Decadal changes in bathymetry of the Yangtze River Estuary: human impacts and potential saltwater intrusion

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Abstract: This study analyzed bathymetric changes of the 77-km Yangtze River Estuary in China over the past ten years in order to understand the impacts of recent human activities on the estuary of a large alluvial river. Morphological changes were assessed by analyzing digitized bathymetric data of the estuarine channels from 2002 to 2013. Additionally, multi-beam bathymetric measurements made in 2012, 2014 and 2015 were utilized to investigate microtophographic bedforms of the lower reach of the estuary. Our results showed that the middle and upper reaches of the Yangtze River Estuary experienced substantial channel bed erosion in the past 10 years. A sharp decline of sediment supply was found mainly due to the recent human activities in the South Channel and the middle and upper reaches of the North Channel. These included the construction of a 70 km^2 reservoir along the Yangtze River Estuary, the Qingcaosha Reservoir, for drinking water supply for the City of Shanghai, which has caused progressive bed erosion in the North Channel. The net volume of channel erosion in the Hengsha Passage from 2002 to 2013 was 0.86×10^8 m^3. A large amount of the eroded sediment was trapped downstream, causing overall accretion in the upper reach of the North Passage. The middle and upper reaches of the South Passage also experienced intense erosion (0.45×10^8 m^3) in the past ten years, while high accretion occurred in the lower reach because of the Deepening Waterway Project. The channel dredging left a large range of dredging marks and hollows in the North Passage. The increasing saltwater intrusion found in the Yangtze River Estuary may have been a consequence of either dredging or erosion, or both combined.

Keywords: estuarine morphology; bathymetric dynamics; saltwater intrusion; estuarine bedforms; multi-beam profiling; Yangtze River Estuary

1. Introduction

Many estuaries in the world have been interrupted by human activities, such as the damming of the river, building of reservoir and dredging for waterway (Blott et al., 2006; Benedet and List., 2008; Talke et al., 2009; Day et al., 1989). Remarkable consequences of these human activities in estuaries include morphological changes of the channel beds and saltwater intrusion; they have therefore been the foci of several scientific enquiries (Thomas et al., 2002; Nichols and Howard-Strobel., 1991; Gong et al., 2012).

Several studies have indicated that human activities could have pronounced effects on estuarine hydrodynamics and morphology. For instance, in the Ems Estuary in Germany, the estuarine dynamics and the erosion and sedimentation process were affected, pushing the position of the turbidity maximum zone upstream because of channel dredging (De Jonge et al., 2014). Due to the construction of the Aswan Dam, annual erosion rate for the area around Rosetta Promontory was reported to be 10×10^6 m^3 in the Nile delta (Inman and Jenkins., 1984). Lane (2004) reported that the volume of the Mersey Estuary in UK decreased by 0.1% in the past 150 years because of channels dredging and construction of retaining walls.

Seawater intrusion has been found to have intensified across the world in the recent decades due to human activities (Savenije., 2005; Barlow and Reichard., 2010). For instance, Yuan and Zhu (2015) found that dredging in the Pearl River estuary in China has strongly affected saltwater instruction. Omar et al. (2016) reported that over-pumpage of aquifers in the Mediterranean region has led to intensified seawater intrusion. However, few studies have investigated human effects on channel morphology of large alluvial river estuaries, such as the Yangtze River Estuary in China.

The Yangtze River Estuary is a continental-scale alluvial estuary, which has gone through many physical alterations for flood control, navigation, port construction, and urban development of the City of Shanghai, the most vibrant and largest economy in China.

Shanghai is located near the Yangtze River Estuary and the Yangtze River is the major source of freshwater supply for the city. There are four large drinking water reservoirs within the estuary area that provide freshwater for about 50 million people living on the Yangtze River Delta. Like other tidal-controlled estuaries, the Yangtze River Estuary has been found to be affected by saltwater intrusion in recent years (Cheng and Zhu., 2013). This has raised serious concerns over freshwater supply (Wu and Zhu., 2010; Li et al., 2012a; Mao et al., 2001) and future economic development in the region (Chen et al., 2016).

Human interventions in the Yangtze River basin, e.g., the construction of the Three Gorge Dam (TGD) in the middle reach of the Yangtze River, have changed flow conditions in the river's lower reach and estuary (Zhang et al., 2009). In the recent decade, two large engineering projects - the Yangtze estuarine Deepening Waterway project and the Qingcaosha Reservoir project - may have particularly affected the morphology of the Yangtze River Estuary. Several studies (Jiang et al., 2012; Li et al., 2008; Liu et al., 2005; Dai et al., 2013) reported a morphological change of several sand bars of the Yangtze River mouth. However, very few studies have investigated changes across the entire lower estuary reach. Little is known for other parts of the large Yangtze River Estuary impacted by human interventions. In general, there is a knowledge gap as to how the Yangtze River Estuary channel has changed in the recent decade and whether these changes have played a role in saltwater intrusion. A study focusing on such a nature-human coupled complex system has important significance for improving our knowledge of human effects not only on the Yangtze River Estuary but also on other alluvial river estuaries in the world. Such knowledge can be crucial for developing effective management plans for coastal protection against sea level rise, erosion and land loss.

This study aimed to assess the recent morphological changes of the channel beds using bathymetric survey charts, high-resolution multi-beam data, river discharge and sediment load data. The primary goal was to document bathymetry change in the Yangtze River Estuary in order to understand the relationship between human activities and the channel morphology, as well as the potential risk of saltwater intrusion. Results gained from this work can be useful for river channel morphology research, river water management and coastal protection. It can also serve as an example for the remediation and development of other estuaries under similar natural and anthropogenic influences.

2. Methods

2.1. Study area

Draining a land mass of approximately 1.8 million km^2, the Yangtze River (Fig. 1) is the world's fourth largest river in terms of sediment load (Yang et al., 2005). There is a tidal influence in the Yangtze River extending 650 km upstream. The last 120 km section of the estuary below Xuliujing shows a "three-consecutive bifurcations with four outlets. It is first divided into the South and North Branches by the Chongming Island (Fig. 1). The South Branch is then divided into the South and North Channels by the Changxing Island and the Hengsha Island. The South Channel is again divided by the Jiuduan Shoal into the South and North Passages. The mouth bar section is geographically located between 121°45′-122°30′ E and 30°45′-31°45′ N (Fig 2A). The turbidity maximum zone exists in the river mouth-bar area all year round, with high solid concentrations due to the interaction of freshwater and tidal flows (Chao et al., 2015; Li and Wu., 2011).

Long-term discharge at Datong Hydrological Gauging Station, located about 600 km upstream from the river mouth, averaged 29 300 m^3/s (Cheng et al., 2004). The river flow fluctuates seasonally, generally low in January or February (dry season) and high during July or August (wet season) (Pu et al., 2015). The annual mean suspended sediment load from the Yangtze River from 1956 to 2009 was 388.6 million tons (Jiang et al., 2012). It has been estimated that 40% of the annual sediment load is deposited in the Yangtze River Estuary (Zhu et al., 2015). The sediment deposit in the Yangtze River Estuary is mainly composed of fine sand, silt and clay (Liu et al., 2010).

The Yangtze River Estuary is characterized as a mesotidal estuary in terms of tidal range (Wu et al., 2009). Tides are regular semi-diurnal out of the mouth, and non-regular semi-diurnal inside. The long-term mean tidal range at Zhongjun Station nearby the mouth is about 2.67 m, with a tidal velocity amplitude of approximately 1 m/s (Yang et al., 2015a).

2.2. Bathymetric data collection

Digitized bathymetry-derived Digital Elevation Model (DEM) has become a useful tool to study morphological changes of estuaries (Thomas et al., 2002; Lane., 2004; Blott et al., 2006; Jaffe et al., 2007). In order to investigate the morphological changes in the Yangtze River Estuary, the bathymetric surveys have been carried out by the Changjiang Estuary Waterway Administration Bureau (CJWAB), Ministry of Transportation. The digital survey charts of 2002 and 2007 were used in this study. The bathymetric survey charts for 2010 and 2013 in the South and North Channels, and the South and North Passages, provided by Shanghai Estuarine & Coastal Science Research Center, were also used in this study. The marine charts of 2012 in the North Channel and 2013 in the Hengsha Passage, provided by Maritime Safety Administration of the People’s Republic of China (PRC), were also used to investigate the morphological changes. The marine charts (1:15000 scales) were digitalized and used in our GIS analysis (Table 1).

The long-term discharge and sediment load monitored at the Datong station located at the landward limit of the tidal river between 2002 and 2013 published in the Yangtze River Sediment Bulletin, were used to interpret the cause of the morphological changes in the study area.

2.3. Riverbed multibeam measurements

The bedforms of the South and North Channels, the South and North Passages, and the Hengsha Passage in the Yangtze River Estuary were observed by using a Reson Seabat 7125 MBES (Teledyne Technologies Inc, Thousand Oaks, CA, USA) during December 2012, February 2014 and February 2015 (Fig. 2A). The seabat 7125 was operated at the working frequency of 400 kHz, and the transducer was mounted on the left side of the surveying ship by cables and a custom-made shelf. The highest depth resolution is 6 mm. The boat speed was controlled to be as steady as possible at 2.5 m/s. Weather condition was good during the survey period.

2.4 Data analysis

The bathymetric data and charts were digitized and analyzed through creating DEM with ArcGIS software (Fig. 3). First, all charts were georeferenced using ten fixed benchmarks, with known National Grid coordinates. The depth values were transformed into the Beijing 1954 coordinates in Gauss-Kruger Zone 21 N. The Theoretical Lowest Tide Level (which is based on 13 tidal components) was used as the datum for elevations and depths. Subsequently, the Kriging interpolation technique, a widely used method in morphological change analysis of estuaries (Zhao et al., 2015; Van der Wal et al., 2002; Van der Wal and Pye., 2003), was utilized to interpolate each data set to a grid with 200×200 m resolution on the ArcGIS 9.3 platform.

By subtracting the depth of one year from that of another, the changes of bathymetry and 14 cross-sectional areas (Fig. 2B) were determined. To quantify erosion or deposition rates, the volume changes were calculated between 2002 and 2013, which provided basis for sediment mass estimation. The generally errors associated with bathymetric change and sediment volume based on bathymetry and the Kriging interpolation technique were estimated to be less than 10% (Jiang et al., 2012).

The final multi-beam data were processed by draft correction, sound speed correction, and correction for roll, pitch, and yaw. Abnormal beam was removed in the editing module by using PDS 2000 software (Teledyne RESON, Slangerup Denmark). Tidal data at Wusong station were used for tidal correction. The vertical datum of the Wusong tide station level is 202 cm lower than mean sea level. By using the Trimble real-time differential global positioning system (DGPS), the accuracy was at the decimeter level.

3. Results

3.1. Bathymetric changes

For the 77-km North Channel, the bed erosion, accretion and net sediment change in volume before the construction of the Qingcaosha Reservoir project (2002～2007) were 5.49 × 10^8 m^3, 4.51 × 10^8 m^3 and 0.98 × 10^8 m^3, respectively (Fig. 4A). After the project was constructed in 2007, the bed erosion rate nearly doubled (9.84 × 10^8 m^3), while the accretion rate remained almost unchanged (4.29 × 10^8 m^3), resulting in 5 times higher net volume loss (5.56 × 10^8 m^3) (Fig. 4B). Overall, during 2002-2013, net volume loss and average annual net volume loss reached 6.54 × 10^8 m^3 and 0.65 × 10^8 m^3 yr^{-1}, respectively (Fig. 4C).

For the 35-km South Channel, during the period 2002-2013, the bed erosion, accretion, net volume loss and average annual net volume loss reached 2.97 × 10^8 m^3, 1.61 × 10^8 m^3, 1.36 × 10^8 m^3 and 0.12 × 10^8 m^3 yr^{-1}, respectively (Fig. 5A).

For the 9-km Hengsha Passage, the bed erosion, accretion and net sediment loss in volume between 2002 and 2007 were 0.66 × 10^8 m^3, 0.45 × 10^8 m^3 and 0.21 × 10^8 m^3, respectively (Fig. 6A). During 2007-2013, the bed erosion rate was slightly higher (0.84 × 10^8 m^3), while the accretion rate reduced by nearly two thirds (0.19 × 10^8 m^3), resulting in 3 times higher net volume loss (0.65 × 10^8 m^3) (Fig. 6B). Overall, from 2002 to 2013, net volume loss and average annual net volume loss reached 0.86 × 10^8 m^3 and 0.08 × 10^8 m^3 yr^{-1}, respectively (Fig. 6C).

For the 60-km South Passage, during the period of Deepening Waterway Project in the North Passage (NP) of the Yangtze River Estuary (2002–2010), the bed erosion, accretion and net sediment loss in volume were estimated to be 8.31 × 10^8 m^3, 3.63 × 10^8 m^3 and 4.68 × 10^8 m^3, respectively (Fig. 6D). After the completion of the Deepening Waterway Project (2010-2013), the bed erosion was greatly reduced to 3.02 × 10^8 m^3, while the accretion rate reduced slightly (2.72 × 10^8 m^3), resulting in 15 times lower net volume loss (0.3 × 10^8 m^3) (Fig. 6E). Overall, during the period from 2002 to 2013, net volume loss and average annual net volume loss reached 4.98 × 10^8 m^3 and 0.45 × 10^8 m^3 yr^{-1}, respectively (Fig. 6F).

During 2010-2013, the depth of the waterway was increased in the North Passage (Fig. 5B) due to the dredging project. Therefore, no attempt was made to calculate bed erosion and accretion for the North Passage.

3.2. Changes in cross-sectional areas

Cross-section NC1 (Fig. 7) in the middle and upper reaches of the North Channel clearly showed that the northern side experienced about 5 m channel erosion during 2002-2007, while about 5.5 m channel accretion occurred in the central part. The deep trough moved northward in 2007, and the maximum water depth changed from 15 m to 17 m. Between 2007 and 2013 about 3 m and 2 m channel erosion occurred in the northern side and central part, respectively. Cross-section NC2 (Fig. 7) in the upper reach of the mouth bar area of the North Channel showed that the northern and southern sides were scoured about 3 m, respectively, while about 4 m accretion occurred in the central part between 2002 and 2007. During 2007-2013, the southern side experienced about 3 m erosion, while about 0.5 m and 1 m accretion occurred in the northern side and central part, respectively. Cross-section NC3 (Fig. 7) in the middle and lower reaches of the mouth bar area of the North Channel showed that the northern side and central part experienced about 0.5 m and 1 m erosion, respectively, while about 2 m accretion occurred in the southern side from 2002 to 2007. During 2007-2013, the channel in the northern side and central part were scoured about 1 m and 1.5 m, respectively, while strong accretion occurred in the central part (i.e., about 2 m). During 2002-2013, the area of the cross-section NC1 increased 12.4%, while the cross-sections NC2 and NC3 decreased 0.2% and 0.3%, respectively (Table 2).

During the period from 2002 to 2013, cross-section SC1 (Fig. 7) in the upper reach of the South Channel showed that the northern side and central part experienced about 3 m and 2 m channel erosion, respectively, while less marked morphological change occurred in the southern side. Cross-section SC2 (Fig. 7) in the middle reach showed about 5 m and 2 m erosion in the northern side and central part, respectively, while slight accretion of 1m occurred in the southern side. Cross-section SC3 (Fig. 7) in the lower reach showed a similar pattern of morphological changes to cross-section SC2, which included strong erosion in the northern side and central part, as well as slight accretion in the southern side. During 2002-2013, the area of the cross-sections SC1, SC2 and SC3 increased 9.7%, 12.3% and 11.8%, respectively (Table 2).

Cross-section HP1 (Fig. 8) in the north entrance of the Hengsha Passage was scoured entirely between 2002 and 2007, and the main channel shifted toward the Changxing Island. During 2007-2013, the channel in the eastern bank and central part were scoured about 9 m and 23 m, respectively, while a sudden accretion of about 0.2 m occurred in the western bank. The main channel was close to the Hengsha Island with the maximum water depth of 30 m. Cross-section HP2 (Fig. 8) in the middle reach showed that about 7 m accretion and about 3 m erosion occurred in the central part and the western bank, respectively, while the eastern bank showed less marked morphological change during 2002-2007. Between 2007 and 2013 the eastern bank, central part and western bank were scoured about 12 m, 6 m and 2.5 m, respectively. Cross-section HP3 (Fig. 8) in the south entrance clearly showed about 2 m and 1 m erosion in the eastern bank and western bank, respectively, while strong accretion of about 3 m occurred in the central part during 2002-2007. From 2007 to 2013, the eastern bank and central part were scoured about 6 m and 4 m, respectively, while about 4.5 m accretion occurred in the western bank. During the period from 2002 to 2013, the area of the cross-sections HP1, HP2 and HP3 increased 137.2%, 46.4% and 50%, respectively (Table 3).

Cross-section SP1 (Fig. 8) in the upstream opening of the South Passage was heavily scoured between 2002 and 2010. The deep trough moved southward in 2010, and the maximum water depth increased from 10.5 to 12 m. During 2010-2013, the channel in the central part and southern side were scoured about 2 m and 1.5 m, respectively, while the northern side experienced about 1m accretion. Cross-section SP2 (Fig. 8) in the upper reach of the South Passage showed continual erosion in the northern side and central part between 2002 and 2013, while less marked morphological change occurred in the southern side. Cross-section SP3 (Fig. 8) in the middle reach showed that the northern side and central part experienced about 1 m and 2 m erosion, respectively, while about 3 m accretion occurred in the southern side during 2002-2010. From 2010 to 2013, the southern side experienced continual accretion of approximately 2.5 m, while the northern side and central part showed less marked morphological change. Cross-section SP4 (Fig. 8) in the lower reach experienced distinct accretion entirely between 2002 and 2010. During 2010-2013, about 1 m erosion and 0.5 m accretion occurred in the northern side and southern side, respectively, while the central part showed less marked morphological change. During the period from 2002 to 2013, cross-section SP5 (Fig. 8) on the outer estuary showed that the northern side and central part were scoured about 0.5 m and 1 m, respectively, while less marked morphological change occurred in the southern side. During 2002-2013, the area of the cross-sections SP1, SP2, SP3 and SP5 increased 18.1%, 18.7%, 12.6% and 8.6%, respectively, while the area of the cross-section SP4 decreased 7.3% (Table 3).

3.3. Changes in the longitudinal profiles

The longitudinal profile of the North Channel has two peaks (shallow area), and the minimum water depth was approximately 5 m in 2002. During 2002-2013, the middle and upper reaches experienced strong erosion, while distinct siltation occurred in the mouth bar area (Figs. 2B and 9).

The longitudinal profile of the South Channel showed continual channel erosion during 2002-2013 (Figs. 2B and 9). The middle and upper reaches experienced strong erosion and the local depth reached a maximum of 19 m. The water depth increased from 10 m to 12.5 m in the lower reach.

The longitudinal profile of the Hengsha Passage showed that the north entrance experienced strong erosion between 2002 and 2007, while strong accretion occurred in the middle reach and south entrance (Figs. 2B and 9). During 2007-2013, the continual channel erosion occurred in the entire Hengsha Passage, especially the north entrance experienced extremely strong erosion and the local depth reached a maximum of 27 m.

The longitudinal profile of the South Passage has two peaks (shallow area), and the minimum water depth was approximately 5.5 m in 2002 (Figs. 2B and 9). During 2002-2013, intense channel erosion occurred in the middle and upper reaches, while gradual accretion occurred in the lower reach.

4. Discussion

4.1. Variations in discharge and seidment input into the Yangtze River Estuary

Under the influence of the strong human interventions within the Yangtze River basin such as dam construction, water and soil conservation, and river sand mining in recent years, the riverine conditions has changed significantly, especially after the construction of the Three Gorge Dam (TGD) which began to impound water in June 2003 (Zhang., 2009). Although the discharge at the Datong station did not show noticeable change since 2003, sediment supply in the past decade showed a declining trend (Fig. 10). This may has inducing an increased sediment-carrying capacity of flow, which may have contributed to bed erosion of the South Channel and the middle and upper reaches of the North Channel (Figs. 4 and 5A). However, the decrease in the sediment supply to the Yangtze River Estuary only marginally affected morphological changes in the South and North Passages (Jiang et al., 2012; He et al., 2013).

4.2. Influence of local engineering projects

The morphology and topography of the North Channel have been changed significantly due to human interventions, especially the construction of the Qingcaosha Reservoir project (Li et al., 2012b). Before the project (2002-2007), there was erosion in the middle and upper reaches, while accretion occurred in the upper reach of the mouth bar area. After execution of the project started (2007-2012), a large part of the upper North Channel was confined by levees, causing narrowing of the channel from 7.1 km to 4.3 km. This has caused large channel incising and bed scouring. The eroded sediment was transported seaward from the middle and upper reaches, resulting in substantial accretion in the upper reach of the mouth bar area. As the scouring trend continues (Liu et al., 2011a), the upper reach of the mouth bar area also experienced erosion. Hence, the eroded sediment was transported seaward from the upper reach of the mouth bar area, causing strong accretion in the middle and lower reaches of the mouth bar area.

The Hengsha Passage is a unique passage oriented in the N-S direction in the Yangtze River Estuary with the North Channel in its north and the North Passage in its South. The development of the channel was believed to be caused by the phase difference in tidal due to estuarine bifurcation (Kuang et al., 2014). This may be also related to the sediment and water exchange between the North Channel and the North Passage (Cheng et al., 2010). The construction of the Qingcaosha Reservoir project and Changxing Submerged Dike project may have indirectly affected the morphology of the Hengsha Passage (Kuang et al., 2014). The Changxing Submerged Dike project is a part of the Deepening Waterway Project, which is located on the sand spit in the southeast of the Changxing Island with a length of 1 840 m. Before the projects (2002-2007), there was erosion in the north entrance, while accretion occurred in the middle reach and south entrance. After execution of the projects (2007-2013), analysis showed that the middle and upper reaches of the North Channel experienced strong erosion, while the north entrance, middle reach and south entrance in the Hengsha Passage also experienced constant erosion during the same period. A large amount of the eroded sediment from the south entrance of the Hengsha Passage was trapped, resulting in substantial accretion in the upper reach of the North Passage (Figs. 5). Consequently, a large range of scour marks is clearly visible in the bed of the Hengsha Passage (Fig. 11 A).

The ebb flow diversion ratios in the North Passage and the South Passage (the percentage of ebb tidal volume of the North Passage and the South Passage in the total ebb tidal volume) were reported to be about 60% and 40%, respectively, before 1998 when construction of the Deepening Waterway Project was started (Kuang et al., 2014). During the first construction stage of the Project (August 1998–May 2001), two training walls and ten groins were constructed in the North Passage, which led to a significant change in the ebb flow diversion ratio in both the North Passage and the South Passage (Jiang et al., 2012). From the second to the third construction stage (2002-2010), the ebb flow diversion ratio of the South Passage increased significantly, for example, the minimum ebb flow diversion ratio increased from 60% to 70% during the flood season of 2010 (Dai et al., 2015). These findings indicate that the stronger ebb flow may have been the cause for the estuarine bed erosion in the upper reach and the consequent accretion in the lower reach.

The North Passage has been affected by the Deepening Waterway Project carried out in the Yangtze River Estuary between 1998 and 2010 (Song et al., 2013). The main channel has been continually dredged since 1998 from the average water depth of less than 7 m to the present 12.5 m using trailing-suction hopper dredgers (Chen et al., 2015). The water depth of the waterway reached 12.5 m by 2010, and the back siltation increased obviously in the waterway (Jiang et al., 2012). The quantity of back siltation was 80.9 million m^3 between February 2010 and August 2011, and the back siltation mainly concentrated in the middle reach of the North Passage (Ge et al., 2013; Dai et al., 2013; Song and Wang., 2013; Liu et al., 2011b). Therefore, in order to maintain a deep waterway, dredging must be carried out on a continual basis; indeed the annual dredged volume has increased in recent years to more than $6\times10^7 m^3$ (Kuang et al., 2014). A large number of dredging marks and hollows have therefore become apparent in recent years in the North Passage (Figs. 11B and 11 C).

4.3 Saltwater intrusion

Salinity is a key parameter describing aquatic systems in an estuarine environment (Huang and Foo., 2002). Understanding salinity variation in estuaries under different forcing conditions, e.g. extreme drought, climate change or human interventions, can be crucial for helping manage estuarine water resources (Brockway et al., 2006). Salinity in the Yangtze River Estuary is affected by river discharge and oceanic saltwater (An et al., 2009). River discharge freshen the estuary, whereas tide transports salt into the estuary and increases salinity. It is understood that when the salinity level in the Yangtze River Estuary is over 100 mg/l, saltwater intrusion is assumed to occur (Chinese living drinking water and water source standard (CJ302093)).

However, saltwater intrusion in the Yangtze River Estuary may be affected by bathymetry change caused by human interventions in the recent years. It is well known that increased depth can lead to increased saltwater intrusion. It is more complicated why depth increase would lead to saltwater intrusion. Deeper depth would lead to stronger vertical circulation resulting in more saltwater transported upstream at the bottom.

Saltwater transport plays an important role in estuaries and can have impacts on ecological and biogeochemical conditions (Zhou et al., 2008). The residual transports of saltwater in the South Channel are generally seaward and are affected by runoff (Ge et al, 2013). With river flow discharge decreasing, saltwater migrates toward the landward and increases mean salinity (Wu et al., 2006). While our study indicated that the South Channel experienced intense erosion in the recent years. Consequently, the water depth has increased, which will aggravate the saltwater intrusion.

The North Channel is the major outlet of fresh water in the Yangtze River Estuary and residual transport flows seaward (Cheng and Zhu., 2013), Cheng and Zhu (2015) reported that the North Channel has more pronounced salinity increase than the other channels. This may have been a result from the strong erosion that we found in this study in the middle and upper reaches of the North Channel. The landward saltwater transport is strengthened in the North Channel and may further affect the upper reach (Cheng and Zhu., 2015). This can threaten the security of freshwater resources and the ecosystem in the affected area. The Qingcaosha Reservoir provides an average of 7.19 million m^3 freshwater per day, more than half of the daily water supply amount to Shanghai (Yang et al., 2015b). When salinity exceeds 0.45 psu (chlorinity of 250 mg/l), it is considered undrinkable (Dai et al., 2011).

Due to the lower freshwater inflow when compared with the North Channel, salinities in the South and North Passages are relatively higher. Residual transport in the upper North Passage is directed seaward, whereas landward transport occurs in the South Passage and the lower North Passage (Cheng and Zhu., 2013). This landward residual transport in the South Passage is mainly caused by tide and topography, and landward transport in the lower North Passage is controlled by tides (Wu and Zhu., 2010). Intense erosion in recent years experienced in the middle and upper reaches of the South Passage, increased water depth may have aggravated saltwater intrusion in the South Passage.

Increased depth of the waterway due to dredging in the North passage, may have contributed to increased saltwater intrusion, especially during the flood tide when the high-salinity seawater moves onshore into the North Passage (Ge et al., 2013). Saltwater intrusion may have also played an important role in the siltation of the shipping channel as flocculation occurs in a salinity range of 5-10 psu found in the middle region of the waterway (Ge et al., 2013). Consequently, it is possible that saltwater intrusion has intensified siltation because of the freshwater-saltwater mixing, pushing the turbidity maximum zone inland.

5. Conclusions

This study analyzed the bathymetric changes of the Yangtze River Estuary from 2002 to 2013. The results showed that the middle and upper reaches of the estuary experienced strong erosion caused by recent human activities. A large amount of the eroded sediment appeared to be trapped downstream, causing overall channel bed accretion in the lower river mouth reach of the estuary. The navigable depth was deepened in the North Channel because of the construction of a large drinking water reservoir. The South Passage became the chief conduit for seaward transport of sediment because of a channel deepening project. In order to maintain the minimal depth of 12.5 m for the shipping channel, daily dredging amount had to be increased, resulting in more costs in manpower and financial resources. Saltwater intrusion has increased in the South and North Channels, and South and North Passages, likely due to the bathymetry changes caused by human interventions in recent years. These results suggest that human activities have direct effects not only on channel morphology but also on the salinity in the Yangtze River Estuary.

Acknowledgments: This study was financially supported by the Natural Science Foundation of China (Grant Number: 41476075). During preparation of this manuscript, Shuaihu Wu was supported by an award of the China Scholarship Council (File No.201506140113) and Y. Jun Xu received partial support from a grant of the U.S. National Science Foundation (award number: 1212112) and a U.S. Department of Agriculture Hatch Fund project (project number: LAB94230). We are also grateful for three anonymous reviewers and Editor Steve Mitchell for their helpful comments and suggestions.

References

An, Q., Wu, Y.Q., Taylor, S., Zhao, B., 2009. Influence of the Three Gerges Project on saltwater intrusion in the Yangtze River Estuary. Environ Geol 56, 1679-1686.

Barlow, P.M., Reichard, E.G., 2010. Saltwater intrusion in coastal regions of North America. Hydrogeol. J 18, 247–260.

Blott, S.J., Pye, K., van der Wal. D., Neal, A., 2006. Long-term morphological change and its causes in the Mersey Estuary, NW England. Geomorphology 81, 185-206.

Brockway, R., Bowers, D., Hoguane, A., Dove, V., Vassele, V., 2006. A note on salt intrusion in funnel-shaped estuarine: Application to the Incomati Estuary, Mozambique. Estuarine, Coastal and Shelf Science 66, 1-5.

Benedet, L., List, J.H., 2008. Evalation of the physical process controlling beach changes adjacent to nearshore dredge pits. Coastal Engineering 55, 1224-1236.

Cheng, H.Q., Kostaschuk, R., Shi, Z., 2004. Tidal Currents, Bed Sediments, and Bedforms at the South Branch and the South Channel of the Changjiang (Yangtze) Estuary, China: Implications for the Ripple-dune Transition. Estuaries 27, 861-866.

Chao, M., Shi, Y.R., Quan, W.M., Shen, X.Q., 2015. Distribution of Macrocrustaceans in Relation to Abiotic and Biotic Variables across the Yangtze River Estuary, China. Journal of Coastal Research 31, 946-956.

Cheng, H.F., Liu, J., Zhao, D.Z., 2010. Analysis of river bed evolution and prediction of its trend for Hengsha Passage. Journal of Waterway and Harbor 31, 365-369 (in Chinese).

Cheng, Q., Zhu, J.R., 2013. Influence of seasonal runoff regulation by the Three Gorges Reservoir on saltwater intrusion in the Changjiang River Estuary. Continental Shelf Research 71, 16-26.

Cheng, Q., Zhu, J.R., 2015. Assessing the influence of Sea Level Rise on Salt Transport Processes and Estuarine Circulation in the Changjiang River Estuary. Journal of Coastal Research 31, 661-670.

Chen, D., Dai, Z.J., Xu, R., Li, D.J., Mei, X.F., 2015. Impacts of anthropogenic activities on the Changjiang (Yangtze) estuarine ecosystem (1998-2012). Acta Oceanol. Sin 34, 86-93.

Chen, W., Chen, K., Kuang, C.P., Zhu, D.Z., He, L.L., Mao, X.D., Liang, H.D., Song, H.L., 2016. Influence of sea level rise on saline water intrusion in the Yangtze River Estuary, China. Applied Ocean Research 54, 12-25.

Day, J.W., Hall, C.A.S., Kemp, W.M., Yanez-Arancibia, A., 1989. Estuarine Ecology. John Wiley & Sons, Inc., New York, NY, USA.

De Jonege, V.N., Schuttelaars, H.M., van Beusekomc, J.E.E., Talke, S.A., de Swart, H.E., 2014. The influence of channel deepening on estuarine turbidity levels and dynamics, as examplified by the Ems estuary. Estuarine, Coastal and Shelf Science 139, 46-59.

Dai, Z.J., Chu, A., Stive, M., Zhang, X.L., 2011. Unusual Salinity Conditions in the Yangtze Estuary in 2006: Impacts of an Extreme Drought or of the Three Gorges Dam? AMBIO 40, 496-505.

Dai, Z.J., Liu, J.T., Fu, G., Xie, H.L., 2013. A thirteen-year record of bathymetric changes in the North Passage, Changjiang (Yangtze) estuary. Geomorphology 187, 101-107.

Dai, Z.J., Liu, J.T., Wei, W., 2015. Morphological evolution of the South Passage in the Changjiang (Yangtze River) estuary, China. Quaternary International 380-381, 314-326.

Gong, W.P., Wang, Y.P., Jia, J.J., 2012. The effect of interacting downstream branches on saltwater intrusion in the Modaomen Estuary, China. Journal of Asian Earth Sciences 45, 223-238.

Ge, J.Z., Ding, P.X., Chen, C.S., Hu, S., Fu, G., Wu, L.Y., 2013. An integrated East China Sea-Changjiang Estuary model system with aim at resolving multi-scale regional-shelf-estuarine dynamics. Ocean Dynamics 63, 881-900.

Huang, W.R., Foo, S., 2002. Neural network modeling of salinity variation in Apalachicola River. Water Research 36, 356-362.

He, Y.F., Cheng, H.Q., Chen, J.Y., 2013. Morphological Evolution of Mouth Bars of the Yangtze Estuarine Waterways. Journal of Geographical Sciences 23, 219-230.

Inman, D.L., Jenkins, S.A., 1984. The Nile littoral cell and man’s impact on the coastal zone of the South East Mediterranean. In: 19 th Coastal Engineering Conference. Proceedings American Society of Civil Engineers, Houston, Texas 1600-1617.

Jaffe, B.E., Smith, R.E., Foxgrover, A.C., 2007. Anthropogenic influence on sedimentation and intertidal mudflat change in San Pablo Bay, California: 1856-1983. Estuarine, Coastal and Shelf Science 73, 175-187.

Jiang, C.J., Li, J.F., de Swart, H.E., 2012. Effects of navigational works on morphological changes in the bar area of the Yangtze River Estuary. Geomorphology 139, 205-219.

Kuang, C.P., Chen, W., Gu, J., He, L.L., 2014. Comprehensive ananlysis on the sediment silation in the upper reach of the deep-water navigation channel in the Yangtze Estuary. Journal of Hydrodynamics 26, 299-308.

Lane, A., 2004. Bathymetric evolution of the Mersey Estuary, UK, 106-1997: causes and effects. Estuarine, Coastal and Shelf Science 59, 249-263.

Li, X., Wu, D.A., 2011. Study on the Yangtze River estuarine turbidity maximum. Applied Mechanics and Materials, 90-93, 2774-2747.

Li, W.H., Cheng, H.Q., Li, J.F., Dong, P., 2008. Temporal and spatial changes of dunes in the Changjiang (Yangtze) estuary, China. Estuarine, Coastal and Shelf Sciences 77, 169-174.

Li, L., Zhu, J.R., Wu, H., 2012a. Impacts of wind stress on saltwater intrusion in the Yangtze Estuary. Science China Earth Sciences 55, 1178-1192 (in Chinese).

Li, B.C., Wang, J., Tang, M.J., 2012b. Analysis on recent evolution of Beigang branch of Yangtze River Estuary and its regulation countermeasures. Yangtze River 43, 12-16 (in Chinese).

Liu, J., Chen, J.Y., Le, J.H., Huang, R.Y., 2005. Effect of the implementation of the first_stage project of the deepwater channel regulation in the Yangtze River Estuary on the erosion and deposition in the South Passage. Journal of Sediment Research 5, 40-44 (in Chinese).

Liu, H., He, Q., Wang, Z., Weltje, G.J., Zhang, J., 2010. Dynamics and spatial variability of near-bottom sediment exchange in the Yangtze Estuary, China. Estuarine, Coastal and Shelf Science 86, 322-330.

Liu, W.Y., Tang, J.H., Miu, S.Q., 2011a. Study on evolution trend of North Channel of Yangtze River Estuary and influences of related projects. Yangtze River 42, 39-43 (in Chinese).

Liu, G.F., Zhu, J.R, Wang, Y.Y, Wu, H., Wu, J.X, 2011b. Tripod measured residual currents and sediment flux impacts on the silting of the Deepwater Navigation Channel in the Changjiang Estuary. Estuarine, Coastal and Shelf Science 93, 192-201.

Mao, Z.C., Shen, H.T., Liu, J.T., Eisma, D., 2001. Types of saltwater intrusion of the Yangtze Estuary. Science in China (Series B) 44, 150-157 (in Chinese).

Nichols, M.M., Howard-Strobel, M.M., 1991. Evolution of an urban estuarine harbor: Norfolk, Virginia. Journal of Coastal Research 7, 745-757.

Omar, K., Ahmad, A.B., Jean-philippe, G., Mustapha, J., 2016. Impact of Demographic Growth on Seawater Intrusion: Case of the Tripoli Aquifer, Lebanon. Water 8, 1-18.

Pu, X., Shi, J.Z., Hu, G.D., Xiong, L.B., 2015. Circulation and mixing along the North Passage in the Changjiang River Estuary, China. Journal of Marine Systems 148, 213-235.

Savenije HHG, 2005. Salinity and tides in alluvial estuaries. Elsevier, Amsterdam, p194.

Song, D.H., Wang, X.H., Cao, Z.Y., Guan, W.B., 2013. Suspended sediment transport in the Deepwater Navigation Channel, Yangtze River Estuary, China, in the dry season 2009: 1. Observations over spring and neap tidal cycles. Journal of Geophysical Research – Oceans 118, 5555-5567.

Song, D.H., Wang, X.H., 2013. Suspended sediment transport in the Deepwater Navigation Channel, Yangtze River Estuary, China, in the dry season 2009: 2. Numerical simulations. Journal of Geophysical Research: Oceans 118, 5568-5590.

Thomas, C.G., Spearman, J.R., Turnbull, M.J., 2002. Historical morphological change in the Mersey estuary. Continental Shelf Research 22, 1775-1794.

Talke, S.A., de Swart, H.E., Schuttelaars, H.M., 2009. Feedback between residual circulations and sediment distruibution in highly turbid estuaries: an analytical model: Continental Shelf Research 29, 119-135.

Van der Wal, D., Pye, K., Neal, A., 2002. Long-term morphological change in the Ribble Estuary, northwest England. Marine Geology 189, 249–266.

Van der Wal, D., Pye, K., 2003. The use of historical bathymetric charts in a GIS to assess morphological change in estuaries. The Geographical Journal 169, 21–31.

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 Changiang estuary: a numerical study. Estuarine, Coastal and Shelf Science 69, 125-132.

Wu, J.X., Wang, Y.H., Cheng, H.Q., 2009. Bedforms and bed material transport pathways in the Changjiang (Yangtze) Estuary. Geomorphology 104, 175-184.

Wu, H., Zhu, J.R., 2010. Advection scheme with 3rd high-order spatial interpolation at the middle temporal level and its application to saltwater intrusion in the Changjiang Estuary. Ocean modeling 33, 33-51.

Yang, S.L., Zhang, J., Dai, S.B., Li, M., Xu, X.J., 2005. Effect of deposition and erosion within the main river channel and large lakes on sediment delivery to the estuary of the Yangtze River. Journal of Geophysical Research 112, F02005. doi:10.1029/2006JF000484.

Yang, Z.Y., Cheng, H.Q., Li, J.F., 2015a. Nonlinear advection, Coriolis force, and frictional influence in the South Channel of the Yangtze Estuary, China. Science China Earth Sciences 58, 429-435 (in Chinese).

Yang, Y., Chen, X.F., Li, Y.Y., Xiong, M., Shen, Z.Y., 2015b. Modeling the effects of extreme drought of pollutant transport processes in the Yangtze River Estuary. Journal of the American water resources association 51, 625-636.

Yuan, R., Zhu, J.R., 2015. The Effects of Dredging on Tidal Range and Saltwater Intrusion in the Pearl River Estuary. Journal of Coastal Research 31, 1357-1362.

Zhou, M.J., Shen, Z.L., Yu, R.C., 2008. Responses of a coastal phytoplankton community to increased nutrient input from the Changjiang (Yangtze) River. Continental Shelf Research 28, 1483-1489.

Zhang, Q., Xu, C.Y., Singh, V.P., Yang, T., 2009. Multiscale variability of sediment load and streamflow of the lower Yangtze River basin: Possible causes and implications. Journal of Hydrology 368, 96–104.

Zhao, H., Zhou, J.L., Zhao, J., 2015. Tidal impact on the dynamic behavior of dissolved pharmaceuticals in the Yangtze Estuary, China. Science of the Total Environment 536, 946-954.

Zhu, W.W., Li, J.F., Sanford, L.P., 2015. Behavior of suspended sediment in the Changjiang Estuary in response to reduction in river sediment supply. Estuaries and Coasts 38, 2185-2197.

Table 1. Bathymetric charts used as the main source for morphological change analysis for the Yangtze River Estuary.

Year	Channel	Scale	Source
2002	South and North Channels, South and North Passages and Hengsha Passage	1:10000	CJWAB
2007	North Channel and Hengsha Passage	1:10000	CJWAB
2010	South and North Passages	1:60000	SECSRC
2013	South Channel, South and North Passages	1:60000	SECSRC
	North Channel and Hengsha Passage	1:15000	Maritime safety administration of P.R.C.

CJWAB: Changjian Estuary Waterway Administration Bureau (CJWAB), Ministry of Transportion of China.

SECSRC: Shanghai Estuarine & Coastal Science Research Center.

Table 2. Changes of six cross-sectional areas in the North Channel and South Channel（negative means increase, plus means decrease）

	NC1	NC2	NC3	SC1	SC2	SC3
	m^2	m^2	m^2	m^2	m^2	m^2
2002	54973	45620	36392	59726	58293	55409
2007	56343	44905	40372			
2013	61811	45514	36280	65537	65482	61955
2002-2013	12.4%	-0.2%	-0.3%	9.7%	12.3%	11.8%

Table 3. Changes of eight cross-sectional areas in the Hengsha Passsage and the South Passage（negative means increase, plus means decrease）

	HP1 m^2	HP2 m^2	HP3 m^2	SP1 m^2	SP2 m^2	SP3 m^2	SP4 m^2	SP5 m^2
2002	9122	8255	9109	29327	25265	39521	92169	92453
2007	13126	7062	8906					
2010				33175	29402	43034	85563	100380
2013	21634	12086	13668	34631	29981	44513	85405	100424
2002-2013	137.2%	46.4%	50%	18.1%	18.7%	12.6%	-7.3%	8.6%

Figure(s)

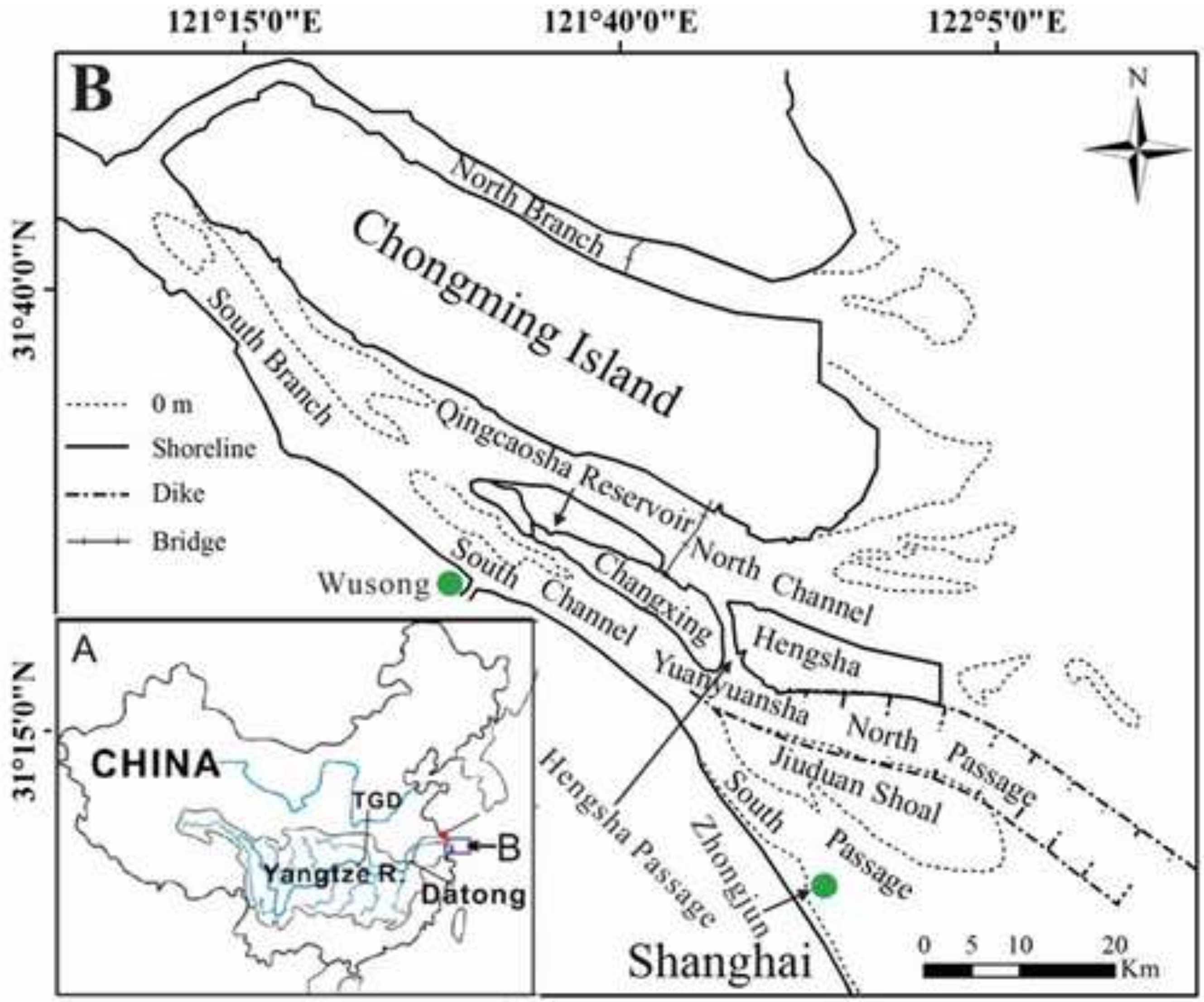

Fig. 1. Geographical location of the study area – the Yangtze River Estuary in China, with Chongming Island, the Changxing Island, Hengsha Island, the North and South Branches, the North and South Channels Passages, Hengsha Passage and the Jiuduan Shoal.

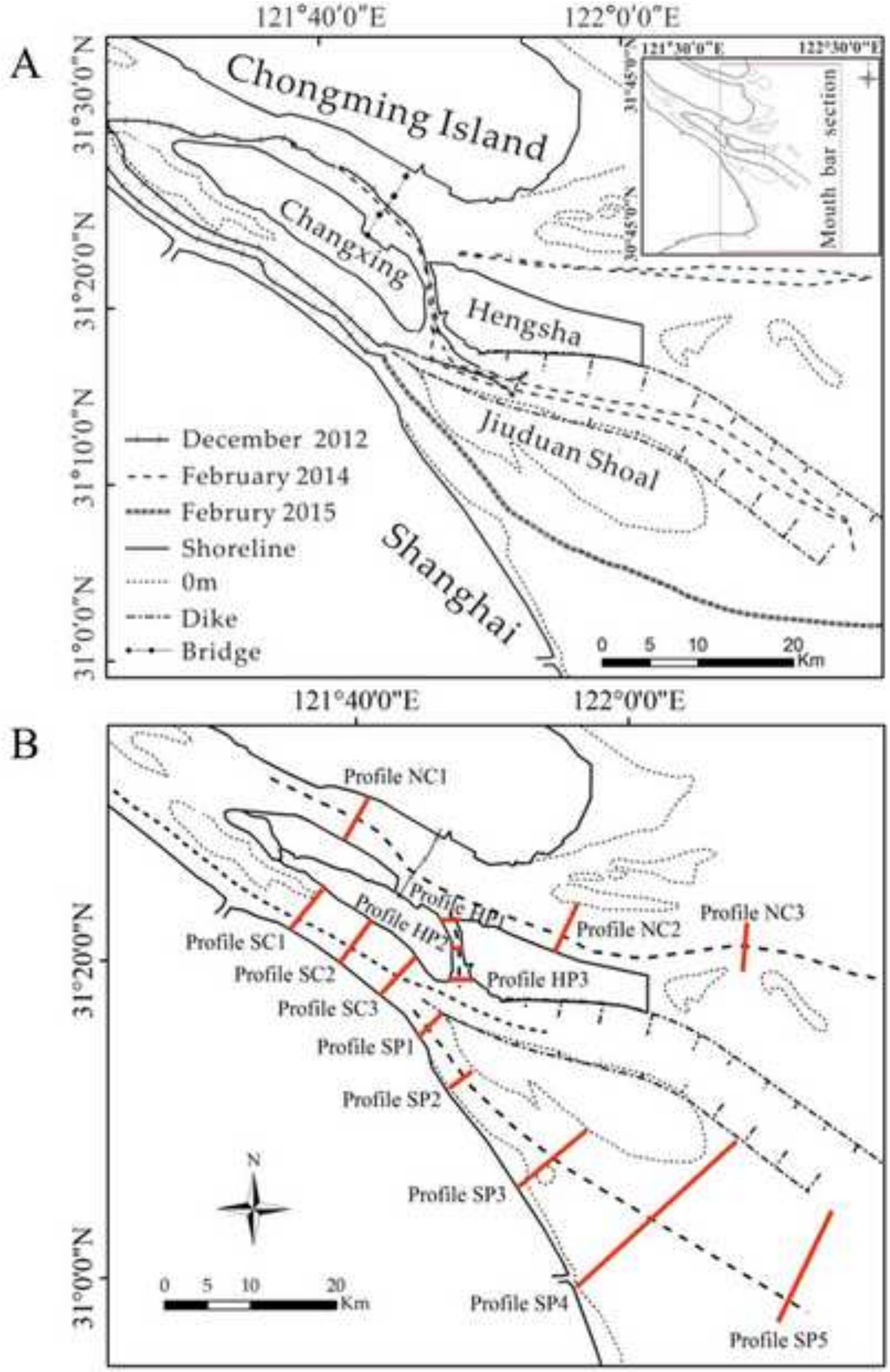

Fig. 2. Field measurement routes and location of the mouth bar section of the Yangtze River Estuary (A). Location of 14 cross sections (red solid lines) and 4 longitudinal sections (black dotted lines) along the North Channel and South Channels, the Hengsha Passage and the South Passage (B).

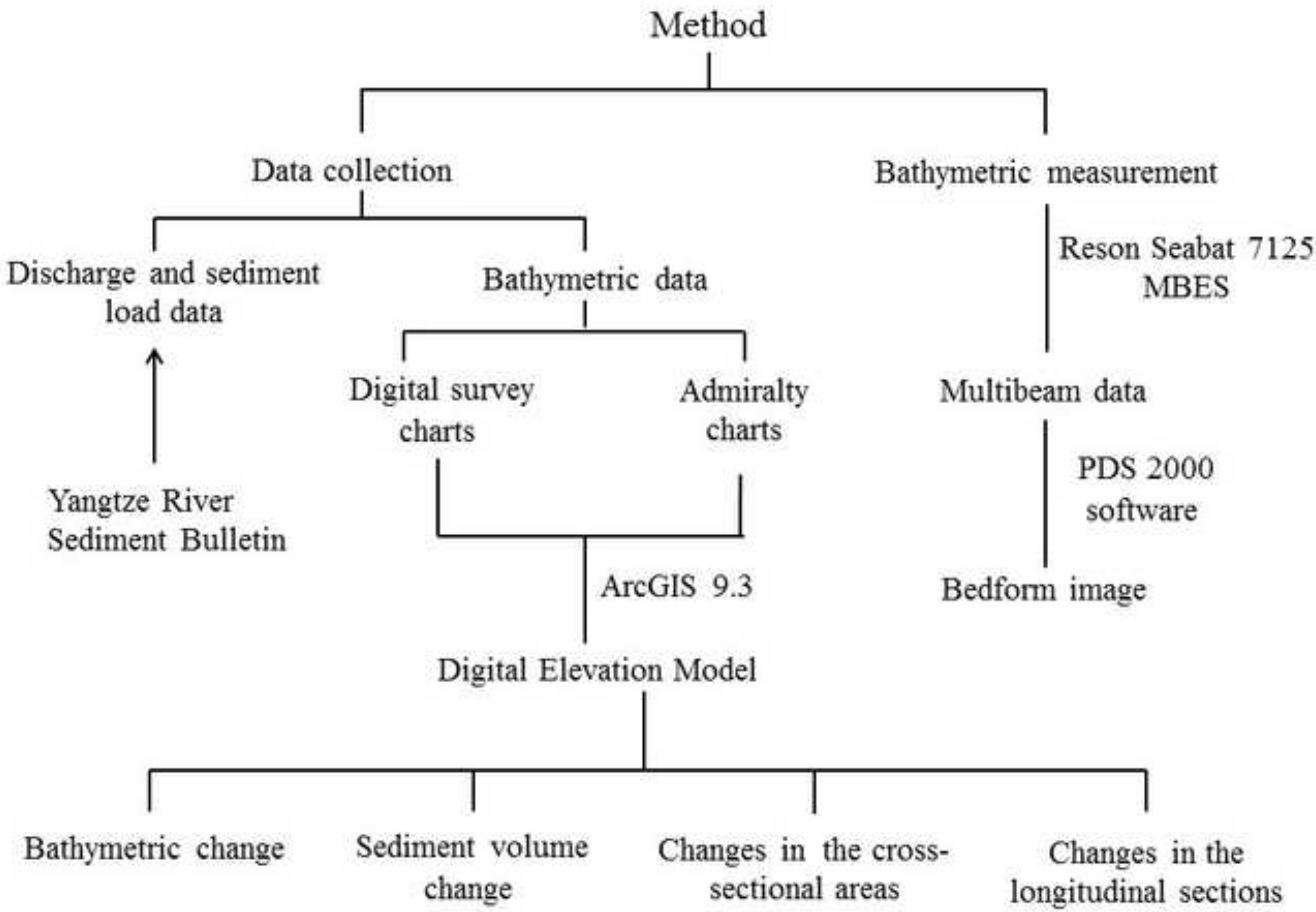

Fig. 3. Schematic diagram of the data collection and analysis in the present study

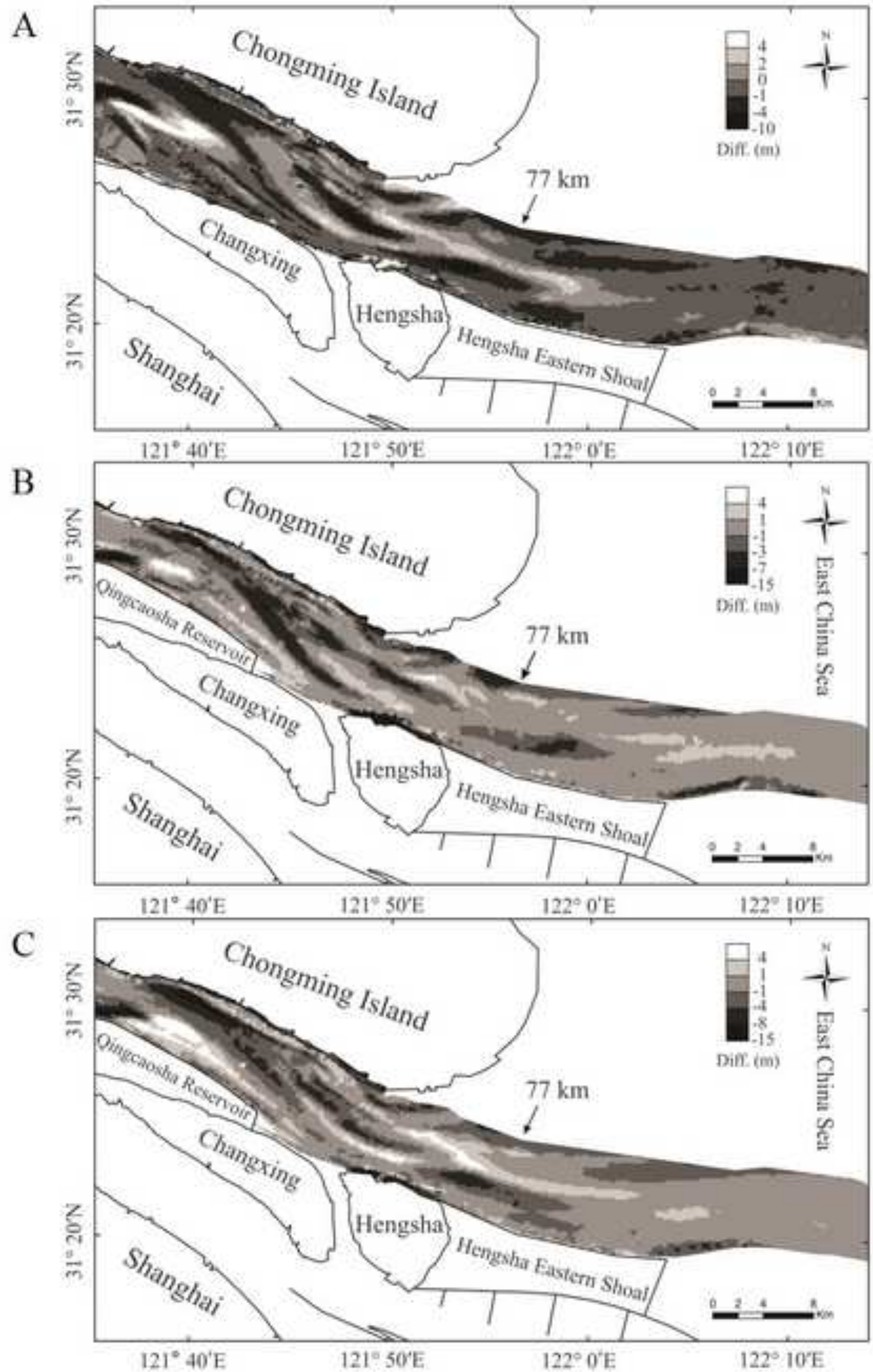

Fig. 4. Bathymetric elevation changes in the North Channel from 2002 to 2007 (A), 2007 to 2013 (B) and 2002 to 2013 (C) (negative values indicate net erosion; positive values indicate net accretion).

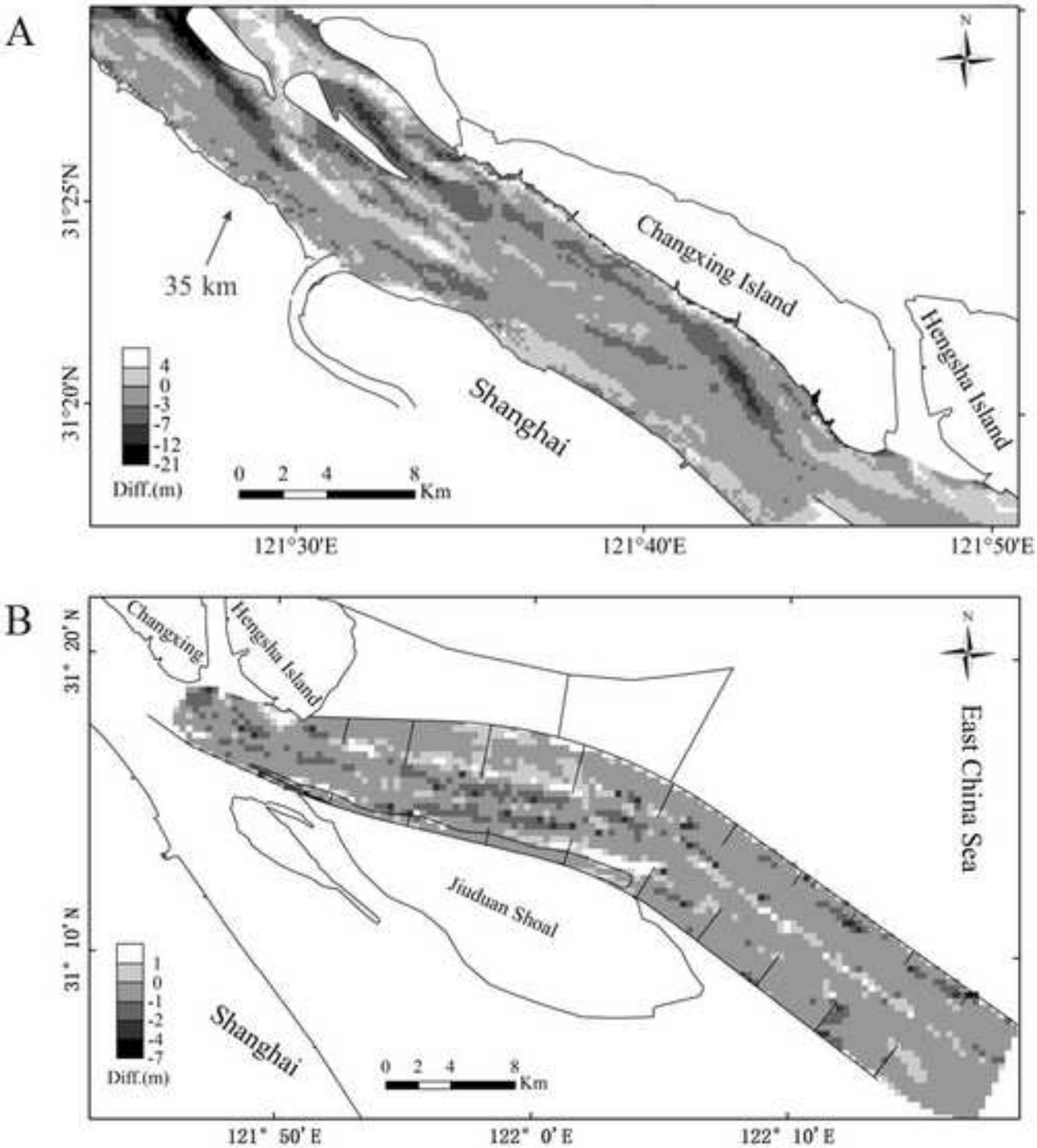

Fig. 5. Bathymetric elevation changes in the South Channel from 2002 to 2013 and in the North Passage from 2010 to 2013 (negative means erosion, positive means deposition).

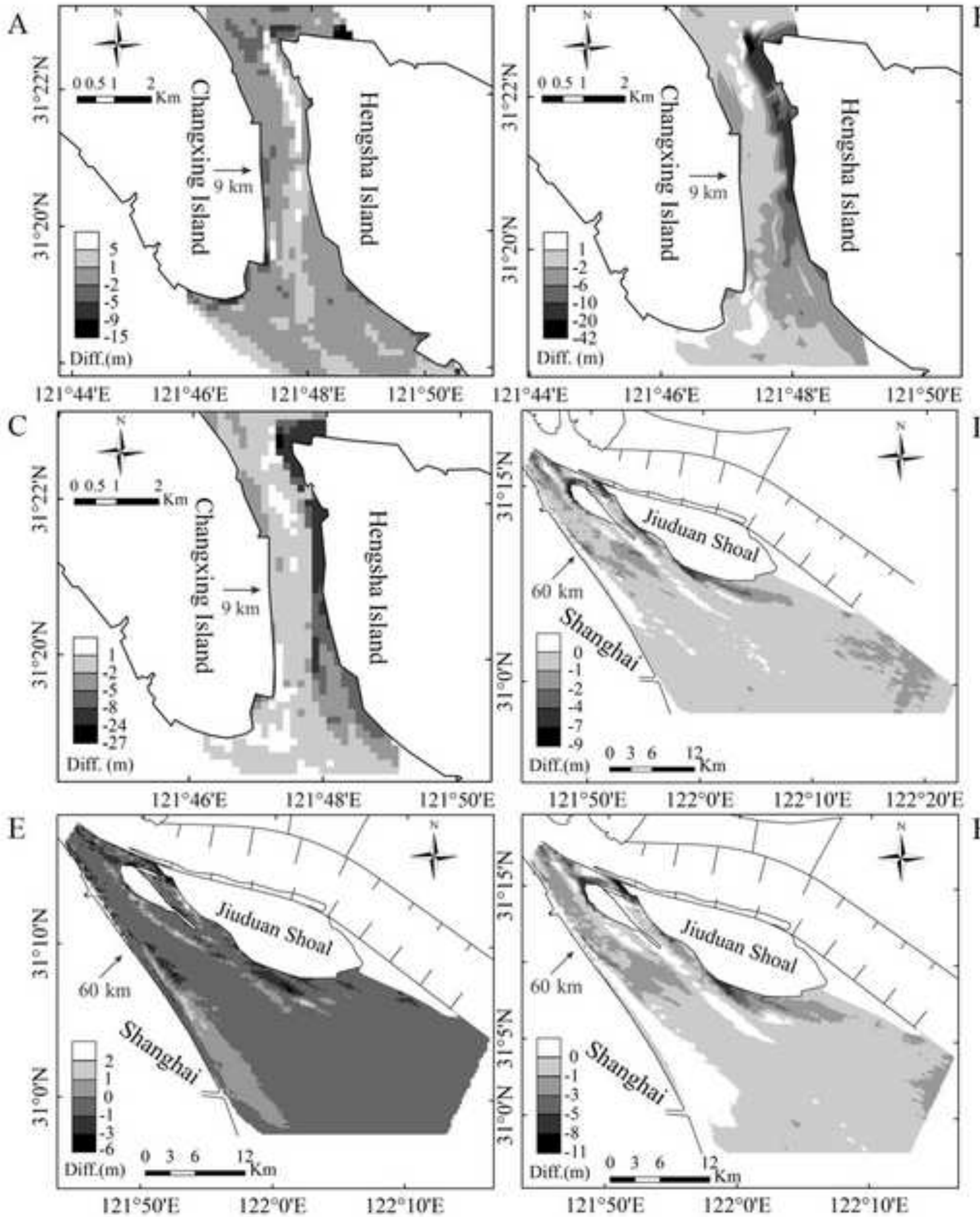

Fig. 6. Bathymetric elevation changes in the Hengsha Passage from 2002 to 2007 (A), 2007 to 2013 (B) and 2002 to 2013 (C), and in the South Passage from 2002 to 2010 (D), 2010 to 2013 (E) and 2002 to 2013 (F) (negative means erosion, positive means deposition).

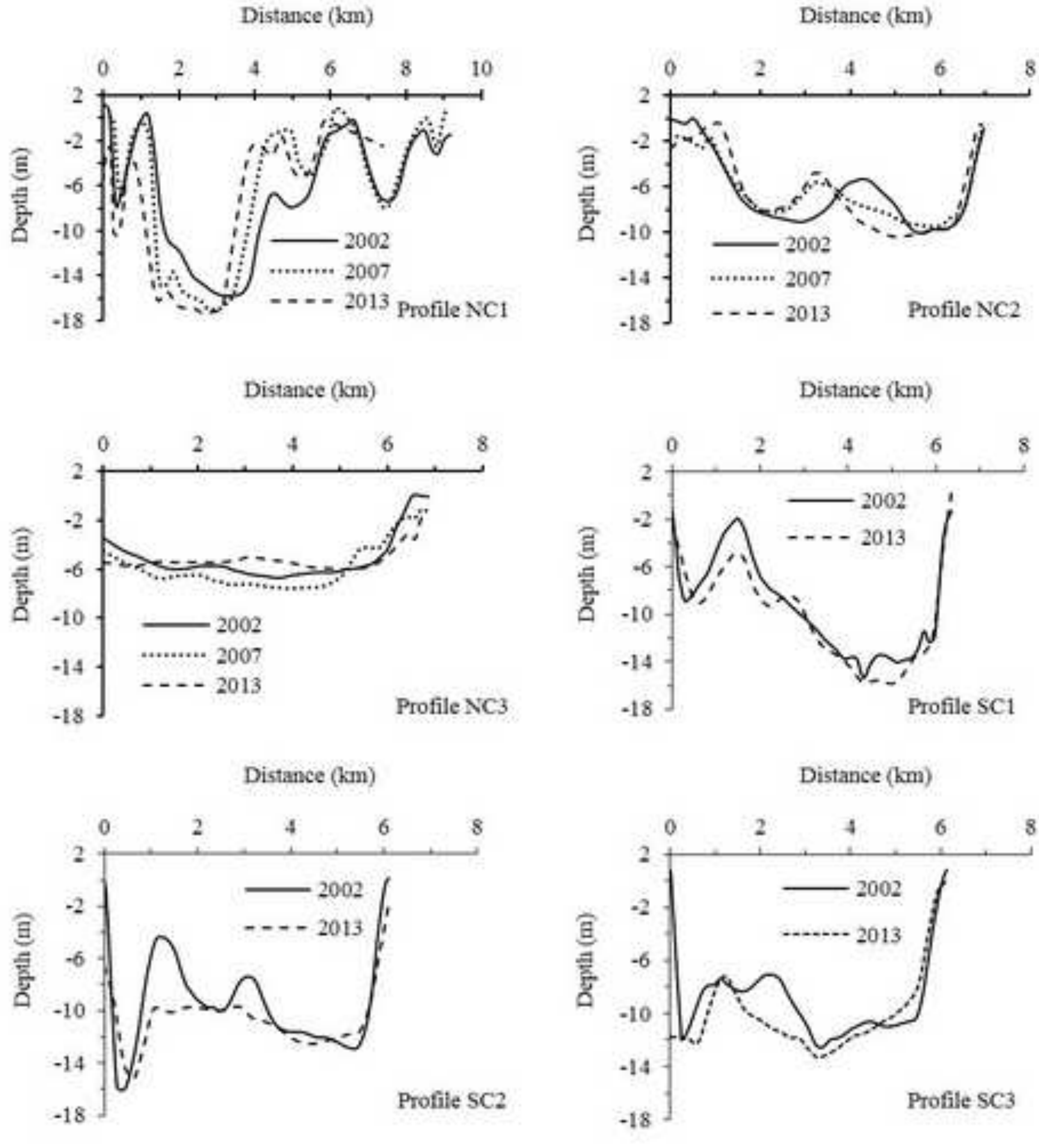

Fig. 7. Channel profiles at 6 different cross-sections (for location see Fig. 2B) in 3 or 2 different years in the North and South Channels. Distance was measured with respect to the northern edge of these cross-sections.

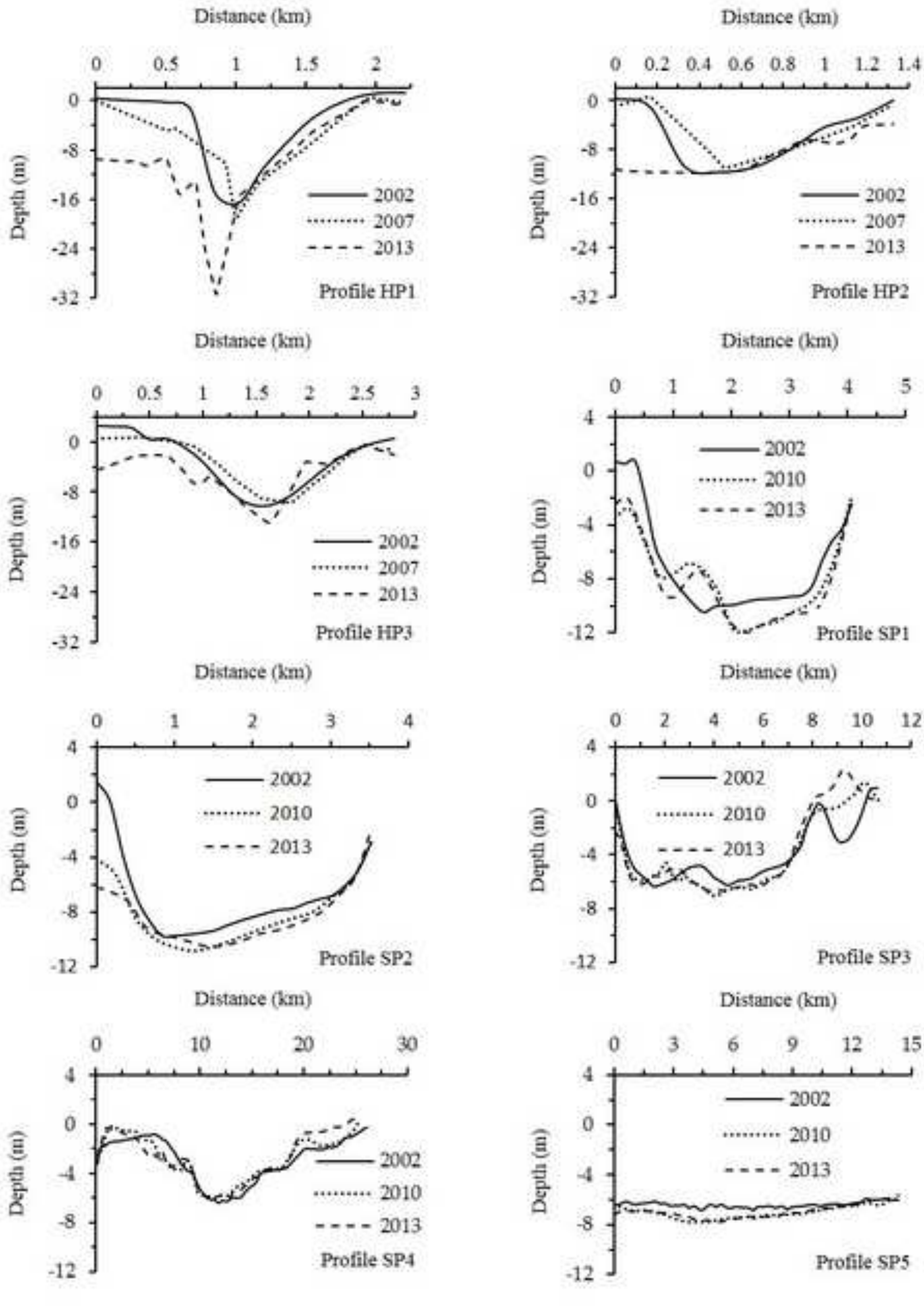

Fig. 8. Channel profiles at 8 different cross-sections (for location see Fig. 2B) in 3 different years in the Hengsha Passage and the South Passage. For the Hengsha Passage and the South Passage, distance was measured with respect to the eastern edge and northern edge of the cross-sections, respectively.

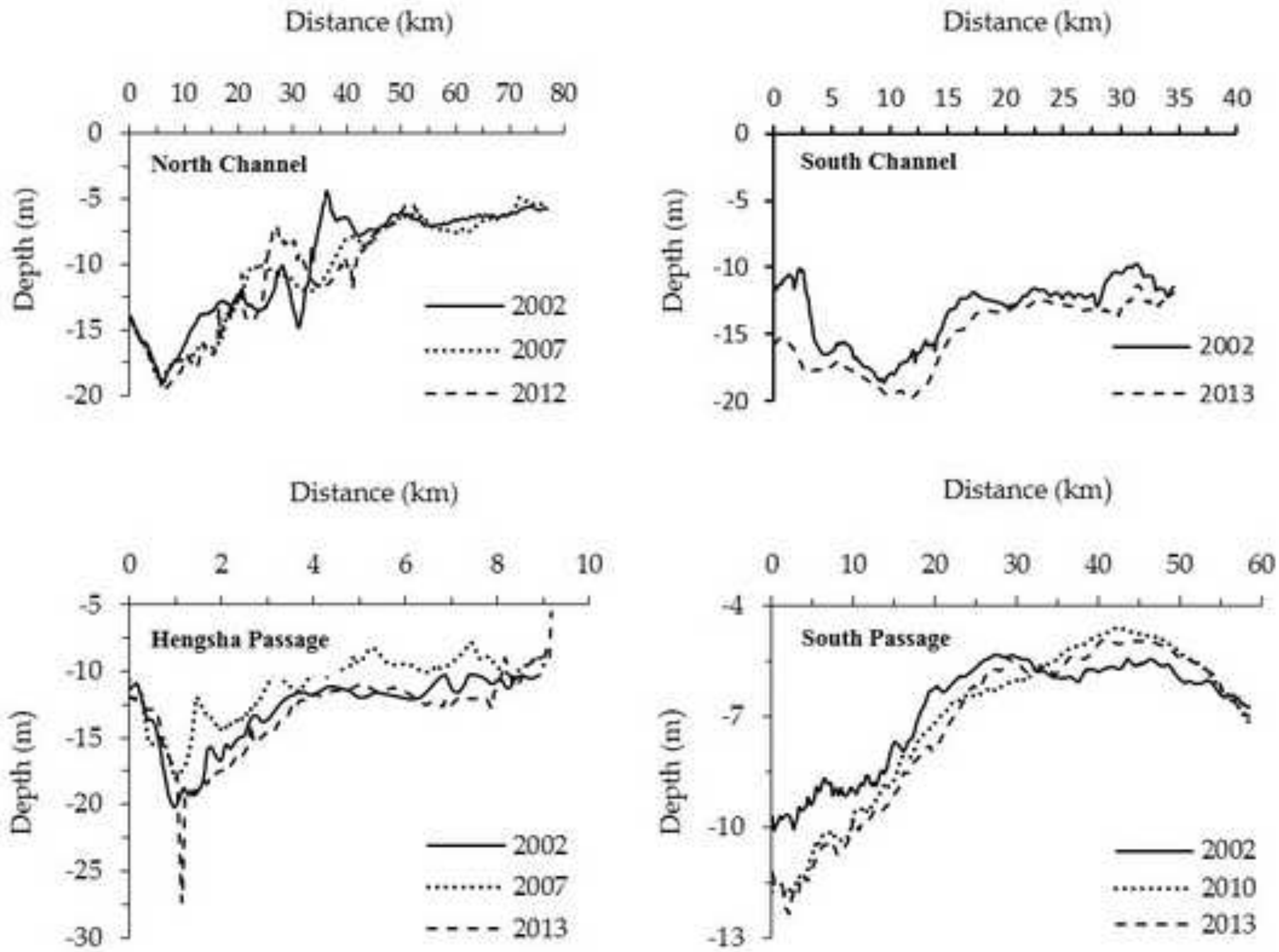

Fig. 9. Longitudinal changes of thalweg of the four studied channels in the lowermost Yangtze River Estuary (for locations see Fig. 2B) in 3 or 2 different years. Distance was measured with respect to the western edge of the profiles in the South and North Channels and the South Passage. For the Hengsha Passage, distance was measured with respect to the northern edge of the profile.

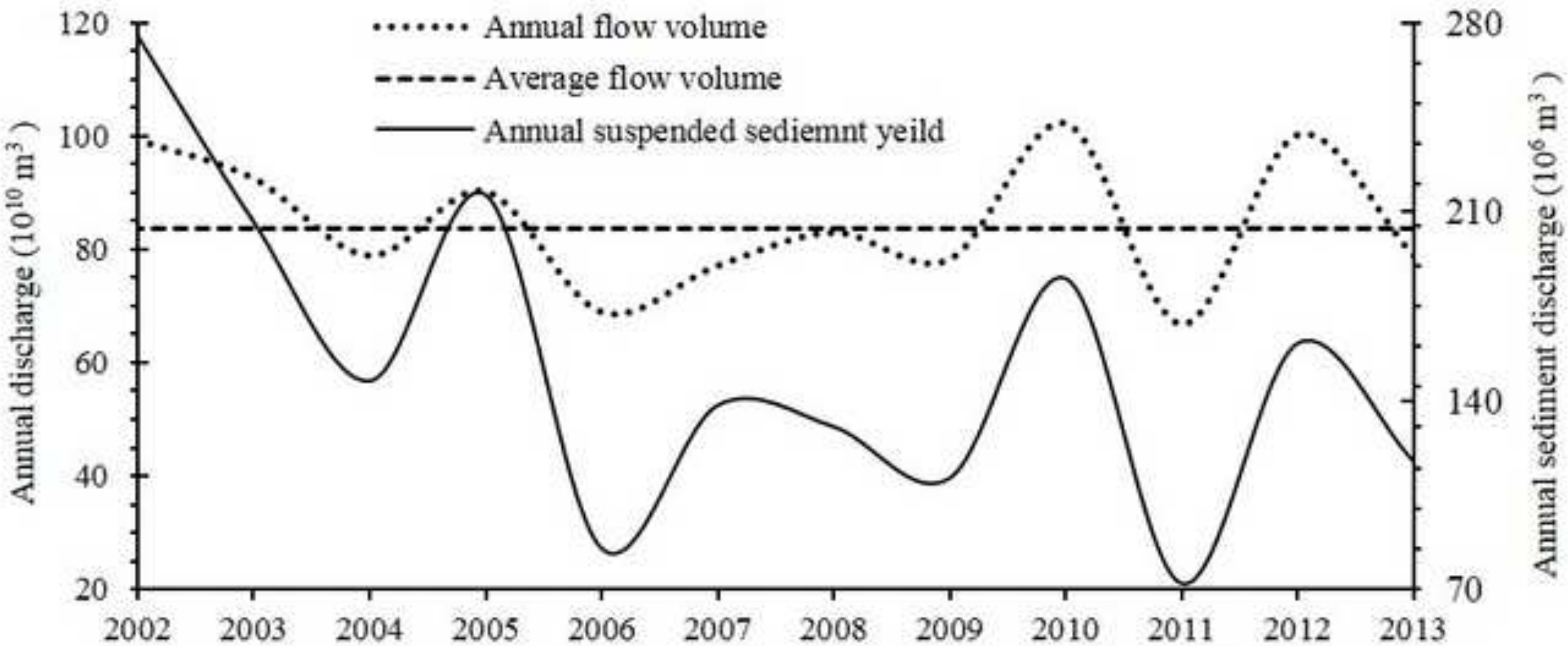

Fig. 10. Trend of the annual flow volume and suspended sediment yield at the Datong station on the Yangtze River in the past decade.

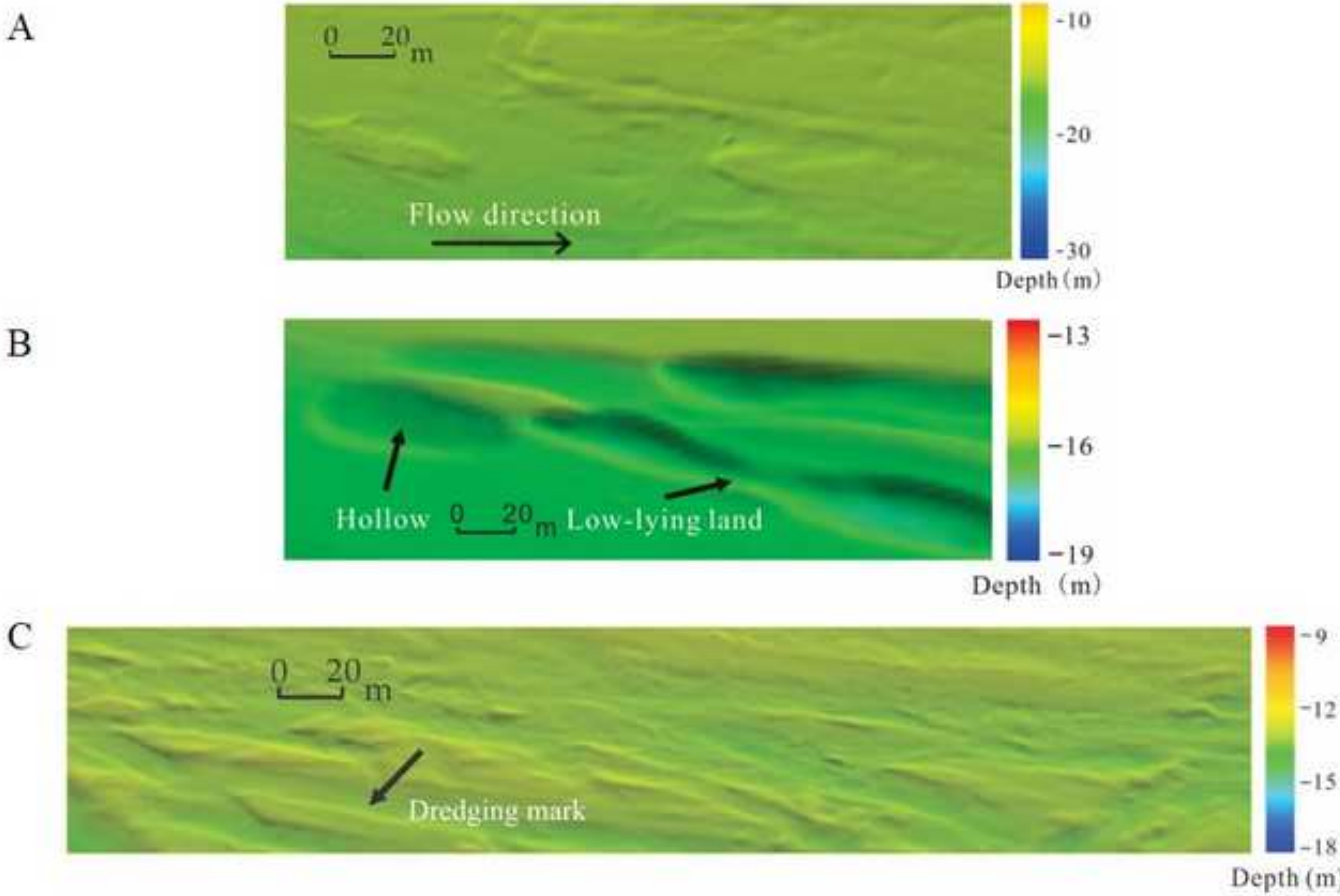

Fig. 11. Scour mark (A) in the Hengsha Passage, and hollow (B) and dredging mark (C) in the North Passage (measured in February 2014).