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The influence of cyclic channel-shoal dynamics on sediment pathways on the ebb-tidal delta of Ameland

Introduction

The ebb-tidal delta of Ameland (Dutch Wadden Sea) is known for its cyclic behavior (Figure 1). One cycle has a period of 50 to 60 years, during which the inlet transforms from a one-channel system to a two-channel system and back and shoals form on the ebb-tidal delta, which migrate and attach to the downdrift island.

Tidal currents and incoming wave energy result in a continuous sediment exchange between ebb-tidal delta, the back-barrier basin and the barrier islands of Ameland and Terschelling. The long-term changes in bathymetry affect the patterns of currents and waves. Therefore, the sediment fluxes through the inlet, towards the islands and over the ebb-tidal delta, are possibly also cyclic.

Main Question

Does the cyclic behavior of the ebb-tidal delta affect the sediment exchange between the back-barrier basin and the ebb-tidal delta?

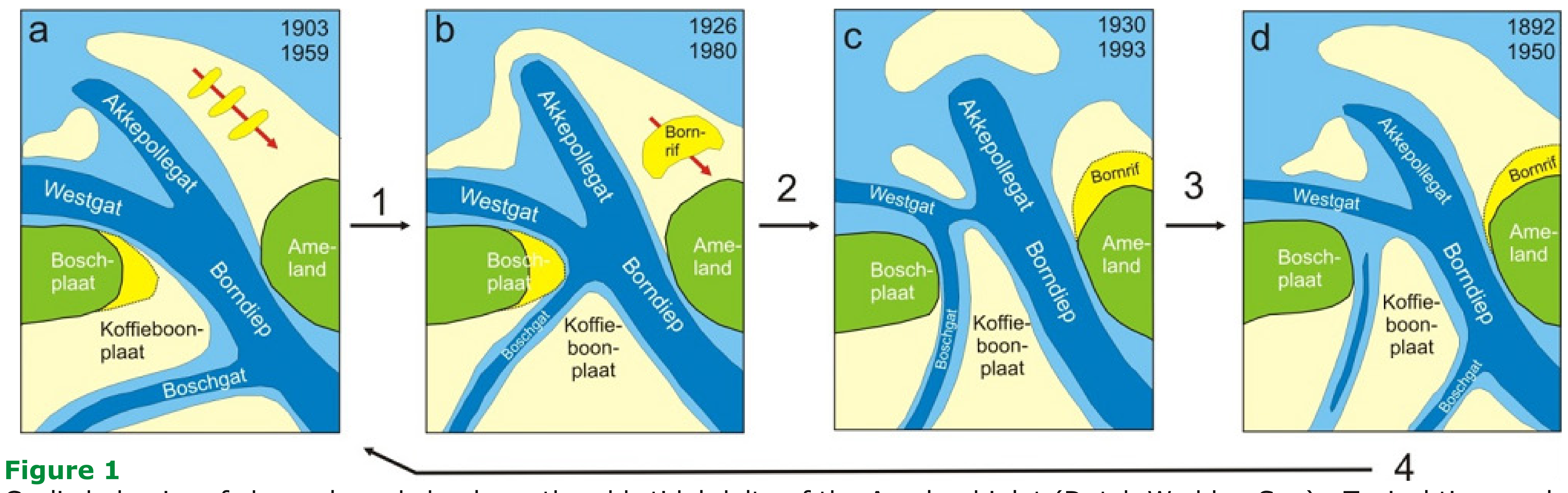

Figure 1
Cyclic behavior of channels and shoals on the ebb-tidal delta of the Ameland inlet (Dutch Wadden Sea). Typical time scale is 50-60 years. Source*: Israel & Dunsbergen (1999)*.

Methodology

- Delft3D/SWAN model in a high spatial (30 m) and temporal (12 s) resolution.
- Hydrodynamic forcing: combination of tides and waves.
- Tides: at seaward boundaries a representative tide is forced, including storm surge, the diurnal (D_1) and semidiurnal (D_2) constituents and several overtides (D_4, D_6, etc.).
- Waves: distinction between 3 classes and 4 directions (Table 1). The significant wave height and mean wave period are based on 20 years of wave data collected at an offshore wave buoy.
- Sediment transport formulation: Van Rijn et al. (2004), bed-load and suspended load (d_{50} = 0,25 mm).
- Four historic (i.e., measured) bathymetries to test the effect of cyclic ebb-tidal delta. Bathymetries of 1971, 1989, 1999 and 2011 were reconstructed.

	West	Northwest	North	Northeast
Calm	H_s = 0,72 m T_{m02} = 3,68 s	H_s = 0,69 m T_{m02} = 4,49 s	H_s = 0,54 m T_{m02} = 4,28 s	H_s = 0,54 m T_{m02} = 3,50 s
Intermediate	H_s = 1,62 m T_{m02} = 4,58 s	H_s = 2,05 m T_{m02} = 5,51 s	H_s = 1,51 m T_{m02} = 5,10 s	H_s = 1,3 m T_{m02} = 4,30 s
Storm	H_s = 3,63 m T_{m02} = 6,35 s	H_s = 5,46 m T_{m02} = 8,16 s	H_s = 3,99 m T_{m02} = 6,99 s	H_s = 2,88 m T_{m02} = 5,77 s

Table 1
Significant wave height H_s and mean wave period T_{m02} for the different classes (calm weather, intermediate weather and storm) and directions (West, Northwest, North and Northeast).

Results

Sediment transport is calculated for each bathymetry as the weighted mean of the 12 wave and tide scenarios. Figure 2 shows the total load transport for four different years, as well as the integrated transport across four defined transects.

- Sediment transport through the cross-sections north, west and east of the ebb-tidal delta are an order of magnitude smaller than that through the inlet.
- The sediment transport though the inlet indicates a cyclic transition from a sediment importing in 1971 to an exporting tidal basin (especially in 1999) and back.
- For all bathymetries sediment is exported in the deep channel located in the east of the inlet.
- The 1971-bathymetry shows import of sediment over the shallow banks west of the deep channel. This feature is not found for the other bathymetries.

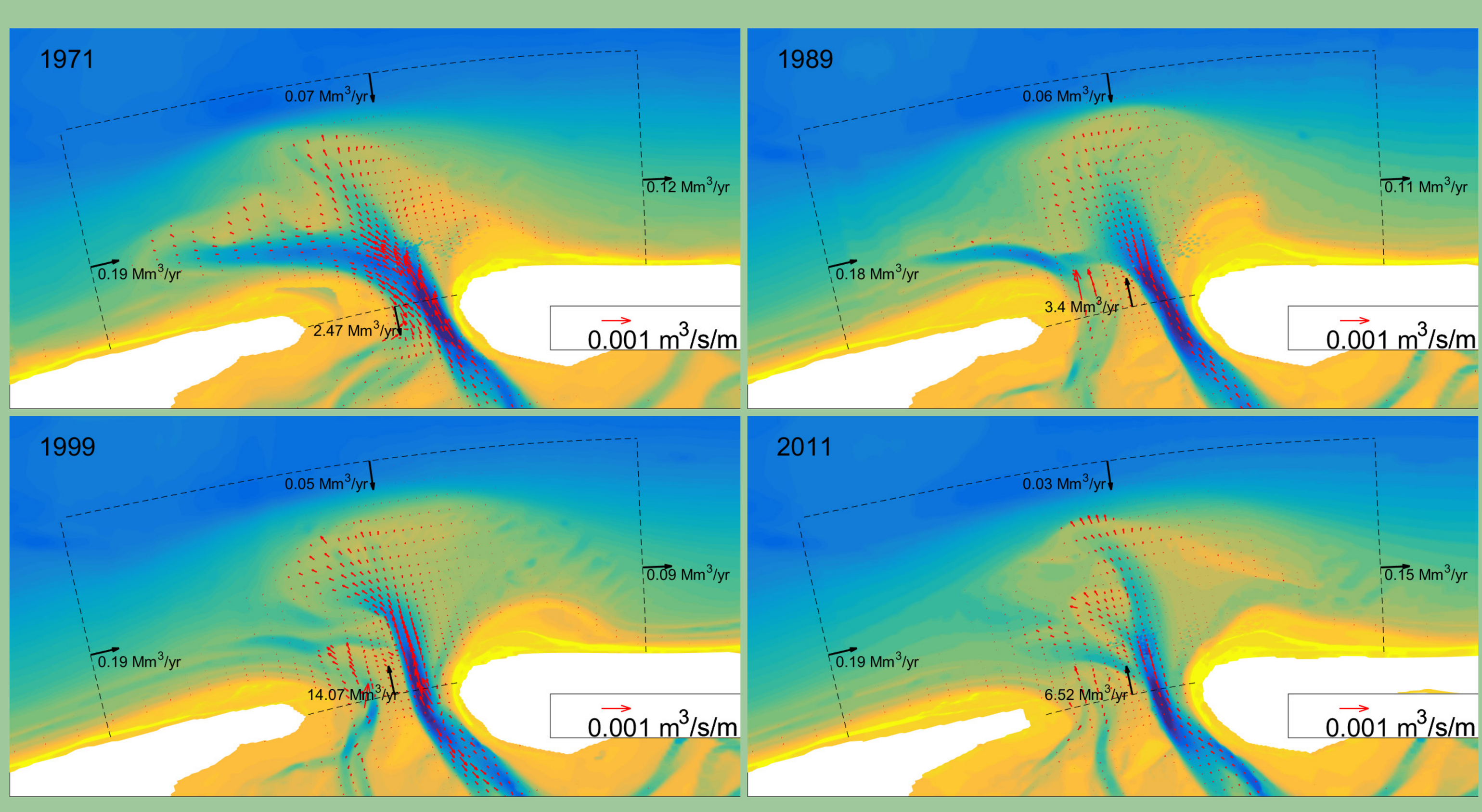

Figure 2
Weighted mean of total load sediment transport (red vectors). Bathymetry shown in colors, ranging from -25 m (blue) to 5 m (yellow). Dashed lines are cross-sections over which sediment transport over a year is calculated (black arrows and numbers).

The relative contribution of calm weather, intermediate weather and storms to the sediment import/export across the inlet is shown in Figure 3.
- During storms, the back-barrier basin imports sediment for all bathymetries.
- The magnitude and even direction of the sediment flux during calm and intermediate weather (i.e., more tidally dominated conditions) changes with bathymetry.

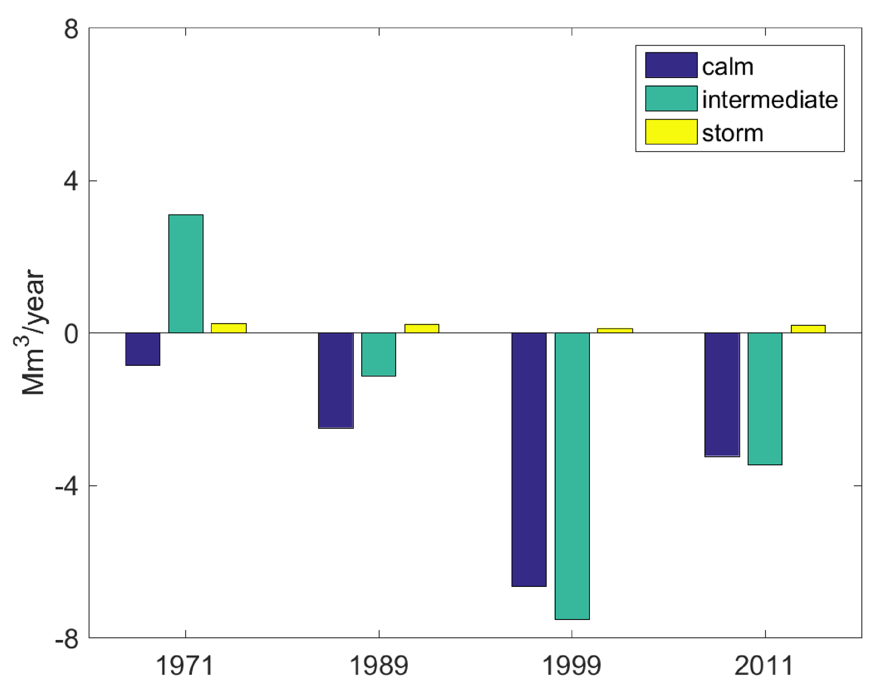

Figure 3
Bar plot of the sediment import/export for the four historic bathymetries, differentiating between calm weather, intermediate weather and storm. Positive (negative) values indicate import (export).

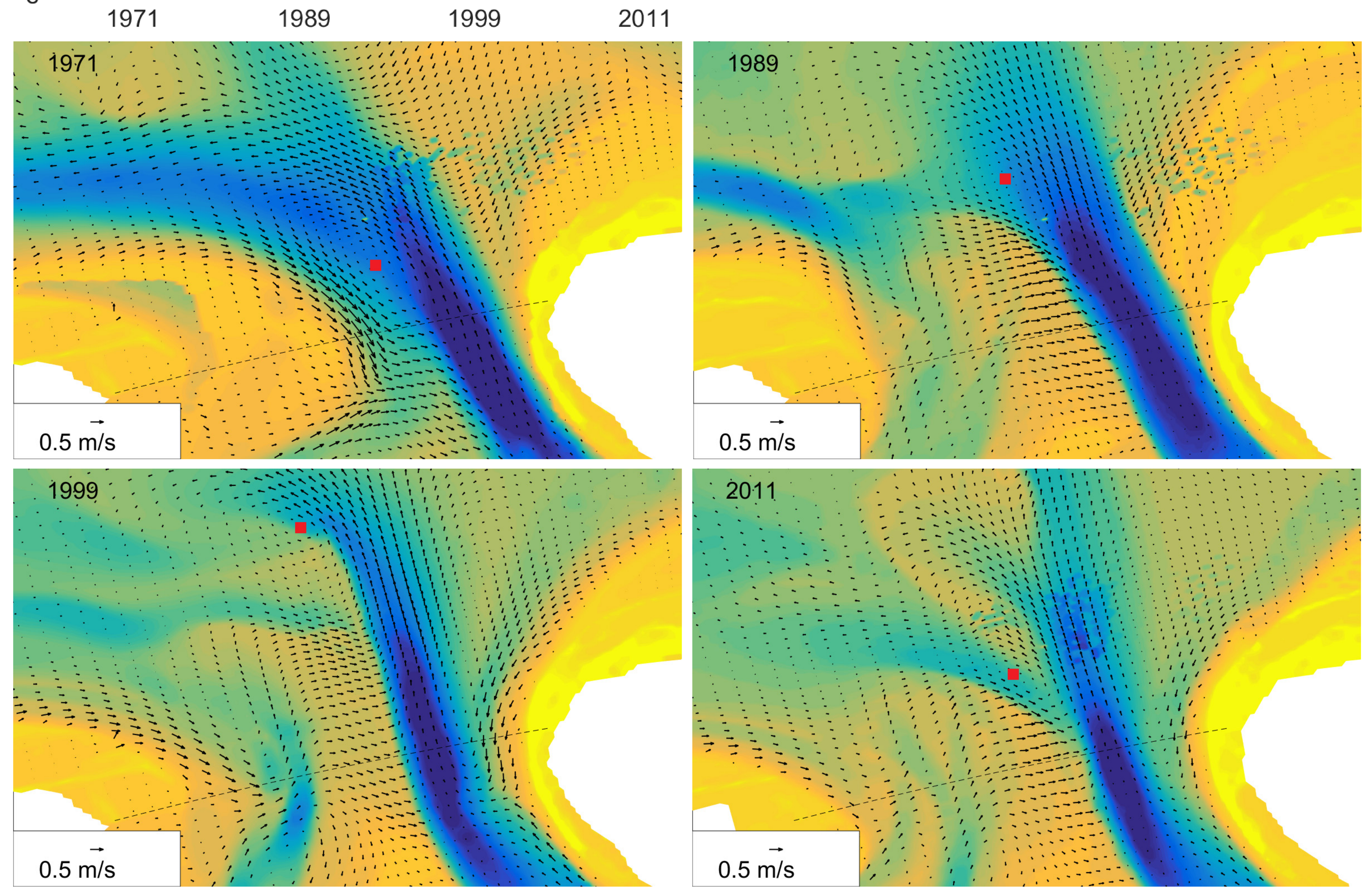

Figure 4
Vector plot of the residual depth-averaged flow for intermediate, Northwest wave conditions. The center of the residual circulation cell is indicated by a red dot. Bathymetry shown in colors, ranging from -25 m (blue) to 5 m (yellow). Dashed line represents same cross-section in inlet as in Figure 2.

The run with intermediate waves coming from the Northwest (dominant condition) is exemplary and therefore examined more closely. The residual depth-averaged flow for the four bathymetries are shown in Figure 4.
- For the 1971-bathymetry, a residual cell is located in the inlet with southward flow in the west and northward flow in the east.
- This residual cell is located closer to the ebb-tidal delta for the other bathymetries, and, as a result, less (residual) southward flow crosses the inlet.
- For the 1999-bathymetry, the cell is northernmost located and sediment export is largest.

Discussion

The modeled trend of sediment export agrees with observations that indicate growth of the ebb-tidal delta between 1935 and 2005 (Elias et al. 2012). The cyclic import/export of sediment suggests a strong coupling between the basin and ebb-tidal delta, and that parts of the basin also evolve cyclic. The observed back-barrier basin infilling resulted from sediment depositions near the Vlie-Ameland tidal divide.

The sediment export in the deep channel and sediment import over the shallow banks west of the deep channel in 1971 resemble the findings of Brown & Davies (2009). They found that a combination of tides and waves can result in sediment import over shallow banks next to a exporting deep channel.

Model results suggest a critical wave condition for which the system becomes sediment importing. Additional model runs will further specify the relative effect of waves and tidal currents on the sediment transport patterns.

Conclusions

- The exchange of sediment between back-barrier basin and inlet is cyclic and is closely linked to the cyclic behavior of the ebb-tidal delta.
- The changes in import/export of sediment near the inlet seem to be caused by changes in the position of tidal residual circulation cells.

References

Brown, J. M., & Davies, A. G. (2009), 'Methods for medium-term prediction of the net sediment transport by waves and currents in complex coastal regions', *Continental Shelf Research*, **29**(11), 1502-1514.
Elias, E. P. L., Van der Spek, A. J. F., Wang, Z. B. & De Ronde, J. (2012), `Morphodynamic development and sediment budget of the Dutch Wadden Sea over the last century', *Netherlands Journal of Geosciences* **91**(03), 293-310.
Israel, C. G. & Dunsbergen, D. W. (1999), 'Cyclic morphological development of the Ameland Inlet, the Netherlands', *Proceedings IAHR Symposium on river, coastal and estuarine morphodynamics, Department of Environmental Engineering, University of Genoa*, pp. 705-714.