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Changing tidal hydrodynamics during different stages of eco-geomorphological development of a tidal marsh: A numerical modeling study

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ABSTRACT

The eco-geomorphological development of tidal marshes, from initially low-elevated bare tidal flats up to a high-elevated marsh and its typical network of channels and creeks, induces long-term changes in tidal hydrodynamics in a marsh, which will have feedback effects on the marsh development. We use a two-dimensional hydrodynamic model of the Saeftinghe marsh (Netherlands) to study tidal hydrodynamics, and tidal asymmetry in particular, for model scenarios with different input bathymetries and vegetation coverages that represent different stages of eco-geomorphological marsh development, from a low elevation stage with low vegetation coverage to a high and fully vegetated marsh platform. Tidal asymmetry is quantified along a 4 km marsh channel by (1) the difference in peak flood and peak ebb velocities, (2) the ratio between duration of the rising tide and the falling tide and (3) the time-integrated dimensionless bed shear stress during flood and ebb. Although spatial variations in tidal asymmetry are large and the different indicators for tidal asymmetry do not always respond similarly to eco-geomorphological changes, some general trends can be obtained. Flood-dominance prevails during the initial bare stage of a low-lying tidal flat. Vegetation establishment and platform expansion lead to marsh-scale flow concentration to the bare channels, causing an increase in tidal prism in the channels along with a less flood-dominant asymmetry of the horizontal tide. The decrease in flood-dominance continues as the platform grows vertically and the sediment-demand of the platform decreases. However, when the platform elevation gets sufficiently high in the tidal frame and part of the spring-neap cycle is confined to the channels, the discharge in the channels decreases and tidal asymmetry becomes more flood-dominant again, indicating an infilling of the marsh channels. Furthermore, model results suggest that hydro-morphodynamic feedbacks based on tidal prism to channel cross-sectional area relationships keep the marsh channels from filling in completely by enhancing ebb-dominance as long as the tidal volume and flow velocities remain sufficiently high. Overall, this study increases insight into the hydro-morphodynamic interactions between tidal flow and marsh geomorphology during various stages of eco-geomorphological development of marshes and marsh channels in particular.

1. Introduction

Tidal marshes along estuaries and coasts form a unique habitat and are highly valuable (Barbier et al., 2013). Their ecological functioning provides benefits to society such as improvement of water quality (e.g., Mitsch et al., 2012), carbon sequestration (e.g., McLeod et al., 2011; Mitsch et al., 2013; Ouyang and Lee, 2014) or flood and shoreline erosion protection (e.g., Stark et al., 2016; Gedan et al., 2010; Spalding et al., 2014; Temmerman and Kirwan, 2015; Temmerman et al., 2013). The sustainability of tidal marshes and their functions is however under pressure by among others sea level rise and anthropogenic impacts (Kirwan and Megonigal, 2013; Kirwan et al., 2016). A key aspect for the functioning and sustainability of tidal marshes are the fluxes of water and the physical, chemical and biological materials it contains (i.e., sediments, nutrients, pollutants, seeds, larvae, plankton, etc.) through tidal channels that connect marshes with the adjacent estuary or sea. For example, denitrification (e.g. Mitsch et al., 2012)

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or biogenic silica recycling (e.g. Struyf et al., 2005) depend on the water exchange between marshes and adjacent seas or estuaries and are therefore closely related to the tidal prism (Fagherazzi et al., 2013). Other ecological functions such as carbon and nitrogen burial are related to sediment deposition in marshes (McLeod et al., 2011; Mitsch et al., 2012) and hence to the sediment transport through marsh channels. The tidal asymmetry in the channels, which describes the difference in magnitude and duration of flood and ebb fluxes, determines whether marsh systems are a net sink (import) or source (export) of these materials (e.g. Fagherazzi et al., 2013; French and Stoddart, 1992; Friedrichs and Perry, 2001). Moreover, a flood or ebb dominant asymmetry respectively generates net sediment import or export and ultimately determines the marshes' ability to build up sediments and hence to sustain themselves in balance with sea level rise (e.g. Ganju et al., 2015, 2013; Reed, 2002).

In general it is well-known that the tidal wave is distorted and may become asymmetric as it propagates through shallow channels due to processes including bottom friction, channel convergence and advective inertia (e.g. Aubrey and Speer, 1985; Friedrichs and Aubrey, 1988; Parker, 1984; Speer and Aubrey, 1985; Wang et al., 1999). A distinction can be made between the asymmetry of the vertical tide (i.e., water levels) and of the horizontal tide (i.e., discharges and velocities). Vertical tidal asymmetry is here quantified by the difference in duration of the flood and ebb periods. The vertical tide is considered flood dominant if the duration of the flood period is shorter than the duration of the ebb and ebb-dominant if the ebb is shorter than the flood. Horizontal tidal asymmetry is expressed by the difference between peak currents or discharges during flood and ebb. The horizontal tide is considered flood dominant in case when the peak flood velocities are higher than the peak ebb velocities, and vice versa. The difference in duration of the slack waters (i.e. periods with negligible flow velocities) after high and low tide is another indicator for horizontal tidal asymmetry, as it relates to the deposition of fine sediments after flood and ebb (Dronkers, 1986). However, intertidal marsh channels fall dry at low tide and experience long periods of low water slack without any physical meaning for sediment transport. Therefore, this characterization of tidal asymmetry is deemed not applicable in intertidal channels.

For tidal marshes specifically, numerous field studies have quantified the tidal asymmetry and associated net import or export of materials through marsh channels (e.g. Boon, 1975; French and Stoddart, 1992; Ganju et al., 2015, 2013; Green and Hancock, 2012; Pethick, 1980). However, the factors determining the direction and magnitude of tidal asymmetry in marsh channels are still poorly understood. We hypothesize that one such factor may be the stage of eco-geomorphological development of the combined channel-marsh system. The development of a channel network on an originally bare intertidal flat is most likely initiated by small topographic depressions, which lead to a concentration of tidal flow and thereby locally to higher shear stresses and eventually to creek formation (D'Alpaos et al., 2005; Stefanon et al., 2010). Further development towards a marsh system with a channel network and a vegetated platform is strongly influenced by the establishment of patches of pioneer vegetation. Vegetation patches reduce flow velocities locally and enhance sedimentation inside the patches (Christiansen et al., 2000; De Lima et al., 2015; Mudd et al., 2010), while the flow is accelerated and shear stresses are higher leading to erosion adjacent to the patches (Bouma et al., 2013; D'Alpaos et al., 2006; Temmerman et al., 2007; Vandenbruwaene et al., 2013; Zong and Nepf, 2010). This positive feedback mechanism causes vegetation patches to expand due to increased sedimentation wherever vegetation is present and marsh channels to grow due to increased erosion in between vegetation patches, eventually leading to merging of vegetation patches and the formation of the typical marsh landscape consisting of elevated vegetated platforms dissected by a non-vegetated channel network (Allen, 2000; D'Alpaos et al., 2007; Kirwan and Murray, 2007; Stefanon et al., 2010; Temmerman et al., 2012; Vandenbruwaene et al., 2013). Over the course of a few decades, sedimentation on the vegetated areas raises the elevation of the marsh platform up until around mean high water level (MHWL) (Allen, 2000; Temmerman et al., 2003), depending on external factors including sediment supply and rate of sea level rise (e.g., French, 2006; Kirwan et al., 2010; Temmerman et al., 2004). It may be expected that the establishment of marsh vegetation and the elevation increase of the vegetated platform induce contradicting effects on the flow pattern through the marsh channels. The friction caused by the vegetation and the vertical growth of the marsh platform are expected to enhance flow concentration towards the channels and thereby increase the tidal discharge in the channels. However, less water can be stored on higher platforms, leading to a smaller tidal prism and lower tidal discharge through the channels (D'Alpaos et al., 2006; Temmerman et al., 2007). Along with these effects of marsh developmental stage on tidal discharges in the channels, we may expect that the degree of tidal asymmetry, and hence the net material fluxes, will change during different stages of marsh and channel development, but this has not been systematically documented.

Here, we assess tidal hydrodynamics in marsh channels during different stages of marsh development, starting from a low-lying, almost bare tidal flat situation up to a high-elevated, vegetated marsh with a platform elevation around mean high water level. The selection of these marsh developmental stages is based on observations over a long time scale (ca. 80 years) in a large marsh (ca. 3000 ha) in the Netherlands (Wang and Temmerman, 2013). A validated two-dimensional hydrodynamic model for this channel-marsh system (Stark et al., 2016) is used to assess vertical and horizontal tidal asymmetry for a number of observed successive stages of marsh development. Finally, we discuss the implications of our model results in terms of expected effects on net material flux and how this evolves during different stages of marsh development.

2. Methods

2.1. Study area

We study tidal hydrodynamics in the intertidal channels of the 'Verdronken Land van Saeftinghe' (in the following: 'Saeftinghe'), a ca. 3000 ha tidal marsh along the Western Scheldt (Fig. 1). The present-day marsh is surrounded by levees in the south and the west and bordered by the subtidal estuary channel in the north and east. Three large intertidal channels characterize the marsh geomorphology throughout its development since 1900. (Fig. 2a–c). The most eastward channel (*'Hondegat'*) and adjacent marshes are the subject of this study. Detailed field measurements of tidal water level movements (Stark et al., 2015) and a validated two-dimensional hydrodynamic model (Stark et al., 2016) are available for this area. The marsh platform is covered by various types of vegetation, of which *Elymus athericus* and *Scirpus maritimus* are the most abundant (Vandenbruwaene et al., 2015). Nowadays, a semi-diurnal macrotidal regime induces a tidal range of 4.0–5.6 m in the estuary channel adjacent to the study area. High water levels at the study area vary between 2.18 m and 3.15 m above NAP (NAP is the Dutch ordnance level, close to mean sea level), with a MHWL of 2.76 m.