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Effect of river discharge and geometry on tides and net water transport in an estuarine network, an idealized model applied to the Yangtze Estuary

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ABSTRACT

Tidal propagation in, and division of net water transport over different channels in an estuarine network are analyzed using a newly developed idealized model. The water motion in this model is governed by the cross-sectionally averaged shallow water equations and is forced by tides at the seaward boundaries and by river discharge. Approximate analytical solutions are constructed by means of a harmonic truncation and a perturbation expansion in a small parameter, being the ratio of tidal amplitude and depth. The net water transport results from an imposed river discharge and from residual water transport generated by nonlinear tidal rectification. Two new drivers are identified that contribute to the net water transport in tidal estuarine networks, viz. the generation of residual water transport due to gradients in dynamic pressure and due to a coupling between the tidally averaged and quarter diurnal currents through the quadratic bottom stress. The model is applied in a case study on the Yangtze Estuary, to investigate tides and division of net water transport over its multiple channels during the wet and dry season, as well as before and after the construction of the Deepwater Navigation Channel. Model results agree fairly well with observations. Process analysis reveals that the decrease in tides from dry to wet season is due to enhanced bottom stress generated by river-tide interactions. Also, the seasonal variations in net water transport are explained. It is furthermore shown and explained that due to the Deepwater Navigation Channel tidal currents have increased and net water transport has decreased in the North Passage. These changes have profound implications for net sediment transport and salinity intrusion.

1. Introduction

Many estuaries around the world exhibit branching characteristics, with river water being divided over the different channels and eventually ending up in the ocean (e.g. the Yangtze Estuary, Fig. 1, the Mahakam Delta, and the Pearl River Delta). Apart from being affected by the geometry of the network, the division of river induced water transport is also influenced by the propagation of the tide through the estuarine network. First, additional residual water transport due to nonlinear tidal rectification is generated (cf. (Longuet-Higgins, 1953; Ianniello, 1977)), hence the combination of river induced transport and tidal residual water transport determines the net water transport through the network (Buschman et al., 2010). Second, net water transport also has an effect on the tidal propagation and river transport division through subtidal friction, implying a feedback (Buschman et al., 2009). Knowledge of the net water transport through an estuarine network is important for e.g. computing salinity intrusion, flushing of pollutants and sediment transport.

Tidal propagation in estuarine networks has been investigated by e.g. Lorentz (1926), Hill and Souza (2006), Zhang et al. (2012), Alebregtse et al. (2013), Alebregtse and de Swart (2014) and Cai et al. (2014). These studies focused on tidal properties, such as tidal sea surface amplitude, and phase propagation, and not on net water transport. Net water transport in networks due to different forcings was investigated among others by Ridderinkhof (1988), Buschman et al. (2010), Li et al. (2010), Sassi et al. (2011) and Zhang et al. (2011). Ridderinkhof (1988) considered a network consisting of two channels and did not account for river discharge or the effect of residual currents on tidal damping. He found that a net water transport occurs towards the deeper and/or narrower channel for identical tidal forcing on both channels. Buschman et al. (2010) used a numerical model to investigate the division of

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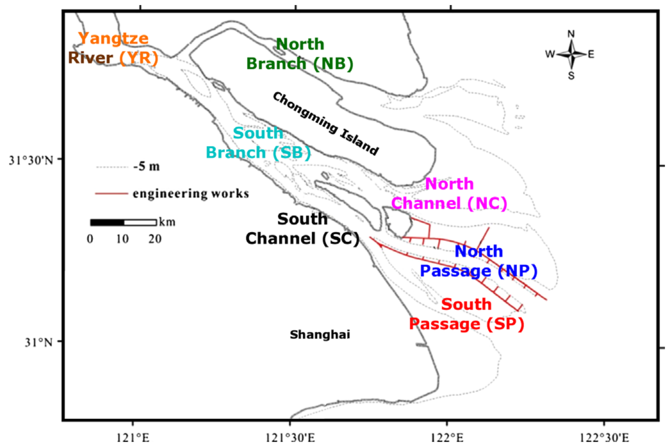

Fig. 1. Map of the Yangtze estuary from Jiang et al. (2013). Channels are from North to South the Yangtze River (YR), North Branch (NB), South Branch (SB), North Channel (NC), South Channel (SC), North Passage (NP), and South Passage (SP). The training walls, groins and jetties from the Deepwater Navigation Channel (DNC), a large-scale human intervention, are indicated in red. Figure after Jiang et al. (2013). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

net water transport at a tidally influenced junction. They found that the residual water transport due to nonlinear tidal rectification increases net water transport in the channel with the highest river transport, except when the bottom friction parameter in one of the channels was changed. Sassi et al. (2011) found that the tidal influence also decreases the asymmetric division of river water, due to so-called differential water level setup. The latter occurs because in a single channel the residual set-up increases with river transport due to increased sub-tidal friction. Since at the junction the dynamic pressure in both channels has to be equal, the water mass associated with the excess pressure associated with this set-up is discharged through the channel with the smaller transport. Another source of influence on net water transport division at riverine channel junctions, is the angle between the channels (Shettar and Keshava Murthy, 1997). If one of the branches is at a sharp angle, it will receive less discharge, as forward momentum will propel the water into the other branch. However, at a tidally influenced junction this effect will only be strong during peak tides, while it will be small during most of the tidal cycle. Therefore, it is hypothesized that this effect is small in tidal environments. Finally, Li et al. (2010) and Zhang et al. (2011) determined the water division ratio in the Yangtze Estuary, which is the amount of net water transport through a branch, relative to the upstream net water transport. Li et al. (2010) applied a numerical model for this, and found that increasing river discharge leads to a more equal division of net water transport at all junctions in the Yangtze Estuary. Zhang et al. (2011) used data on tidal and salinity characteristics to infer net water transport through different channels of the Yangtze Estuary. They found a decrease in net water transport in the North Passage due to the construction of a navigation channel. Neither of these studies isolated the role of residual currents generated by the nonlinear tidal rectification.

The results of Buschman et al. (2010) and Sassi et al. (2011) show the importance of nonlinear tidal dynamics in determining the net water transport in estuarine networks. However, it has not been investigated which nonlinear processes (e.g. generation of overtides by advection, depth dependent friction, and Stokes transport) are most important in producing tidally induced residual transport. Therefore, this study will extend the existing literature in three ways. First, by investigating the propagation of tides, which are subject to river-tide interactions, through an arbitrary estuarine network. Second, by computing residual and quarter diurnal currents that result from the nonlinear terms in the equations of motion in an estuarine network using a semi-analytical model. Third, tidal damping is coupled to both the tidal and the residual velocity. The semi-analytical model is obtained by applying a harmonic truncation to the time signal of the water motion (retaining only a limited number of tidal constituents), and a subsequent scaling analysis of the dominant processes. Quadratic bottom stress is linearized with the use of Chebyshev polynomials, as described by Godin (1991, 1999). The analytical nature of the model allows for an identification of the dominant processes in determining the net water transport.

The model is designed to study tides and net water transport in arbitrary tidal estuarine networks. Here, it will be used to investigate the Yangtze Estuary, China, as a case study. The Yangtze Estuary is of high interest, because it is a representative tidal estuarine network (similar to, e.g., the Mahakam Delta, and the Pearl River Delta), and it is characterized by a strong seasonal cycle in river discharge. The latter exerts a marked influence on the tides through enhanced friction at higher discharges, as reported by Guo et al. (2015). Furthermore, the estuary has been subject to multiple anthropogenic changes to its geometry in the past decade. One change was due to the construction of the Deepwater Navigation Channel (DNC), which consists of two training walls and a deepening of the main fairway in the North Passage of the estuary (Fig. 1). These constructions led to a decrease of ebb directed transport in the North Passage, which resulted in sedimentation in the upstream part and erosion in the downstream part of this channel (Jiang et al., 2012, 2013). Model results obtained for the wet and dry season will be compared with each other to identify the dominant processes governing net water transport in different seasons. Furthermore, model results for geometries resembling Yangtze Estuary in its current and historic state (i.e. post and pre-DNC) are compared to identify how these processes change due to anthropogenic influences. Differences between the model results for the various cases will be investigated and explained, with a focus on changes in net water transport.

The manuscript is structured as follows. Section 2 presents the model equations and the characteristics of the study area. Section 3 presents the results, while Section 4 analyses which processes govern the net water transport through a tidal estuarine network and discusses model limitations. Section 5 contains the main conclusions.

2. Materials and methods

2.1. Model

2.1.1. Domain

Estuarine networks comprise multiple channels that are connected to each other, in which water motion mainly results from

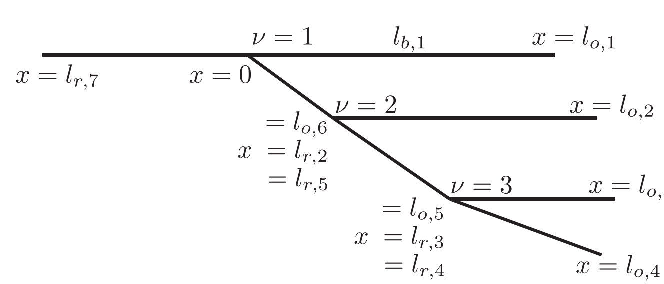

Fig. 2. A scheme of a general estuarine network. The along-channel coordinate, x, increases downstream (towards sea). Each channel has a length $l_{b,j}$. The different $l_{o,j}$ denote the channel boundaries pointing towards the ocean, while the $l_{r,j}$ denote the boundaries pointing towards the river.