Journal of Hydrology 564 (2018) 588–604

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Unravelling the causes of tidal asymmetry in deltas

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ARTICLE INFO

This manuscript was handled by Marco Borga, Editor-in-Chief

Keywords:
Tidal asymmetry
Nonstationary tides
River flow
Deltas

ABSTRACT

Tidal asymmetry in deltas is caused by both the intrinsic asymmetry, resulting from the combination of astronomical tides, and by nonlinear tidal interactions that occur in shallow water. The relative importance of these sources of tidal asymmetry in delta channel networks have remained poorly studied, partly due to the limitations of classical harmonic analysis (HA) in hindcasting nonstationary tides. The Pearl River Delta (PRD) is a multi-channel system with rapidly changing bathymetry, subject to severe human interventions. This work applies a nonstationary harmonic model (NS_TIDE) to hydrological data from 15 stations in the PRD spanning the period 1961–2012. The spatiotemporal variation of multiple sources of tidal asymmetry is quantified by a skewness metric, revealing how similar or dissimilar the development of alternative sources of tidal asymmetry develop in the delta subject to study. A relative sensitivity coefficient (RSC) is introduced to decompose the contribution of tidal amplitude variations to multiple tidal asymmetries. Analytical results show the development of tides becoming gradually more asymmetric as they propagate into delta channel networks, and how this depends on the river flow. Variation in the orientation of tidal asymmetries induced by different combinations of tidal constituents leads to a complex pattern of the overall tidal asymmetry in the PRD. Our results show that tidal asymmetry in deltas can be significantly dependent on the river flow.

1. Introduction

1.1. Tidal asymmetry

Tidal asymmetry refers to a periodic difference between the falling and rising tidal periods (Boon and Byrne, 1981; Speer et al., 1991). Specifically, a shorter duration of the rising tide indicates a flood dominant tidal asymmetry, and a shorter duration of falling tide indicates an ebb-dominant tidal asymmetry (Speer and Aubrey, 1985; Friedrichs and Aubrey, 1988). In a semidiurnal tidal regime (tidal form number $F = (A_{K1} + A_{O1})/(A_{M2} + A_{S2}) < 0.25$, where A denotes amplitude), the occurrence of tidal asymmetry is mainly associated with the interaction between the M_2 tide and its first harmonic: the shallow water constituent M_4 (Speer and Aubrey, 1985; Friedrichs and Aubrey, 1988; Van de Kreeke and Robaczewska, 1993). It is common practice to characterize the degree of distortion and the nature of tidal asymmetry by the amplitude ratio (M_4/M_2) and relative phase ($2M_2$-M_4) (Friedrichs and Aubrey, 1988; Savenije and Veling, 2005; Lu et al., 2015). Thus, the generation of M_4 is considered the main source of asymmetry in a number of studies. Asymmetry in the tidal motion can also be produced through the generation of compound overtides (Parker, 1991; Wang et al., 1999), and even in absence of shallow-water tides, there is asymmetry inherent in the astronomical tides (Hoitink et al., 2003; Nidzieko, 2010; Song et al., 2011). In particular, in semi-diurnal regimes, the combination of M_2 tide with the compound tide MS_4 and $2MS_6$ ($M_2/S_2/M_4/MS_4$, $M_2/S_2/M_4/2MS_6$) can produce asymmetrical tides (Byun and Cho, 2006). In mixed or diurnal regimes where the K_1 and O_1 tides are stronger than the M_2 tide, the interaction of astronomical diurnal and semidiurnal tides may be the main source of tidal asymmetry, primarily through the combination of K_1, O_1 and M_2 tides (Ranasinghe and Pattiaratchi, 2000; Hoitink et al., 2003, 2006; Woodworth et al., 2005).

Any combination of tidal constituents with angular frequencies ω_1, ω_2 and ω_3 (pairs or triads) that satisfy either the frequency relationship

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https://doi.org/10.1016/j.jhydrol.2018.07.023
Received 26 March 2018; Received in revised form 11 June 2018; Accepted 11 July 2018
Available online 20 July 2018

$2\omega_1 = \omega_2$ or $\omega_1 + \omega_2 = \omega_3$ can contribute to tidal asymmetry. The contribution of different combinations of constituents to the overall asymmetry in the rise and fall of water levels can be conveniently quantified adopting a skewness based approach, which was proposed by Nidzieko (2010) and extended by Song et al. (2011). By quantifying skewness in the probability density function (PDF) of water levels from 335 hydrological stations around the world, Song et al. (2011) obtained a global view on the sources of tidal asymmetry. The latter analysis only addresses coastal and ocean stations. The spatial evolution of skewness in water level PDFs for delta channel networks, where significant nonlinear tidal interactions occurs, has rarely been discussed.

1.2. Evolution of tidal asymmetry and related morphological development

Analysis of the historical evolution of tides can reveal natural and human-induced changes in tidal river dynamics (Hoitink and Jay, 2016) and morphological evolution (Hoitink et al., 2017; Wang et al., 2002). Numerous studies have been conducted to investigate the relationship between tidal asymmetry and morphological development (Postma, 1961; Pingree and Maddock, 1978; Friedrichs and Aubrey, 1988; Van de Kreeke and Robaczewska, 1993; Van de Kreeke et al., 1997; Van der Molen, 2000; Lanzoni and Seminara, 2002; Wang et al., 2002; Bolle et al., 2010; Guo et al., 2016). Tidal asymmetry is one of the factors generating residual sediment transport, controlling the formation of shoals and tidal flats (Speer and Aubrey, 1985; Fry and Aubrey, 1990; Moore et al., 2009; Brown and Davies, 2010). Flood dominant tides generally produce a residual landward sediment transport and ebb dominant tides are associated with sediment export (Dronkers, 1986; Van de Kreeke and Dunsbergen, 2000). Changes in morphology may in turn alter the tidal asymmetry significantly, especially under severe human interventions (e.g. dredging, sand extraction, dam construction) (Bolle et al., 2010; Vellinga et al., 2014). Shallow inlet systems tend to be flood dominant. An increase in channel depth may lead to a reduction of the flood-dominant type of asymmetry, while the presence of large inter-tidal basin storage is found to enhance flood dominance (Dronkers, 1986; Lanzoni and Seminara, 1998; Wang et al., 2002).

It is difficult to investigate the temporal evolution of tidal asymmetry in deltas in response to changes of morphology. Too short a length of record and too long a sampling interval of a tidal record subject to a harmonic analysis limit the degree in which the obtained amplitudes and phases adequately capture tidal asymmetry. In nonstationary tidal systems such as deltas, the problem is further complicated by the need to obtain the time-series of fluvial processes (e.g. river discharge). Bolle et al. (2010) examined the evolution of tidal asymmetry in the Western Scheldt Estuary, expressed by amplitude ratios and phase differences between 1970 and 2002, and related the established changes to the deepening of the river channels. The work of Bolle et al. (2010) only considered the M_2, M_4 and M_6 tides, ignoring the contributions of other tidal combinations to the total asymmetry of the water level PDF. Guo et al. (2016) used a 1-D model to explore alternative types of tidal interactions inducing tidal asymmetry in an estuary, but mainly focused on the morphodynamic impacts of multiple tidal asymmetries. The responses of multiple tidal asymmetries to varying river discharge in delta channel networks has remained virtually unstudied.

1.3. Harmonic analysis for nonstationary tides

Classical harmonic analysis (HA) is traditionally used to analyze oceanic tides in seas and coastal shelves. However, the HA method, based on the assumption that the tides are stationary and independent of other forcings (Darwin, 1892; Doodson, 1921; Flinchem and Jay, 2000), usually fails to predict river tides as the stationary assumption is not fulfilled, due to nonstationary interactions of tides with channel geometry, bottom friction, and river flow. River tides do not respond simply to astronomical forcing and in a complex channel network may exhibit a degree of chaos (Maas and Doelman, 2002). Although short-term HA can be applied to resolve major tidal constituents (Guo et al., 2015), it is inappropriate for the analysis of river tides when the river discharge variability is high. In recent decades, substantial research efforts have been devoted to analyzing nonstationary tides. The continuous wavelet transforms (CWT) is found to be more accurate than HA and can resolve nontidal variations, which made it an effective tool in analysis of nonstationary records. A major limitation of CWT is that it is unable to distinguish between tidal constituents within a tidal species when tidal-fluvial interactions are strong (Jay and Kukulka, 2003). Matte et al. (2013) modified T_tide (Pawlowicz et al., 2002) and proposed a harmonic model adapted to nonstationary tides, NS_TIDE, which builds nonstationary forcing directly into the tidal basis functions. The utility of NS_TIDE has been demonstrated by applying it to the Columbia River estuary (Matte et al., 2013) and the St. Lawrence fluvial estuary (Matte et al., 2014) where the oceanic tides are strongly modified by the river flow. Results showed that NS_TIDE can represent tidal-fluvial dynamics much better than HA, especially in the upper parts of tidal rivers. Recently, Cai et al. (2018) applied NS_TIDE to water levels for an entire channel network to investigate the spatio-temporal variations of river-tide dynamics, demonstrating that complex channel networks can be synoptically analyzed using this method. Cai et al. (2018) mainly focused on the contributions of river-tide dynamics on the changes in the residual water level in the Pearl River Channel networks. Here, we apply NS_TIDE again to the Pearl River Delta, to shed light on the spatial variation of tidal asymmetry resulting from tidal-fluvial dynamics in its distributary delta channels.

1.4. Aim and methodology

The purpose of this paper is to establish and understand the spatiotemporal variation in tidal asymmetry in a delta channel network in terms of pairs and triads of tidal constituents contributing to the overall asymmetry. Specifically, we examine (1) the spatiotemporal variation of tidal asymmetries induced by dominant combinations of astronomical tides (i.e., $K_1/O_1/M_2$) and by shallow water interactions (i.e., $M_2/S_2/MS_4$, M_2/M_4, $M_2/M_4/M_6$) in the Pearl River Delta, (2) the extent to which multiple tidal asymmetries respond to delta morphology developments that have occurred over the past decades, (3) the degree in which changes in tidal harmonics and river discharge yield change of tidal asymmetry.

This paper is structured as follows. The next section describes the study region, data processing and the analysis methods. Sections 3 presents the spatiotemporal variations of the main tides in the Pearl River Delta and the resulting multiple tidal asymmetries. The impact of river flows on tidal asymmetry is then evaluated. Section 4 discusses the preloading of tidal asymmetry in other deltas and estuaries, the contribution of tidal asymmetry and river discharge to residual sediment transport and the impact of tidal amplitude attenuation and phase shift on tidal asymmetry. Finally, our conclusions are presented in Section 5.

2. Setting, data and methods

2.1. The pearl river delta

The Pearl River Delta (PRD) is located at the south part of china. It is bell-shaped with a catchment area of approximately 17,200 km^2 (Zhang et al., 2009). The Pearl River is the third largest river in China debouching in a multichannel delta system with many bifurcations and intersections. The three largest tributaries of the Pearl River are the West River, the North River and the East River. River runoff from the Pearl River flows into the South China Sea (SCS) through eight outlets (Fig. 1). The complicated channel network renders the tidal-fluvial processes in the PRD very distinct. The complex geometry and morphology of the PRD are a result of both natural processes and human activities, including dredging and sand mining. The associated