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# Dynamic analysis of riverbed evolution: Chengtong Reach of Yangtze Estuary

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## ABSTRACT

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This paper proposes a new approach to improve the analysis by extensively using the numerical model results. A 2D hydrodynamic model based on the Delft 3D suite is first set up and validated with the field measurement data. The model is then used to examine the hydrodynamic responses of the estuary to the change of local bathymetry or upstream discharge. This approach is applied to the Chengtong Reach of Yangtze Estuary as an example. The net discharge ratio (NDR) is used as an index to demonstrate the trend of channel development. The results show that the net discharge ratios (NDRs) at the main channels of Fujiangsha, Tongzhousha and Langshansha sub-reaches decrease with increase of upstream river discharge in general; however, the NDR at the main channel of Rugaoshu sub-reach increases first, and then decreases with increase of upstream river discharge when the river discharge is larger than 45,000 m<sup>3</sup>/s. This difference is related to the local bathymetry as well as the ebb-dominated or flood-dominated characters in those sub-reaches.

**ADDITIONAL INDEX WORDS:** Numerical modelling, net discharge ratio, channel development

## INTRODUCTION

The analysis of riverbed evolution is crucial for the better understanding of natural processes in estuaries, and also important for the assessment of the impact of engineering works, such as estuarine regulation projects in estuaries. The traditional way to analyze the riverbed evolution is fully based on the analysis of the surveyed bathymetry and hydrologic data at the sites of interest (e.g. Yang *et al.*, 2006; Liu *et al.*, 2007; Jiang *et al.*, 2011). The main drawback of this approach is that the analysis requires a large quantity of field measurement data, which may not always be available. In addition, the measured bathymetry data may not coincide in time with the measured hydrologic data, resulting in a weak consistency among the raw data. In order to overcome those difficulties, this paper proposes a new approach by extensively using numerical results to provide more coherent datasets, so as to analyze the effects of local bathymetry and upstream discharge on the evolution of the estuary. As an example, the approach is used to analyze the riverbed evolution at Chengtong Reach of Yangtze Estuary, China.

The Chengtong reach is located at the upper part of Yangtze Estuary, which is shown in Figure 1. The length of the entire reach is about 90 km. Since 1980s, the riverbed has been found considerably changed, either due to the natural processes or the

anthropogenic impacts (Yang *et al.*, 2002; Wang *et al.*, 2008; Hu *et al.*, 2009; Wu *et al.*, 2009; Yang *et al.*, 2014).

In recent years, several on-going or completed large scale hydraulic engineering projects, such as Three-Gorge Dam project, South-to-North Water Diversion Project and Yangtze River-Taihu Water Transfer Project have been constructed at the upstream of Yangtze River. Those projects inevitably altered the hydrodynamic and morphodynamic conditions in the Chengtong reach. How the riverbed responds to the changes of those conditions becomes increasingly important, but yet not fully understood.

In the past decades, there have been many research studies on the analysis of riverbed evolution of the Chengtong Reach (e.g. Tao *et al.*, 1998; Cao *et al.*, 2000; Du *et al.*, 2002; Zhong *et al.*, 2009). The majority of these studies focused on the qualitative descriptions of riverbed evolution based on the analysis of historical bathymetry data. There lacks the quantitative analysis of hydrodynamic and morphodynamic processes, particularly in the scale of whole reach. In this paper we combine the traditional analysis with the hydrodynamic models to analyze the dynamic relationship between the riverbed evolution and the change of hydrodynamic conditions at upstream. This relationship can be applied to analyze the potential influence of hydrodynamic changes due to either natural or anthropogenic reasons on the future evolution of riverbed. It can help us to have a better understanding of possible changes of riverbed evolution corresponding to the hydrodynamic changes by the hydraulic engineering projects at the upstream of Yangtze River.

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Figure 1. Location of study area (Chengtong reach is in the red square).

**METHODS**

Figure 2 illustrates the framework of methodology used in this study. The surveyed bathymetry data is directly used to investigate the riverbed changes of the estuary in the past. Using tools such as Surfer and CAD software, we can easily find the spatial and temporal variations of bathymetry at the area of interest, which helps us to understand the trend of riverbed changes in history. In the meantime, the Delft 3D suite is used to set up a hydrodynamic model covering the entire study area. After model validation, two subsequent numerical experiments are carried out. One is changing the bathymetry conditions but keeping the same upstream & downstream conditions, to investigate the effect of bathymetry changes on the net discharge ratio, which is considered as an important index to indicate the trend of riverbed evolution at different channels. The other is keeping the same bathymetry conditions but changing the river discharge conditions at upstream boundary, to understand the effect of discharge conditions on the net discharge ratio and to indicate the response of channel evolution at various sub-reaches to the change of discharge at upstream. Based on the numerical results, we can gain insights into the index of net discharge ratio at the main and secondary channels, and predict possible changes of riverbed if the upstream discharge conditions are changed.

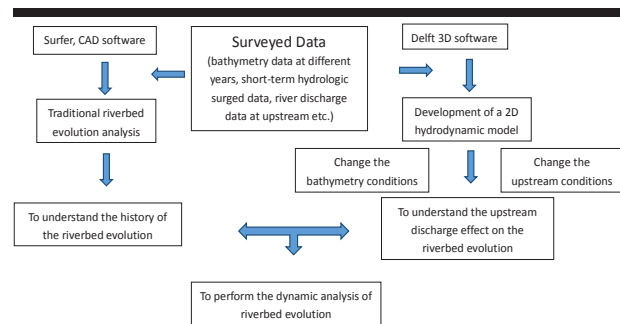


Figure 2. Illustration of the framework of methodology

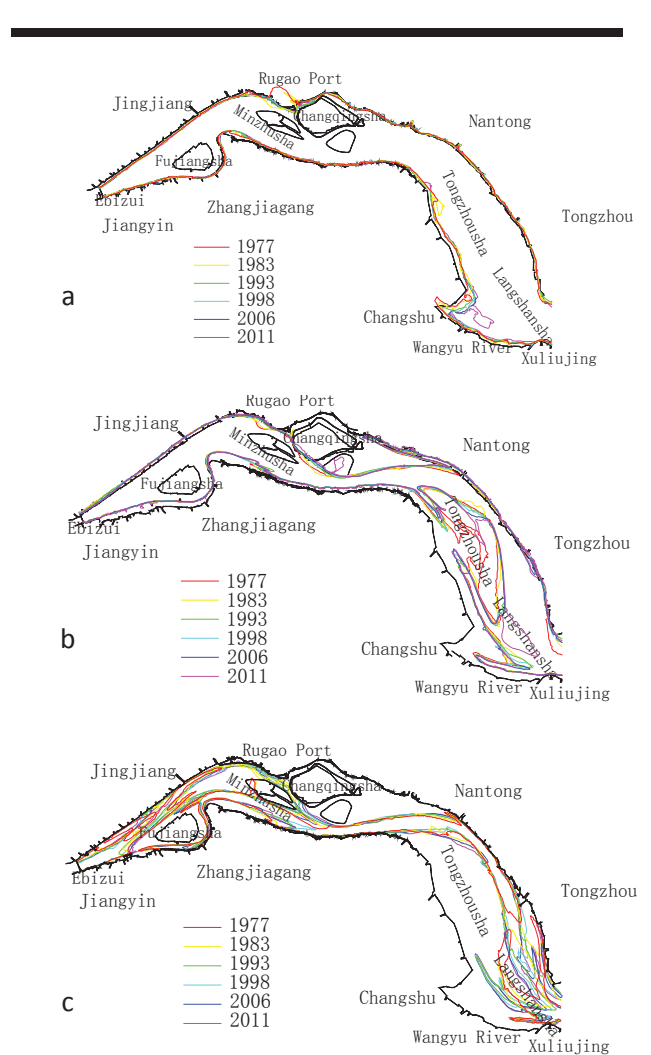


Figure 3. Bathymetry changes of Chengtong Reach from 1977 to 2011 at the contours of (a) 0m, (b) -5m and (c) -12.5m.

**RESULTS**

The bathymetries measured in 1977, 1983, 1993, 1998, 2006, 2011 are used to analyze the riverbed evolution at three contour levels, namely: 0 m representing the river banks; -5.0 m representing the shoals; and -12.5 m representing the deep channels. The changing of the bathymetry contours from 1977 to 2011 show that the river banks are mostly stable over the 34-year period, with only noticeable changes being found near the Rugao Port and Wangyu River (Figure 3a). However, the shoals are more active, particularly in the sub-reaches of Tongzhousha and Langshangsha. The frequent movement of Tongzhousha and Langshangsha shoals has resulted in remarkable bathymetric changes (Figure 3b). The changes of -12.5m contours indicate that the main channel in the estuary are very dynamic, especially at the north channel of Fujiangsha and the downstream end of Fujiangsha (Figure 3c).

The results show that the evolution of Chengtong reach is dynamic and active, whilst the banks appear to more stable, mainly as a result of bank regulation projects in the past 30 years.

In order to understand the erosion and accretion patterns in the study area, the volumetric changes, average bed level changes and annual erosion/accretion rates under 0 m contours are calculated between the adjacent survey years. As shown in Table 1, it is found that the Chengtong reach was general stable in the period of 1977-2006. However, after 2006, there was a rapid increase in erosion. The erosion rate in 2006-2011 is approximately 6 times of that over previous 30 years. It is believed that this significant change is strongly related to the change of upstream hydrodynamics and sediment supplies from the upstream.

Table 1. The erosion/accretion rate of the Chengtong Reach

Period	Volume (10 m <sup>3</sup> )	erosion/accretion thickness(cm)	erosion/accretion rate(cm/a)
1977-1983	2.56	0.512	0.09
1983-1993	-86.45	-17.29	-1.73
1993-1998	49.42	9.88	1.98
1998-2006	63.51	12.70	1.59
2006-2011	289.19	57.84	11.57

Note: positive value indicates erosion; negative value indicates accretion.

**Numerical model**

To further investigate the effect upstream conditions on the riverbed evolution of the Chengtong reach, a depth-averaged 2D hydrodynamic model is established by using the Delft 3D suite. The model covers the area from Datong to the outside of Yangtze Estuary. The orthogonal curvilinear grid system is used with the resolution ranging from 200 m to 3000 m, as shown in Figure 4.

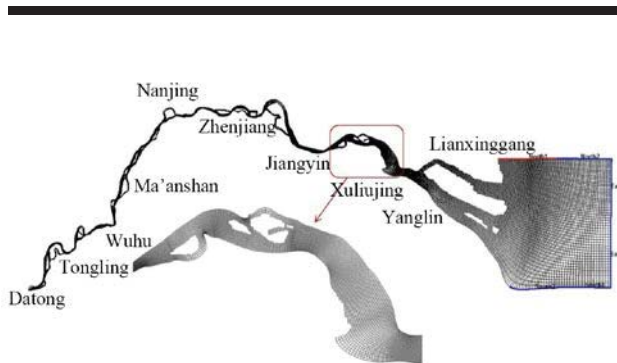


Figure 4. Orthogonal curvilinear grid system

The model is capable of simulating the depth-averaged flood and ebb flows, as well as the tidal levels at the computational

grids. The model is validated with the field data measured in flood season (8/2004-9/2004) and dry season (1/2005-2/2005) at 15 water level stations and 15 tidal current stations. Due to the page limitation, only part of validation results are shown in Figure 5 and 6. From these figures, we can see that the computed water levels and current velocities agree well with the field measurements, which provides us a strong confidence for using this 2D model in the further study.

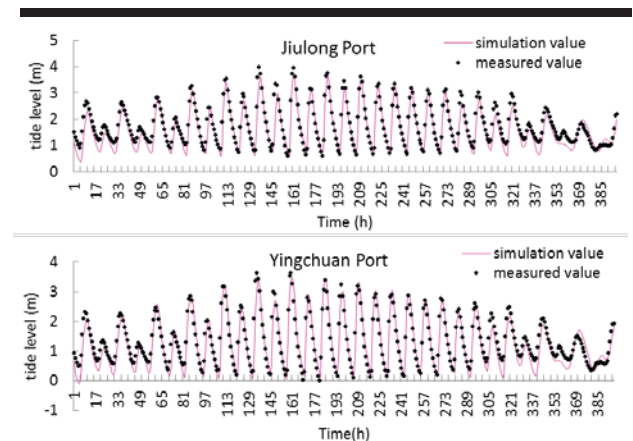


Figure 5. Comparison of computed and measured tidal levels at the stations of Jiulong Port and Yingchuan Port

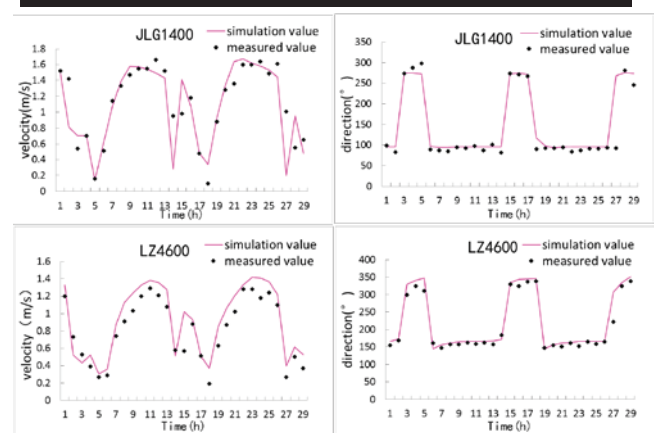


Figure 6. Comparison of computed velocity (left: absolute value; right: direction) at the stations of JLG1400 and LZ4600

A series of numerical experiments are first carried out. Six different sets of field-measured bathymetry data during 1977 to 2011 are used, with the same upstream and downstream conditions in the model. The rationale of these experiments is that the topographic conditions at Jiangyin (upstream of Chengtong reach) and Xuliujing (downstream of Chengtong reach) are found almost unchanged in the past 30 years. They can be seen as two controlling points. This will enable us to investigate the effect of bathymetry changes under the same upstream/downstream conditions.

Although not shown here, the computed ebb/tidal flow patterns confirm that the bathymetry has a significant effect on the flow pattern, particularly in the sub-reach of Rugaosha, where the north channel has disappeared, and the sub-reach of Langshansha, where the main current stream has changed from the middle channel to the east channel.

In order to quantify the relationship between the bathymetry evolution and the hydrodynamic changes, an index named as net discharge ratio (NDR) is introduced, in which the net discharge is defined as the difference of tidal discharge between the ebb and flood phases during a tidal cycle, and the ratio is defined as the percentage of net river discharge of the studied channel to all channels at the selected cross-section. In this study, four cross-sections are selected (Figure 7) to represent the four main sub-reaches, i.e., Fujiangsha, Rugaosha, Tongzhousha and Langshansha, in the Chengtong reach.

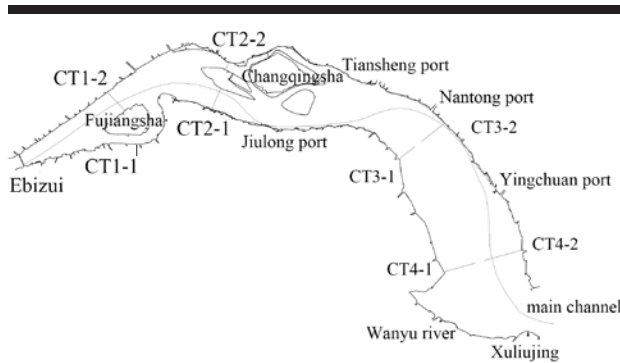


Figure 7. Locations of four sub-sections in the Chengtong reach. Sections of CT1-1, CT1-2 represent Fujiangsha sub-reach; Sections CT2-1, CT2-2 represent Rugaosha sub-reach; CT3-1, CT3-2 represent Tongzhousha sub-reach and CT4-1, CT4-2 represent Langshansha sub-reach. The main channel runs cross respective sections of CT1-2, CT2-1, CT3-2 and CT4-2.

Figure 8(a)~(d) show the variations of NDR with the cross-section area at the main channel of the selected cross-sections in different survey years. It can be seen that the NDR has a good correlation with the cross-sectional area ratio, which implies the NDR could be used as an index to demonstrate the development trend of main channel at the Chengtong reach.

Another series of numerical experiments are carried out by changing the river discharge conditions at upstream boundary. 9 different discharges, i.e. 5,000 m<sup>3</sup>/s, 10,000 m<sup>3</sup>/s, 20,000 m<sup>3</sup>/s, 30,000 m<sup>3</sup>/s, 40,000 m<sup>3</sup>/s, 50,000 m<sup>3</sup>/s, 60,000 m<sup>3</sup>/s, 70,000 m<sup>3</sup>/s and 80,000 m<sup>3</sup>/s, are used as representative upstream discharges for the numerical study. Figure 9(a)~(d) show the variations of NDR with increase of upstream river discharge at the main and secondary channels of four selected cross-sections.

According to the numerical results, the net discharge ratio of main channel at the sub-reaches of Fujiangsha, Tongzhousha and Langshansha decrease with increase of upstream discharge, It indicates that less percentage of water will flow into the main channel in the flood period, which may benefit for the development of secondary channel; On the contrary, more

percentage of water will flow into the main channel in the dry period, which may benefit for the development of main channel.

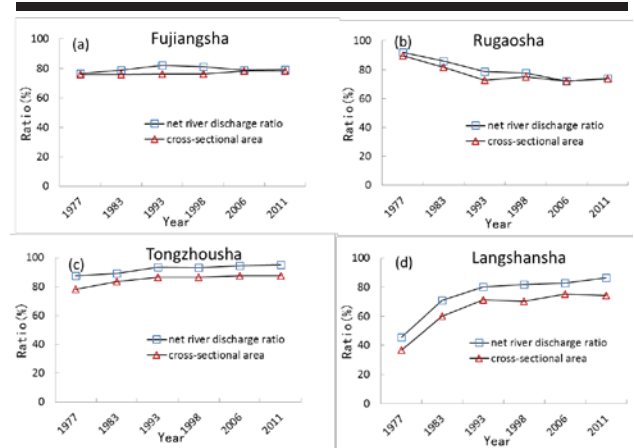


Figure 8. The variations of net discharge ratio with the cross-sectional area at the main channel of cross-section: (a) CT1- Fujiangsha (b) CT2- Rugaosha, (c) CT3- Tongzhousha and (d) CT4- Langshansha in different survey years

The variation of NDR at the main channel of Rugaosha sub-reach is slightly different from other sub-reaches. It can be seen from Figure 9(b) that the NDR increases with increase of upstream discharge at first, and then decreases when the discharge is over 45,000m<sup>3</sup>/s. The reason is related to the flood-dominated characters of Tiansheng Port channel, which is located near the end of Rugaosha sub-reach. As it has become a flood tide dominated channel, the shallow water area in the upper part of Tiansheng Port channel make the flood current difficult to flow into the main channel of Rugaosha sub-reach. When the upstream discharge is relatively small, the change of NDR is dominated by the flood current. However, with further increase of the upstream discharge, the ebb tide gradually dominates the flow pattern, resulting in the NDR at the main channel of Rugaosha sub-reach having the same character as that at other three sub-reaches.

**DISCUSSION**

The better understanding of the net discharge ratio at the main and secondary channels of those sub-reaches can help to understand the long-term evolution of the Chengtong reach. It can be expected that the secondary channels of the Chengtong reach have a tendency of development when the upstream river discharge is relatively large. However, the upstream water conservancy projects, such as the Three Gorge Dam, will alter the monthly distribution of upstream river discharge in a year. Under the so-called “flood clipping” effect, the discharge ratio of main channels along the entire reach will show a general increase. This may have a positive effect on the development of the main channel from the hydrodynamic viewpoint.

There is no doubt that the sediment conditions are very important for the morphological changes of the channels in this area. It is clear that the significant volumetric changes after 2006 are directly related to the decrease of sediment supply from the

upstream. However, the present study has only focused on the effect of hydrodynamic changes on the riverbed evolution. The next study will include hydro- and morpho-dynamic interactions under different sediment supply conditions, so that the possible changes of the riverbed due to the large-scale hydraulic engineering projects can be investigated.

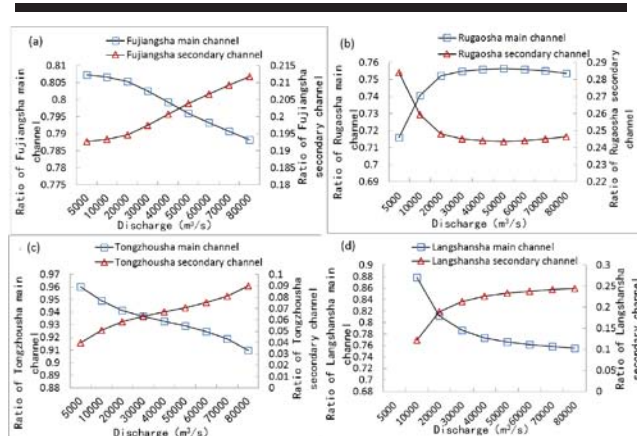


Figure 9. The variations of net discharge ratios with the upstream discharge at the sub-sections of (a) CT1- Fujiangsha (b) CT2- Ruogaoshasha, (c) CT3- Tongzhousha and (d) CT4-Langshansha

**CONCLUSIONS**

In this paper, a new approach to analyze the river evolution combined with the numerical simulation techniques is proposed. Based on the well-validated 2D numerical model, a series of numerical experiments are carried out. The effect of upstream discharge is quantitatively investigated by the comparisons of the net discharge ratios at the main and secondary channels of four main sub-reaches.

As the net discharge ratios through different channels can be used for the analysis of riverbed evolution, the results from the numerical experiments by changing the upstream discharge conditions show that the net river discharge ratios of main channels at Fujiangsha, Tongzhousha and Langshansha decrease with increase of upstream discharge; however, the net discharge ratio of the main channel at Rugaoshasha increases first with increase of upstream discharge but changes to a decreasing trend when the upstream discharge is over 45,000 m<sup>3</sup>/s. The findings can be directly related to the local bathymetry and characters of the tide-dominance in the corresponding sub-reaches.

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