The ‘Voordelta’, the contiguous ebb-tidal deltas in the SW Netherlands; Impacts of large-scale engineering 1965-2013

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1. Introduction
The estuaries in the SW Netherlands, a series of distributaries of the rivers Rhine, Meuse and Scheldt known as the Dutch Delta, have been engineered to a large extent as part of the Delta Project, a flood protection scheme that was developed and executed after the dramatic storm surge disaster of February 1, 1953. The project included separation of the respective estuaries with dams and subsequent damming of their seaward sides. Moreover, sluices were planned to be built in the Haringvliet dam in order regulate the discharge of the rivers Rhine and Meuse. Only the Western Scheldt would remain an open estuary, since it is the entrance to the port of Antwerp. Later adaptations of the scheme included the building of a storm-surge barrier in the inlet of the Eastern Scheldt, in order to preserve the valuable inshore tidal ecosystem and the successful commercial shellfish culture. The complete or partial damming of the estuaries had an enormous impact on the contiguous ebb-tidal deltas, known as the Voordelta. This paper presents an integral analysis of the morphodynamic changes of the Voordelta, based mainly on repeated bathymetric surveys executed by Rijkswaterstaat, the water management authority of The Netherlands, over the period 1964-2012.

2. Morphologic Developments
The complete damming of the Grevelingen and Haringvliet estuaries resulted in strong shoreface erosion and landward sediment transport. Wave action has pushed the ebb-delta margin landward and built long but narrow, coast parallel sub- to intertidal sand bars while the closed-off channels have filled in with both sand and mud. These observations are in correspondence with existing conceptual models. Reduction of the tidal prism of an inlet will result in a decrease in sand supply by the ebb current and, hence, wave-driven sand transport will increase relatively. This results in net sediment transport in landward direction and erosion of the delta front. Since the dams block transport of sediment into the estuaries, the volumes of the ebb-tidal deltas did not decrease as would be expected from the Walton & Adams (1976) relationship. Coast-parallel sand transport is the only way of volume reduction. Part of the sand eroded from the Grevelingen delta front was transported along the coast of Goeree island, towards the Haringvliet ebb-tidal delta. The latter does not have an outlet for sediment since it is blocked in the north by the seaward extension of Rotterdam harbour.

Partial closure of the Eastern Scheldt with a storm-surge barrier has reduced its tidal prism with c.28%, but tidal flows are sufficient to maintain the main channels on the ebb-tidal delta. With a reduction of the shore-normal tidal flow, shore-parallel tidal currents became more dominant which promoted scouring of the north-south running channels on the ebb-tidal delta. This eroded and reshaped the Banjaard shoal. Its seaward part is pushed landward and northward by waves. Part of the eroded sediment is transported to the north, to the neighbouring Grevelingen ebb-tidal delta.

Large-scale landward retreat of the ebb-tidal delta margin is not observed in the Western Scheldt ebb-tidal delta. The latter retained a near identical 2-channel configuration with large tidal channels along the southern and northern margin, despite major dredging activities in the estuary.

Despite the large morphodynamic changes in the Voordelta, the net sediment volume changes over the

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entire period 1965 to 2010 are small; 0.1 to 0.2 million m$^3$/year increase in Haringvliet and Grevelingen, and a 1 million m$^3$/year volume reduction of the Western Scheldt and Eastern Scheldt ebb-deltas. The sediment volumes that are transported from one ebb-tidal deltas to the next, are in the same order of magnitude or larger than the net changes.

![Figure 1. The bathymetry of the Voordelta for the years (a) 1967-1969 and (b) 2009-2011. The morphological changes over this interval are shown by the sedimentation-erosion patterns in panel (c).](image)

The well-monitored changes in the Voordelta, showing the differences in responses of the ebb-tidal deltas to reductions in tidal volume, provide clear insight in the underlying processes and allow us to refine existing general concepts and models of ebb-tidal delta dynamics. Despite anthropogenic dominance, existing conceptual models and knowledge, based on natural inlets can still explain the observed developments. In essence, reduction of the tidal prism of an inlet will result in a decrease in sand supply by the ebb current and, hence, wave-driven sand transport will increase relatively. This results in net sediment transport in landward direction and erosion of the delta front (Grevelingen and Haringvliet). Since the sediment cannot be transported into the estuary because of the dams, the only way to export sediment is lateral transport. Moreover, with a reduction of the shore-normal tidal flow, shore-parallel currents will became more dominant which will promote shore-parallel flow through the channels on the ebb-tidal delta and increase the sediment exchange between the individual delta’s. This will cause adaptations in the ebb-tidal delta morphology (Eastern Scheldt). Finally, the decreased tidal flow triggers infilling of the tidal channels, both with sand eroded from the shoals and mud imported from the North Sea.

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