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Human impacts on morphodynamic thresholds in estuarine systems

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ABSTRACT

Many estuaries worldwide are modified, primarily driven by economic gain or safety. These works, combined with global climate changes heavily influence the morphologic development of estuaries. In this paper, we analyze the impact of human activities on the morphodynamic developments of the Scheldt Estuary and the Wadden Sea basins in the Netherlands and the Yangtze Estuary in China at various spatial scales, and identify mechanisms responsible for their change. Human activities in these systems include engineering works and dredging activities for improving and maintaining the navigation channels, engineering works for flood protection, and shoreline management activities such as land reclamations. The Yangtze Estuary is influenced by human activities in the upstream river basin as well, especially through the construction of many dams. The tidal basins in the Netherlands are also influenced by human activities along the adjacent coasts. Furthermore, all these systems are influenced by global changes through (accelerated) sea-level rise and changing weather patterns. We show that the cumulative impacts of these human activities and global changes may lead to exceeding thresholds beyond which the morphology of the tidal basins significantly changes, and loses its natural characteristics. A threshold is called tipping point when the changes are even irreversible. Knowledge on such thresholds or tipping points is important for the sustainable management of these systems. We have identified and quantified various examples of such thresholds and/or tipping points for the morphodynamic developments at various spatial and temporal scales. At the largest scale (mega-scale) we consider the sediment budget of a tidal basin as a whole. A smaller scale (macro-scale) is the development of channel structures in an estuary, especially the development of two competing channels. At the smallest scale (meso-scale) we analyze the developments of tidal flats and the connecting channels.

1. Introduction

Tidal basins such as estuaries and tidal lagoons are important ecosystems and are often located in densely populated areas. The morphodynamic development of a tidal basin or estuary is influenced by human activities, not only those within the tidal basin itself but also those in the upstream river and adjacent coastal areas (De Vriend et al., 2011; Wang et al., 2012; Wang et al., 2013). Human activities include engineering works and dredging activities for improving and maintaining the navigation channels, engineering works for flood protection, mining activities, and shoreline management activities including land reclamations and setbacks. Most relevant human activities in the upstream river basin are the constructions of dams, which change the flow and sediment transport regimes of the river (Yang et al., 2011). Important human interventions along the adjacent coasts of tidal basins are land reclamations and (hard and soft) coastal protection works. Furthermore, tidal basins are influenced by global changes through (accelerated) relative sea-level rise (i.e. land subsidence plus sea-level rise) and changing weather conditions.

It is well known that estuarine human interventions may influence the tidal amplitude (Kerner, 2007; Winterwerp et al., 2013), turbidity (Winterwerp et al., 2013; Van Maren et al., 2015a, 2015b) and morphodynamics (Jeuken and Wang, 2010; Monge-Ganuzas et al., 2013). However, many human interventions take place concurrently whereas the morphologic response is often slow. Therefore the response of estuaries or tidal lagoons to a specific human intervention is difficult to quantify. Moreover, we are becoming increasingly aware that the cumulative impacts of human activities and global changes may lead to exceeding of

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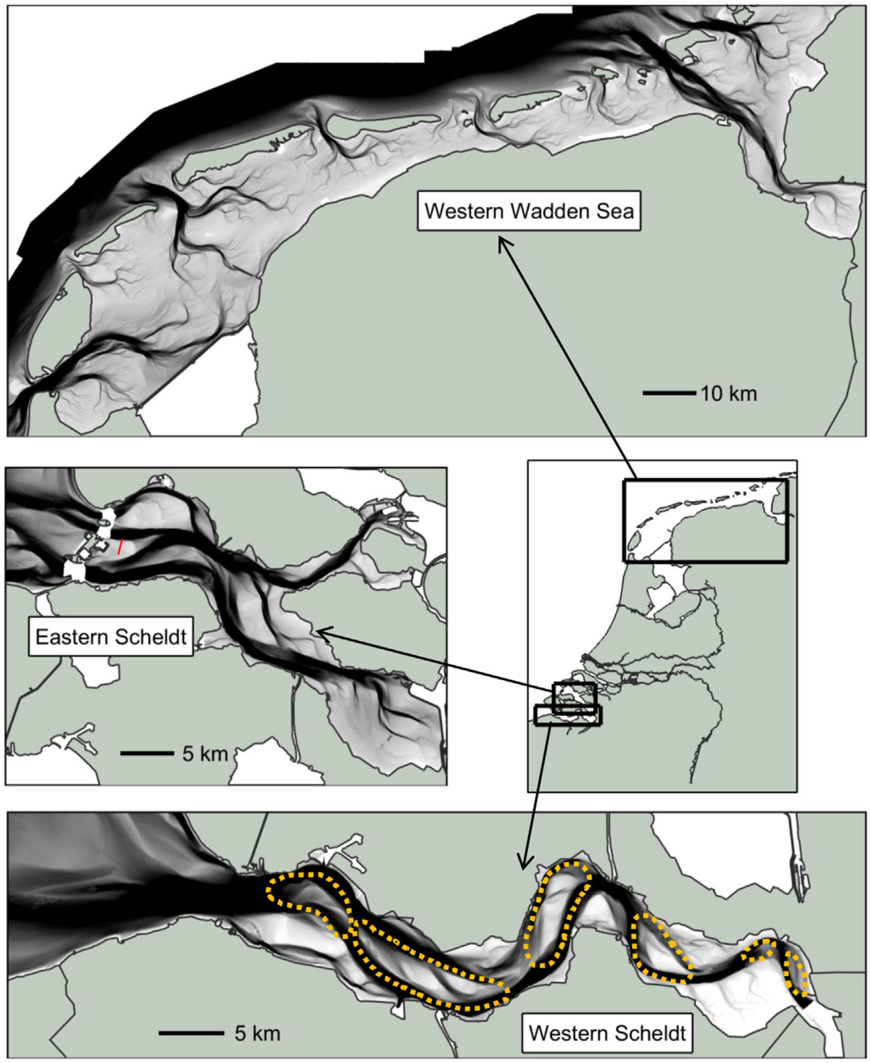

Fig. 1. Tidal basins in the Netherlands: the Wadden Sea, the Eastern Scheldt and the Western Scheldt. The red solid line in Eastern Scheldt indicates the location of the cross-section depicted in Fig. 11. The macro-cells in the Western Scheldt are indicated with yellow dotted lines. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.).

thresholds, beyond which the morphology significantly and sometimes even irreversibly changes, and loses its natural characteristics. As an example, regime shifts in an number of small, narrow, and converging estuaries in Europe have been identified by Winterwerp et al. (2013, see also Winterwerp and Wang, 2013). River engineering works, such as narrowing and deepening, have triggered a shift from low-turbid conditions with weak tidal amplification to high-turbid conditions with strong tidal amplification in these estuaries, due to the interaction between effective hydraulic drag, fine sediment import, and tidal amplification. For the sustainable management of these systems, identification of such thresholds and insight into the mechanisms behind them is needed.

In this paper we identify and attempt to quantify such thresholds for morphodynamic developments at various spatial and temporal scales in a number of tidal systems contrasting in size, dominant sediment transport processes and type of human intervention. We focus on tidal basins in the Netherlands (Fig. 1) influenced by sand extraction (the Western Scheldt), semi-closure (the Eastern Scheldt) and subsidence (the Wadden Sea) and on an estuary modified by large-scale engineering works and upstream reservoirs: China's Yangtze Estuary (Fig. 2).

Most of the estuaries in the southwestern part of the Netherlands were closed after a large-scale flooding in 1953. The Western Scheldt is the only estuary that remained open, and forms the estuarine part of the Scheldt River (355 km length, catchment area 21.9×10^3 km^2). The Western Scheldt is about 5 km wide at the mouth and about 60 km long. The average tidal range at its mouth is about 3.75 m. The discharge of the Scheldt River is only about 100 m^3/s, in the order of 1/1000 of the averaged tidal discharge. Consequently, the Scheldt estuary is well-mixed and the fluvial sediment input is negligible.

The adjacent Eastern Scheldt used to be similar to the Western Scheldt. However, as part of the Delta Works, this estuary is closed off from any river inputs and it can be closed off the sea by a storm surge barrier at the mouth (completed in 1986).

The Wadden Sea is the world's largest coastal wetland formed by an uninterrupted stretch of tidal flats and barrier islands spanning a distance of nearly 500 km along the northern part of the Netherlands, and the North Sea coast of Germany and Denmark. The Dutch part of the Wadden Sea (Fig. 1) consists of extensive systems of branching channels, tidal flats and salt marshes (Elias et al., 2012). The tidal range in the Dutch Wadden Sea increases eastward from about 1.5 m in Texel Inlet to more than 2 m in the Ems Estuary.

The Yangtze Estuary in China is the lowest part of the Yangtze