaped planform, amplifying the incoming tides and initiating a positive feedback process that links tidal flat loss, sediment import, and channel aggradation. Overall, the shift in branch dominance is a combined result of a natural south-eastward realignment of the deltaic distributary channels and extensive reclamation. One management option to mitigate channel aggradation is to stop the aggressive reclamation and allow tidal flats to build up, which might reduce the sediment import and eventually lead to a morphodynamic equilibrium in the longer term. Understanding the impact of tidal flat reclamation is informative for the management of similar tidal systems under strong human interference.

Key words: Changjiang; Morphodynamics; Flood dominance; Reclamation; Regime shift

1. Introduction

Tidal estuaries and basins can be flood- or ebb-dominant depending on the basin geometry, tidal properties, the amount of inter-tidal flats, and river discharge magnitude (Friedrichs and Aubrey, 1988; Ridderinkhof et al., 2004; de Swart and Zimmerman, 2009). In general, short tidal basins without significant tidal flats and no river discharge are more likely to be flood-dominant because tidal wave deformation in shallow waters leads to shorter rising tides and stronger flood currents (Friedrichs and Aubrey, 1988; Lanzoni and Seminara, 2002). The presence of a significant number of inter-tidal flats tends to enhance ebb currents owing to the hydraulic storage effect of inter-tidal flats (Speer and Aubrey, 1985). A (seaward) Stokes' return flow in long basins may also benefit ebb dominance (van der Wegen and Roelvink, 2008; Guo et al., 2014). River flow enhances tidal wave deformation by prolonging the falling tide and intensifying ebb currents, which reinforces ebb dominance (Guo et al., 2014). Ebb or flood dominance is defined herein as the seaward or landward tide-averaged sediment transport, respectively. Flood-dominant estuaries import sediment from the sea, leading to basin infilling and accretion of tidal flats. In contrast, ebb-dominant systems export sediment to the sea, leading to basin emptying and enlarged channel volumes. The nature of tidal asymmetry plays a dominant role in controlling the large-scale estuarine morphology in the longer term. Thus, it is of practical importance to understand the dynamic behaviour and controlling processes of tidal asymmetry.

While tidal asymmetry and net dominance have been extensively studied in single-channel environments with minimal river discharge influence (Dronkers, 1986; Ridderinkhof et al., 2004), the variability of branch dominance is insufficiently studied in branched estuaries where multiple bifurcated branches exhibit different dynamics. The Changjiang Estuary is such a case: four branches connect to the coastal ocean, of which the South Branch and its seaward channels and passages are the main conduits of river-borne freshwater and sediment. In contrast, the North Branch is currently a tide-dominant branch with limited river influence. Accordingly, the South Branch is ebb-dominant and the North Branch is flood-dominant, where sediment import leads to continued net deposition and channel aggradation (Dai et al., 2016). This has raised management concerns regarding the fate of the North Branch if it is expected to be continuously infilled.

Research on the North Branch has been limited compared with that on the other parts of the Changjiang Estuary. Few studies have examined the tidal bores (Chen, 2003), reverse flow and salt intrusion (Wu et al., 2006; Zhang et al., 2019, 2020), and sedimentation and aggradation of the North Branch (Yun, 2004; Dai et al., 2016; Li et al., 2020; Obodoefuna et al., 2020). The North Branch was once one of the main branches discharging riverine water and sediment to the sea, implying a regime of ebb dominance, but became flood-dominant since the 1950s (Yun, 2004). However, it remains poorly understood how the hydrodynamic regime in the North Branch has changed over time and what caused the regime shift from ebb to flood dominance. Such knowledge is a prerequisite for sustainable management and restoration opportunities in the North Branch and can also inform management of tidal basins and estuaries elsewhere that are undergoing similar human interventions and changes. For instance, land reclamation across the Pearl River Delta has substantially extended the shoreline towards the sea and induced shrinkage of the channel volume (Liu et al., 2019). In the Western Scheldt Estuary, reclamation and dredging have similarly caused channel shrinkage and tidal amplification (de Vriend et al., 2011). In this study, we provide a synthesis of the centennial hydro-morphodynamic evolution of the North Branch based on field data to clarify historical changes and the impact of human activities. Further exploration of the governing mechanisms by using a numerical hydro-morphodynamic model will be presented in a future paper.

2. Physical settings and data

The Changjiang Estuary is one of the world's largest tidal estuaries in terms of the magnitude of river discharge, strength of the tide, and spatial scale of the tidally influenced reach. It is forced by a river discharge of 10,000–60,000 m^3/s seasonally at the tidal wave limit and semi-diurnal tides with a spring tidal range up to 5.9 m. Wind and wave effects and alongshore currents are also significant but of secondary importance compared with rivers and tides. The Changjiang Estuary is dynamically divided into a tidal river upstream of Jiangyin where river forcing dominates, and a seaward tidal estuary, where both the river and tides are important (Guo et al., 2015). The tidal estuary has a funnel-shaped planform, and morphologically, it features by three bifurcations into four main branches entering the East China Sea (Figure 1a).

The division between the North Branch and South Branch formed as a result of the first bifurcation, and the latter is presently the major conduit of river-borne freshwater and sediment. The South Branch and its seaward channels have been scientifically examined in much more detail than the North Branch owing to the importance of the former for navigation and water supply. However, saltwater intrusion in the North Branch could reach the South Branch and threatens the freshwater intake and supply for the reservoir surrounding the South Branch (Wu et al., 2006). The strong saltwater intrusion is explained by sub-tidal sea water accumulation in the upper part of the North Branch because of converged Stokes' transport in response to channel narrowing (Zhang et al., 2020). To mitigate saltwater intrusion, there is a plan to construct a barrier (with gates) at the mouth of the North Branch, but the impact on the ecosystem and the fate of the North Branch remains open questions.

The present North Branch is a convergent tide-dominant branch with minor river influence (Figure 1b). Its upper part, from the inflow section to the bend around Qinglong, has a length of 20 km, which is relatively narrow in width, i.e., a mean bankfull width of ~2.0 km. The middle and lower parts, downward the bend until the mouth area, have a combined length of ~60 km, creating a funnel-shaped channel with a high convergence rate. The branch width increases to ~12 km at the mouth section around Lianxing. The North Branch is shallower than other branches in the Changjiang Estuary, with a mean depth of 2–4 m (Dai et al., 2016), as a result of sediment import and intensive sedimentation over the past century. The mean tidal range at the mouth is 3.2 m, and it increases up to 3.8 m in the middle segment and then decreases to 2.6 m in the inflow section. Tidal bores are observed in the upper part of the North Branch owing to strong wave amplification, and the maximum tidal range is 5.0 m (Chen, 2003). Elongated tidal sand ridges developed in the lower part of the branch, and a mouth bar formed in the region seaward of the mouth.

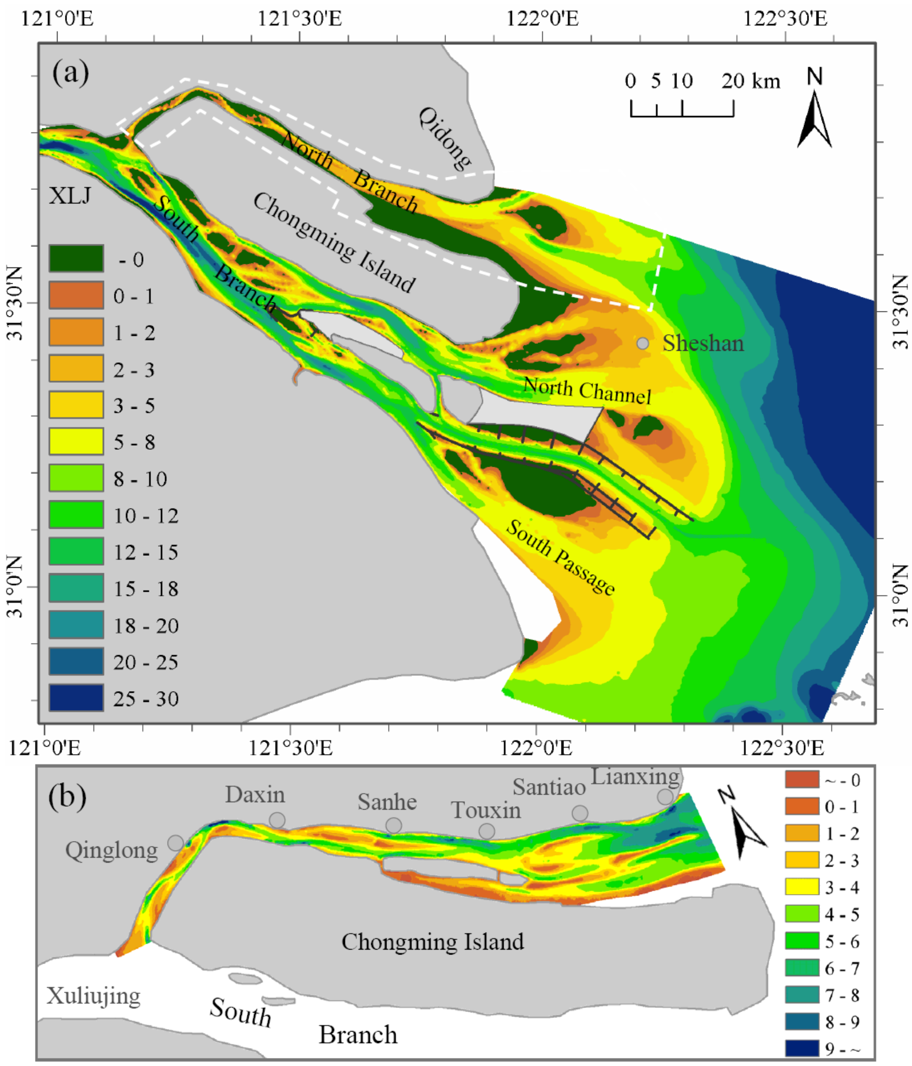

Figure 1. (a) The tidal estuary part of the Changjiang Estuary with its bathymetry in 2016; (b) the North Branch with its bathymetry in 1998. XLJ is

the abbreviation of Xuliujing. The water depth and elevations reference to the lowest tides.

We collected data in the form of historical maps showing the large-scale topography of the delta, instrumental bathymetry data of the North Branch detailing the underwater morphology, and satellite images. Historical maps published since the 17th century were collected to illustrate the planform changes throughout the estuary and in the North Branch (see sections 3.1 and 3.2). The majority of the historical maps were collected from the University of Texas library (http://legacy.lib.utexas.edu/maps/historical/), the Virtual Shanghai website (https://www.virtualshanghai.net), the David Rumsey Map Collections (https://www.davidrumsey.com), and the United States Library of Congress (https://www.loc.gov), unless otherwise specified. Digitized bathymetric data from 1958, 1978, 1998, and 2019 were geo-referenced and analysed in-depth using GIS tools (see section 3.3). Satellite images captured since 1974 were collected from Landsat (https://earthshots.usgs.gov), and historical coastline changes were identified based on the dikes and levees.

3. Hydro-morphodynamic evolution

3.1 Initial branch bifurcation

The initial formation of the North Branch is part of the development story of the entire Changjiang delta. The development of the present sub-aerial delta started from the infilling of an incised valley seaward of Yangzhou formed during the low sea-level conditions (Figure 2; Chen et al., 1985). The present delta began to prograde eastward when rising sea levels reached a height close to present levels, which was around 6000–7,500 aBP (Wang et al., 2018). The tides play a role in enhancing sediment deposition (Uehera et al., 2002). Several sand bars and shoals successively developed in the river valley (Figure 2; Chen et al., 1979; Li et al., 2002), which later developed into large shoals and/or merged into the northern delta plain (Li et al., 2000, 2002; Zhang and Meng, 2009; Jiang et al., 2020). The distributary channels over the delta then moved south-eastward step-by-step with an infilled valley and delta build-up (Figure 2).

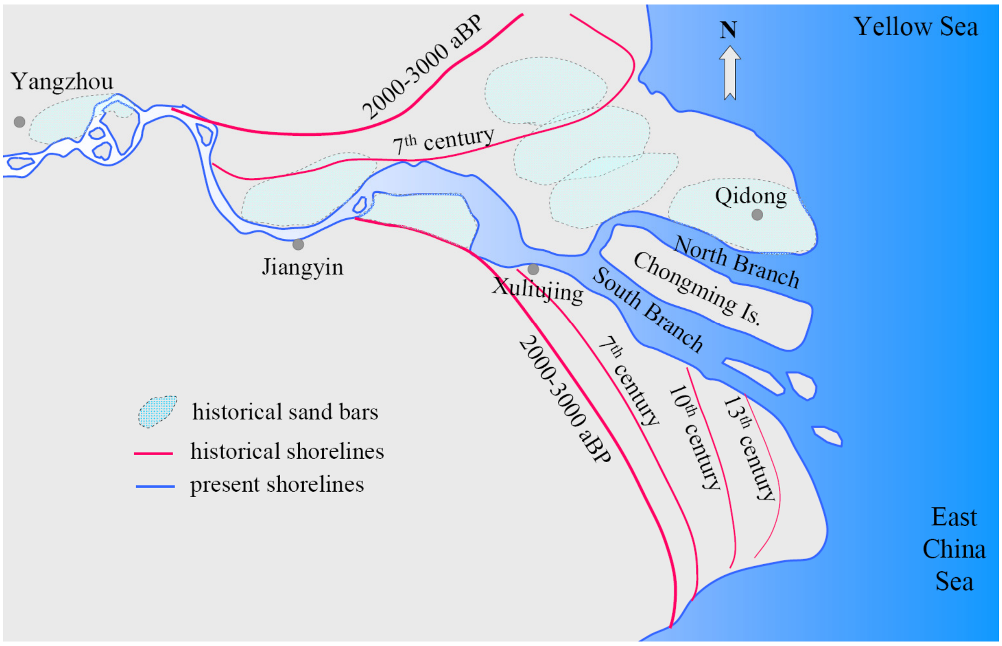

Figure 2. A sketch of the historical development of the Changjiang River delta over the past 2,000 years, with identified historical coastlines and sand bars Adopted from Chen et al. (1985).

The sand bars scattered throughout the estuary changed profoundly in size and location owing to channel migration, and no stabilized channels were identified prior to the 7th century owing to alternating erosion and deposition processes. Thereafter, several small mid-channel sand bars were combined to produce one large sand bar, which formed the base of the present Chongming Island. Starting from the 7th century, human settlements on the sand bars and other human activities helped to stabilize the coastlines of this island (Chen et al., 1979, 1985). The stabilized Chongming Island then led to a stable bifurcation between the South Branch and the North Branch.

3.2 Stabilized development

Field data of the North Branch are rare prior to the 1950s, and the morphological evolution of this branch is interpreted mainly based on historical geography maps and geological studies. The North Branch was a main distributary channel flushing a major portion of fluvial water and sediment to the sea prior to the 1860s (Yun, 2004), with a sub-tidal flow partition rate (i.e., the ratio of the tide-averaged flow towards the North Branch compared to the total of North and South branches) exceeding 50%. Deposition of river-supplied sediment within the North Branch caused rapid development of the northern delta plain and an overall south-eastward realignment of the entire delta (Figure 3). As a result, the majority of the fluvial water and sediment has been diverted into the South Branch since the 19th century, and the North Branch has since become a secondary distributary channel (Chen and Li, 2002).

Historical maps reveal the planform changes in a straightforward manner, although they lack details of the underwater bathymetry (Figures 3 and S1–S2). The initial North Branch was fairly wide and appeared to be a sub-basin rather than a branch; it was initially called the North Entrance following its formation. Continued sedimentation led to the development of a series of sand bars and shoals inside the North Branch. In the late 19th century, the sand bars that formed around the mouth section merged into the northern bank, resulting in a profound south-eastward advance of the northern delta plain (i.e., eastward by ~27 km and southward by ~15 km) between 1842 and 1912 (Figure 3; Yun, 2004). Since then, the changes along the northern coastline of the North Branch became limited owing to shoreline protection activities. The inflow section of North Branch had a width of 15 km, and the mouth section was 36 km in width in 1842 (Yun, 2004). However, the inflow segment narrowed significantly after the 1860s due to the formation and merging of sand bars into the northern bank, leading to a reduction in width to 5.8 km in 1915 (see Figure 4a).

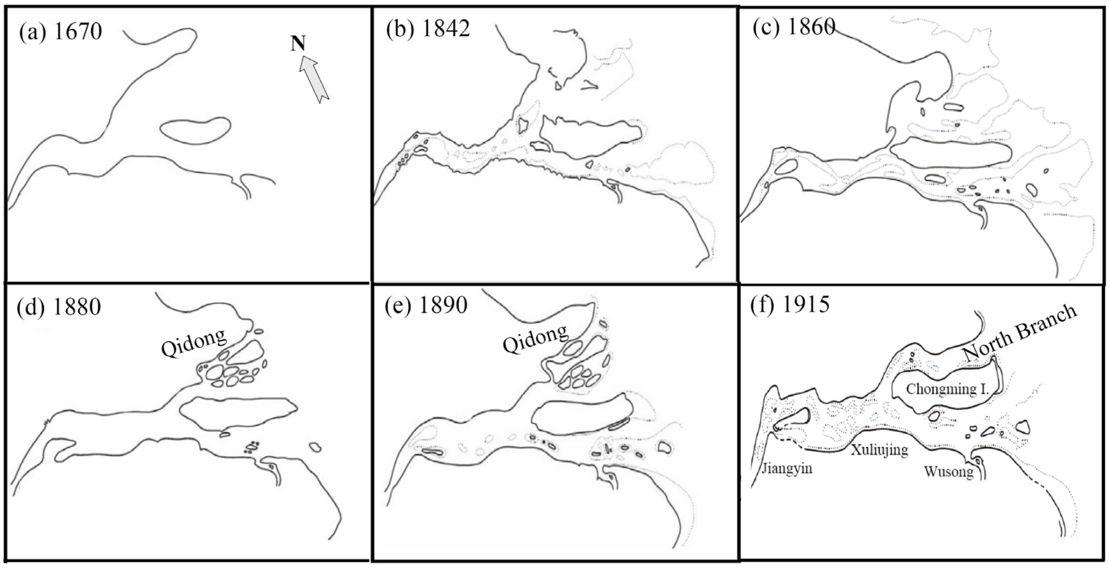

Figure 3. Planform changes of the Changjiang Delta and the North Branch in the past 300 years: (a) 1670, (b) 1842, (c) 1860, (d) 1880, (e) 1890, and (f) 1915. Adopted from Huang (1986) and Yun (2004) and historical maps (see Figures S1 and S2).

More details regarding the underwater bathymetry are available in maps published in 1915–1917 (see Figure S2). The North Branch was nearly uniform in width at that time, although it had a curved planform (Figure 4a). The sub-tidal flow partition ratio reduced to approximately ~25% in 1915, which implies a significant fluvial influence (Zou, 1981; Chen et al., 1988). Meandering channels and sand bars developed inside the North Branch, and the overall channel-shoal configuration was consistent with the curved planform (Figure 4a). Deeper ebb channels developed toward the outer bends of the meanders while flood channels flanked the sand bars. In the mouth zone, sedimentation produced a mouth bar, and the ebb tidal delta grew larger over time. This channel-shoal pattern is typical of that in long tidal basins and estuaries (van Veen et al., 1950).

Beginning in 1958, the North Branch became much narrower, predominantly owing to strong sedimentation along the southern bank (Figure 4b); however, the northern bank had also retreated by 2–3 km on average between 1907 and 1958 (Zou, 1987; Yun, 2004). The width of the Qinglong section decreased from 6 km in 1917 to 2 km in 1958, while that of the Sanhe section decreased from 8.5 km in 1917 to 4.0 km in 1978 (Chen et al., 1985). Convergence in planform started to emerge owing to more width reduction in the upper regions of the branch. Moreover, the North Branch also became shallower and the meandering channel-shoal structure vanished. Its sub-tidal flow partition rate declined to ~7.6% in 1958 (Zou, 1987; Yun, 2004), implying a decreased river influence and a change towards tide dominance. Tidal bores began forming in the 1940s (Chen and Shen, 1988). In addition, the partition rate of the sub-tidal flow was negative during the spring tides in the dry season as early as 1959, suggesting a reversed flow and the occurrence of flood dominance. Sediment import led to a net deposition of 1.45 km^3 between 1915 and 1958 within the North Branch (Zou, 1987). Therefore, the previously present meandering channel-shoal structure was replaced by disconnected shallow tidal channels and elongated sand ridges (Figure 4).

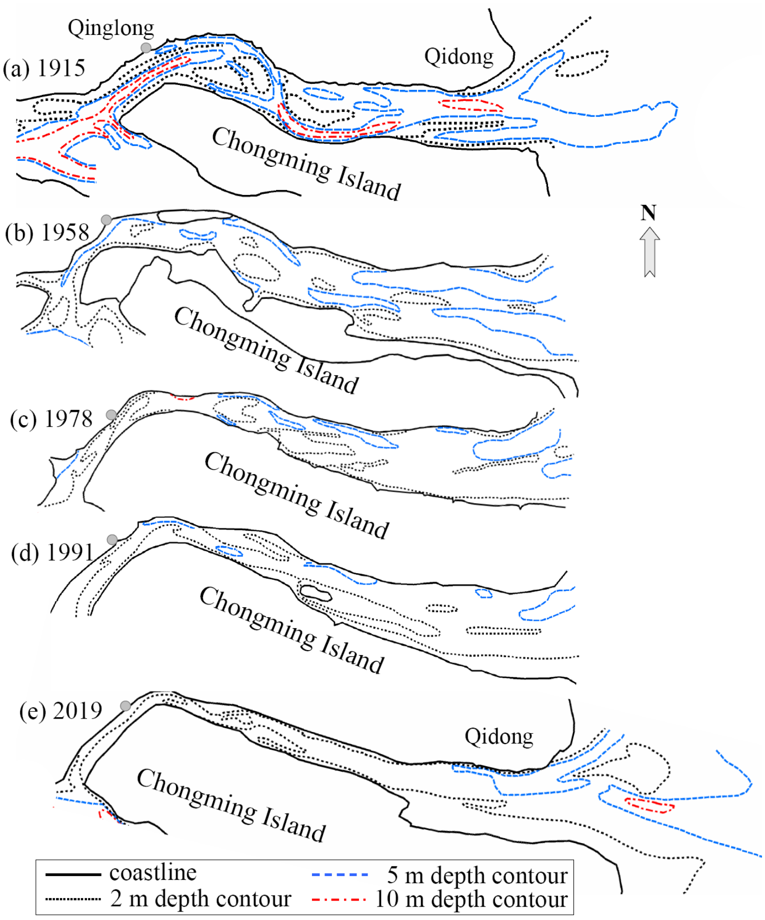

Figure 4. Sketches of the topography changes of the North Branch in (a) 1915, (b) 1958, (c) 1978, (d) 1991, and (e) 2019. Historical data prior to 1991 are acquired from Zou (1987) and Yun (2004).

3.3 Human-forced evolution

The hydro-morphodynamic evolution has accelerated since 1958 owing to increased human intervention. The Xuliujing section, the river reach that controls the division between the South and North branches, was narrowed due to the merging and diking of the sand bars along the northern bank during the 1970s–1990s. As a result, the inflow section of the North Branch was further narrowed as well, which substantially altered the inflow conditions and the tidal regime (Figures 4 and 5). Severe sedimentation occurred in the inflow segment of the North Branch due to tide-induced sediment trapping. Both changes reduced the cross-sectional area of the inflow section. The channel alignment of the inflow segment developed nearly normal to the main branch stretching from Xuliujing to the South Branch; this deteriorated inflow further reduced the partition rate and fluvial influence on the North Branch. For example, the flood current duration in the Qinglong section decreased from ~4.5 hours in 1958 to ~3.6 hours in 1985 (Chen, 1994; Yun, 2004). The sub-tidal flow partition ratio declined to 1–2% after the 1950s (e.g., it was 1.5% in 1984) (Huang, 1986). The North Branch eventually became predominantly tide-dominant with very limited river influence. The tides were strongly amplified in the upper part of the North Branch, leading to the formation of tidal bores. The mean tidal range increased by 0.25 m in 1978 compared with that in 1958. The energetic flow conditions enhanced the suspended sediment concentrations in the upper reaches (Yang et al., 2020), where the bottom sediments were much sandier than those in the lower reaches.

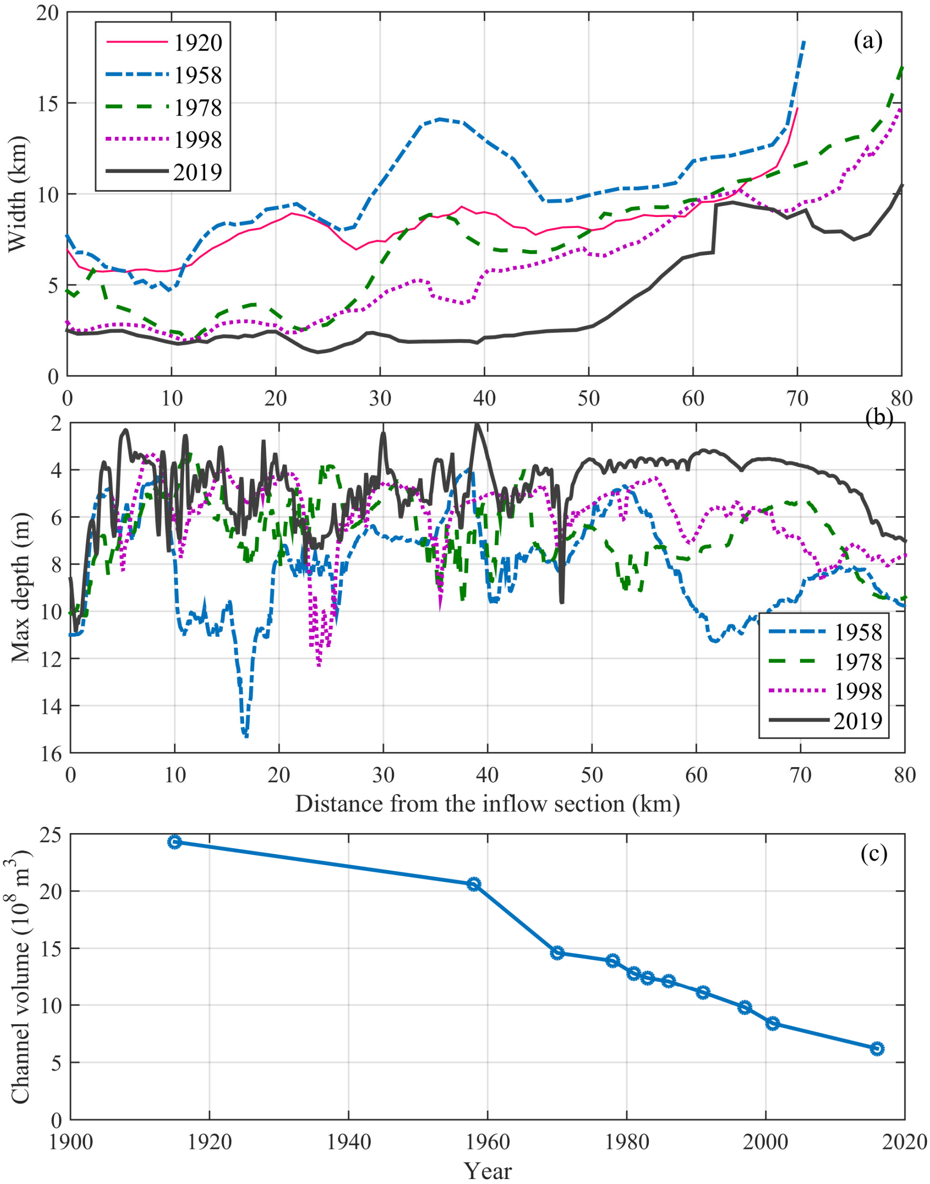

Figure 5. Changes in the (a) channel width at the mean water level, (b) cross-sectional averaged depth (referencing to the lowest tide), and (c) channel volume below the mean water level in the North Branch. Historical data of the channel volume in panel (c) are acquired from Zhang and Cao (1998) and Yun (2004, 2010).

The infill of the North Branch continued in the 1980s, as depicted in the satellite images available since 1974 (Figure 6). The narrowing trend continued in the upper and middle reaches, as the shoals formed close to the southern bank were reclaimed, merging into Chongming Island. The length of the North Branch increased slightly because of the seaward advance of the Qidong spit and southern Chongming Island (see Figure 5a). The surface planform area of the North Branch declined by 51% over ~60 years, i.e., from ~6.9×10^7 m^2 in late 1958 to ~5.5×10^7 m^2 in 1984 and ~3.4×10^7 m^2 in 2019. As of 2019, the narrowest inflow section was <2 km in width and that of the mouth section was 7.5 km.

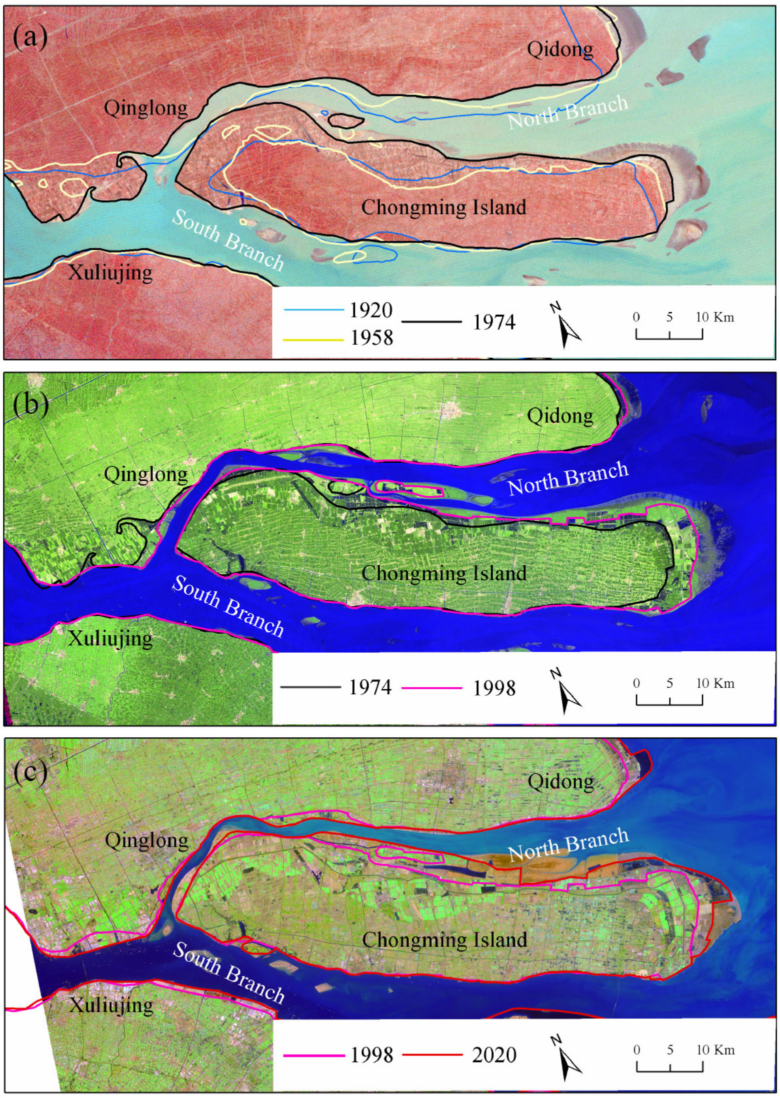

Figure 6. Satellite images of the North Branch in (a) 1974, (b) 1998, and (c) 2020 (during high tide), together with the identified coastlines. The shorelines in 1920 and 1958 were obtained from historical maps (see Figure S2).

More readily available bathymetric data since 1958 enabled the quantification of changes in the tidal flat area and channel volume (Figure 7).

The northern bank of the North Branch underwent erosion and a shoreline retreat of 1.7–2.6 km on average between the 1950s and 1980s (Chen et al., 1985). Thereafter, the northern shorelines were protected with dikes, and the shoreline retreat ceased. The southern bank of the North Branch advanced by ~4.5 km on average between 1900 and 1998. The length of the branch was increased by approximately 10 km in response to the advanced northern delta plain and the expansion of Chongming Island during 1958–2019 (Figure 6). However, the surface area of the North Branch decreased from 6.9×10^7 m^2 in 1958 to 3.4×10^7 m^2 in 2019. The channel width at the inflow section decreased from ~5.1 km in 1958 to 2.5 km in 2019, while the width of the mouth section decreased from ~15 km to ~7.5 km accordingly (Figure 5a). In addition, the maximum depth decreased from 11 m in 1907 to 7 m in 1958 and 5.8 m in 1991 (Zhang and Cao, 1998), while the mean depth of the branch decreased from 5.3 m in 1958 to 3.5 m in 2019. This indicates a significant shoaling trend (Figure 5b). The channel volume below the 0 m contour (referencing to the lowest tide, which indicates the sub-tidal channel volume) decreased from 2.90×10^9 m^3 in 1958 to 1.54×10^9 m^3 in 1978 and 0.67×10^9 m^3 in 2019 (see Figure 5c), as a result of the combined influence of channel infilling and width reduction. Compared with the situation in 1915, the majority of the channel volume reduction occurred prior to 1958. Accordingly, the mean sedimentation rate within the North Branch was 33.8×10^6 m^3 yr^{-1} between 1915 and 1958 (Huang, 1986; Zou, 1987); it increased to 46.0×10^6 m^3 yr^{-1} during 1958–1978, 73.8×10^6 m^3 yr^{-1} during 1978–1998, and to 83.0×10^6 m^3 yr^{-1} during 1998–2019. This suggests an increased sedimentation rate over time.

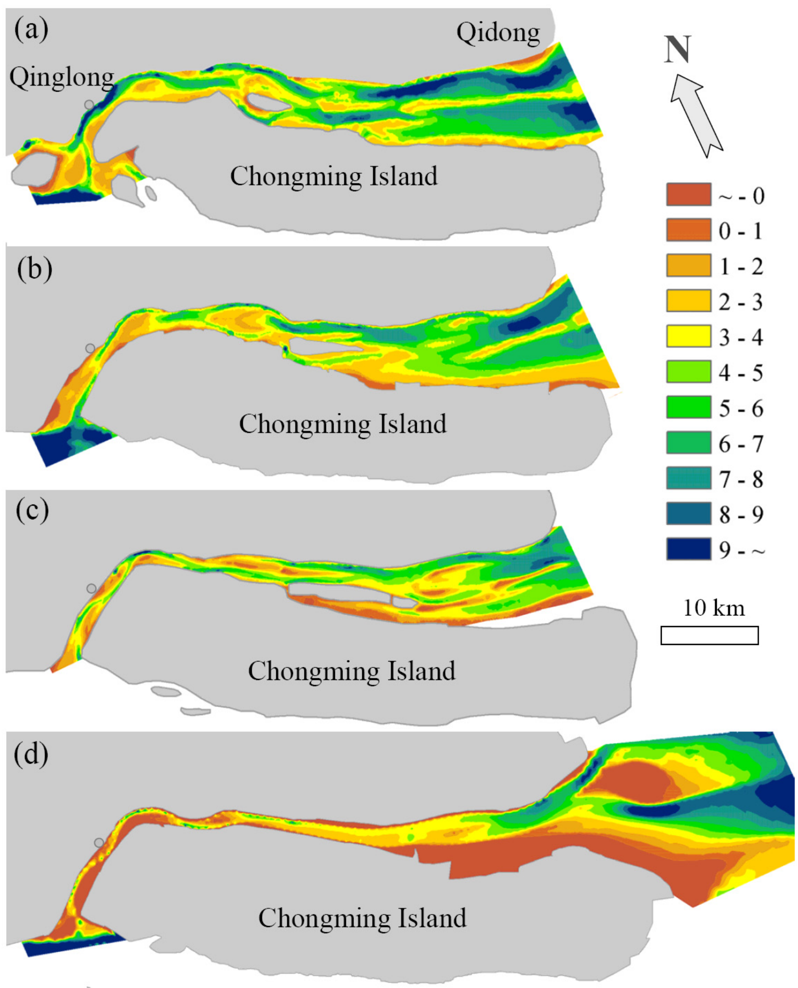

Figure 7. Bathymetry of the North Branch in (a) 1958, (b) 1978, (c) 1998, and (d) 2019. The depth is relative to the lowest tide.

4. Discussion

4.1 Impact of human activities

Human activities have played an important role in modulating the hydro-morphodynamics in the North Branch, particularly since the 1950s. The river-supplied sediment to the estuary has declined since the mid-1980s owing to hydropower dams and reforestation measures in the watershed (Guo et al., 2019), but its impact on the North Branch is thus far limited given its tide-dominant nature. Engineering projects in other parts of the estuary, e.g., the navigation channel regulation plans in the North Passage (see Figure 1a), are not expected to have direct influence on the North Branch either. The main type of human intervention is diking and reclamation of the sand bars and tidal flats surrounding the North Branch; activities such as dredging and barrier construction are rare (Figure 8). Human settlement on Chongming Island since the 7th century has enhanced the bifurcation between the North and South branches. Shoreline protection by dikes along the northern bank has prevented its erosion since the 1970s. Additionally, reclamation of the sand bars and shoals around the Xuliujing section between 1958 and 1972 narrowed the inflow segment (Chen and Li, 2002), resulting in a significant decline of its sub-tidal flow partition ratio.

In addition, the embankment of sand bars and tidal flats along the southern bank has played a substantial role in altering channel convergence. Since 1954, the northern bank close to the Qinglong section has been protected from erosion by dikes. A series of sand bars that formed in the middle segment of the North Branch, e.g., the Yonglong, Xinglong, and Huanggua shoals, have been reclaimed successively since the 1970s and have merged into the southern bank. The upper and middle segments significantly narrowed between 1915 and 1970, and the narrowing mainly occurred in the middle and lower parts of the branch since the 1970s. In the past 50 years, the cumulative reclamation area along the bank of the North Branch has been about ~940 km^2, which explains the significant reduction in the surface area (Figure 8).

Overall, extensive tidal flat embankment has profoundly reduced the bankfull channel width and surface area of the North Branch. The width reduction was much more significant in the upper and middle reaches, which enhances the width convergence. Subsequently, the incoming tidal waves were more amplified, and the associated tidal asymmetry led to flood dominance and sediment import. Human activities have likely played a substantial role in accelerating the aggradation of the North Branch since the 1950s, when it became tide-dominant.

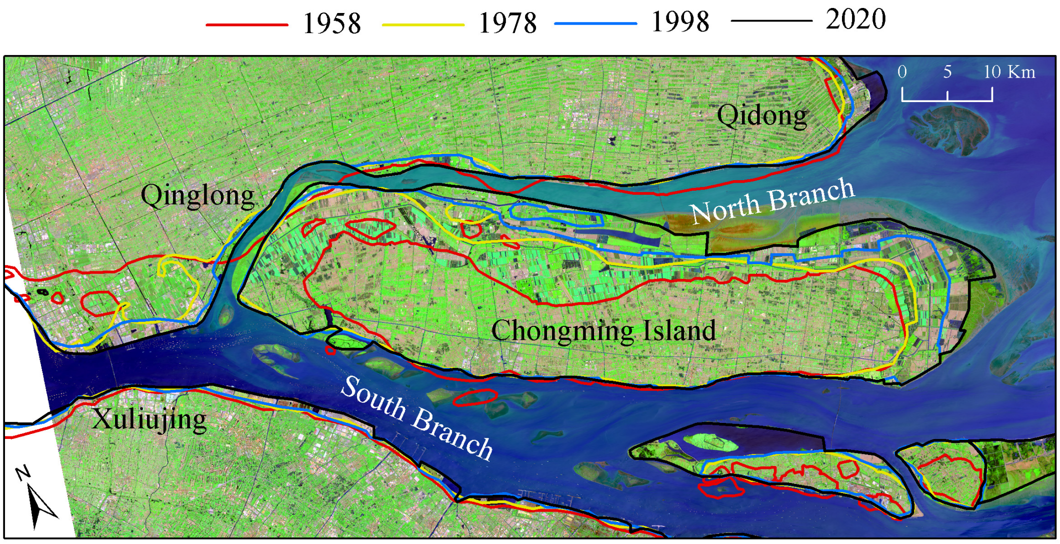

Figure 8. Illustrated coastline changes of the North Branch between 1958 and 2020 based on a satellite image obtained during a low tide in May 2020.

4.2 Causes of the regime shift

The centennial morphodynamic evolution of the North Branch features channel shrinkage and a regime shift. In the period prior to 1915, the fluvial influence was still significant in supplying sediment and flushing sediment seaward in the wide North Branch. Between 1915 and 1958, the sand bars around the inflow and outflow segments merged into the northern delta plain and the configuration of the North Branch became more funnel-shaped with a profoundly reduced river influence and partition rate compared with that of the South Branch. Tides became strongly amplified (see Figure S4) and became the primary forcing condition initiating sediment trapping. Since 1958, intensified human interferences in terms of tidal flat reclamation has further enhanced the channel convergence, which has possibly resulted in accelerated sedimentation. Because of the deteriorated inflow configuration, a shift from a river-tide mixed influence towards tide and flood dominance occurred when the sub-tidal flow partition ratio decreased to <5% since the 1950s.

The regime shift from ebb to flood dominance is the combined result of the natural morphodynamic adaptation of the delta and human interference. Under the combined strong river and tidal forcing, the distributary channels migrated southeastward, while the sand bars and shoals moved north-westward. The sand bars also underwent erosion to the south-east side and sedimentation to the northwest side (Chen et al., 1985). This large-scale behaviour is ascribed to the influence of incoming oceanic tidal waves from the south-east, the Coriolis force (which favours channel realignment to the right-hand side in the northern hemisphere), and the southward alongshore currents. This natural trend is in line with the observed accretion along the southern bank and erosion of the northern bank within the North Branch. In addition, this pattern is also believed to facilitate the development of the distributary branches to the south of the delta and the degeneration of the branch to the north. This large-scale pattern of deltaic channel adjustment may explain the sedimentation and fate of the North Branch on the longer term.

As the inflow section continued to narrow and the sub-tidal flow partition rate decreased, the amplified tides continued to dominate over the fluvial influence. The tide-dominant environment leads to a shorter rising tide duration, stronger flood currents and associated sediment import and channel infilling (see Figure S5). The rising tide duration was 5.4 hours at the mouth and decreased to 3.1 hours at Qinglong based on data between 1988 and 2001 (Yun, 2004). It benefits larger flood currents and the development of flood dominance and sediment import (Figure S5). Other than the seaward residual sediment transport in the utmost reaches landward of the Qinglong section owing to the remaining river influence, landward residual sediment transport dominated in the middle and lower parts of the branch owing to strong tidal asymmetry (Yang and Liu, 2002). The convergence of residual sediment transport explains strong sedimentation and shoaling in the upper reaches. Such shoaling persists until today, as indicated by the development of tidal flats that are not submerged even during high tide (see Figure 6c). The formation of the tidal flats in the inflow section tends to reduce the channel width to <1 km therein. In the lower reaches, although the sediments imported into the North Branch are derived from the sea side, these sediments mainly originate from the Changjiang River that are flushed to the nearshore region through the North Channel, which are then pumped into the North Branch by the tides (Shi et al., 1985; Chen and Li, 2002).

Human activities play a role in accelerating the regime shift by reducing the inflow section width and inter-tidal hydraulic storage over inter-tidal areas, enhancing the channel convergence, and stabilizing the channel configuration (see section 4.1). Moreover, progressive tidal flat reclamation following the establishment of tide dominance may initiate a positive feedback process (Figure 9). Inter-tidal flats favour the development of ebb dominance owing to their hydraulic storage effect; in contrast, tidal flat reclamation and the subsequent loss of tidal flat areas and storage volumes is to the advantage of flood dominance and sediment import. Sediment import stimulates tidal flat accretion and development, which attracts more reclamation and in turn enhances sediment import. This positive feedback explains the progressive and persisting sedimentation and infilling of the North Branch in the most recent half century (Figure 9).

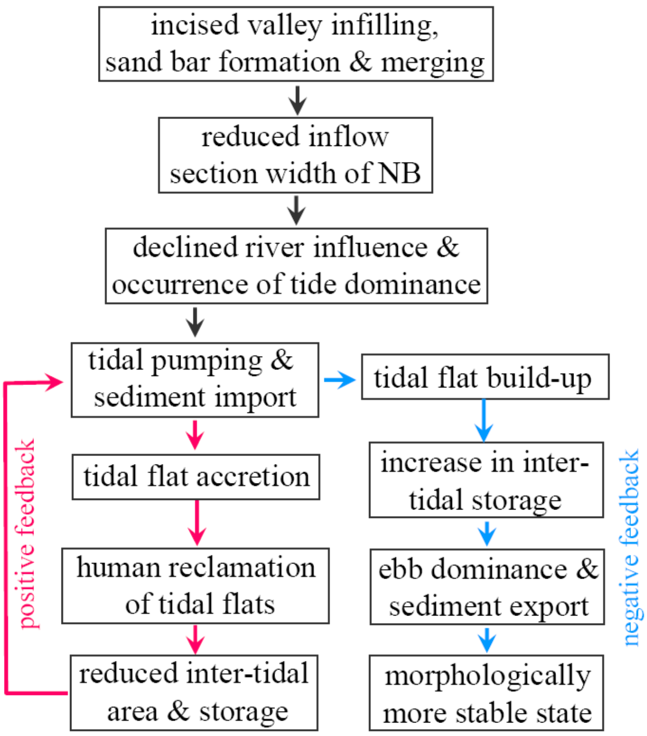

Figure 9. A conceptual diagram of the positive feedback between

human-initiated tidal flat embankments and sediment import in the North Branch, and a possible negative feedback when tidal flat reclamation ceases.

It is worthwhile to note that ebb dominance and net sediment export may occur in tide-dominant estuaries. For instance, van der Wegen et al. (2008) have modelled ebb dominance in a schematized tidal basin with a similar size to that of the North Branch; the ebb dominance was ascribed to the impact of a seaward Stokes' return flow and inter-tidal flats. We believe that the occurrence of flood dominance and sediment import in the North Branch is the result of a limited fluvial influence owing to a small partition rate and the development of a highly convergent planform which substantially amplifies the tides. The tides are dominant over the river influence and hydraulic impact of little inter-tidal flats. High sediment availability from the Changjiang River and the nearshore regions may also contribute to the persistent sediment import. Further in-depth examination of the mechanisms governing the flood dominance and its spatio-temporal variations using a numerical model will be performed in a future study.

4.3 Water resource and ecological management perspectives

Flood dominance and the associated sediment import have been detected in many tidal basins and estuaries worldwide, which is considered to be beneficial for water resource and ecological management given the worldwide sediment deficiency and sea-level rise. For instance, sediment budget analysis has indicated a net sediment import in the Humber Estuary in the U.K., predominantly owing to a low river flow and strong tidal asymmetry that pumps mud into the estuary (Townend and Whitehead, 2003). In the Dutch Wadden Sea, persistent sediment import through multiple tidal inlets helps to restore tidal flats, which counteracts the inundation impact of sea-level rise (Wang et al., 2018). The flood dominance and sediment import in the North Branch in this case, however, necessitate mitigation, because too strong a sediment import process results in fast channel aggradation and loss of channel volume, which raises concerns on its disconnection from the remaining parts of the estuary.

There are multiple objectives to be considered in the integrated management of the North Branch. The shallow water and tidal flats provide important habits for birds and fish and associated valuable ecosystem services. The saltwater intrusion into the South Branch threatens the function of the reservoirs that supply freshwater resources for >10 million people in Shanghai. The North Branch also provides a waterway for small boat shipping and accommodates sewage from the factories and industries surrounding the branch. A big concern is that continued sediment import may lead to severe aggradation of the North Branch in the medium to long term. Such changes would mitigate saltwater intrusion but indicate a loss of a connected branch with significant ecosystem value and as a drainage channel for the surrounding cities. There is a plan to build a barrier with gates at the mouth of the North Branch to regulate tidal intrusion and sediment flushing, but no consensus has been achieved thus far regarding its potential impact on the ecosystem or the estuary as a whole.

Authorities much protect the branch from continuous aggradations while simultaneously alleviating the impact of saltwater intrusion and preserving the wetlands. Considering the positive feedback impact of tidal flat reclamation, one management option is to cease tidal flat embankment and allow the tidal flats to build up naturally inside the branch. Once the inter-tidal flat area and storage volume are restored, the flood dominance and sediment import may decline, and a morphodynamic equilibrium may be established. One remaining question is at what time scale the branch is likely to be restored to equilibrium, considering no additional anthropogenic interference. A decline in sediment availability from the Changjiang River is likely to prolong this adaptation time scale.

The embankment of tidal flats and the construction of dikes have long been used as effective measures in protecting coasts from erosion and flooding. However, because of high maintenance costs and the low but possible risk of infrastructure failure under episodic catastrophic events, it becomes increasingly clear that sustaining waterfront tidal flats and salt marshes is beneficial for both coastal and ecosystem protection (Temmerman et al., 2013). While delta land has increased globally (Nienhuis et al., 2020), global tidal flats have decreased as a result of human-initiated reclamation (Murray et al., 2019). A mindset change from hard engineering projects (e.g., dikes and groins) to soft eco-engineering (e.g., salt–marshes and similar ecological measures) is occurring in the coastal management community. Management that allows for nature to adjust and adapt to external changes such as managed retreat also increase the system's resilience to floods and sea-level rise (Townend and Pethick, 2002; Temmerman et al., 2003). Abandoning tidal flat embankment would likely be of similar value for long-term stability and resilience in the North Branch, particularly when considering a decline in suspended sediment concentrations and sediment availability on the marine side (Yang et al., 2020).

5. Conclusions

In this study, we revisited the centennial hydro-morphodynamic evolution of the North Branch, a bifurcated branch in the fluvio-deltaic Changjiang Estuary, based on a literature review and reanalysis of historical maps, satellite images and bathymetric data. We see that the North Branch was once a major distributary branch (sub-tidal flow partition >50%) and then became a secondary branch with a sub-tidal flow partition rate reduced to ~25% in 1915, when it was still ebb-dominant and developed alternative meandering channels and sand bars that are typical of tidal estuaries. Continuous deposition of river-borne sediment leads to a narrowing of the branch, particularly in the outflow regions where the northern delta plain advanced quickly. In the inflow regions, human-initiated reclamation of tidal flats reduced the bankfull width and modified the channel configuration. Its sub-tidal partition rate has reduced to <5% since the late 1950s, and since then the North Branch became funnel-shaped in planform and tide- and flood-dominant under forcing conditions, in which tidal bores and sand ridges developed.

We argue that the regime shift and aggradation of the North Branch are a combined result of natural evolution and human activities. The south-eastward realignment of the entire delta leads to abandonment of the distributary channels to the north, e.g., the North Branch. As the sub-tidal flow partition rate decreases below a threshold, the strongly amplified tides dominate over the fluvial influence, leading to the establishment of tide dominance. Subsequent tidal asymmetry then induces flood dominance and sediment import, while subsequent human activities in terms of extensive tidal flat reclamation accelerate the changes by reducing the channel width and increasing channel convergence. A positive feedback process is identified between human-initiated flat embankment and enhanced sediment import, which explains the persisting sediment import in the past century. Management of the North Branch must be performed considering the interactions among different branches within the delta as a whole. We believe that abandoning aggressive tidal flat reclamation may help to restore tidal flats which would mitigate sediment import and channel aggradation on the longer term. Further exploration of the regime changes and governing mechanisms will be presented in an accompanying paper when using a numerical modelling tool.

Acknowledgements

This work is supported by the project 'Coping with deltas in transition' within the Programme of Strategic Scientific Alliance between China and The Netherlands (PSA), financed by the Ministry of Science and Technology, P.R. China (MOST) (No. 2016YFE0133700) and Royal Netherlands Academy of Arts and Sciences (KNAW) (No. PSA-SA-E-02), and also partly by MOST (No.

2017YFE0107400), Natural Science Foundation of China (Nos. 51739005, U2040216, 41876091), and Shanghai Committee of Science and Technology (Nos. 18DZ1206400; 19QA1402900; 20DZ1204700).

References

Chen B.C., 1994. The change of the general form and the transport of the water, load and salt about the North Branch of the Changjiang River mouth. Chinese Geographical Science 4(3), 242-251.

Chen J.Y., Yun C.X., Xu H.G., Dong Y.F., 1979. The developmental model of the Changjiang River estuary during the last 2000 years. Acta Oceanologia Sinica 1, 103-111.

Chen J.Y., Li D.J., 2002. Regulation of the Changjiang Estuary: past, present and future. In: Chen J.Y., Eisma D., Hotta K., and Walker H.J. (eds.), Engineered Coasts, Kluwer Academic Publishers, Netherlands, pp. 185-197.

Chen J.Y., Shen H.T, 1988. Some key point on harnessing the Changjiang estuary. In: Processes of Dynamics and Geomorphology of the Changjiang Estuary. Shanghai Scientific and Technical Publishers. pp. 419-423 (in Chinese).

Chen J.Y., Zhu H.F., Dong Y.F., Sun J.M., 1985. Development of the Changjiang Estuary and its submerged delta. Continental Shelf Research 4, 47-56.

Chen S.L., 2003. Tidal bore in the North Branch of the Changjiang Estuary. In Proceedings of the International Conference on Estuaries and Coasts, Hangzhou, China. pp, 233-239.

Chen Z.Y., Stanley D.J., 1998. Sea-level rise on eastern China's Yangtze Delta. Journal of Coastal Research 14, 360-366.

Dai Z.J., Fagherazzi S., Mei X.F., Chen J.Y., Meng Y., 2016. Linking the infilling of the North Branch in the Changjiang (Yangtze) estuary to anthropogenic activities from 1958 to 2013. Marine Geology 349, 1-12.

de Vriend H.J., Wang Z.B., Ysebaert T., Herman P.M.J., Ding P.X., 2011.

Eco-morphological problems in the Yangtze Estuary and the Western Scheldt. Wetlands, doi:10.1007/s13157-011-0239-7.

Dronkers J., 1986. Tidal asymmetry and estuarine morphology. Netherland Journal of Sea Research 20(2/3), 117–131.

Guo L.C., Su N., Townend T., Wang Z.B., Zhu C.Y., Zhang Y.N., Wang X.Y., He Q., 2019. From the headwater to the delta: A synthesis of the basin-scale sediment load regime in the Changjiang River. Earth-Science Reviews 197, 102900, doi.org/10.1016/j.earscirev.2019.102900.

Guo L.C., van der Wegen M., Roelvink J.A., He Q., 2014. The role of river flow and tidal asymmetry on 1D estuarine morphodynamics. Journal of Geophysical Research: Earth Surface 119, 2315-2334, doi: 10.1002/2014JF003110.

Guo L.C., van der Wegen M., Jay D.A., Matte P., Wang Z.B., Roelvink J.A., He Q., 2015. River-tide dynamics: exploration of nonstationary and nonlinear tidal behavior in the Yangtze River estuary. Journal of Geophysical Research: Oceans 120, doi:10.1002/2014JC010491.

Friedrichs C.T., Aubrey D.G., 1988. Non-linear tidal distortion in shallow well-mixed estuaries: a synthesis. Estuarine, Coastal and Shelf Science 27, 521-545.

Huang S., 1986. The evolution characteristics of the Changjiang Estuary. Journal of Sediment Research 4, 1-12.

Jiang F., Zhao X.S., Chen J., Liu Y., Sun Q.L., Chen J., Chen Z.Y., 2020. Depocenter shift and en-echelon shoal development in the pre-holocene incised valley of the Yangtze Delta, China. Marine Geology, doi.org/10.1016/j.margeo.2020.106212.

Lanzoni S., Seminara G., 1998. On tide propagation in convergent estuaries. Journal of Geophysical Research 103(C13), 30793–30812.

Li C.X., Chen, Q.Q., Zhang J.Q., Yang S.Y., Fan D.D., 2000. Stratigraphy and paleoenvironmental changes in the Yangtze Delta during the Late Quaternary. Journal of Asian Earth Science 18, 453–469.

Li C.X., Wang P., Sun H.P., Zhang J.Q., Fan D.D., Deng B., 2002. Late quaternary incised-valley fill of the Yangtze Delta (China): its stratigraphic framework and evolution. Sedimentary Geology 152, 133-158.

Li X., Zhang X., Qiu C.Y., Duan Y.Q., Liu S.A., Chen D., Zhang L.P., Zhu C.M., 2020. Rapid loss of tidal flats in the Yangtze River Delta since 1974. International Journal of Environmental Research and Public Health 17, 1636, doi:10.3390/ijerph17051636.

Liu F., Xie R.Y., Luo X.X., Yang L.Z., Cai H.Y., Yang Q.S., 2019. Stepwise adjustment of deltaic channels in response to human interventions and its hydrological implications for sustainable water management in the Pearl River Delta, China. Journal of Hydrology 573, 194-206.

Nienhuis J.H., Ashton A.D., Edmonds D.A., Hoitink A.J.F., Kettner A.J., Rowland J.C., Tornqvist T.E., 2020. Global-scale human impact on delta morphology has led to net land area gain. Nature 577, 514-518.

Meng Y., Cheng J., 2005. The atrophy of the estuarine North Branch of the Yangtze River (Changjiang River). Marine Geology Letters 21(1), 1-10. (in Chinese)

Murray N.J., Phinn S.R., DeWitt M., Ferrari R., Johnston R., Lyons M.B., Clinton N., Thau D., Fuller R.A., 2019. The global distribution and trajectory of tidal flats. Nature 565, 222-225.

Obodoefuna D.C., Fan D.D., Guo X.J., Li B., 2020. Highly accelerated siltation of abandoned distributary channel in the Yangtze Delta under everchanging social-ecological dynamics. Marine Geology 429, 106331, https://doi.org/10.1016/j.margeo.2020.106331.

Pethick J.S., 1994. Estuaries and wetlands: function and form. In: Wetland Management, Thomas Telford, London, pp. 75-87.

Ridderinkhof W., de Swart H.E., van der Vegt M., Alebregtse N.C., Hoekstra P., 2014. Geometry of tidal inlet systems: A key factor for the net sediment transport in tidal inlets. Journal of Geophysical Research: Oceans 119 (10), 6988-7006, doi: 10.1002/2014jc010226.

Shi L.R., Wei T., Shen H.S., 1985. The diffusion of seaward sediments from Yangtze River and the source of depositing sediments in the North Branch. Journal of Yangtze River Scientific Research Institute 2, 8-19.

Speer P.E., Aubrey D.G., 1985. A study of non-linear tidal propagation in shallow inlet/estuarine systems Part II: theory. Estuarine, Coastal and Shelf Science 21, 207–224.

Temmerman S., Meire P., Bouma T.J., Herman P.M.J., Ysebaert T., de Vriend H.J., 2013. Ecosystem-based coastal defense in the face of global change. Nature 504, 79-83.

Townend I.H., Pethick J., 2002. Estuarine flooding and managed retreat. Philosophical Transactions of the Royal Society A 360, 1477-1495.

Townend I.H., Whitehead P., 2003. A preliminary net sediment budget for the Humber Estuary. Science of The Total Environment 314-316: 755-767.

Uehara K., Saito Y., Hori K., 2002. Paleotidal regime in the Changjiang (Yangtze) estuary, the East China Sea, and the Yellow Sea at 6ka and 10 ka estimated from a numerical model. Marine Geology 183, 79–192.

van der Wegen M., Roelvink J.A., 2008. Long-term morphodynamic evolution of a tidal embayment using a two-dimensional, process-based model. Journal of Geophysical Research 113, C03016, doi:10.1029/2006JC003983.

van Veen J., 1950. Ebb and flood-channel systems in The Netherlands tidal water. Netherlands Geographical Studies 67, KNAG, Utrecht, pp.305–325. (in Dutch)

Wang Z.H. Saito Y., Zhan Q., Nian X.M., Pan D.D., Wang L., Chen T., Xie J.L., Li X., Jiang X.Z., 2018. Three-dimensional evolution of the Yangtze River mouth, China during the Holocene: impacts of sea level, climate and human activity. Earth-Science Reviews 185, 938-955.

Wang Z.B., Elias E.P.L., van der Spek A.J.F., Lodder Q.J., 2018. Sediment budget and morphological development of the Dutch Wadden Sea: impact of accelerated sea-level rise and subsidence until 2100. Netherlands Journal of Geosciences 97, 183-214.

Wu H., Zhu J.R., Chen B.R., Chen Y.Z., 2006. Quantitative relationship of runoff and tide to saltwater spilling over from the North Branch in the Changjiang Estuary: A numerical study. Estuarine, Coastal and Shelf Science 69, 125–132.

Yang H.F., Li B.C., Zhang C.Y., Qiao H.J., Liu Y.T., Bi J.F., Zhang Z.L., Zhou F.N., 2020. Recent spatial-temporal variations of suspended sediment concentrations in the Yangtze Estuary. Water 12, 818, doi:10.3390/w12030818.

Yang O., Liu C.Z., 2002. Analysis on sediment transport patterns and sediment sources of North Branch of Changjiang Estuary. Journal of Hydraulic Engineering 2, 79-84. (in Chinese with an abstract in English)

Yu W.C., Lu J.Y., 2005. Morphological evolution and regulation of the Changjiang River. China Water & Power Press, Beijing, 505 pp.

Yun C.X., 2004. Recent evolution of the Yangtze River estuary and its mechanisms. China Ocean Press, Beijing, 302 pp. (in Chinese)

Yun C.X., 2010. A picture guide of the Yangtze River estuary evolution. China Ocean Press, Beijing, 260 pp. (in Chinese)

Zhang C.Q., Cao H., 1998. Evolution trend of the North Branch in the Changjiang Estuary. Yangtze River 29, 32-34.

Zhang E.F., Gao S., Savenije H.H.G., Si C.Y., Cao S., 2019. Saline water intrusion in relation to strong winds during winter cold outbreaks: North Branch of the Yangtze Estuary. Journal of Hydrology 574, 1099-1109.

Zhang J.H., Meng Y., 2009. Formation and evolution of the North Branch in the Changjiang Estuary. Yangtze River 40(7), 14-17. (in Chinese)

Zhang J.Y., Huang Z.L., Hu Z.Y., 2007. Effect of reclamation project on the North Branch of Yangtze River Estuary. The Ocean Engineering 25(2), 72-77. (in Chinese with an abstract in English)

Zhang W., Feng H.C., Zhu Y.L., Zheng J.H., Hoitink A.J.F., 2020. Subtidal flow reversal associated with sediment accretion in a delta channel. Water Resources Research 55, https://doi.org/10.1029/2019WR025945.

Zou D.S., 1981. Hydro-morphodynamic changes in the recent 100 years and the future trend of the North Branch in the Changjiang Estuary. Jiangsu Water Resources 1, 52-64. (in Chinese)

Zou D.S., 1987. Morphological evolution and future trend of the North Branch in the Changjiang Estuary. Journal of Sediment Research 1, 66-76.

Supplementary Information

Figure S1. Development of the Changjiang Delta and the North Branch illustrated in historical maps: (a) 1670, (b) 1705, (c) 1751, (d) 1824, (e) 1840, (f) 1872, (g) 1900, (h) 1909, and (i) 1917. The big island in the river mouth is the Chongming Island, with the North Branch (NB) to the north of it. The space scales of the historical maps were not consistent and the maps are included here to display the topography changes but not for reference of detailed morphology.

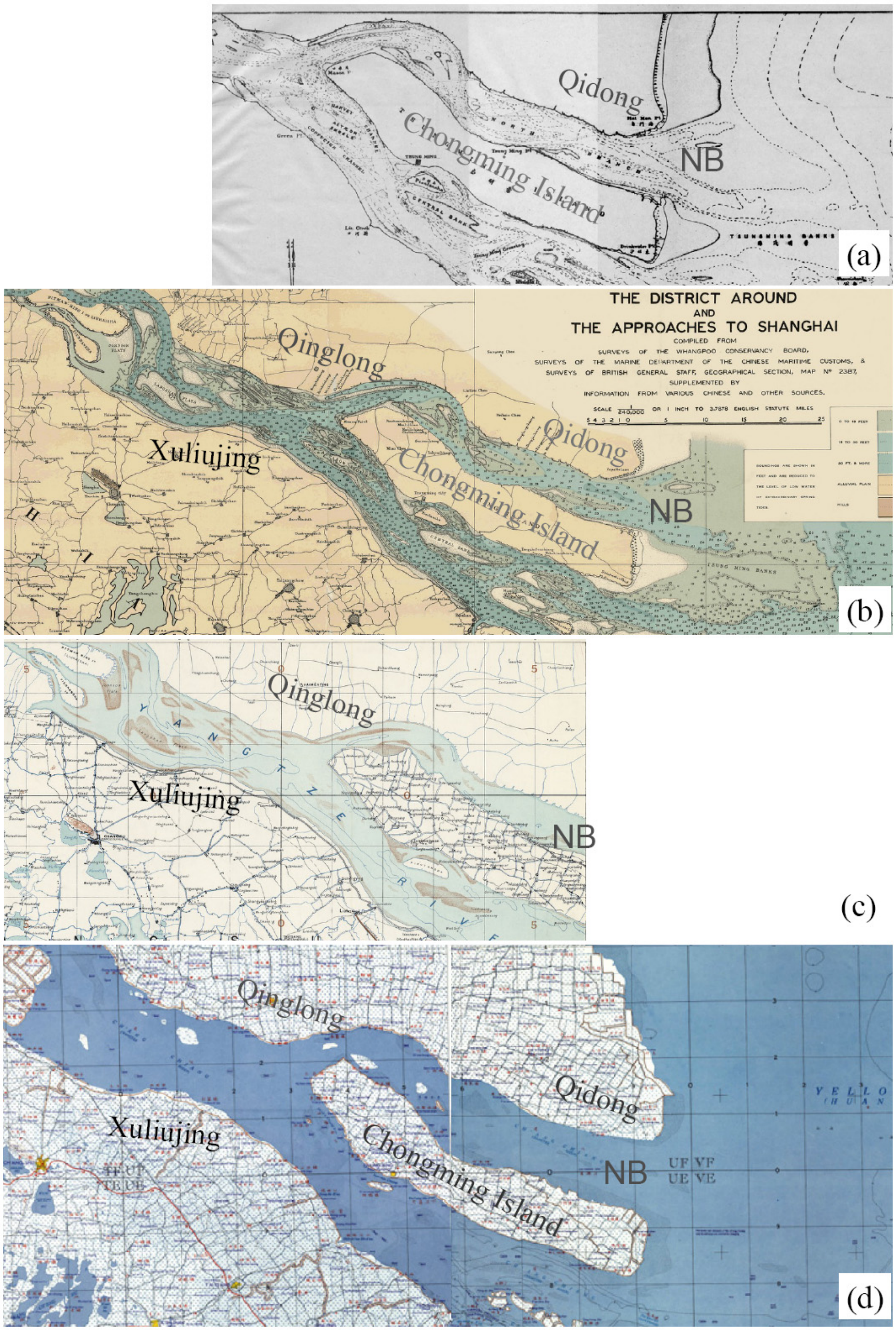

Figure S2. Illustrated topography changes of the North Branch in historical maps in (a) 1915, (b) 1920, (c) 1927, and (d) 1940s. These maps are from Virtual Shanghai website.

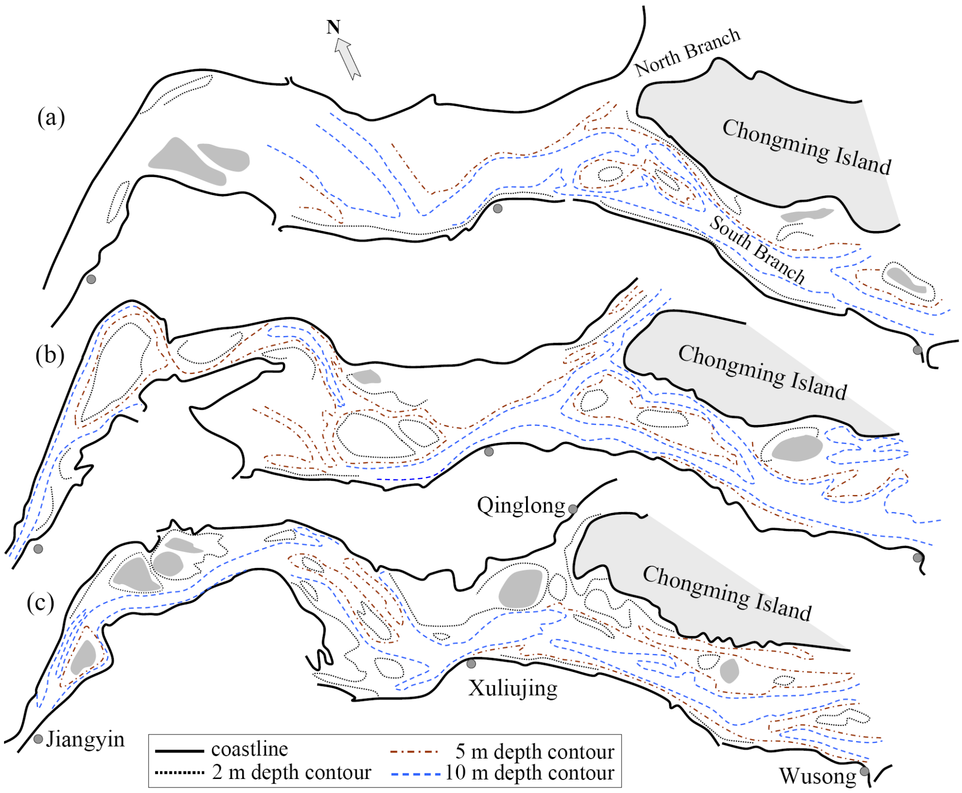

Figure S3. Sketches of the topography and depth contours of the Jiangyin-Wusong reaches and inflow section of the North Branch in (a) 1860, (b) 1915, and (c) 1958. Adopted from Yu and Lu (2005) and Yun (2004).

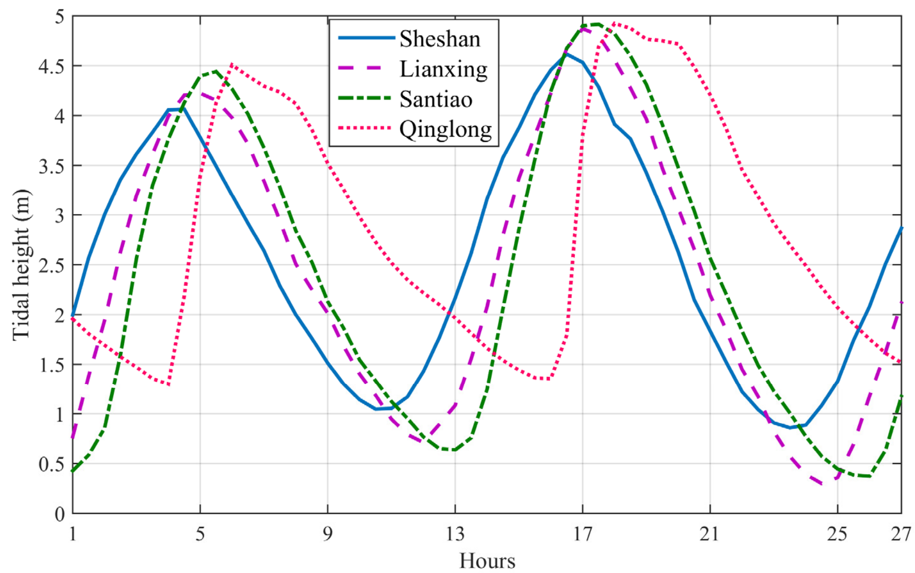

Figure S4. Tidal wave amplification and deformation inside the North Branch. Data were obtained in 1982.

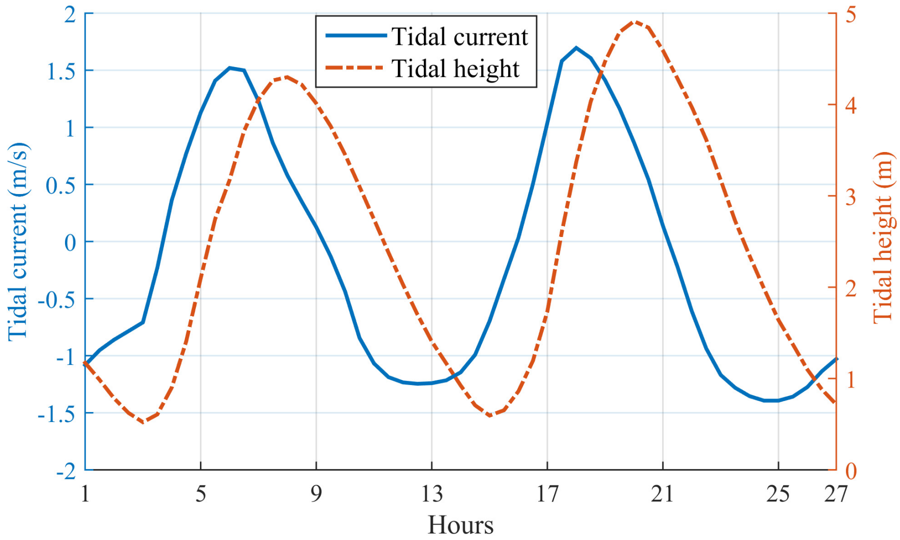

Figure S5. Tidal currents and water level at a station close to Lianxing, which shows stronger flood currents than ebb currents. Date measured in Nov. 2003 and adopted from Meng and Cheng (2005).