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The sand and mud budget of the Zeeschelde since the start of the 21^{st} century

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ABSTRACT

Purpose: Understanding trends in residual sediment transport is of great interest to target a sustainable morphological management of estuaries, addressing natural sediment transport, anthropogenic interference and climate change. To provide managers with additional information to optimize their sediment management strategy, a sand and mud budget has been derived for the Flemish part of the Belgian-Dutch Schelde estuary. The calculation of the budget was performed for three periods over the first 2 decades of the 21^{st} century.

Materials and methods: The sand and mud budget is calculated by combining information from topo-bathymetric surveys, ecotope maps and bed samples. Surveys provide spatial information on the volume changes over time, while ecotopes and bed samples were used to transform the volumes in quantities of sand and mud mass. For this budget, the estuary was divided in spatial segments of ~5 km, for which the residual sediment transport was calculated at both its down-estuarine and up-estuarine boundary. At the most up-estuarine boundary, measured sediment fluxes were used as the boundary condition.

Results and discussion: The residual sand transport was found to be up-estuary over a large part of the Zeeschelde. Temporal differences are rather small, while spatial patterns relate to the geometric characteristics of the estuary, as transports decrease up-estuary as also width and depth reduce. The residual mud transport was found to be down-estuary over almost the full Zeeschelde. Temporal and spatial differences are relatively small. Changes between sand and mud transport are explained by means of a 1D sediment transport model.

Conclusions: Variation of freshwater discharge was found as an explanation of the temporal variation in residual transport, both for sand and mud. The knowledge of processes controlling sediment budgets is crucial to optimize future sediment and morphological management of the estuary. These new insights, obtained from data-analysis, emphasize the importance of good data (especially topo-bathymetric data), and will allow the improvement of state-of-the-art numerical models, that can be used to improve our system understanding and optimize sediment management.

1. INTRODUCTION

Estuaries and coastal marine ecosystems are cited among the most productive biomes of the world, and also serve as important life-support systems for human beings (Costanza et al. 1997). Estuaries support many important ecosystem functions: mitigation of floods, maintenance of biodiversity and biological production, port accessibility, etc. Morphology plays a crucial role in facilitating these ecosystem services. Channel geometry and depth in combination with adjacent tidal flats will influence tidal propagation (Lanzoni and Seminara 1998; van Rijn 2011) and are important for safety against flooding, port accessibility and ecology (Meire et al., 2005; Smolders et al., 2015).

The morphology of an estuary is the result of the interaction between natural processes (e.g. geologic non-erodible layers, climate, hydro- and sediment dynamics) and human interference. Temporal and spatial variation in erosion and sedimentation leads to morphological changes. Therefore, knowledge of the sediment transport patterns and residual sediment budgets is crucial to get a better insight in the past, present and future evolution of estuaries. The understanding of the sediment transport becomes more important taking into account future challenges like sea level rise and changes in fresh water discharge (Oppenheimer et al. 2022). Changing hydrodynamic conditions will definitely impact the sediment transport and therefore the estuarine functions.

Where morphological changes are dominated by coarser sediments, finer sediments will be mainly transported in suspension. The impact on morphology of these finer sediments is rather limited, although in regions with low dynamic conditions, fine sediment can be deposited and impact the bed composition. Suspended sediment is dominated by finer grains (in estuaries mainly muddy (cohesive) sediment), which influence the light penetration in the water column and play an important role for ecology (Grobbelaar 1985; Cloern 1987). These sediments can be trapped in the estuarine turbidity maximum (ETM) resulting in very limited ecological functioning and even formation of a fluid mud layer at the bed (Abril et al. 2000; Jonge et al. 2014). The importance of sediment is also illustrated within the scope of the Water Framework Directive (WFD), as hydro-morphological parameters are considered to evaluate the status of the specific system (Lemm et al. 2021). Among these parameters, channel geometry, erosion/deposition character and flow are used to evaluate the status of river basins (Weiß et al. 2008).

Sediment budgets are regularly calculated in coastal, river and estuarine engineering and science studies to develop understanding of the sediment sources, sinks, transport pathways and magnitudes for a selected region of the river or coast and within a defined period of time (Bowen and Inman 1966; Patchineelam et al. 1999; Townend and Whitehead 2003; Frings and Ten Brinke 2018; Meire et al. 2021). Within the Elbe sediment management plan (IKSE 2014), the sediment balance is used as a parameter in the evaluation of the Elbe basin within the WFD. All these calculations are performed based on only one sediment class.

In riverine systems residual sediment transport for all sediment fractions is downstream orientated (Frings et al. 2019). However, in estuaries and coastal systems, characterized by tidal currents, residual sediment transports are not necessarily down-estuary. This was found in the origin of bed samples in the Schelde-estuary, as both sediment from marine and fluvial origin were found in the estuary (Wartel et al. 1993, 2004; Wartel and Chen 1998). A gradient exists along the estuary, as the marine contribution reduces more up-estuary. Furthermore, residual patterns may also differ between non-cohesive and cohesive fractions. Where most of the calculated sediment budgets do not make a difference between the non-cohesive and cohesive fraction (e.g. Vandebroek et al. 2017; Wang et al. 2018), making a distinction between the budget of cohesive and non-cohesive sediment is necessary to optimize the sediment management strategy, especially in estuaries where both types of sediment are present. Colina Alonso et al. (2024) focused on the behavior of the cohesive fraction (mud) in the Wadden Sea. With a limited supply, mud is a limited resource that requires adapted sediment management strategies, e.g. in order for tidal flats to keep growing under accelerated sea level rise.

Recently, Dam et al. (2022) demonstrated the differences by calculating both the mud and sand budget for the Westerschelde, the down-estuarine part of the Schelde-estuary (KM0 – KM55). Where they made use of a three-dimensional subsurface model (Stafleu et al. 2011), this paper presents an alternative method for calculating the mud and sand budget based on in situ bed samples. The method will be applied to the Zeeschelde, the most up-estuarine part of the Schelde-estuary (KM55 – KM155). The application of this method on the Westerschelde is not possible, as very little data is available on sand and mud content of bed samples in the Dutch part of the estuary.

2. STUDY SITE

The Schelde-estuary is a 180 km long macro-tidal estuary in Belgium (BE) and SW Netherlands (NL) (Fig. 1). A shallow mouth, the Vlakte van de Raan (KM -20 to KM 0 | NL), connects the estuary with the North Sea and has several deeper channels (Elias et al. 2017). The Westerschelde (KM 0 to KM 55 | NL) consists of a multiple channel system, with ebb and flood channels divided by intertidal sandbars. Further up-estuary, near the Dutch-Belgian border, the morphological system changes into a single channel system, the Zeeschelde (KM 55 to KM 155 | BE). Tributaries and side-branches include the Rupel (KM 92), Durme (KM 102) and Dender (KM 122) rivers.

The estuary is characterized by macrotidal semi-diurnal tides, creating ebb and flood currents which carry both cohesive (mud) and non-cohesive (sand) sediment loads (Baeyens et al. 1998). Along the estuary a gradient exists in median grain size of bed sediment, decreasing from medium sand (350 µm) down-estuary to very fine sand (100 µm) up-estuary (Van Eck 1999). Cohesive sediment is present in the water column along the estuary and can be found at intertidal areas (tidal flats and marshes).

Since the Middle Ages, human interference has influenced the water and sediment dynamics in the estuary. Poldering has reduced the area of the estuary over the last centuries (Van Den Berg and Jeuken 1996). Since the start of the 20th century, dredging works occurred to guarantee the accessibility to the different ports in the estuary (Plancke et al. 2006) of which the Port of Antwerp (KM 60-80) is the most important (Maes et al. 2022). Since 1970 the navigation channel has been enlarged three times (up to 131 dm tide-independent draught), while maintenance dredging works take place continuously, with an average dredging volume of ~10 $Mm^3\ y^{-1}$ (mainly sand) in the Westerschelde and ~4 $Mm^3\ y^{-1}$ (mostly mud) in the Zeeschelde (Nicolai et al. 2023). Since the 1950s sediment extraction has taken place, both for commercial purposes as for dyke construction works. In the Westerschelde more than 100 Mm^3 of sand have been extracted since the middle of the 20th century. Furthermore, since the start of 20th century human interventions have led to changes in the geometry of the estuary, straightening some parts of the estuary, constructing hard borders (eg. groynes and flow deflecting walls) and constructing tidal docks along the estuary.

All of these human interventions have influenced and still influence the tidal penetration in the estuary (Stark et al. 2017), leading to changes in hydrodynamics, geomorphology and ecology. Data analysis and model simulations (Vandenbruwaene et al. 2020) show that the increase in channel depth, due to sediment extraction and channel enlargement, results in an increase in tidal range. In addition, the increase in channel depth results in an increase of low water celerity, and thus a decrease in flood dominance and tidal asymmetry. On the other hand, historical poldering along the Schelde estuary has led to an increase in flood dominance and tidal asymmetry.

3. METHODS AND MATERIALS

3.1. Sediment budget – the concept

A sediment budget is the application of the conservation of sediment mass taking into account all sediment sources and sinks, within a series of specified control volumes "boxes", over a given time. The concept of the sediment budget and new considerations intended to make the sediment budget process more reliable, streamlined, and understandable were given in (Rosati 2005). Within this paper, an explicit distinction is made between the mud and sand budget. It was already mentioned that both fractions may have a different residual behavior, and this is explicitly investigated with this method. The distinction between sand and mud is made on the grain size, with the fraction having a grain size of 63 µm and coarser being sand, while the fraction finer than 63 µm being mud.

As with any accounting system, the algebraic difference between sediment sources and sinks in each cell, and therefore the entire sediment budget, must equal the rate of change in sediment mass occurring within that region, accounting for possible engineering activities. Expressed in terms of variables (rate of change of mass, in Tons Dry Weight [TDW] per year), the sediment budget equation is:

$$\Delta m_{box} = mf_{up} - mf_{down} + m_{disp} - m_{dredge} - m_{extrac} \quad (1)$$

With:

Δm_{box} change in sand or mud mass in a box over period of time [TDW y^{-1}];

mf_{up} sand or mud transport at the up-estuarine boundary over period of time [TDW y^{-1}];

mf_{down} sand or mud transport at the down-estuarine boundary over period of time [TDW y^{-1}];

m_{disp} mass of sand or mud disposed within the box over period of time [TDW y^{-1}];

m_{dredge} mass of sand or mud dredged within the box over period of time [TDW y^{-1}];

m_{extrac} mass of sand or mud extracted from the box over period of time [TDW y^{-1}].

For each box, all but one component are known, with the down-estuarine sediment flux being calculated from the known parameters. At the most up-estuarine box, the up-estuarine flux is known from the measurements. The calculated down-estuarine flux from this box will be equal to the up-estuarine flux for the next box. In this way a chain of boxes arises, for which the fluxes are calculated. For the Zeeschelde (Fig. 1), the spatial resolution ("boxes") was chosen equal to the segments used in the OMES-monitoring (Meire et al. 1997). These segments have a length varying between 6 and 12 km.

3.2.Sediment budget – mud-sand composition

Dam et al. (2022) used a spatial map with lithoclasses (sand, gravel, clay or peat) in order to make a distinction between sand and mud. In our method, we opt to make use of grain size distribution characteristics from more than 1500 bottom samples which were taken within the MONEOS-program (Plancke et al. 2012) and additional campaigns in the period 2001-2019. The samples are taken in an annual monitoring campaign throughout the Zeeschelde. Samples are collected over different [deep/moderate deep/undeep subtidal, intertidal, supratidal, anthropogenic subtidal, anthropogenic intertidal] ecotopes (Van Ryckegem et al. 2020). These ecotopes are defined by combining different abiotic aspects of each point, among which the depth and hydrodynamics (Bouma et al. 2005). Previous studies (Dolch and Hass 2008; Vandenbruwaene et al. 2017) have illustrated the spatial differences of bed composition in water systems in relation to the ecotope classes. From the grain size analysis, among others, the relative mud (< 63 µm) and sand (63 - 2000 µm) contribution in the bed is derived. A GIS-analysis was performed assigning each sample to a box (along the estuary) and ecotope-class (over the vertical). Based on this classification of the samples, characteristics of the bed (sand and mud content) belonging to a combination of one box and ecotope were derived. For this family of samples the median value (P50) of the mud and sand content was determined. Additionally P10 and P90 values were calculated to perform a sensitivity analysis on this parameter.

3.3.Data

The most important datasets in order to calculate a sediment budget are topo-bathymetric surveys from two different moments. Within the MONEOS-program, an annual survey of Beneden-Zeeschelde (KM55- KM90) is foreseen, while for the Boven-Zeeschelde (KM90 - KM155) a survey is performed every 3 years. Bathymetric surveys (subtidal part) are performed using a multi-beam echo sounder (MBES). Topographic information of inter- and supratidal parts are collected using LiDAR. The subtidal (MBES) and intertidal (LiDAR) dataset overlap in the lower intertidal parts. They are combined in one spatial grid, using the MBES-data as the starting point and adding data in the missing intertidal part from the LiDAR-data. The combined topo-bathymetric grids of the full Zeeschelde have a spatial resolution of 1 x 1 m. Since 2000, 4 different years (2001, 2011, 2016 and 2019) were available, allowing the calculation of the sand and mud balance over 3 periods (2001-2011, 2011-2016 and 2016-2019). It can be noted that the timespan of these 3 periods are different, therefore calculated budgets will be expressed [TDW y^{-1}].

The sand and mud balance requires information at the most up-estuarine boundary. In contrast to other sediment budgets for different subparts of the Schelde-estuary (Nederbragt and Liek 2004; Haecon 2006; Schrijver 2020; Dam et al. 2022) where an assumption is used at the up-estuarine boundary, measurements are used to calculate the influx of fluvial sediment at the up-estuarine boundary. To calculate the fluvial sediment import, measurements of discharge (acoustic device) and sediment concentration (direct sampling and/or turbidity measurements) at the up-estuarine boundary of the Zeeschelde and its tributaries are used. High-frequent (every 15 minutes) calculation of the sediment fluxes at the up-estuarine boundaries (in total 6 tributaries) are made, which are integrated over the time period of the sediment budget.

Besides these natural processes, human interventions – sediment extraction, dredging and relocation – are taken into account. 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 (Ides and Plancke 2013). 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 to the required spatial scale of the boxes. When a dredging/disposal/extraction location is located in 2 adjacent boxes, the total mass was divided over the boxes proportionally with the overlap of the surface of the location within the boxes.

3.4.Sediment budget – volume to mass conversion

To calculate the sediment budget, different data sources are needed. Sometimes, these data are available in volumetric units (eg. changes in topo-bathymetry, dredging/disposal information). Other data (eg. fluvial sediment import, dredging/disposal information) are available in gravimetric units. As it was decided to set up the sediment budget as a mass balance, a conversion of volumes to mass is necessary. In order to make this conversion, an estimate of the in-situ porosity is needed. Previous studies have indicated that porosity not only changes with median grain size, but is influenced by the composition of the sediment mixture (Beard and Weyl 1973; Koltermann and Gorelick 1995). The fractional packing model from Koltermann and Gorelick (1995) is used here to calculate the porosity for each ecotope, depending on its average sand-mud-content (Fig. 4):

$$\text{If } \varphi_v < 0.4: \quad \phi_{mix} = \phi_{Sd} - \varphi_v \,.\, \varphi_m^{-1} \,.\, (\phi_{Sd} - \phi_m) \tag{2}$$

$$\text{If } \varphi_v \geq 0.4: \quad \phi_{mix} = \phi_m + (\varphi_v - \varphi_m) \,.\, (1 - \varphi_m)^{-1} \,.\, (\phi_{Sh} - \phi_m) \tag{3}$$

With φ_v being the relative mud fraction of volume concentration [-], ϕ_{mix}, ϕ_{Sd} and ϕ_{Sh} respectively the porosity of the mixture, pure sand and pure mud [-] and ϕ_m the minimum porosity occurring for mud fraction equal to 40% [-]. Porosity of pure sand was selected equal to 0.4, after in situ measurements (Curry et al. 2004). The porosity of pure mud, which is found rather at intertidal habitats, was selected equal to 0.8. This matches a dry bulk density of 530 kg m^{-3} which was found representative for tidal flats in the Schelde-estuary (Temmerman et al. 2004).

Applying the porosity in combination with the sand-mud composition, it is possible to convert volumes [m³] into masses [TDW]. For the sediment density (ρ_{sand} and ρ_{mud}), a fixed value of 2.65 t m^{-3} was taken.

$$m_{sand} = \rho_{sand} \,.\, \phi_{mix} \,.\, (1 - \varphi_v) \,.\, V_{tot} \tag{4}$$

$$m_{mud} = \rho_{mud} \,.\, \phi_{mix} \,.\, \varphi_v \,.\, V_{tot} \tag{5}$$

A sensitivity analysis was performed on the importance of (1) the mud and sand content in this conversion method and (2) fractional packing model versus a fixed porosity.

4. RESULTS

4.1. Sand-mud composition

Within the sediment budget, the sand-mud-content was determined for all 7 different ecotopes (Fig. 3). As not all ecotopes have the same total surface, differences occur in the available number of bed samples (Table 1). For the Zeeschelde, most samples (~850 each) were available at the deep and moderate deep subtidal areas, followed by the tidal flats (~720 samples). The anthropogenic area, mainly access channels to locks and tidal docks, cover the smallest part of the estuary, and the number of available samples was limited to ~175.

It was found that subtidal ecotopes are characterized by the largest sand content, with P50 -values ranging from 80 to 90% for the deep and moderate deep ecotopes, to 58% for the undeep subtidal ecotopes (Fig. 5). Anthropogenic ecotopes consist mainly of low-current areas and are characterized by a smaller sand content (P50 ~ 30 to 45%). Intertidal ecotopes are also dominated by muddy sediments, with a sand content (again P50-values) of 51% for tidal flats and 41% for tidal marshes.

4.2. Topo-bathymetric changes

Figure 6 presents the changes in mass (both sand and mud) for each box and ecotope-class, for the last two periods. As the estuary has a funnel shape, channel dimensions decrease up-estuary (eg. width reduces from ~1500 m near the border to ~50 m at the up-estuarine border (Vandenbruwaene and Plancke 2013)), resulting in smaller absolute changes.

The largest changes in sand mass occur in the deep subtidal. This can be explained by (1) the fact that this ecotope covers the largest area of the estuary and (2) the high sand content in this ecotope. The down-estuarine boxes (box 9 – 11) have an erosive character in both periods, while more up-estuary the changes are more variable.

The changes in mud mass have a similar pattern, as they are also derived from the same topo-bathymetric changes. However, more up-estuary changes in mud mass are dominated by the intertidal ecotopes. For most boxes intertidal ecotopes function as a sink for muddy sediment, emphasizing the important role of tidal flats and marshes as accommodation space for finer sediments.

4.3.Sand balance

The sand balance for all periods is presented in Fig. 7. It 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 (Fig. 4). The location where the residual transport changes from down- to up-estuarine transport, moves progressively more down-estuary when going back in time.

In general, (residual) sand transport rates decrease more up-estuary, which is related to the funnel shape of the estuary and the channel dimensions that decrease from the down-estuarine part of the Zeeschelde towards the up-estuarine boundary. The residual sand transport in the Beneden-Zeeschelde (box 9 – 13) has a smaller reduction (0.69 to 0.31 TDW y^{-1}) of the up-estuarine transport over the last period, compared to previous periods (1.59 to 0.19 TDW y^{-1} and 1.06 tot 0.04 TDW y^{-1}).

Tributaries without freshwater discharge (Durme and Tijarm) import sand over all periods. The Rupel-tributary, which has a continuous influx of fresh water, is characterized by a net sand export.

4.4.Mud balance

The mud balance for all periods is shown in Fig. 8. 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 up-estuary. The Durme and Tijarm tributaries are characterized by an influx of mud, while the Rupel tributary exports mud, identical to the behavior of sand transport.

In contrast to sand transport, the mud transport rates remain similar along the estuary. Exception is the most down-estuarine part of the Zeeschelde, where the residual mud transport is much larger than in the other parts of the estuary. This is related to 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 that is applied in this area, uses disposal locations (box 11) up-estuary from the major dredging locations (box 9 and 10). The recirculation of this sediment is shown clearly by the calculated mud balance.

4.5.Sensitivity analysis

Extensive results of the sensitivity analysis can be found in Plancke et al. (2023) and Vos et al. (2023), and are not shown in this paper. A first topic that was investigated was the impact of the spatial variation of the sand and mud content. The analysis shows important differences per ecotope, while the spatial variation over the different boxes was less pronounced. Therefore it was decided to apply a different value of the sand and mud content per ecotope-class only, not varying the values per box.

A second aspect that was analyzed, was the effect of the sand and mud content on the sediment budget. Changing the sand and mud content from the median (P50) value to the lower (P10) and upper (P90) extremes, did not alter the residual sediment transport in the sand and mud budget significantly. An effect is visible, but other factors seem to be dominant in the temporal variation of the sediment budget.

Finally the effect of the porosity on the sediment budget was studied. Therefore the fractional packing model was compared with a fixed porosity (n = 0.5) model. In general the influence was rather limited, although once the mud content is dominant, differences in mud mass increase. This is explained by the larger differences that arise for higher mud content: for 100% mud, porosity will be 0.8 in the fractional packing model, while only 0.5 in the fixed model. The fractional packing model was used in the results presented here.

5. DISCUSSION

The sand and mud balance for the Flemish part of the Schelde-estuary demonstrate a different behavior in residual transport of both types of sediments: residual sand transport is mainly up-estuarine, while the residual mud transport is largely down-estuarine. In order to understand this different behavior, the general advection-diffusion equation, used to describe the sediment transport, is analyzed.

The general formula was reduced in its 1D-form, allowing the analysis of differences between mud and sand, and estimating the contribution of the different processes. Therefore the tidal flow and the sediment concentration was simplified to its major tidal components (M2 and M4), which was also applied in de Swart and Zimmerman (2009). Solving this equation results in different terms of which only the leading and first order are considered in this analysis. The leading order concentration C0(x,t) is found to contain only M0 (residual) and M4 tidal components. The first order concentration C1(x,t) contains M2 and M6 tidal constituents, the latter of which will be ignored hereafter as it does not contribute to net sediment transport. As leading order flow and sediment contain different tidal components, they do not contribute to tidally averaged sediment transport. The dominant contribution to the net sediment transport F comes from products of leading order and first order flow and sediment. It is found that the net total (sand + mud) sediment transport per unit width F is given by:

$$F = \frac{\alpha}{2\gamma}U_2^2 U_0 \frac{3+a^2}{1+a^2} + \frac{3\alpha}{4\gamma}U_2^2 U_4\, f(a)(1+3a^2)\cos\Delta\phi - \frac{3\alpha}{2\gamma}U_2^2 U_4\, f(a)a^3 \sin\Delta\phi - \frac{9\alpha}{8\gamma\omega}U_2^3 \frac{dU_2}{dx} a f(a)(1+2a^2) \qquad (6)$$

In this formula α is an erosion parameter, γ the deposition parameter (related to the settling velocity), ω the angular velocity, U0 the residual velocity related to river flow, U2 and U4 the M2 and M4 tidal components of the velocity respectively, Δϕ the phase difference between M4 and 2.M2 and a and f(a) parameters depending on γ.

In this equation the first term (black) is the transport due to river contribution (always ebb dominated). The second term (red) covers the transport due to velocity amplitude asymmetry. It will be dominant for coarse sediment. The third term (blue) represents the tidal duration asymmetry and is more relevant for fine sediment. The last term (green) is related to the spatial settling lag. This requires no overtides but a spatially varying M2 velocity. This is also more relevant for fine sediment.

In order to calculate the net sediment transport, both tidal velocity (U0, U2, U4) and sediment characteristics (settling velocity and erosion parameter) are required. Tidal velocity components were derived - using U-Tide (Codiga 2011) - from modelled velocities over the total length of the Schelde-estuary. The model which was used is a MIKE-11 model for the Schelde-estuary which is used for water level predictions, and is validated for water levels and discharges (Coen et al. 2018).

The U0-component varies with varying freshwater discharge and is dominant in the first term. The M2 - component of tidal velocity (80±20 cm s^{-1}) is almost one order of magnitude larger than the M4 - component (15±5 cm s^{-1}) for most of the estuary (box 9 to box 16), while in the most up-estuarine part (box 17 – box 19) this difference reduces to factor 2. To calculate the residual sediment transport for both sand and mud, a different settling velocity, based on Stokes' Law (Stokes 1851), was applied: 10 mm s^{-1} for sand (D50 ~ 100 µm) and 0.1 mm s^{-1} for mud (D50 ~ 10 µm). These median grain sizes are representative for the sand and mud in the Schelde-estuary (Vos et al. 2011; Plancke et al. 2018).

Applying these values in the above formula allows for the calculation of the net sediment transport. The residual sand and mud transport was calculated for different freshwater discharges. First, the transports were calculated for the median (P50) freshwater discharge over the period 2011-2019. Additionally, an estimation was made for the residual transport occurring at low (P5) and high (P95) discharges (Table 2).

The residual sand transport for mean freshwater discharge is flood-dominant along the estuary. Only the most up-estuarine station (box 19) is found to have an ebb-dominant sand transport. At the most up-estuarine station, the river flow (first term) becomes dominant, resulting in ebb-dominant sand transport. More downstream, the second term in equation 6 becomes dominant, yielding flood-dominant sand transport in most of the Sea Scheldt. This pattern is in agreement with findings in other systems which are characterized by limited freshwater discharge. Sea arms like the Zwin (Bowman 1993), or inner seas like the Wadden Sea (Elias et al. 2012) have been characterized by long-term sedimentation due to flood-dominated sediment transport from the sea. However, the importance of local geometrics and hydrodynamic conditions, should be emphasized (Brouwer et al. 2018; Boelens et al. 2018). In periods with low (P5) freshwater discharge, the sand transport becomes flood-dominant over the entire estuary. In periods with high (P95) freshwater discharge, the sand transport becomes ebb-dominant over a larger part of the estuary (up-estuary, box 16 – box 19).

The residual mud transport is ebb-dominant along the entire estuary for mean and high freshwater discharge. This is related to the dominance of the river flow, which is captured by the first term in equation 6. For low freshwater discharge (P5), the net mud transport becomes flood dominant at the down-estuarine part of the Zeeschelde (box 9). This is due to the increased relative importance of the spatial settling lag (last term of equation 6). It should be noted that a distinction should be made between the residual mud transport on the longer timescale (years) as was calculated from the mud budget, and the behavior on the shorter (seasonal) timescale, which is characterized by the spatial variation of the position of the ETM (Kappenberg and Grabemann 2001; Talke et al. 2009; Burchard et al. 2018).

Transport of sand and mud in the past centuries has been influenced by “natural” evolutions in hydrodynamic boundary conditions, eg. sea level rise (Khojasteh et al. 2021) or changes in fresh water discharge (Monbaliu et al. 2014; Kreibich et al. 2019). Over the last decades, the Schelde-estuary has been exposed to longer periods with very low fresh water discharge (De Sutter *et al.*, 2011; Plancke *et al.*, 2023a). For the last two periods over which the sand and mud budget was calculated, median (P50) freshwater discharge were lower over the last period: 10.6 $m^3 s^{-1}$ (2016-2019) vs. 20.8 $m^3 s^{-1}$ (2011-2016). Also the lowest values (P5) decreased significantly: 0.6 $m^3 s^{-1}$ (2016-2019) vs 3.0 $m^3 s^{-1}$ (2011-2016). This difference in freshwater discharge can be an explanation for the larger flood-dominance for both sand and mud transport in the most recent period. Future evolutions in freshwater discharge (more extreme droughts and floods) due to climate change, can affect the residual sand and mud transport

6. CONCLUSIONS

Topo-bathymetric surveys were combined with ecotope maps and sand-mud fraction from a large number of bed samples, to calculate the sand and mud budget for the Flemish part of the Schelde-estuary. Different ecotopes showed important differences in bed sediment composition, with deep subtidal habitats being predominantly sandy, while intertidal habitats having a much more balanced sand-mud composition. Where cohesive (mud) and non-cohesive (sand) sediment are characterized by a different behavior in sediment transport, a method was developed to divide the total sediment budget in the mud and the sand budget. Over the period 2001-2019, the budgets were derived for three different periods, starting from the available surveys of the estuary.

The residual sand transport was found to be up-estuary over a large part of the Zeeschelde. This pattern can be explained by the importance of the velocity amplitude asymmetry in the total transport, as this term is dominant over the other contributions for transport of coarse sediments (sand). Differences over the three periods are relatively small, showing variation in magnitude of the calculated transports, but without major shifts in the residual transport direction.

The residual mud transport was found to be down-estuary over almost the full Zeeschelde. This pattern can be explained by the importance of the river contribution in the total sediment transport, as this term is dominant over the other contributions for mud transport. Differences over the three periods are relatively small. Dredging and relocation works have a large contribution in the mud budget, as the present strategy relocates the dredged material (mud) up-estuary from the dredging location, working against the natural transport direction.

This analysis has shown and (partially) explained the temporal and spatial variation in sand and mud transport. This knowledge of processes controlling sediment budgets is crucial in order to optimize future sediment and morphological management of the estuary (Port of Antwerp Authority 2012). In order to optimize future management, both expertise, monitoring and numerical and physical scale modelling will play an important role (Peters et al. 2006).

7. AKNOWLEDGEMENT

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9. FIGURES

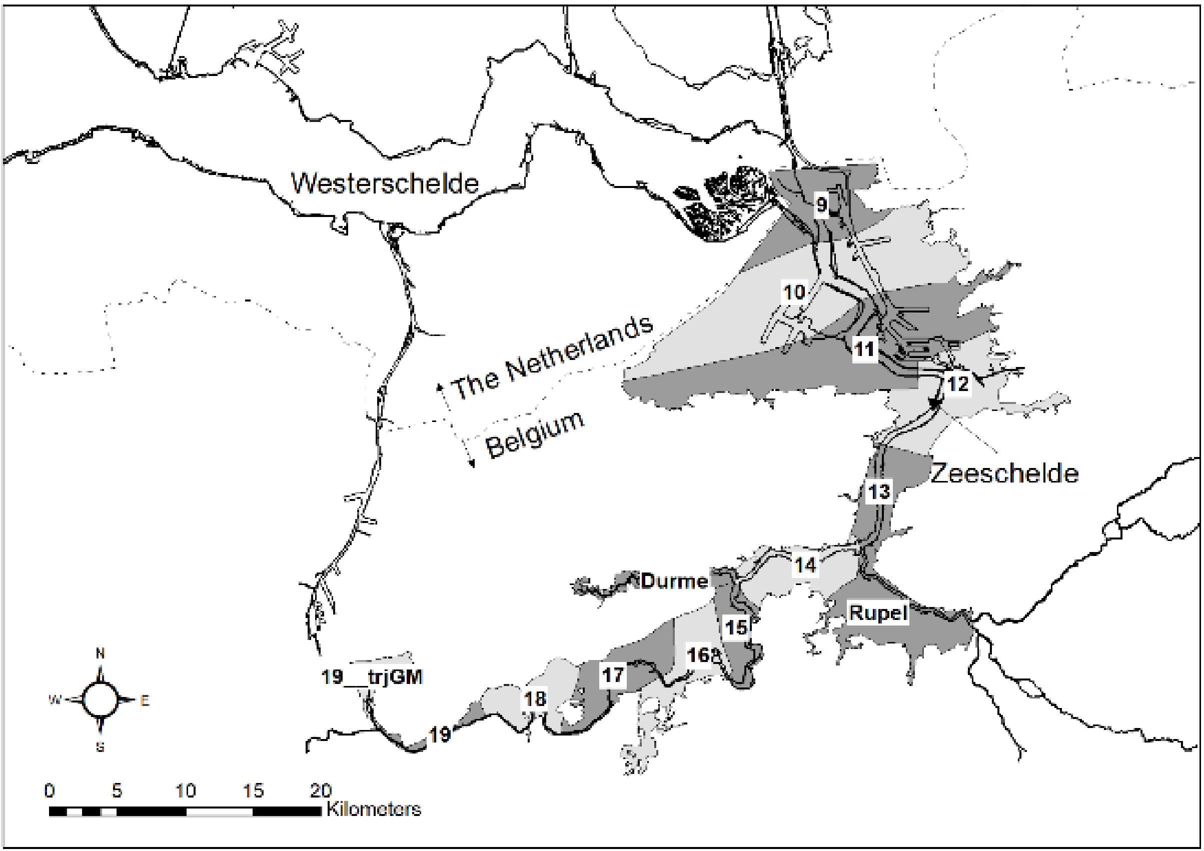


Figure 1 – Schelde-estuary with boxes used for sediment budget calculation in Zeeschelde

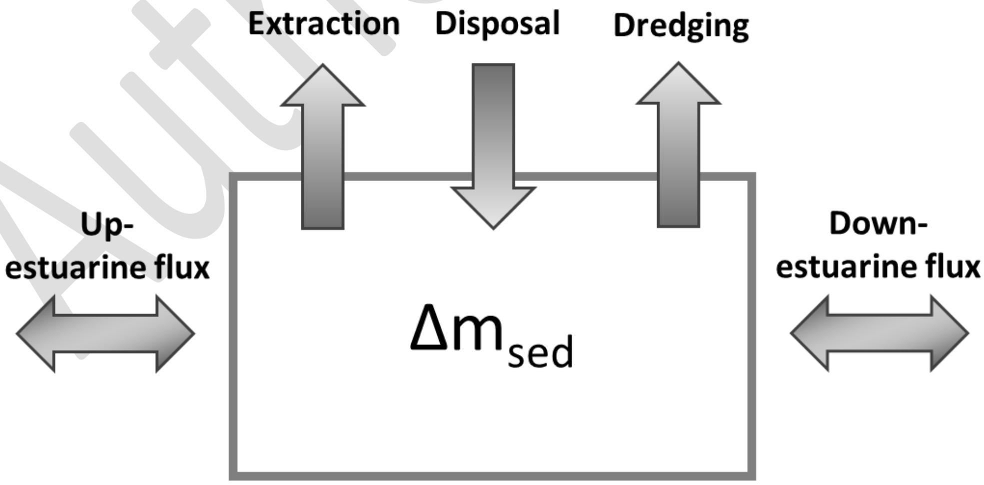


Figure 2 – Concept of sediment budget

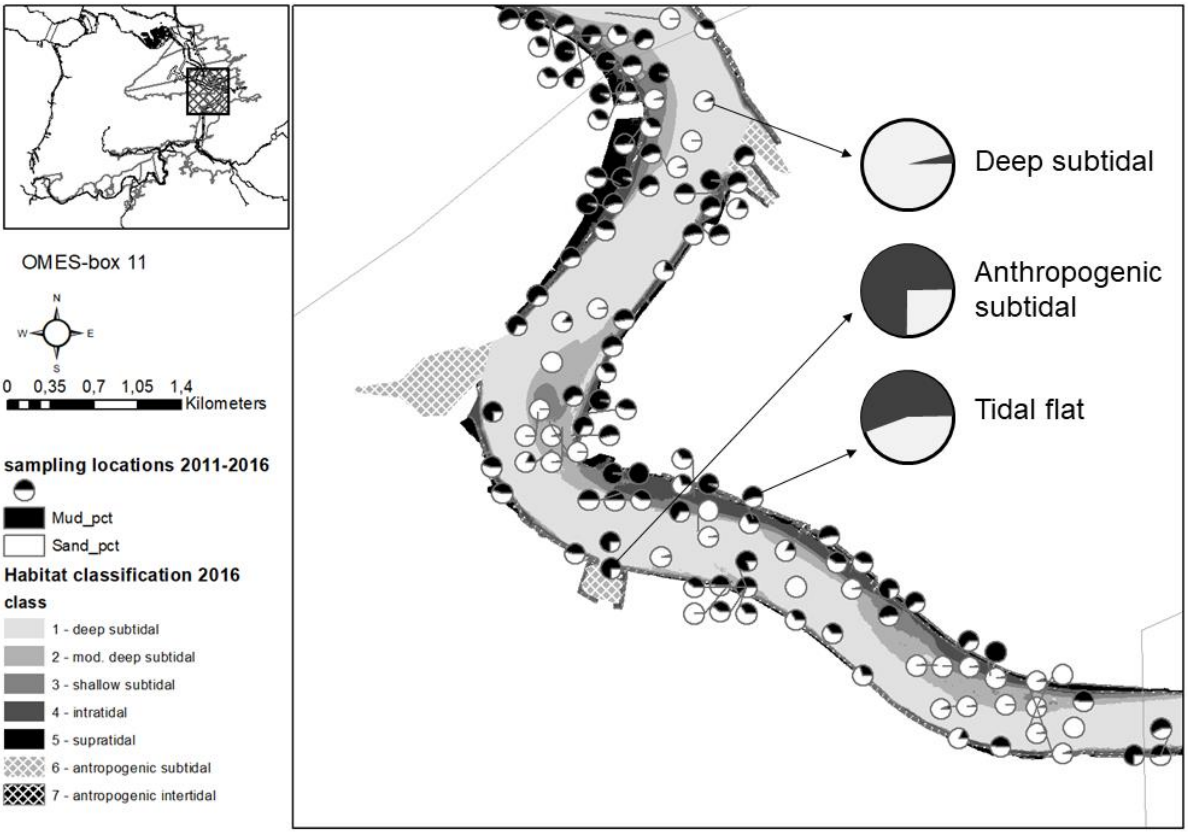


Figure 3 –Ecotope map for box 11; habitats are shown using different hatching/color per type; pie-chart show sand-mud-fraction from bed samples for all available locations in this box; for 3 points a detailed presentations is shown, indicating the difference in sediment composition between different habitats

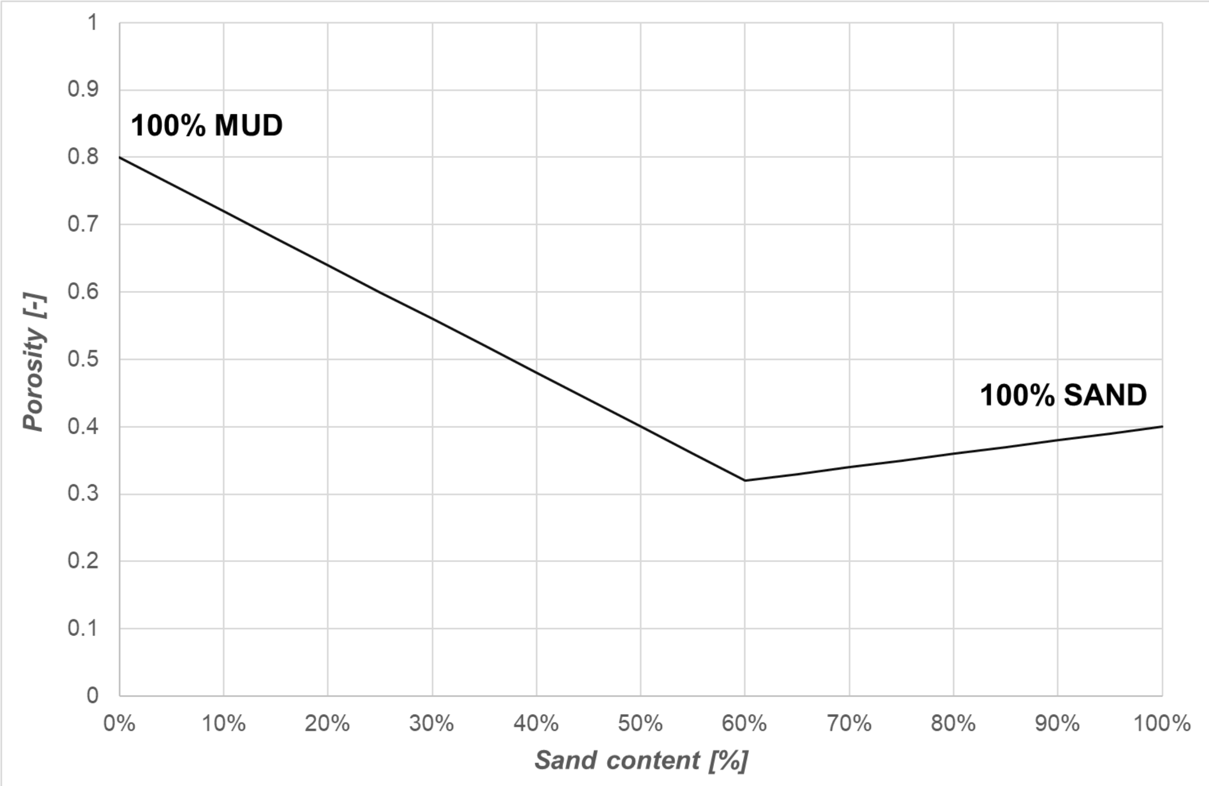


Figure 4 – Fractional packing model (after (Koltermann and Gorelick 1995)*)*

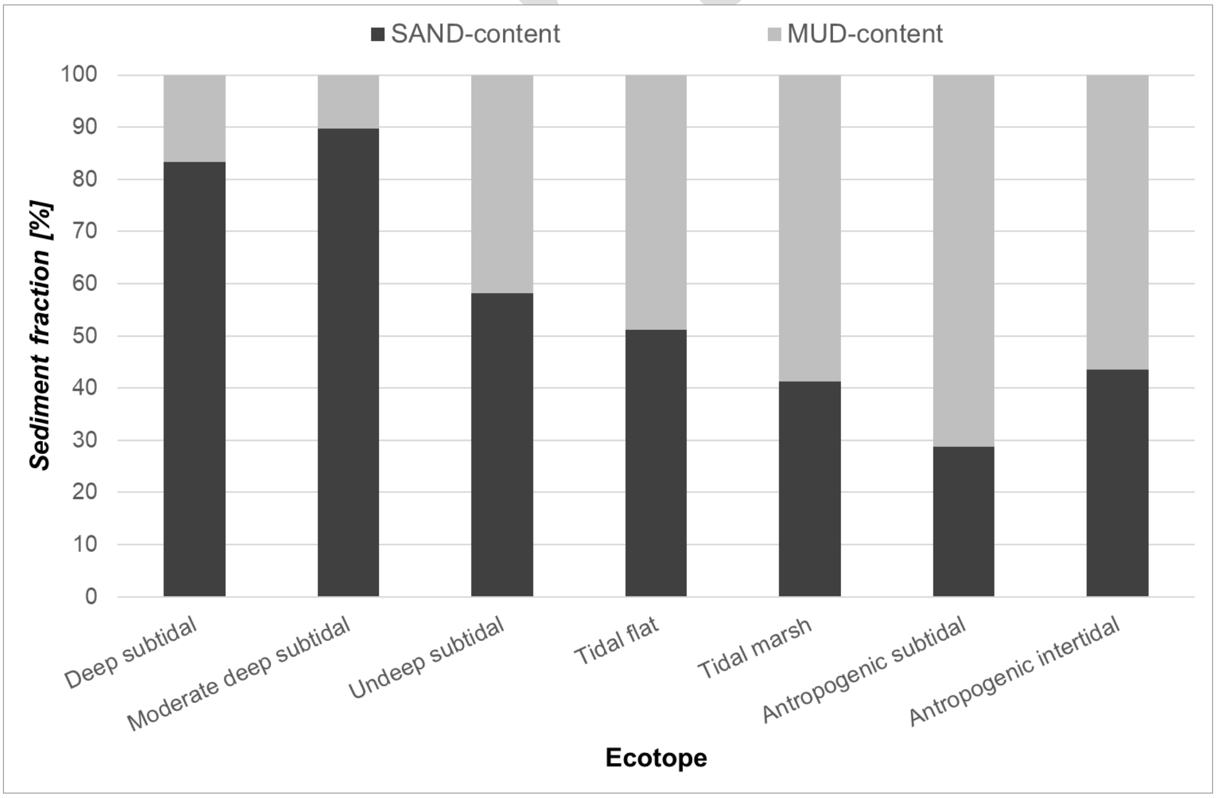
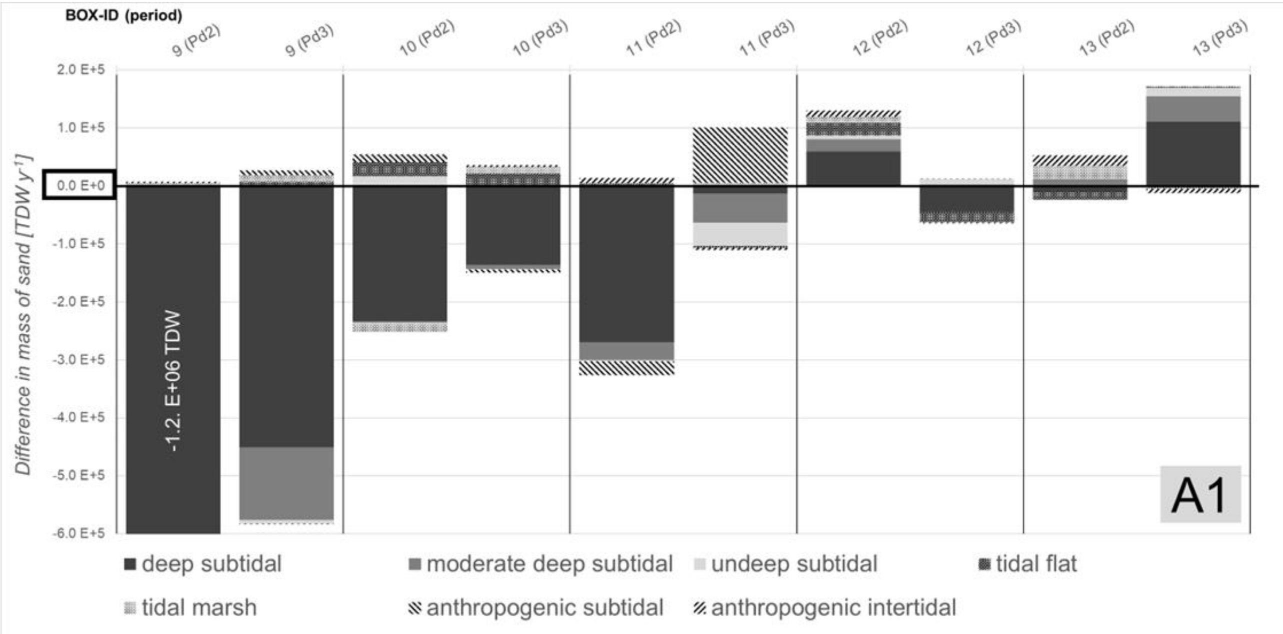
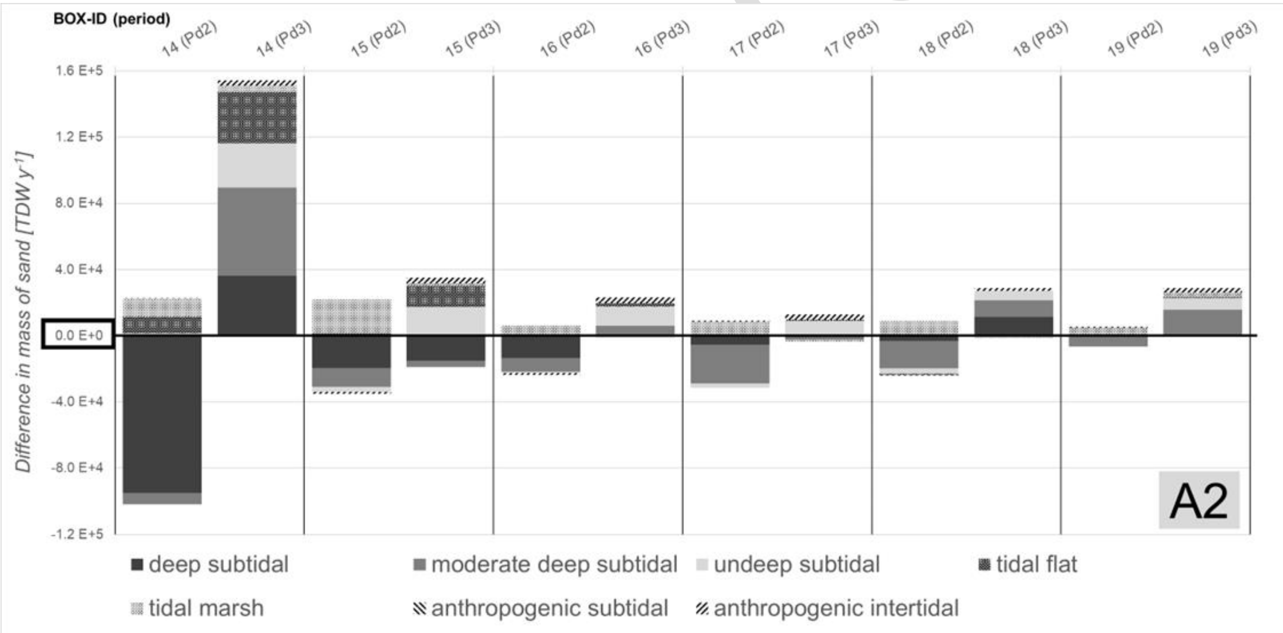


Figure 5 – Sand-mud content for different ecotopes (median (P50) values)


BOX-ID (period)
9 (Pd2)
9 (Pd3)
10 (Pd2)
10 (Pd3)
11 (Pd2)
11 (Pd3)
12 (Pd2)
12 (Pd3)
13 (Pd2)
13 (Pd3)
2.0 E+5
1.0 E+5
0.0 E+0
-1.0 E+5
-2.0 E+5
-3.0 E+5
-4.0 E+5
-5.0 E+5
-6.0 E+5
Difference in mass of sand [TDW y-1]
-1.2. E+06 TDW
A1
deep subtidal
moderate deep subtidal
undeep subtidal
tidal flat
tidal marsh
anthropogenic subtidal
anthropogenic intertidal


BOX-ID (period)
14 (Pd2)
14 (Pd3)
15 (Pd2)
15 (Pd3)
16 (Pd2)
16 (Pd3)
17 (Pd2)
17 (Pd3)
18 (Pd2)
18 (Pd3)
19 (Pd2)
19 (Pd3)
1.6 E+5
1.2 E+5
8.0 E+4
4.0 E+4
0.0 E+0
-4.0 E+4
-8.0 E+4
-1.2 E+5
Difference in mass of sand [TDW y-1]
A2
deep subtidal
moderate deep subtidal
undeep subtidal
tidal flat
tidal marsh
anthropogenic subtidal
anthropogenic intertidal

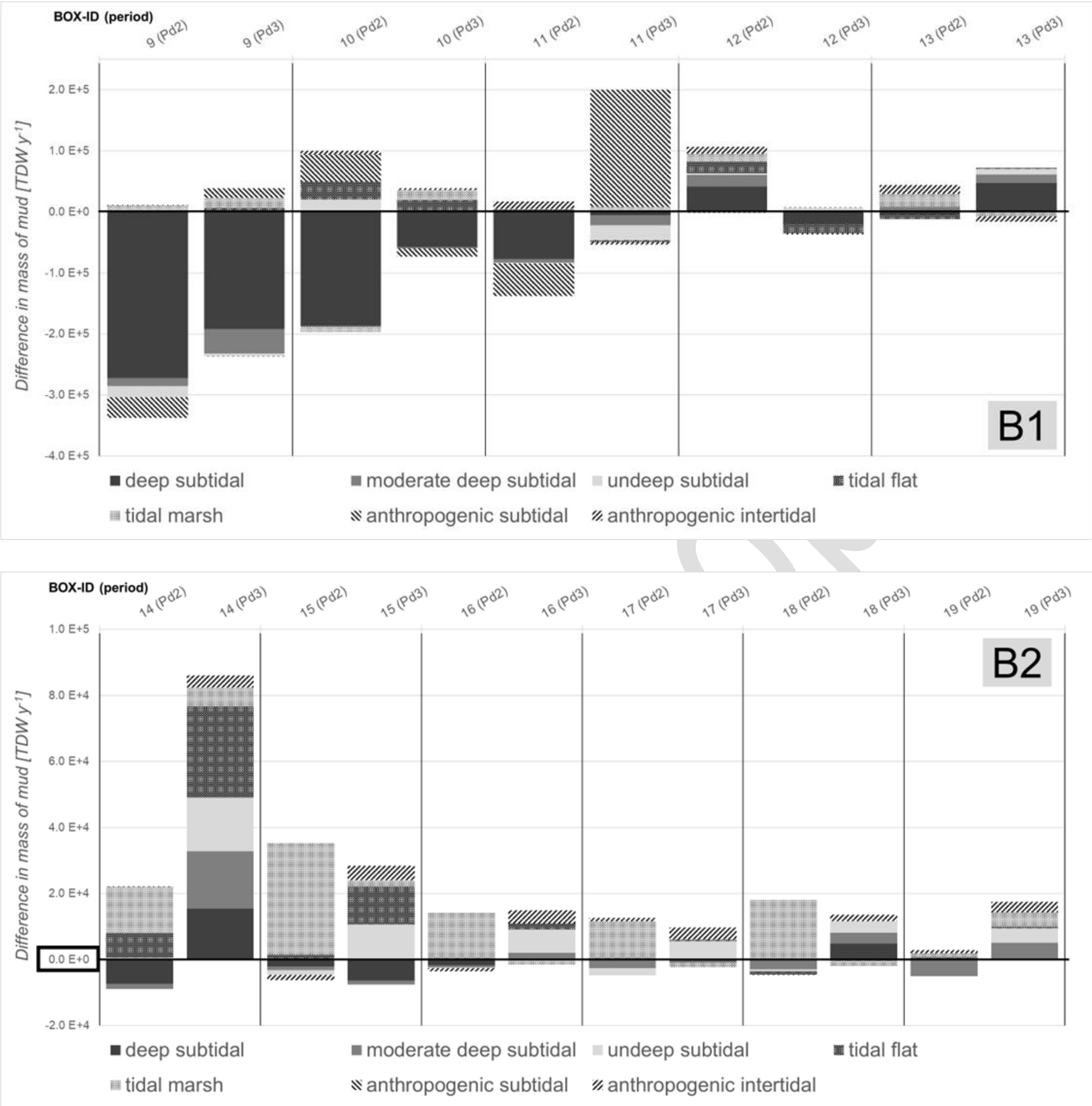


Figure 6 – Topo-bathymetric mass changes for sand-fraction (top A1-A2) and mud-fraction (below B1-B2) per OMES-box (A1, B1 most down-estuarine boxes | A2, B2 most up-estuarine boxes) and for different habitats (different hatching) for period 2 (Pd2, 2011-2016) and period 3 (Pd3, 2016-2019)

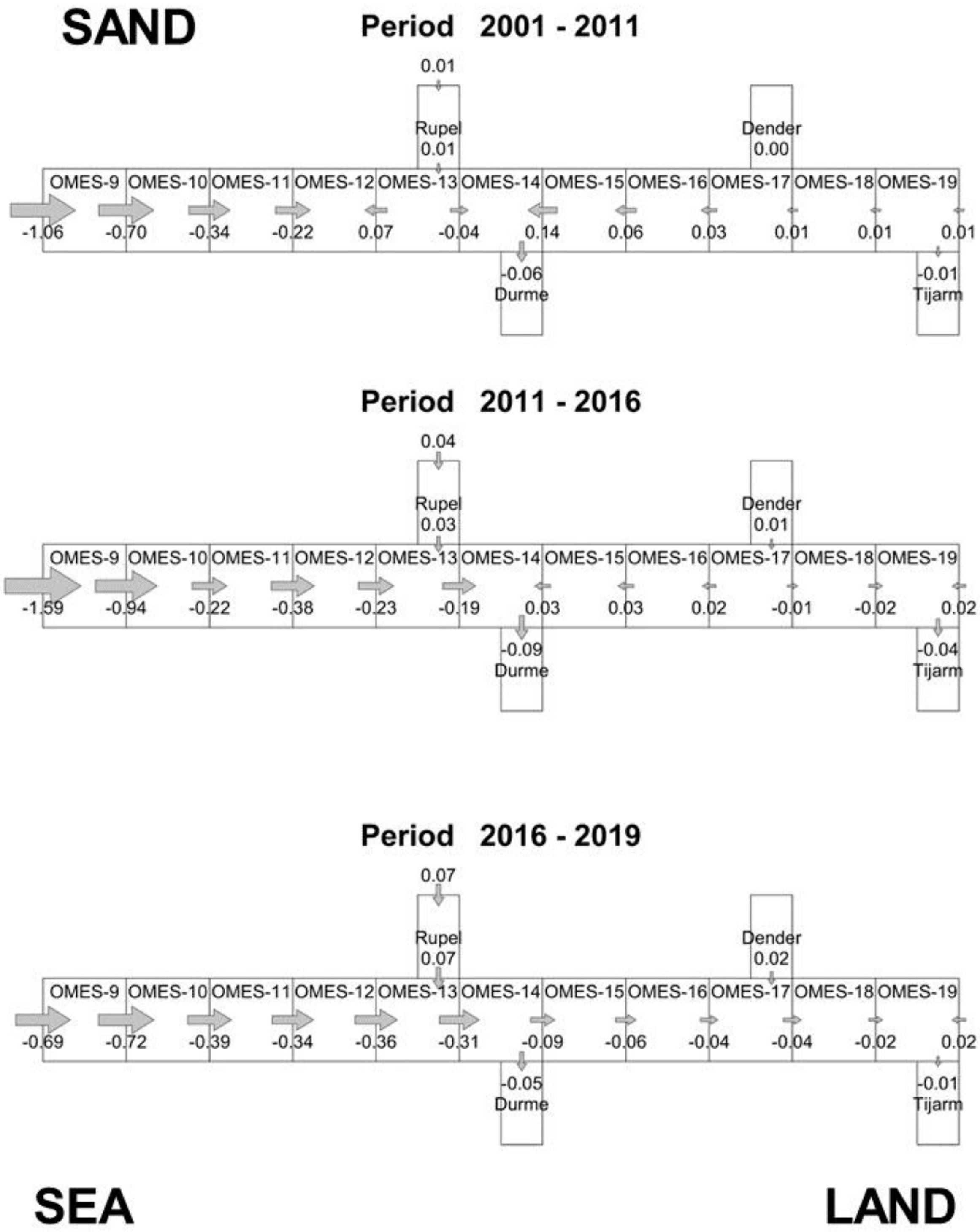


Figure 7 – Sand budget for Zeeschelde for all periods, expressed as a yearly mass flux [TDW yr^{-1}]. Left-facing arrows and positive values indicate down-estuarine transport. Right-facing arrows and negative values indicate up-estuarine transport.

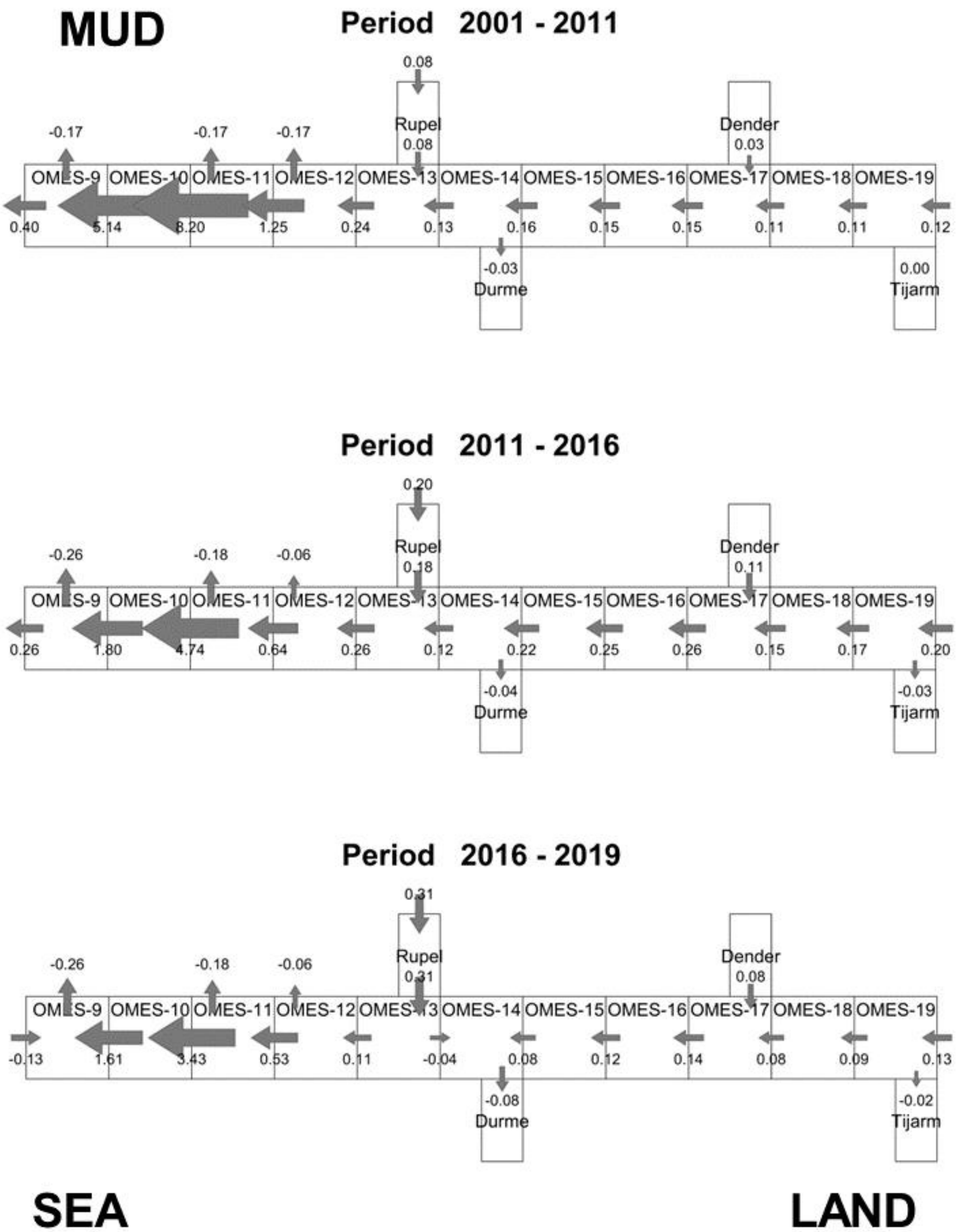


Figure 8 – Mud budget for Zeeschelde for all periods, expressed as a yearly mass flux [TDW yr^{-1}]. Left-facing arrows and positive values indicate down-estuarine transport. Right-facing arrows and negative values indicate up-estuarine transport.

10. TABLES

Table 1: Overview of sediment samples and sand content for different ecotope types

Ecotope class	***# samples***	***Sand content***		
		P10 [%]	***P50 [%]***	***P90 [%]***
Deep subtidal	859	25.8	83.3	97.1
Moderate deep subtidal	853	32.4	89.7	97.7
Undeep subtidal	381	27.1	58.2	97.1
Tidal flat	720	23.6	51.2	87.9
Tidal marsh	150	22.3	41.3	57.3
Antropogenic subtidal	24	20.2	28.7	50.6
Antropogenic intertidal	148	26.4	43.5	68.5

Table 2: Overview ebb/flood dominance based on the 1D advection-diffusion equation for different boxes and variation in freshwater discharge (between brackets is the term (T) from equation 6 that becomes dominant)

Fresh Water Discharge	**Sediment**	**Box 9**	**Box 14**	**Box 16**	**Box 19**
Mean (P50)	Sand	***Flood (T2)***	***Flood (T2)***	***Flood (T2)***	Ebb (T1)
	Mud	Ebb (T1)	Ebb (T1)	Ebb (T1)	Ebb (T1)
Low (P5)	Sand	***Flood (T2)***	***Flood (T2)***	***Flood (T2)***	***Flood (T2)***
	Mud	***Flood (T4)***	Ebb (T1)	Ebb (T1)	Ebb (T1)
High (P95)	Sand	***Flood (T2)***	***Flood (T2)***	Ebb (T1)	Ebb (T1)
	Mud	Ebb (T1)	Ebb (T1)	Ebb (T1)	Ebb (T1)

11. Contributions

Y. Plancke: main author of paper integrating all available information from mother project and project leader of this project in which the sediment budgets were calculated within the Flemish-Dutch Scheldt Commission. Performed the analysis of the residual sediment transport for sand and mud.

G. Vos: performed calculation of sand and mud budget (GIS-analysis); author of underlying report (in Dutch) within the mother project.

D. Meire: major reviewer of the mother project and this paper, making suggestions to improve the quality of the work, both in mother project as this paper.

G. Schramkowski: reviewer of this paper, major contribution on 1D-sediment transport model.

J. Vanlede: project lead of first (volumetric) sediment balance for sand and mud of the Sea Scheldt for 2001-2011; reviewer of this paper.

B. De Maerschalck: reviewer of this paper and presented results on SedNet 2023 conference.

12. CONFLICT OF INTEREST STATEMENT

The authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest, or non-financial interest in the subject matter or materials discussed in this manuscript.