The residual sand and mud transport in the Schelde-estuary, based on the calculation of the sediment balance

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ABSTRACT: A sand and mud balance is calculated for the Schelde-estuary for 3 different periods since 2001. The balances are calculated over different segments of the estuary, each 5 to 10 km long, using topo-bathymetric surveys. The differences in volumes are explained by sediment transport at both the up-estuarine and down-estuary boundary, but also by human interventions (e.g. dredging, disposal, extractions). The distinction between sand and mud was made based on bottom samples, taken along estuary, covering all habitats. The sand transport shows an up-estuarine transport over the entire estuary. The mud transport has a different pattern, with a down-estuarine transport over most of the estuary.

1 INTRODUCTION

Sediment transport is important for several estuarine functions. The morphology determines both the tidal penetration in the estuary and the port accessibility (Smolders et al. 2015). Suspended sediment influences the light penetration in the water column and therefore it is crucial for ecology (Meire et al. 2005). The residual sediment transport is crucial for the future evolution of the estuary. To visualise this residual sediment transport on a longer time scale (years), a sediment balance was calculated for the Flemish part of the Schelde-estuary.

1.1 Schelde-estuary

The Schelde-estuary is a macro-tidal estuary with a length of 180 km in Flanders and the southern part of the Netherlands (Figure 1). The sediment balance is calculated for the Zeeschelde, the part up-estuary of the Dutch-Belgian border (KM 60 to KM 160). The morphology is characterised by single channel system with neighbouring tidal flats and salt marshes. The estuary is characterised by semi-diurnal tides, causing ebb and flood currents with important sediment transports of both cohesive as non-cohesive sediments (Baeyens et al. 1998). The Schelde-estuary serves different estuarine functions and therefore faces managers with multiple challenges: increasing tidal propagation vs. safety against flooding; sedimentation in the navigation channel vs. port accessibility; changing dynamics vs. ecology.

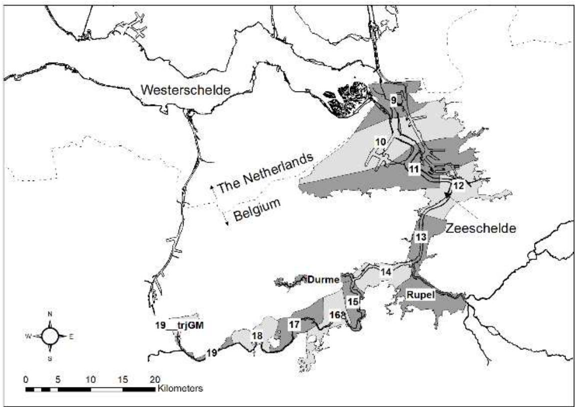

Figure 1. The Schelde-estuary and the schematisation in boxes

2 METHODOLOGY

2.1 Sediment balance concept

The sediment balance (Rosati 2005) is calculated starting from the principle of conservation of mass applied to a simplified schematisation (boxes) of the system (Figure

2). The boxes were defined as 5 to 10 km-long segments (Figure 1), which were previously defined within the OMES-project. Within a certain box, changes in sediment volume are explained by (1) an up-estuarine flux of sediment, (2) an down-estuarine flux of sediment and (3) external factors creating a flux of sediment (eg. sediment mining). The changes in volumes are derived from topo-bathymetries for different moments. At the most up-estuarine boundary, the sediment flux is derived from measurements. The external fluxes are derived from registrations. Starting from these known parameters the down-estuarine sediment flux is derived, which is also the up-estuarine flux for the neighbouring box.

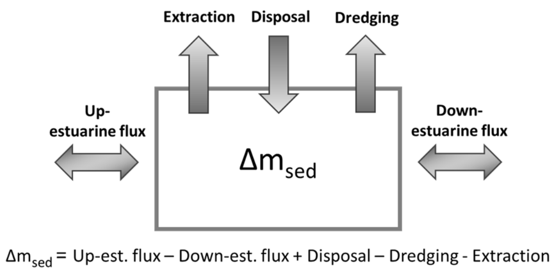

Figure 2. Concept of sediment balance

Where non-cohesive (sand) and cohesive (mud) sediment have a different influence on ecosystem services, it was decided to make a distinction between both sediment fractions. Therefore a sand balance and a mud balance was calculated.

2.2 Topo-bathymetry

For the Schelde-estuary topo-bathymetric information is available for several decades. However, the sediment balance requires a full coverage of the estuary, this was only available since 2001. Within the last 20 years, 4 topo-bathymetric datasets were available, allowing the calculation of the balances for 3 different time periods:

- 2001-2011
- 2011-2016
- 2016-2019

Bathymetric data was collected using singlebeam echo sounding (2001) and multibeam echo souding (2011, 2016, 2019). Topographic data (intra- and supratidal) was collected using LIDAR. Different datasets were merged to get a full coverage of the estuary.

2.3 Fluvial sediment influx

At the up-estuarine boundaries, fluvial sediment fluxes are available. These fluxes are calculated from daily values of discharge and sediment concentration measurements (Vandenbruwaene et al. 2022). For each period, the total fluvial influx can be calculated.

2.4 Human interventions

Within the Schelde-estuary sediment is extracted at several locations, both for commercial purposes, as for dike construction/improvement. Also dredging and disposal takes place to guarantee port-accessibility. With regard to this last aspect, detailed information is available containing the exact location and time of the dredging and disposal works. For the sediment extraction the information is aggregated at a larger spatial scale, however this information was converted at the required spatial scale of the boxes. In this way, the external sediment fluxes are taken into account in the calculation of the sediment balance.

2.5 Sand-mud distinction

The distinction between sand and mud was made based on the sand-mud-percentage for several 100’s of bottom samples. The samples were taken over different habitats [deep/moderate deep/undeep subtidal, intertidal, supratidal, anthropogenic subtidal, anthropogenic intertidal (Van Ryckegem et al. 2022)], and results showed important differences per habitat. The respective fraction of sand (>63 µm) and mud is determined on the samples. Subtidal habitats are dominated by a large (~ 80%) sand content, while inter- and supratidal habitats have a more muddy content. Therefore a specific sand-mud-percentage as applied per habitat-class.

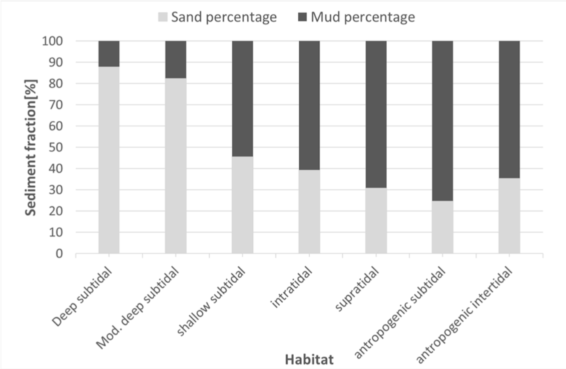

Figure 3. Sand-mud percentage for different habitats

2.6 Volumes to mass conversion

Some data were available as volumes (changes in topo-bathymetry, some dredging/disposal information) while other (fluvial influx, some dredging/disposal information) were available as masses. Therefore it was necessary to convert the values - and the choice was made to convert the volumes to masses, using both porosity and sediment density. Based on Koltermann et al. (1995) the porosity was derived depending on the sand-mud-percentage within the specific habitat:

If $\boldsymbol{\varphi_v} < \mathbf{0.4}$

$$\boldsymbol{\phi} = \phi_{Sd} - \frac{\boldsymbol{\varphi_v}}{\varphi_m} * (\phi_{Sd} - \boldsymbol{\phi_m}) \quad (1)$$

If $\boldsymbol{\varphi_v} \geq \mathbf{0.4}$

$$\boldsymbol{\phi} = \boldsymbol{\phi_m} + \frac{(\boldsymbol{\varphi_v} - \varphi_m)}{(\mathbf{1} - \varphi_m)} * (\phi_{Sh} - \boldsymbol{\phi_m}) \quad (2)$$

With: $\boldsymbol{\varphi_v}$: relative mud fraction [-]

$\boldsymbol{\phi_{Sd}}$: porosity of pure sand = 0.4 [-]

$\boldsymbol{\phi_{Sh}}$: porosity of pure mud = 0.8 [-]

$\boldsymbol{\phi_m}$: minimum porosity = 0.24 [-], occurring for mud fraction equal to 40%

From the porosity, the mass of a certain sediment volume can be calculated. A sensitivity analysis was performed on the importance of this conversion method (vs fixed porosity overall).

3 RESULTS

3.1 Sand balance

The sand balance for the period 2016-2019 (Figure 4) shows up-estuarine transport of sand over the entire estuary. For the previous periods 2011-2016 and 2001-2011 the most upstream parts of the estuary show down-estuarine transports (Figure 4). The location where the residual transport changes from down- to up-estuarine transport, moves progressively more down-estuary when going back in time. What causes this shift still has to be determined. The sensitivity analysis shows that differences in sand-mud percentages cannot account entirely for the differences in sediment transport, and human interventions haven’t changed much through the years.

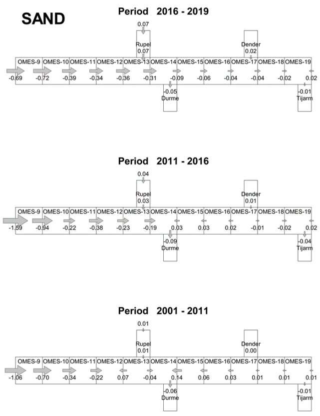

Figure 4. Sand balance for different periods (see figures 4 and 5 at the end of the paper)

3.2 Mud balance

The mud balance for all periods is shown in Figure 5. The residual transport is down-estuary throughout most of the estuary Only for the period 2016-2019 the transport at the downstream border of the Zeeschelde is directed upstream, while the Durme tributary is characterised by an influx of cohesive sediment (mud).

At the most down-estuarine part of the Zeeschelde, the residual mud transport is much larger than in the other parts of the estuary; This is related by the dredging and disposal of muddy sediments in the navigation channels and tidal docks of the port of Antwerp-Bruges in this region. The disposal strategy in the shown periods, is characterised by disposal locations (OMES 11) up-estuary from the major dredging locations (OMES 9 and 10). The recirculation of this sediment comes clearly out of the calculated mud balance.

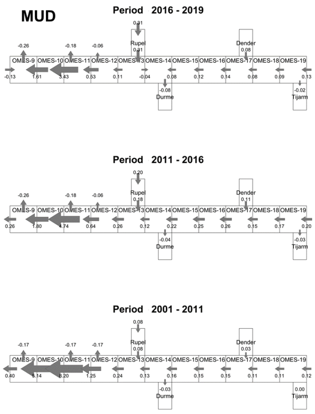

Figure 5. Mud balance for different periods (see figures 4 and 5 at the end of the paper)

4 CONCLUSIONS

Starting from different topo-bathymetric surveys, the sand and mud balance for the Flemish part of the Schelde-estuary was calculated. It was chosen to convert all data into masses in order to calculate a mass balance.

The sand balance shows an up-estuarine transport over the entire estuary. This can be explained by the importance of higher flow velocities in the sand transport, where the sand transport relates to velocity to the power 3 to 5 (eg. Engelund-Hansen formula). The Schelde-estuary is characterised by higher flood velocities, leading to a flood dominance in sand transport.

The mud transport has a different pattern, with a down-estuarine transport over most of the estuary. Only at the most downstream location, mud transport is up-estuarine. For mud transport the classic advection-diffusion equation is valid. The tidal asymmetry (increase of ebb period up-estuary) and the increasing importance of fresh water discharge up-estuary, will result in a more ebb-dominant transport.

Comparing different periods shows similar residual transport directions, although the magnitude varies between different periods. A possible explanation is the temporal variation of fresh water discharge in the Schelde-estuary. This will certainly have an effect on the mud transport, but seems to have an effect on the sand transport as well.

This analysis has shown the temporal and spatial variation in sand and mud transport is an instrument that can be used in future estuarine management.

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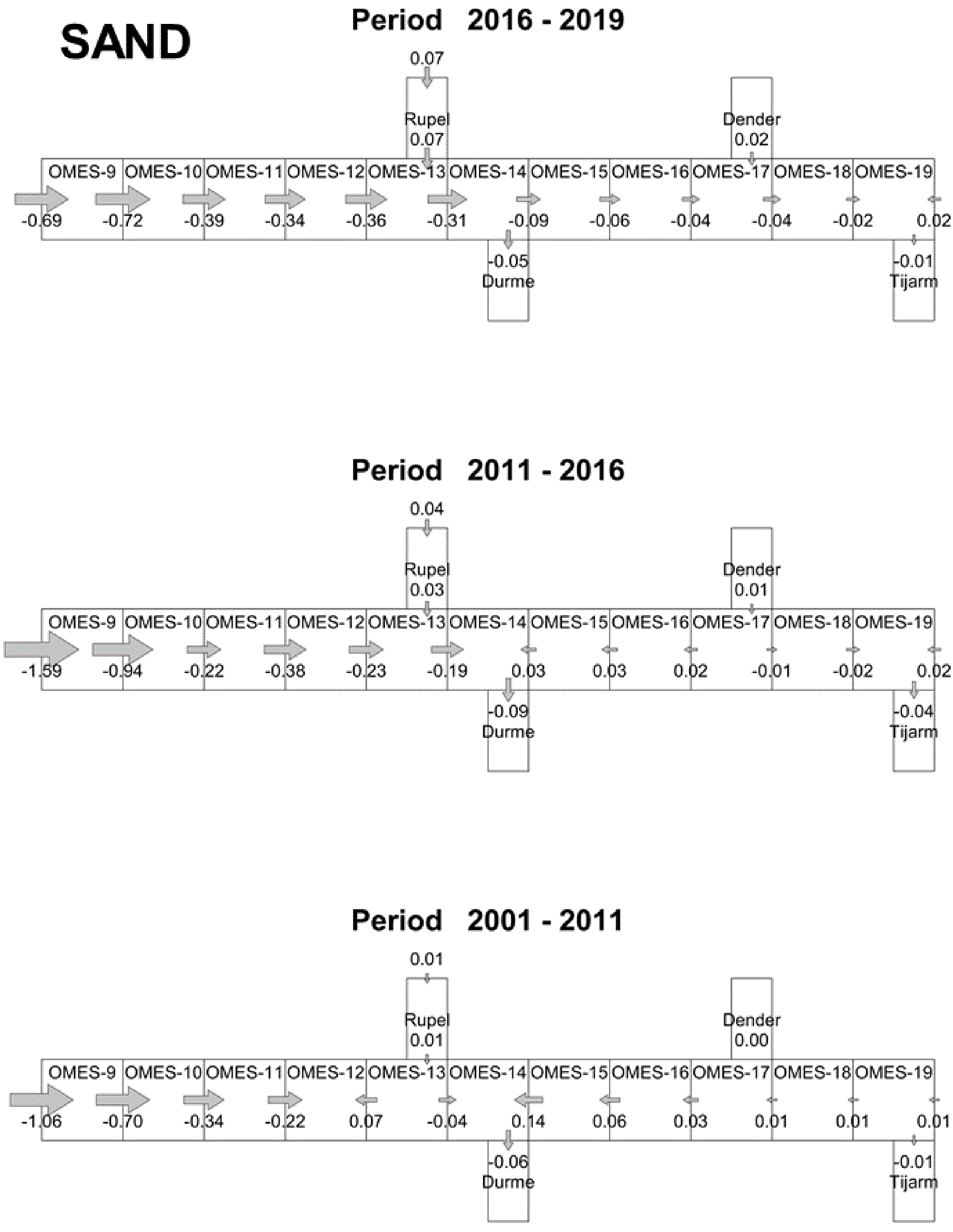

Figure 4. Sand balance for different periods

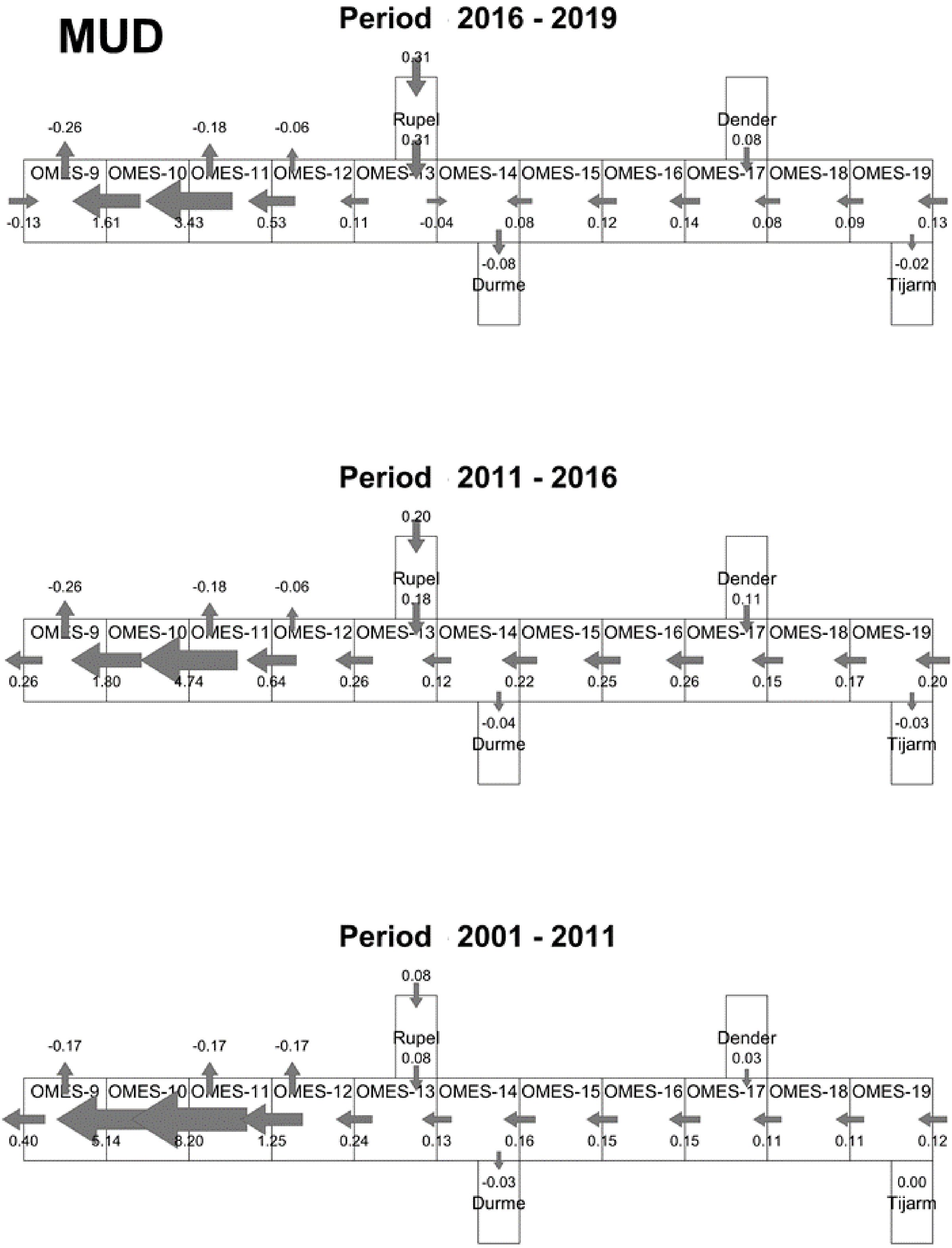

Figure 5. Mud balance for different periods