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Invited review

Holocene evolution of tidal systems in The Netherlands: Effects of rivers, coastal boundary conditions, eco-engineering species, inherited relief and human interference

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ABSTRACT

Estuaries and tidal embayments are partly enclosed coastal bodies of water with a free connection to the open sea at their tidal inlet and with minimal (tidal embayments) or substantial fluvial input (estuaries). Their tidal inlets can only remain open over multiple centuries to millennia when (1) the formation of accommodation space exceeds infilling or (2) the inlet system is in dynamic equilibrium (i.e., sediment input equals output). Numerical modeling studies often suggest that estuaries and tidal embayments can develop toward a dynamic equilibrium under constant boundary conditions and consequently remain open over centuries to millennia, whereas in the Holocene sedimentary record many estuaries and tidal embayments are observed to have filled up and closed off. This raises the questions whether and how tidal inlets can remain open over long timescales (centuries to millennia), and what the effects are of river inflow and sediment supply. Here we compare the long-term evolution of contrasting tidal systems along the Dutch coastal plain to empirically identify the most important factors that control their long-term evolution. We study tidal systems along the Dutch coast because of (1) high data density, (2) abundant well-preserved and well-described estuaries and tidal embayments with contrasting boundary conditions and morphodynamic evolution and (3) their low-sloping setting with soft boundaries. This makes contrasting estuarine dimensions and development largely dependent on initial conditions, boundary conditions and internal biogeomorphological processes.

In the Middle Holocene, Dutch estuaries and tidal embayments were mainly formed by rapid relative sea-level rise. In the late Holocene, they were predominantly the result of natural and human-induced subsidence in coastal plain peatlands. Tidal inlets connected to rivers (estuaries) persisted and attained dynamic large-scale equilibrium while tidal embayments without or with a marginal fluvial inflow were unstable and closed off under abundant sediment supply. Estuaries probably attained a quasi-stable configuration wherein sediment input equaled export due to river-enhanced ebb flow, until fluvial influx was cut off by upstream avulsion causing transition to an embayment and system closure. Long-term net import of sediment from the sea into Dutch tidal embayments is favored by strong, flood-dominated, tidal asymmetry along the Dutch coast, the shallow sand-rich floor of the North Sea, erosion of inherited coastal promontories, and the abundance of mud in the coastal area supplied by the Rhine and Meuse rivers. While sandy tidal embayments without fluvial feeders and with fixed boundaries may obtain dynamic equilibrium and remain open over long timescales, we hypothesize that an abundance of mud and eco-engineering species often culminates in continuous embayment filling with fine sediment and the growth of intertidal and supratidal areas, eventually resulting in closure of the embayment.

1. Introduction

Estuaries and tidal embayments (or lagoons) are ubiquitous in coastal areas worldwide. Here, we define them as semi-enclosed coastal bodies of water with a free connection to the open sea at their tidal inlet, and with freshwater input ranging from no to marginal in what we here call tidal embayments, to substantial in what we here call estuaries. These systems typically include multiple of the following morphological elements; ebb-tidal delta, flood-tidal delta, shoals, sand bars, channels, tidal flats, salt marshes to freshwater marshes and

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natural levees. Estuaries and tidal embayments form on inherited topography and substrate under rising relative sea level, fluvial and coastal sediment inputs by tidal currents, waves, density-driven circulation, and biogeomorphological processes (e.g., Pritchard, 1967; Boyd et al., 1992; Dalrymple et al., 1992; Perillo, 1995; Gingras et al., 1999; Van Ledden et al., 2004; De Swart and Zimmerman, 2009; Wang et al., 2012; Seminara et al., 2012; Coco et al., 2013; Bouma et al., 2014).

Estuaries and tidal embayments are important for many reasons and have many functions. They exhibit a high species density and diversity and harbor highly productive natural habitats (e.g., Howard and Frey, 1975; Gingras et al., 1999; Beck et al., 2001). At the same time they are of pivotal societal importance for agriculture, fishing, shipping, ports, and urban building (e.g., Savenije, 2005). Sustainable exploitation of estuaries and tidal embayments is, however, continuously threatened by accelerating sea-level rise, changing river inflow and increasing human interference with sedimentary processes and ecology (e.g., Craft et al., 2008; Syvitski et al., 2009; Bouma et al., 2014; Yang et al., 2015). How these threats will influence the future evolution of estuaries and tidal embayments around the world is largely unknown. Reconstructing the impact of past climatic changes on estuaries and tidal embayments may reveal how these systems will respond to future environmental changes. Moreover, in areas where humans have interfered with the natural landscape for centuries to millennia such reconstructions may also help to unravel the relative effects of natural versus human-induced forcings on the long-term evolution of tidal systems.

Most present-day estuaries and tidal embayments formed early in the middle Holocene (8500–7500 yr BP) when sea level rose rapidly, continental shelfs were flooded and shifting coast lines were approaching their current positions (Stanley et al., 1994; Smith et al., 2011; Hijma et al., 2012). Pre-Holocene topography determined the initial planform of many estuaries in that low-lying glacial and river valleys were inundated first (e.g., Dalrymple et al., 1992; Hori and Saito, 2007; Rossi et al., 2011; Tanabe et al., 2015; Wetzel et al., 2017). The subsequent evolution of estuaries and tidal embayments is mainly determined by the balance between the formation and infilling of accommodation space (e.g., Nichols, 1989). Here, we study how different paths of development arise depending on this balance. Estuaries and tidal embayments are very efficient sediment traps, with sediment potentially being delivered from rivers and the sea (e.g., Boyd et al., 1992; Metcalfe et al., 2000; Atwater et al., 2001; Dalrymple and Choi, 2007). Over their lifetime, many of the forcings affecting estuaries and tidal embayments change and many estuaries have therefore been constantly adjusting to changing boundary conditions over time. Some estuaries and tidal embayments that formed during the early to middle Holocene transgression still persist today, whereas others have completely filled in (e.g., Dalrymple et al., 1992; Martinius and Van den Berg, 2011). This raises the question if, and under which conditions, estuaries and tidal embayments can be in large-scale equilibrium with balanced sediment input and output and consequently remain open over centuries to millennia, and what determines the timescales of adaptation to changing boundary conditions.

Current understanding and predictive capabilities of long-term and large-scale estuary and tidal embayment development have critical gaps regarding long-term effects of mud accretion, eco-engineering species and externally imposed geometry of the drowned valley or sedimentary coastal plain, size of rivers feeding freshwater and sediments, sea-level change and human interference. Past ecological work, numerical morphological modeling and geological reconstructions remain poorly linked and have not yet resulted in a comprehensive conceptual model from which to proceed with long-term numerical modeling. Physics-based models convincingly reproduced hypsometry and channel-shoal patterns in sandy estuaries and tidal embayments from tidal range, river inflow, and sand input and output conditions (Lanzoni and Seminara, 2002; Hibma et al., 2004; Townend, 2012; Van der Wegen and Roelvink, 2012; Savenije, 2015; Braat et al., 2017), indicating that the fundamental processes of water and sand motion largely control the morphology of channels and bars. However, these models must assume a planform shape with fixed perimeters and a given characteristic length of exponential widening (Savenije, 2015; Dronkers, 2017) lest the banks continue to erode (Van der Wegen et al., 2008). Recent modeling that includes fluvial mud supply shows that mud can stabilize the otherwise erosive estuarine banks (Braat et al., 2017) in a similar manner as river floodplains with mud and vegetation stabilize river channels (Kleinhans, 2010). Yet, assuming a fixed planform shape ignores dynamically evolving boundary conditions and possibly large effects of biogeomorphological interactions, particularly at the system margins (e.g., Temmerman et al., 2007; Kirwan and Megonigal, 2013). Eco-engineering species can significantly change their environment at the landscape scale (Jones et al., 1994) as is well-known for rivers (e.g., Kleinhans, 2010; van Asselen et al., 2017), but at present large-scale effects on tidal system development remain poorly understood. Mapping shows that tidal system dimensions and development in many cases largely depend on pre-Holocene surface (e.g., Boyd et al., 1992, 2006) while many other cases initiated largely independently from inherited relief, and as a result of storm-surge ingressions or river floods (van der Spek, 1995; van de Plassche et al., 2006; Vos, 2015; Pierik et al., 2017). Fossil biota, often abundant in the sedimentary record (e.g., Gingras et al., 1999; Vos and Van Kesteren, 2000; Dashtgard, 2011; Gingras and MacEachern, 2012), imply significant eco-engineering effects that often remain unquantified or unmentioned in reconstructions. Reconstructions of tidal-system evolution compiled from geological data are hardly informed and constrained by physics-based modeling and may therefore be biased toward particular conceptual models or present-day analog systems. Clearly, there is a wide gap between the detail of processes and sedimentary products qualitatively postulated in palaeogeographical reconstructions, in which it is difficult to specifically identify biophysical interactions, and the idealized numerical models applied to millennial timescales that usually ignore biogeomorphological processes and have overly simplistic initial and boundary conditions.

The objective of this paper is to identify the main processes that determine the evolution of estuaries and tidal embayments on timescales of centuries to millennia. In particular, we study effects of river discharge, sediment supply by riverine and coastal processes, and eco-engineering species in combination with mud trapping, on the long-term evolution of estuaries and tidal embayments. We then address the question whether and how estuaries and tidal embayments can develop into a state of long-term equilibrium. To this end, we combine results of numerous palaeogeographical reconstructions from literature, which have been based on a vast amount of data on Holocene deposits of estuaries and tidal embayments in The Netherlands. The presence of multiple (> 20) tidal systems with different initial settings and boundary conditions gives us some degree of control, allowing isolation of important processes (a few examples of studied tidal systems are given in Figs. 1 and 2).

Below we first develop the main research questions of the paper on the basis of literature. Then we summarize current understanding of the Holocene evolution of the Dutch coast and synthesize the long-term evolution of estuaries and tidal embayments and the effects of multiple boundary conditions thereon. Based on this framework of data, reconstruction and generalization we then infer trends and causes, and formulate generic hypotheses and open questions.

1.1. Problem definition

1.1.1. Long-term dynamic equilibrium in estuaries and tidal embayments?

An estuary or a tidal embayment can be considered to be in dynamic equilibrium if the overall planform shape and size and hypsometry of an estuary or tidal embayment undergo little or no change due to a balance between the input and output of marine and riverine sediment under the prevailing boundary conditions (e.g., Pethick, 1994; Dyer, 1997; Pye and Blott, 2014). Such a dynamic equilibrium may be maintained