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# Tidal impacts on the subtidal flow division at the main bifurcation in the Yangtze River Delta

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ABSTRACT

Flow division at bifurcations in the Yangtze Estuary has received ample attention, since it may control the pathways of terrestrial sediments over downstream river branches including the 12.5 m Deepwater Navigation channel. While some efforts have been made to interpret flow division at the bifurcations of the Yangtze Estuary, little attention has been paid to the role of tides. Flow division at estuarine bifurcations is made complicated by tides that propagate from the outlet of the tidal channels into the delta. To quantify the tidal influence on the distribution of river discharge, and more generally, to understand the mechanisms governing the subtidal flow division at the tidally affected bifurcation in the Yangtze River Delta, a two-dimensional hydrodynamic model is employed. In this model, the landward boundary is chosen beyond the tidal limit, where the tidal motion has faded out entirely. The seaward boundary is chosen such that the river discharge does not influence the water level. Subtidal discharges are decomposed using the method of factor separation, to distinguish between the effects of tides, river discharge and river-tide interactions on the subtidal flow division. Results indicate that tides modify the river discharge distribution over distributary channels in the Yangtze River Delta, particularly in the dry season. A significant difference in the subtidal flow division during spring tide and neap tide shows that the tidally averaged flow division over the distributaries in the delta greatly depends on tidal amplitude. By varying the river discharge at the landward boundary and amplitudes and phases of the principal tidal constituents at the seaward boundary of the established model, the sensitivities of the subtidal flow division to the river discharge and tidal amplitude variation were investigated in detail. Generally, the tidal impacts on the subtidal flow division are around 12% to 22%, with river discharge varying from 30,000 $m^3s^{-1}$ to 20,000 $m^3s^{-1}$. This effect on the flow distribution can even overwhelm the effects induced by river discharge based on geometry only, when the flow discharge is lowest. Furthermore, the fortnightly tidal cycle plays an important role in enhancing the inequality of the subtidal flow division caused by the $M_2$ tidal component solely at the tidal bifurcation in the Yangtze River Delta during low flow.



## 1. Introduction

Bifurcating channels are ubiquitous in anabranching rivers (Burge, 2006), in braided rivers (Richardson and Thorne, 2001) and in river deltas in particularly (Sassi et al., 2011). In these distributary channels, bifurcations play a crucial role in dividing the flow and sediment over the downstream river branches (Kleinhans et al., 2008), which directly determine the fluvial material dispersal and transport from river networks to shorelines. Thereby, bifurcations greatly affect river channel, estuary, and coastal evolution (Wolinsky, 2010).

The processes governing the flow division at river bifurcations have been investigated theoretically. Wang et al. (1995) indicated that flow division over two downstream river branches is determined by channel dimensions and hydraulic roughness in the downstream channels. A theoretical analysis based on a simple

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one-dimensional approach of steady, uniform flow was proposed by Bolla Pittaluga et al. (2003) to predict the long-term evolution of a channel network as well as to study the equilibrium configurations and bifurcation stability in braided gravel-bed rivers. Several numerical models were also employed to understand the flow division of delta distributary networks. Lane and Richards (1998) predicted the spatial distribution of depth-averaged velocity and eddy viscosity to study the evolution of the geomorphology of distributary networks. Dargahi (2004) modeled the lower reach of the River Klarälven to investigate the flow features of the river bifurcation and short-term sediment transport patterns by using a 3-D numerical flow modeling. Laboratory experiments based on a physical model of a river bifurcation were conducted, to explore the applicability of a general nodal point relation to express the distribution of flow and sediment at channel bifurcations (Federici and Paola, 2003; Islam et al., 2006; Bertoldi and Tubino, 2005).

So far, bifurcation studies have mainly concentrated on river channels. The effects of tides intruding from the mouths of the tidal channel, however, are often ignored. In fact, tides assert a significant control on the flow division over delta distributaries, which can be attributed mainly to Stokes fluxes (Buschman et al., 2010). The Stokes transport, which is the drift associated with a propagating wave that can be calculated as the Lagrangian mass transport minus the Eulerian mean, can be different in two adjacent channels that join at a bifurcation (Friedrichs and Aubrey, 1994; Sassi et al., 2011). A crucial difference between a single channel and a multiple channel system is that, in absence of a river discharge, the Stokes flux in a particular channel is not necessarily equal to the Eulerian-mean return flux (Buschman et al., 2010). The mass flux generated by nearly in-phase variation of the water level and cross-section averaged flow velocity in a certain tidal channel can be returned to sea by a mean flow in a different channel. This appeared to have significant implications for the flow division at tidal bifurcations.

In terms of the asymmetries in the distributaries' channel depth (Jonge et al., 2014; Vellinga et al., 2014), length, width (Yankovsky and Iyer, 2015) and bed roughness (Heathershaw and Langhorne, 1988), tides can either cancel or enhance the inequality in flow distribution that occurs in the absence of the tidal modulation. Buschman et al. (2010) found that the importance of tides in enhancing the inequality in subtidal flow division when one of the sea-connected branches is deeper or shorter, whereas bed roughness differences could result in an opposing effect. Sassi et al. (2012) continued to quantify the tidal signature on delta morphology and indicated that the influence of tide on the flow division at bifurcations increases with the bifurcation order.

The Yangtze Estuary (Fig. 1), one of the largest estuaries in the world, is a major freshwater source to the western Pacific Ocean (Chen et al., 1988). The river has built a typical tide-dominated delta, which is divided into a southern branch (SB) and a northern branch (NB) by the Xuliujing bifurcation in the Yangtze Estuary (Fig. 2). This bifurcation plays a key role in flow and sediment transport from land to the sea, which in turn, has great influence on the coastal engineering in its estuary, particularly, the Deep Waterway Engineering (DWE) (Liu et al., 2011; Jiang et al., 2012). This Deep Waterway Channel, locating along the North Passage and South Channel, was constructed during the period of 1998 until 2011 to enhance the shipping ability of the major channel toward Shanghai Harbor. However, since the construction of the first stage of the DWE started, sedimentation became an important concern. Chen et al. (2007) indicated that the siltation in the Deep Waterway Channel is highly related to the flow and sediment division at Xuliujing bifurcation because it decides the pathway from the upper river to the coast. As a matter of fact, the flow division plays a critical role in determining the sediment division in distributary channels (Sassi et al., 2013). Therefore, understanding the processes governing the flow division should be given the utmost priority. In the Yangtze Estuary, tides are the most energetic sources of water movement and tidal currents even can spill over into the SB from the NB under strong tidal conditions in the dry season (Wu et al., 2006). When the flow division at Xuliujing bifurcation changes with tides motion, the direction of the ebb flow, which dominates sediment transport in the Yangtze River Estuary, has been diverted gradually from east to southeast, resulting in a sediment transport pathway diversion from east to southeast. Consequently, the siltation in the Yangtze River Delta has shifted to the southern river mouth area (Li et al., 2011). Therefore, understanding the process of the flow division with the impact of tides at Xuliujing bifurcation is strongly related to the 12.5 Deepwater navigation channel project. Many researchers have focused on the flow division ratio at this bifurcation in the Yangtze River Delta (Hu et al., 2007; Huang et al., 2003; Yan et al., 2001). Mao et al. (2008) pointed out that the flow division ratio in the NB had reduced obviously from 25% in 1915 to 8.7% in 1958. Liu et al. (2014) further pointed out that this ratio has decreased gradually to a stable value less than 5% nowadays. Interestingly, the tidal current in the NB often intrudes upstream in dry seasons, traveling across Xuliujing bifurcation, and finally running into the SB (Wu et al., 2006; Xu and Milliman, 2009).

The previous studies on the flow division at Xuliujing bifurcation in the Yangtze River Delta only focused on the flow ratio in the long-term time series. The effects of tides in the subtidal process are ignored. In fact, tides can modify the flow distribution pattern at tidal bifurcations (Sassi et al., 2011). Therefore, the objective of this paper is to quantify and understand the tidal impacts on the flow division at the Xuliujing bifurcation in the Yangtze River Delta.

## 2. Study area

The Yangtze River is the third longest river in the world, after the Nile River and the Amazon River. Originating from The Qinghai-Tibet Plateau, it flows into the East China Sea through a large prograding delta called the Yangtze River Delta (Chen et al., 2001). This delta, located on the middle of the east coastline of China (lat. 120°N to 122°30′N and long. 32°30′E to 29°30′E), is a broad funnel-shaped delta with a scale of 13 km wide at the upstream and nearly 90 km wide at the outlet (Fig. 1). This area covers the transition from a narrow channel in the northwest to the continental shelf. The Yangtze River delta bifurcates from a single upper channel to four primary downstream channels separated by alluvial islands and several mouth bars. Consequently, there are three major bifurcations in this multi-channel estuary. The channel is bifurcated into the NB and SB by Chongming Island at Xuliujing (Dai et al., 2016), the first bifurcation of the Yangtze River estuary (Fig. 2) Since Xuliujing bifurcation asserts a significant influence on the river discharge distribution in the Yangtze River estuary, the subtidal flow division at this bifurcation has been primarily studied in this paper.

The annual mean discharge of the Yangtze River is estimated to be in the order of approximately 30,000 $m^3s^{-1}$ (Guo et al., 2014; Qiu and Zhu, 2013), but it changes remarkably as a result of the subtropical monsoon climate. In particular, the proportion of river discharge in the flood season is 70% of the whole year's amount (Fan et al., 2011; Yang et al., 2006). The tides in the Yangtze River Estuary are irregularly semidiurnal with the average tidal range of 2.76 m and the maximum of 4.62 m (Lu et al., 2015). The mean