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Sediment dynamics in the Schelde-estuary

Report 1
Influence of fresh water discharge and tide on the ETM-dynamics in the Schelde-estuary using Delft3D

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Influence of fresh water discharge and tide on the ETM-dynamics in the Schelde-estuary using Delft3D

Plancke, Y.; Dupont, H.; Stark, J.; Kaptein, S.

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Abstract

The Schelde-estuary is subjected to tides, (seasonal) variations in fresh water discharge and natural and man-made changes in bathymetry. These changes affect suspended sediment dynamics and therefore the formation and location of the estuarine turbidity maximum (ETM). An assessment of ETM formation and ETM location under different conditions of river discharge, tides and bathymetry is performed in this study using a Delft3D-numerical model.

Overall results show lower maximum values of suspended sediment concentration (SSC) in the ETM and a movement of the ETM in downstream direction as fresh water discharges become higher. During exceptional high discharges no clear ETM can be discerned as SSC is distributed more evenly. ETM location does not change significantly between spring- and neap tide, however an increase in SSC can be found in the Beneden-Zeeschelde during spring tide conditions. Bathymetric changes between 2011 and 2019 show an upwards shift in ETM location and higher SSC in the ETM.

Preface

This report is written based on the thesis of Hans Dupont (Dupont & Plancke, 2021), performed at the university of Antwerp during the period 2020-2021. In collaboration with Flanders Hydraulics Research, numerical model simulations were performed in order to investigate the influence of the fresh water discharge on the location of the estuarine turbidity maximum (ETM). Results from the master thesis are used in this report.

Additionally, new simulations were performed to investigate the effect of down-estuarine tidal boundary condition.

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1 Introduction

Suspended sediment (mud) dynamics play an important role in the Schelde-estuary due to its effect on navigational and ecological functions. The amount of suspended sediment particles in the water column and on the bed affects marine habitats (Gameiro *et al.*, 2011; Kromkamp *et al.*, 1995), whereas mud deposition can lead to siltation in harbors and navigation channels (International Marine and Dredging Consultants *et al.*, 2009; Peters *et al.*, 1971). Especially zones of increased suspended sediment concentration (SSC), also referred to as the estuarine turbidity maximum (ETM), are subjected to these issues. Thus, having knowledge about the mechanisms of suspended sediment dynamics and more specifically ETM formation and ETM location is crucial to assess and optimize bathymetry and aquatic health.

Equally important to having knowledge on the behavior of suspended sediment, is the ability to predict its behavior. Since the behavior of a natural system is complex, not all processes are understood, let alone described in formula/mathematical relationships (Peters *et al.*, 2006). Numerical models, containing all the available knowledge on hydrodynamics and sediment behavior, have been developed to describe and predict sediment transport both qualitatively as quantitively. A numerical 2D depth-averaged mud transport model for the Schelde-estuary has been developed by Flanders Hydraulics Research (Stark *et al.*, 2021a).

The Schelde-estuary is exposed to variations in river discharge, tidal boundary conditions and topo-bathymetry. A variation in fresh water discharge in the Schelde-estuary occurs under the influence of meteorological seasonal influences, in particular rainfall. River discharges in summer tend to be lower than in winter due to the lesser amount of rain during this period, whereas in winter the opposite occurs and river discharges thus tend to be higher (Cornet *et al.*, 2019). In recent years, longer periods with lower fresh water discharge have occurred, leading to longer residence times of the water in the Boven-Zeeschelde (Vandenbruwaene *et al.*, 2020). These hydrodynamic changes will have an influence on the residual sediment transport, and can be one of the drivers behind the increased sediment concentration in the up-estuarine parts.

Tidal variations occur on different time-scales: water levels change within one tidal cycle (12h25), while high and low water level change within the spring-neap-cycle (14.5 days), but also changes on the longer time scales (month to years) are possible. This analysis focusses on the time scale of the spring-neap-cycle.

Changes in bathymetry occur under man-made (sand mining, dredging) or natural influences, resulting in local and/or global erosion or sedimentation of the bed.

Variations in fresh water discharge, tidal boundary conditions and bathymetry have an effect on suspended sediment dynamics and therefore on ETM formation and ETM location. In this study the numerical model of the Schelde-estuary is used to assess the influence of these parameters (river discharge, tides and bathymetry) on suspended sediment dynamics, ETM formation and ETM location.

2 Model description

2.1 The Delft3D NeVla model

The model used for this scenario analysis is the Delft3D NeVla model. This model has been used extensively to study tidal hydrodynamics and sediment transport in the Scheldt estuary. Extensive calibration and validation exercises regarding the tidal hydrodynamics in the NeVla model were carried out by Maximova *et al.* (2009) and Vanlede *et al.* (2015). In the present modeling exercise, the 2D version of the Delft3D NeVla model is applied. General information on the software itself can be found in the Delft3D-FLOW user manual (Deltares, 2016).

Recently, Stark *et al.* (2021a) applied the two-dimensional version of the Delft3D NeVla model to simulate suspended sediment dynamics in the Zeeschelde. A sensitivity analysis was conducted in which the influence of various sediment characteristics, the simulation period, the upstream discharge, waves and salinity on the spatial distribution of suspended sediment and the formation of an ETM in the Boven-Zeeschelde was assessed. Moreover, Stark *et al.* (2021b) conducted model simulations in which disposal activities were implemented in the Delft3D NeVla model. Earlier, a refined version of the 2D NeVla sediment transport model was applied to model disposal of cohesive sediment fractions by Coen *et al.* (2016a; b). The applied model settings for the present scenario analysis are largely adopted from those former studies.

The following sections give a brief overview of the applied model settings for the present analysis. A more detailed overview of all model settings, including settings for bottom friction and salinity, is given by Stark *et al.* (2021a) who specifically adapted the NeVla sediment transport model for an optimal representation of the estuarine turbidity maximum.

2.2 Settings

2.2.1 Model grid

The curvilinear grid of the NeVla model includes the full Scheldt estuary, its tidally influenced tributaries and part of the North Sea (Figure 1). The model domain is cut off between Westkapelle and Cadzand at the estuary's mouth. By doing so, observed water level series can be used as a downstream boundary condition. The grid resolution varies between 400 m on the North Sea, 100-200 m in the Westerschelde until approximately 30 m near Schelle.

It is noted that the used version of the NeVla model is adopted from the earlier study by Coen *et al.* (2016a; b) and Stark *et al.* (2021a) and is based on the 2011 geometry and bathymetry of the estuary. Several flood control areas that have been constructed during the last decade are therefore not included in the present model runs, potentially leading to deviating tidal hydrodynamics in especially the upstream part of the estuary. For example, the 600 ha large flood control area of Kruibeke-Bazel-Rupelmonde is not implemented in this version of the model.

Figure 1 – The original NeVla grid. White line indicates the offshore boundary used in this study

2.2.2 Bathymetric data

The applied bathymetry is adopted from an earlier modelling study on suspended sediment concentrations in the Schelde-estuary by Coen *et al.* (2016a; b). The bathymetry in the Westerschelde is based on a 2011 dataset from Rijkswaterstaat. The bathymetry of the Sea Scheldt is based on 2011 measurements from Vlaamse Hydrografie. For intertidal areas, LIDAR measurements from 2011 are used.

The horizontal coordinate system is RD Parijs. The vertical reference level is mTAW.

2.2.3 Boundary conditions

Downstream boundary conditions

The downstream boundary between Westkapelle and Cadzand is forced by observed water level conditions for the period 1-1-2019 until 15-2-2019 (Figure 2). The simulation lasts 45 days. In accordance with findings by Maximova *et al.* (2009), the water level time series at Cadzand is implemented with a phase shift of +10 minutes. This phase shift corrects for the 5200 m distance between the Cadzand measurement station and the downstream boundary of the model where the water level time series are implemented.

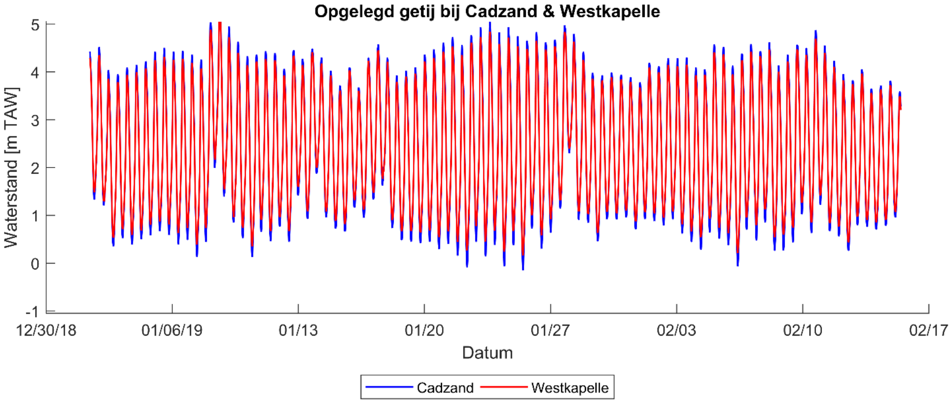

Figure 2 – Downstream water level boundary condition at Cadzand and Westkapelle.

Upstream boundary conditions

For the scenario analysis, the upstream boundaries along the Upper Sea Scheldt and tidally influenced tributaries are forced by a constant discharge. Three sets of discharge conditions are implemented: (1) a low discharge condition corresponding to the P10 values of the daily discharge measurements between 1989 and 2018; (2) a median discharge condition based on the P50 values and (3) a high discharge condition based on P90 values. Discharge data was obtained from the HIC hydrological yearbook (Cornet *et al.*, 2019). Table 1 gives the applied discharge boundary conditions. Note that the discharges at Bath and Terneuzen are kept constant for the low and high discharge runs.

In addition, a validation run with measured daily discharge conditions for the chosen simulation period in January and February 2019 is also performed to briefly address the Delft3D NeVla version's model performance for the 2019 situation.

Table 1 – Upstream boundary conditions for low and high discharge simulations.

Boundary	Low discharge [m^3/s]	Median Discharge [m^3/s]	High Discharge [m^3/s]	SSC [kg/m^3]
Zeeschelde	4.79	22.46	88.45	0.05
Dender	1.12	3.20	13.69	0.05
Zenne	5.12	7.26	15.81	0.05
Dijle	6.15	11.18	28.12	0.05
Grote Nete	2.27	3.82	8.41	0.02
Kleine Nete	2.26	4.80	12.35	0.02
Spuikanaal Bath	10.20	10.20	10.20	0.00
Kanaal Gent-Terneuzen	31.10	31.10	31.10	0.00

Boundary conditions for sediment transport

The downstream boundary has an open boundary condition for the transport of sediment. A reference concentration of 0.03 kg/m^3 is applied here.

2.2.4 Waves

Based on findings by Stark *et al.* (2021a), the present scenario analysis is conducted with a model configuration including (wind) waves, using the Delft3D-WAVE module. In this module, the wave field is computed using a 3rd generation SWAN model (Deltares, 2011). The results of the Delft3D-WAVE simulation (wave height, wave period, mass transfers, bottom shear stress) are online communicated as a forcing in the Delft3D-FLOW simulation.

The wave computation is only forced by a wind forcing of 4.40 m/s (i.e., corresponding to 3 Bft), corresponding to the P50-percentile of the wind speed at Hansweert (Western Scheldt) over the 2000-2019 period. Daily wind data at an elevation of 10m was obtained for that period from the KNMI, i.e., Netherlands Royal Meteorological Institute. The wind direction varies for each tide (i.e., north during 1st tide, east during 2nd tide, south during 3rd tide, west during 4th tide, etc.) so all wind directions occur during the model simulation. There is no external wave forcing at the downstream boundary as the area of interest is in the Sea Scheldt rather than the Western Scheldt. All waves are thus internally generated.

The impact of waves on sediment transport and sediment concentrations mainly results from additional bottom shear stress, which is most profound on shallow zones and thus enhances resuspension of sediment on tidal flats. Stark *et al.* (2021a) also show that a model configuration with waves gives an upstream directed residual sediment load in a part of the Sea Scheldt, which could support the formation of a (stable) ETM.

2.2.5 Sediment transport

The erosion and deposition of fine (cohesive) sediment is computed by the Partheniades-Krone formula (Partheniades, 1965). The suspended sediment transport itself is computed with the formulations of Van Rijn (1993).

One single cohesive sediment fraction is used in this scenario analysis. The applied settings for the cohesive sediment fraction are summarized in Table 2. These settings were estimated based on the results of the sensitivity analyses by Stark *et al.* (2021a) and aim at an optimal quantitative representation of the estuarine SSC variation including the ETM in the Upper Sea Scheldt.

Table 2 – Model settings for cohesive sediment.

Parameter	**Value**
Reference density for hindered settling calculations	c_{ref} = 1600 kg/m^3
Option for determining suspended sediment diameter	IopSus = 0 (i.e., Van Rijn, 1993 method)
Sediment type	Mud
Specific density of sediment fraction	P_{sol} = 2650 kg/m^3
Settling velocity	ω_s = 2.0 mm/s
Critical bed shear stress for sedimentation	$\tau_{kr,d}$ = 1.0 N/m^2
Critical bed shear stress for erosion	$\tau_{kr,e}$ = 0.2 N/m^2
Erosion Parameter	M_E = $2.0 \cdot 10^{-3}$ kg/m^2/s
Dry bed density	CDryB = 550 kg/m^3

Sediment availability

The variable initial thickness of the sediment layer shown in Figure 3 results from a previous model simulation of 45 days. More details on this initial run and the distribution of the sediment layer thickness is given in Stark *et al.* (2021a). Most sediment is situated in sheltered zones along the estuary, such as tidal docks and intertidal areas. The availability of sediment on the bottom of the estuary channel on the other hand is small.

Besides, the initial layer thickness in the Westerschelde is set to 0 m as test runs in the sensitivity analysis by Stark *et al.* (2021a) give unrealistic or erroneous results if sediment is implemented in the vicinity of the downstream boundary between Cadzand and Westkapelle.

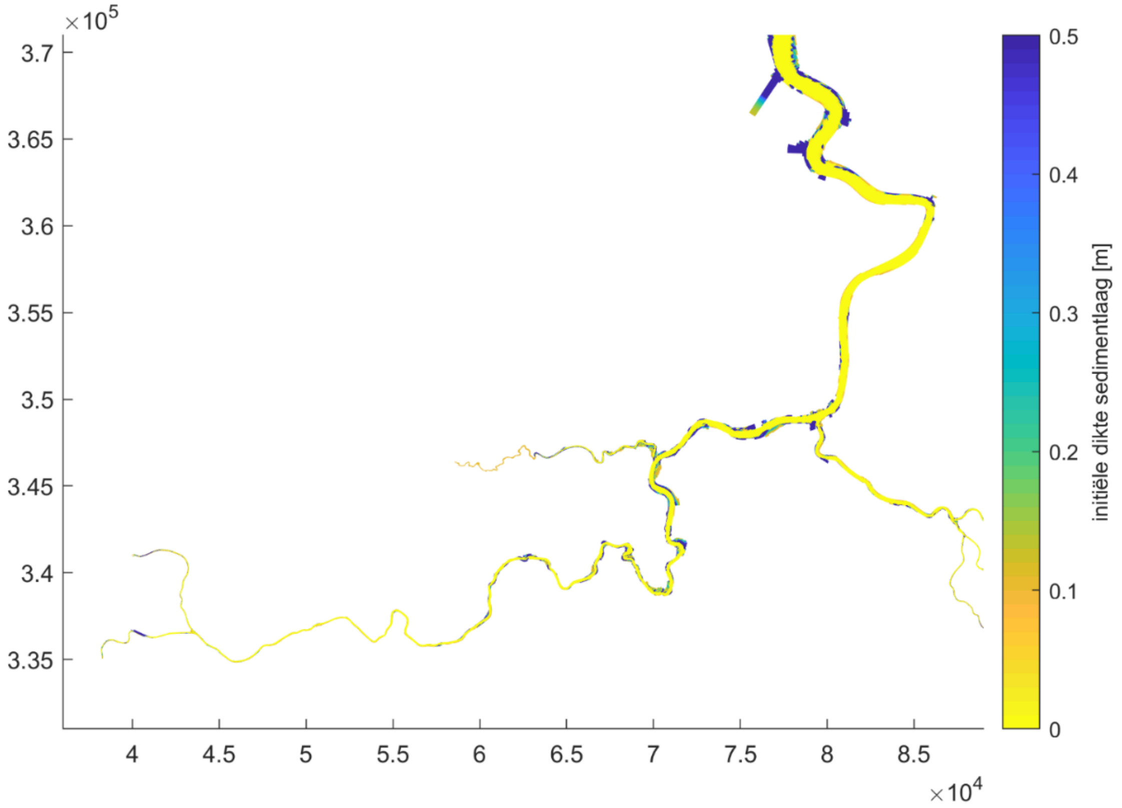

Figure 3 – Initial sediment layer thickness in the Sea Scheldt.

3 Fresh water discharge

3.1 Scenario's

A variation in river discharge in the Schelde-estuary occurs under the influence of meteorological seasonal influences, in particular rainfall. River discharges in summer tend to be lower than in winter due to the lesser amount of rain during this period, whereas in winter the opposite occurs and river discharges thus tend to be higher. These variations in river discharge have an impact on suspended sediment dynamics and therefore on ETM formation and behavior. The goal of this part of the study is to investigate how and to what extent a variation in river discharge influences suspended sediment dynamics, ETM formation and ETM movement.

An assessment of the influence of river discharge can be made by applying different fresh water discharges at the upstream boundaries of the model. These discharge points of fresh water inflow represent the rainfed parts of the Schelde-estuary. "Hydrologisch Informatie Centrum" (HIC) provides daily averaged flow rate measurements over several measuring stations along the Schelde-estuary. Since daily flow rate values show a non-normal distribution, measures of central tendency and dispersion of flow rates, are determined using percentile values. The calculation of the median flow rate and related percentile values, per measuring station, over a so called "normal" period are based on those daily flow rate values. The normal period is defined as a period which is representative for prevailing climate conditions and is used to assess how "normal" the considered year was on a timescale of multiple decennia. Strictly speaking the normal period contains 30 years. However only a limited amount of measuring stations provide data over this period.

In this study, the median flow rate value (P50) and related percentile values (P10, P25, P75 and P90) for the year 2019, provided in the hydrological yearbook 2019,were used as different fresh water inflow values in the upstream model boundaries. For the year 2019 the normal period ranges from 1989 till 2018. Additional percentile values (P35 and P99), and therefore fresh water inflow values, were calculated separately out of daily averaged flow rate values for the appropriate measuring stations over a normal period ranging from 01/01/1992 till 01/01/2021. An overview of the different percentile values at their respective measuring stations used as different fresh water inflow values in the models upstream boundaries are given in Table 3.

Table 3 – Fresh water discharge for different tributaries

Measurement station	Tributary	P10	P25	P35	P50	P75	P90	P99
		Fresh water discharge [m³/s]						
Grobbendonk	Kleine Nete	2.26	3.16	3.72	4.80	7.74	12.4	28.0
Itegem	Grote Nete	2.27	2.92	3.24	3.82	5.54	8.41	16.2
Haacht	Dijle	6.15	7.84	9.04	11.2	17.2	28.1	54.5
Appels	Dender	1.12	1.60	1.95	3.20	6.59	13.7	40.3
Merelbeke	Bovenschelde	4.79	10.1	13.8	22.5	48.0	88.5	215
Eppegem	Zenne	5.12	5.94	6.37	7.26	10.3	15.8	37.8

3.2 Results

The effect of a variation in fresh water discharge on suspended sediment dynamics is assessed on two different scales. A first assessment is made on a spatial scale, presenting the averaged SSC over a complete spring neap tidal cycle (last 14.5 days of the simulation) along the entire length of the estuary. Also average sediment mass over a spring-neap tidal cycle present in subdivisions of the estuary, the so-called OMES-segments, is presented. A second assessment is made on the small time scale of a lunar day (24h50), presenting the behavior of suspended sediment with respect to tidal action at a certain observation point.

3.2.1 SSC with variation in river discharge along the estuary

For each of the different applied fresh water inflows, the averaged suspended sediment concentration (SSC) over a complete spring neap tidal cycle (last 14.5 days of the simulation) was calculated along the estuary. The spatial distribution of the spring-neap-averaged SSC for each simulation with variable fresh water inflow is given in Figure 4. An ETM is formed in the Boven-Zeeschelde (100-120 km from Vlissingen) for different conditions of river discharge. It immediately becomes clear that a variation in river discharge has a significant impact on suspended sediment dynamics and thus on ETM formation and ETM movement.

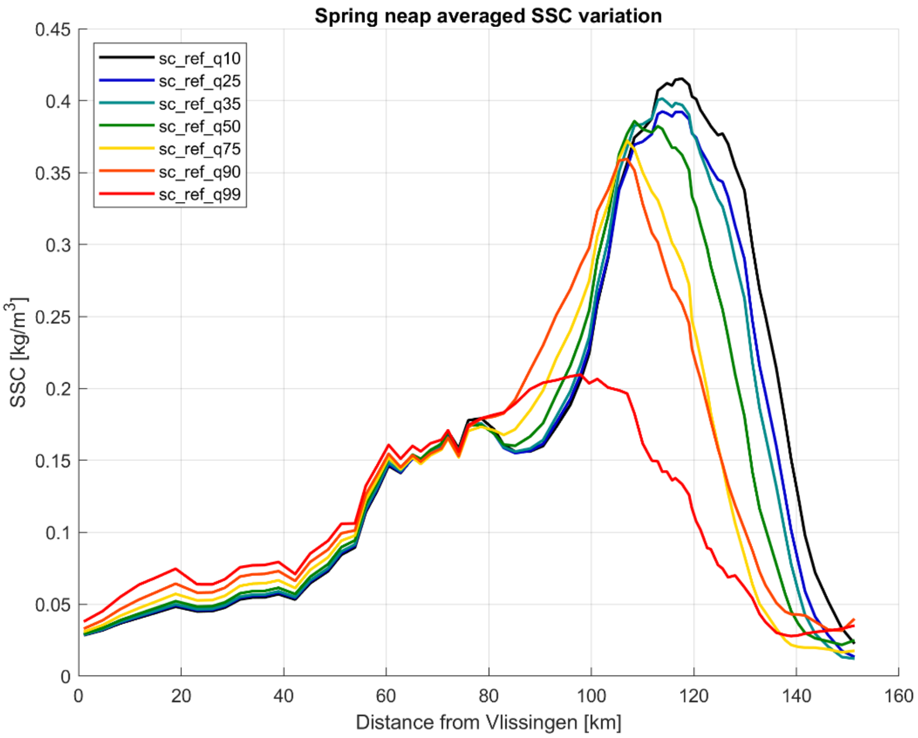

Figure 4 – Spring-neap averaged SSC for different fresh water discharges

The effect of a variation in river discharge on ETM formation in the Boven-Zeeschelde is clearly noticeable. Lower river discharge leads to a higher maximum value of SSC in the ETM, meaning that more sediment remains trapped in the ETM when river discharges are lower. Sediment however tends to be washed out of the ETM as the river discharges becomes higher, resulting in lower maximum SSC values causing the ETM "peak" to drop and move downstream. In case of an exceptional high river discharge (P99), the "peak" almost vanishes and a more plateau-like course of SSC, from 60 till 110 km, is obtained. This probably implies that sediment is no longer trapped in the Upper Sea Scheldt but is washed out over a longer distance.

Secondly, an effect on the location of the ETM due to a variation in river discharge is noticeable. The general trend in Figure 4 shows an ETM that is situated more downstream during high river discharge and more upstream during low river discharge. A closer look into the location of the ETM with respect to a variation of flow rate in the Zeeschelde near Merelbeke (Figure 5) shows the location of the ETM relative to the river discharge. Some kind of leap in location between low and high river discharge can be discerned. For fresh water discharge values from P10 until P35 the ETM remains in the vicinity of KM-115 (i.e., near Driegoten). For the median fresh water discharge (P50) or higher discharges (P75 and P90), the ETM starts to move downstream and stabilizes around the same location (±107 km). The biggest variation in ETM location can thus be seen for fresh water discharge values from P35 until P75.

For the extremely high P99 discharge, the SSC-peak moves even further downstream toward KM-98. However, there is no clear ETM present anymore in this simulation.

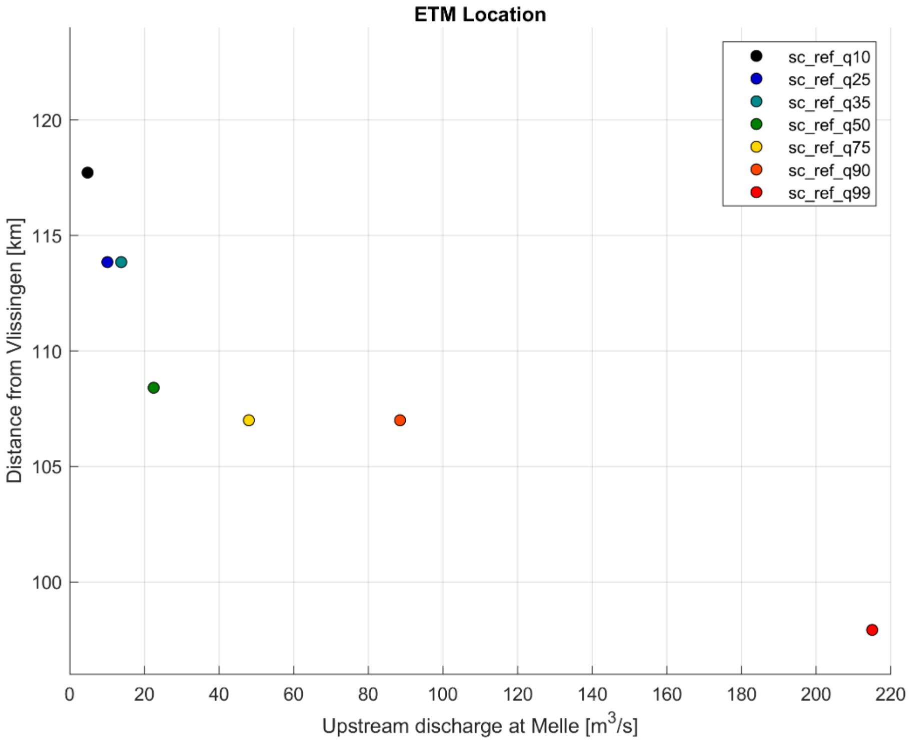

Figure 5 – Location of maximum SSC in relation to fresh water discharge

Whereas in the Boven-Zeeschelde, from 100 to 160 km from Vlissingen, the general trend in SSC shows higher concentrations as the river discharge decreases, a close-up of the SSC in parts of the Westerschelde and Zeeschelde, from 40 to 70 km from Vlissingen, shows an opposite impact (see Figure 6). In this more downstream part of the estuary higher concentrations appear at high river discharge, while lower concentrations can be found during low river discharge. This can be attributed to the wash load that forms for higher discharges, i.e., sediment is transported from the ETM to this lower part of the estuary. Also the difference in absolute SSC values between different river discharges becomes smaller in this part of the estuary.

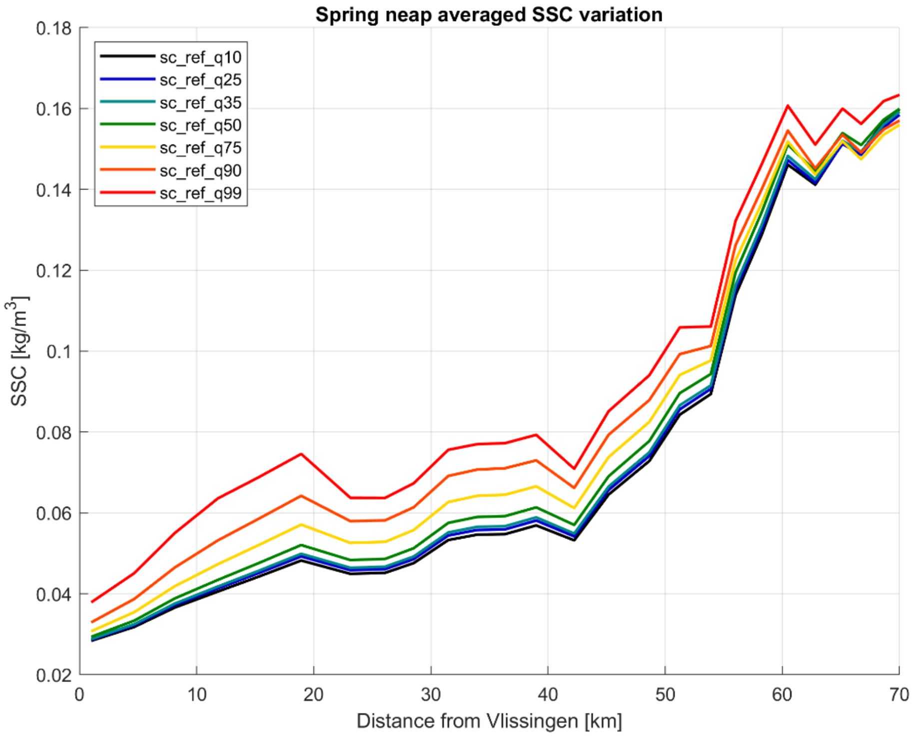

Figure 6 – Spring-neap averaged SSC for different fresh water discharges, detail of Westerschelde

3.2.2 Variation in river discharge at observation points

On the timescale of a lunar day (24h50), containing two tidal cycles generating two high tides and two low tides, the behavior of suspended sediment influenced by tidal action becomes clear. The behavior of suspended sediment with respects to tidal action and a variation in river discharge is shown for different observation points. The behavior at Driegoten is presented in Figure 7.

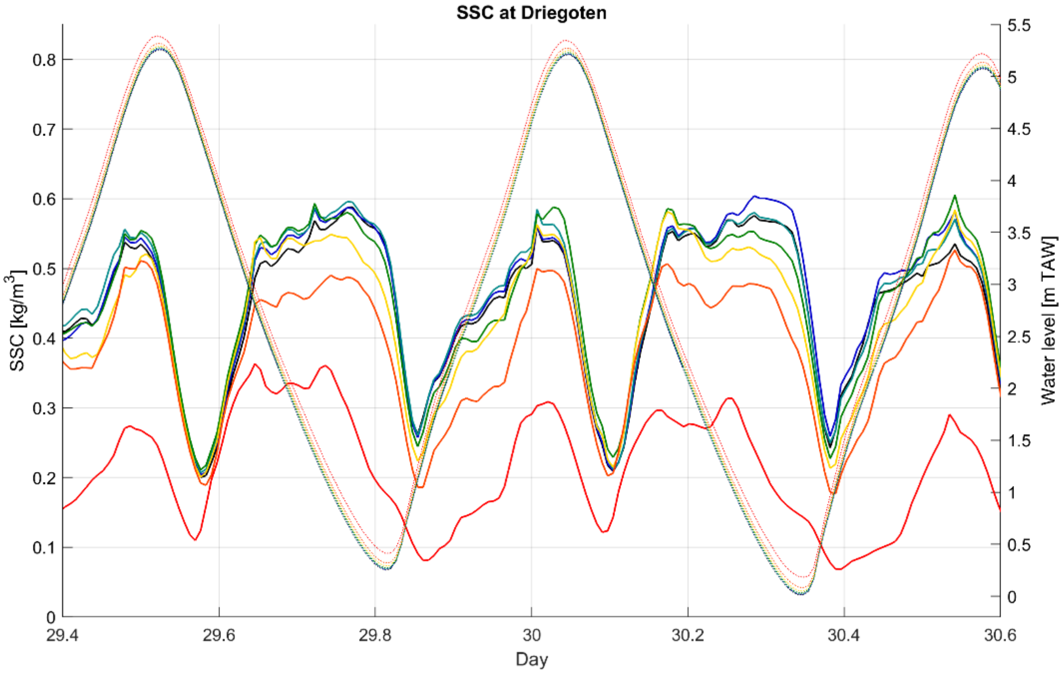

Figure 7 – SSC at Driegoten for different fresh water discharge scenario's

Within a tidal cycle, the temporal pattern shows higher SSC values during both the ebb and flood period, and 2 minima: one just after slack high water and one just after slack low water. Near the moment of slack (HW and LW), flow velocities decrease to (almost) zero, allowing sediment in suspension to settle. This results in lower SSC in the water column (i.e. minima in time series).

The impact of the fresh water discharge shows a gradual increase of SSC values with lower river discharges. P25 however, shows slightly higher SSC values than P10. Regarding SSC distribution, a variation in discharge from P10 till P75 shows little to no difference. For higher discharges, as of P90, SSC is distributed slightly differently compared to discharges from P10 till P75. In particular, SSC values drop significantly for the highest discharge, probably related to the washing out of the ETM at Driegoten.

3.3 Discussion

Model results show the formation of an ETM between the limits of 100 and 140 km from Vlissingen for different conditions of river discharge, except for the highest P99 discharge in which the ETM is washed out. Measurements of SSC conducted during several half-tide-ebb campaigns (HTE) (Figure 8) show a peak in SSC (= ETM) between KM-100 and KM-140 from Vlissingen during summer conditions or during low river discharges (Vandenbruwaene *et al.*, 2018). During winter conditions or high river discharges a peak in SSC between KM-60 and KM-100 from Vlissingen is observed during measurements. Regarding low river discharges (= summer conditions), the modelled location of the peak coincides with observed peak values in SSC during measurements. During high river discharges however the observed peak is formed more downstream compared to the model results. SSC values during measurement however, are not only a function of river discharges but can also be depended on biological factors and/or sediment disposal, which are not accounted for in the model. The downstream situated peak in the observations is most likely caused by disposal activities in this region.

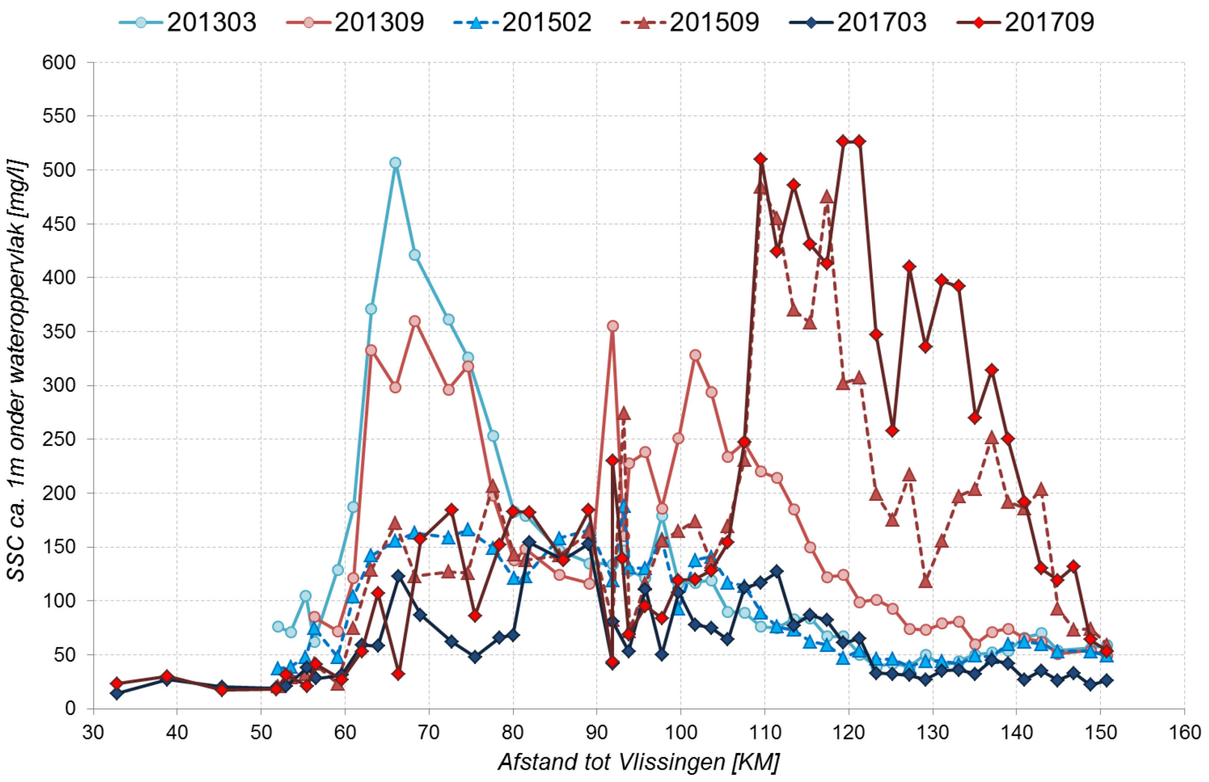

Figure 8 – Measured SSC during “half-tide ebb” measurment campaigns along the Zeeschelde

A variation in river discharge causes differences in the amount of SSC in the ETM and the location of the ETM. Overall, higher river discharges lead to lower SSC in the ETM and a movement of the ETM in the downstream direction. With river discharge reaching higher values, flow velocities in downstream direction become large enough to export sediment out of the ETM in the direction of the sea causing SSC values in the ETM to drop. With export becoming bigger as river discharges increase. At exceptional high river discharges (P99) and thus more ebb-dominant flow conditions, the export of sediment becomes so high the ETM nearly vanishes and SSC is distributed more evenly. No clear ETM can be distinguished at P99.

A variation in low flow rate values, P10 till P35, has little impact on the location of the ETM as the ETM only moves about 5 km downstream between P10 and P35. The same observation can be made for a variation in higher flow rate values, P50 till P90, showing nearly no movement. There is however a small leap in location between these low (P10-P35) and high (P75-P90) flow rates, with the location at low flow rates moving from about 115 km to 107 km as flow rates increase. For additional flow rate values in between P35 and P50 and P50 and P75 an ETM location in line with the current trend in ETM displacement can be expected.

Higher concentrations during high flow rate values in parts of the Westerschelde and Beneden-Zeeschelde, from 40 to 70 km from Vlissingen, can be linked to a bigger seawards export of sediment out of the ETM in the Boven-Zeeschelde. Sediment transported seawards will ultimately lead to higher SSC in parts of the estuary closer to the sea. The influence river discharge has on SSC though, becomes smaller closer to the sea.

4 Topo-bathymetry

4.1 Scenario's

Between 2011 and 2019 the morphology has changed in the Schelde-estuary (Plancke *et al.*, 2021). Both erosion and deposition processes have led to different areas of increased or decreased water depth in different parts of the estuary. These morphological changes, and thus the occurrence of erosion and deposition processes, are more outspoken in the Westerschelde (Figure 9) as larger areas of increased and decreased water depth succeed one another. Changes in water depth in the multiple channel system in the Westerschelde could have an impact on tidal propagation. In the Beneden-Zeeschelde and Boven-Zeeschelde (Appendix 1 Morphological changes Zeeschelde) these morphological changes seem to be way less outspoken.

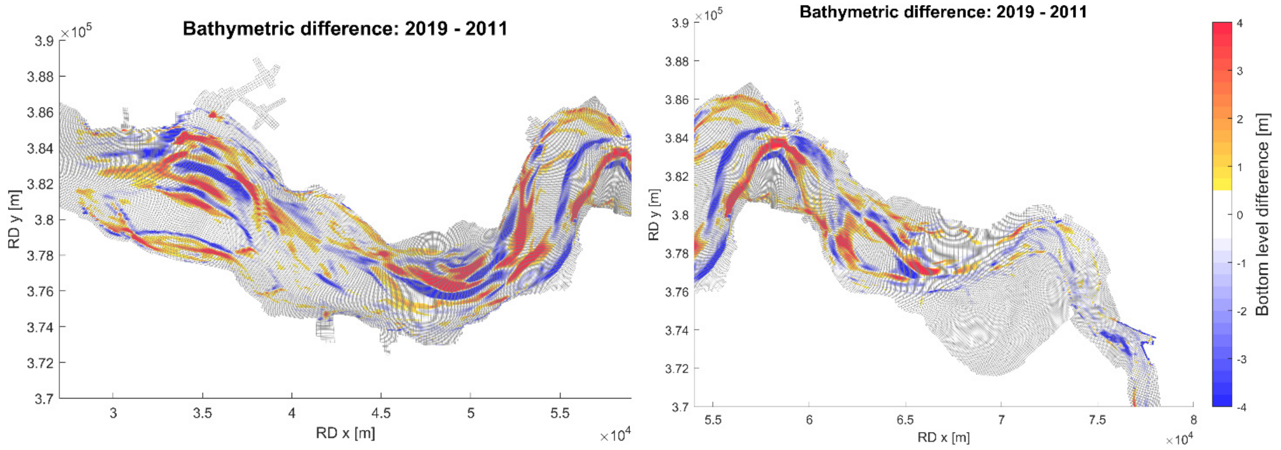

Figure 9 – Morphological changes in the Westerschelde 2011-2019

As bathymetric changes can directly be linked to volumetric changes (increased water depth leading to higher volumes), a more overall view of bathymetric changes between 2011 and 2019 can be given by differences in water volume below low tide per OMES-segment (Barneveld *et al.*, 2018; Meire *et al.*, 1997). In 2019, in the Beneden-Zeeschelde and Boven-Zeeschelde, from OMES-segment 9 till 19, water volumes have mainly increased, with bigger increases in the first part of the Beneden-Zeeschelde (segment 9-11). In the Westerschelde, OMES-segment 1 till 8, sections of increased and decreased water volume succeed one another, with increased water volumes mainly focused closer to the Zeeschelde.

4.2 Results

4.2.1 Hydrodynamics

The changes in morphology cause variation in the hydrodynamics. On a small timescale (within one tidal cycle), differences in water levels and ebb/flood discharges were found. Figure 10 shows the variation for the observation point Driegoten. In 2019 the tidal range seems to have decreased compared to 2011. The tidal asymmetry however, has become bigger in 2019 as the flood period decreased while the ebb period has increased. Differences in ebb and flood discharges occur as well (figure 17). Both flood as ebb discharges, in 2019, have increased. On other observation points similar results regarding changes in water level and discharges are found, with differences becoming larger for up-estuarine stations.

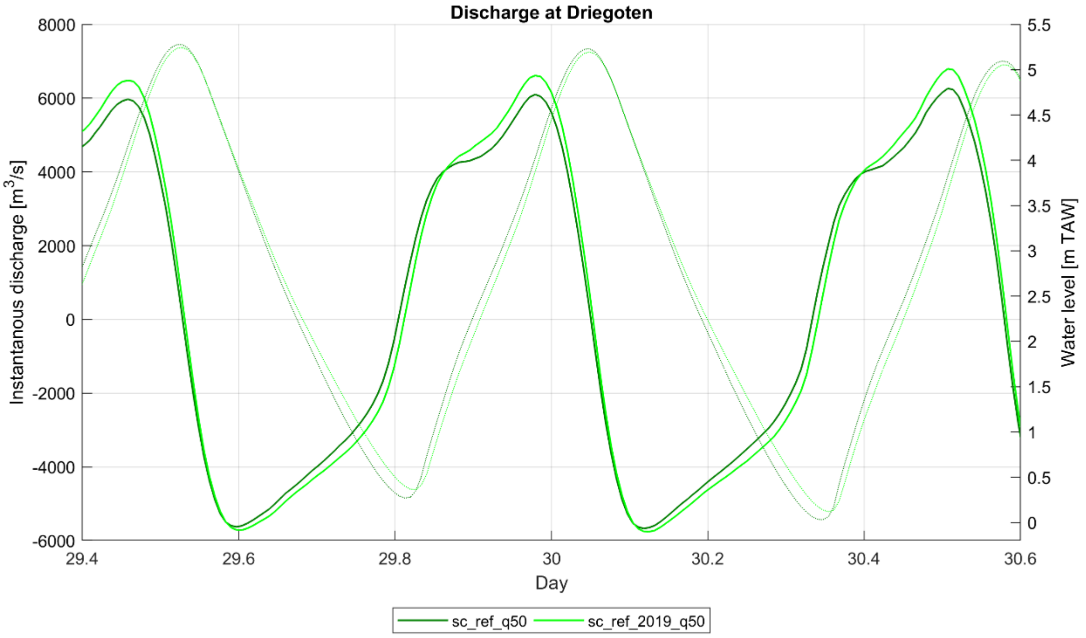

Figure 10 – Variation in water level (dashed lines) and tidal discharge (solid lines) at Driegoten due to changed morphology

4.2.2 Sediment dynamics

For both the topo-bathymetry of 2011 and 2019 the SSC along the estuary was calculated and averaged over a complete spring neap tidal cycle (last 14 days of the simulation), using the median fresh water discharge value (P50) as the models fresh water input in the upstream boundaries. In this way the bathymetry is the only varying parameter affecting SSC along the estuary, allowing an assessment of a variation in bathymetry on suspended sediment dynamics. The spatial distribution of the averaged SSC for both topo-bathymetries is given in Figure 11.

The topo-bathymetry clearly has an effect on the distribution of the SSC along the estuary. The ETM formed in the Boven-Zeeschelde in 2011 has moved from approximately 110 km from Vlissingen to a location situated more up-estuary (±125 km from Vlissingen) in 2019. Additionally, the ETM formed in 2019 shows elevated SSC with regard to that of 2011. More downstream, in a big part of the Zeeschelde, from 60 km till about 110 km from Vlissingen, SSC is lower in 2019 than in 2011. In the lower estuary, from 0 to 60 km from Vlissingen, the SSC shows little to no difference between both bathymetries.

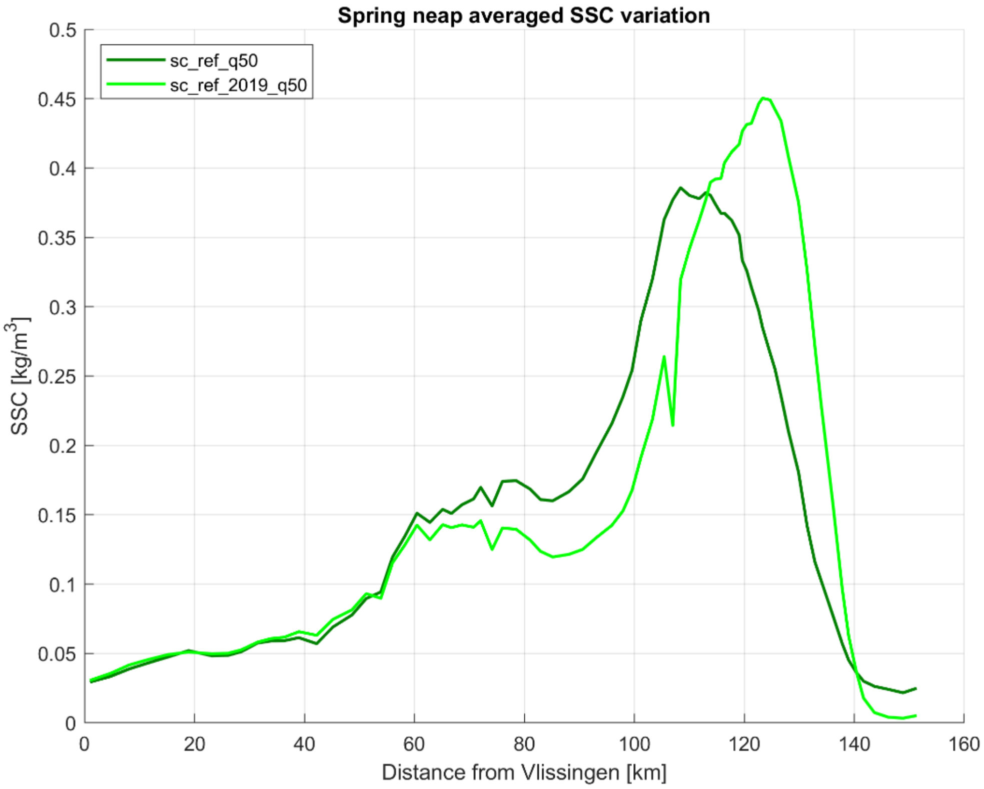

Figure 11 – Spring-neap cycle averaged SSC variation due to changed morphology

4.3 Discussion

Between 2011 and 2019 some local changes in bathymetry, under the influence of erosion and deposition processes, have occurred. An overall view was obtained by comparing changes in water volume under low tide for different segments in the estuary, showing water volumes have mainly increased in the Boven en Beneden-Zeeschelde. Also changes in hydrodynamics (water level and tidal discharges) were observed. Some changes in water motion are likely to impact tidal asymmetry, which could lead to higher flood velocities could give an indication of an upwards shift of the ETM. Flood and ebb velocities should be assessed to confirm this. Additionally, the evolution of flow velocities near the moment of slack high and low water should be analysed in more detail, because these moments are crucial for the settling and resuspension of sediment.

The only direct link with variation in SSC between 2011 and 2019 can be given by an assessment of the net sediment flux over the estuary. Simulation results with the bathymetry of 2019 show an upstream displacement and elevation of the SSC peak with regards to the SSC peak formed during the simulation with bathymetry of 2011. An explanation for these results can be given by comparing the net (averaged over a spring-neap tidal cycle) sediment fluxes over the entire estuary (Figure 12). Apart from KM-90 till KM-110 from Vlissingen, where both 2011 and 2019 show a net upstream transport, there is a net downstream transport of sediment along the estuary. The net downstream transport in the zone between KM-70 and KM-90 from Vlissingen in the 2019 simulation however, seems to be lower compared to that of 2011. This means that in the 2019 simulation a smaller amount of sediment is exported to the sea and a bigger amount of sediment remains present within this zone. This could ultimately lead to an upwards shift of the SSC peak. Further up-estuary, the net sediment flux in 2011 lies just below 0 (= net downstream transport) from KM-160 till about KM-103 from Vlissingen. As of KM-103 the net sediment flux for 2011 becomes positive, whereas in 2019 the net sediment flux already becomes positive as of about KM-110 from Vlissingen. This implies that sediment in 2019 is hold back, by a net upwards transport, approximately 7 km more upstream than in 2011 which could give an indication of elevated SSC and thus a peak in SSC that can be found at a more upstream location.

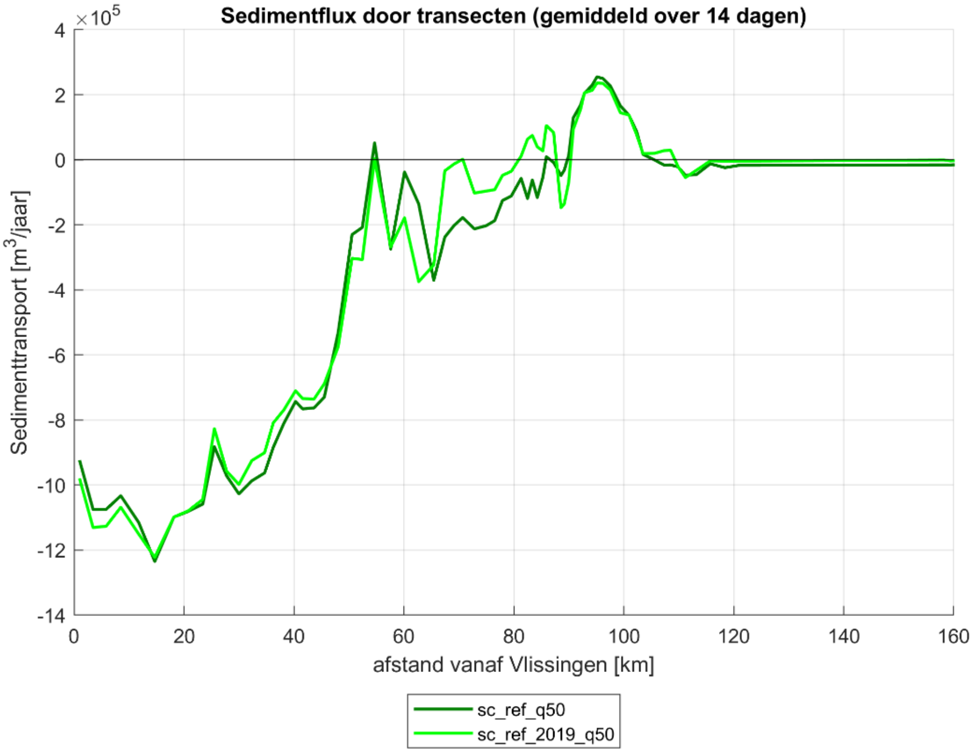

Figure 12 – Spring-neap cycle averaged sediment flux due to changed morphology

5 Tidal boundary condition

5.1 Scenario's

In the previous chapters both the influence of topo-bathymetry and fresh water discharge was investigated. A final parameter that was changed is the down-estuarine boundary condition, i.e. water levels. The previous simulations were performed using measured water levels as boundary condition. This implies that spring-neap variation is implemented in the model.

Simulations were performed using a cyclic down-estuarine boundary condition. A set of 2 semi-diurnal tides was selected from the measured water levels, representing respectively neap, mean and spring tide conditions. It was opted to select 2 tidal cycles, minimizing the effect of the diurnal inequality in the construction of the cyclic tides. Table 4 gives an overview of the tidal characteristics for the different scenario's. Both values of the rising and falling of the semi-diurnal tides are presented. It can be seen that the tidal range for both the mean and spring tide are larger than the average value over the period 2011-2015, however the selected tidal cycles were the best within the available time series used in the previous simulations. Figure 13 gives the temporal variation in water level for the different scenario's.

Table 4 – Tidal characteristics different scenario's

Scenario	Tidal range (2011-2015)	Rising (sim)	Falling (sim)
Mean Tide	3.86 m	4.07 m 4.62 m	4.34 m 4.34 m
Neap Tide	3.06 m	2.84 m 3.22 m	2.84 m 3.22 m
Spring Tide	4.47 m	4.89 m 4.53 m	4.57 m 4.86 m

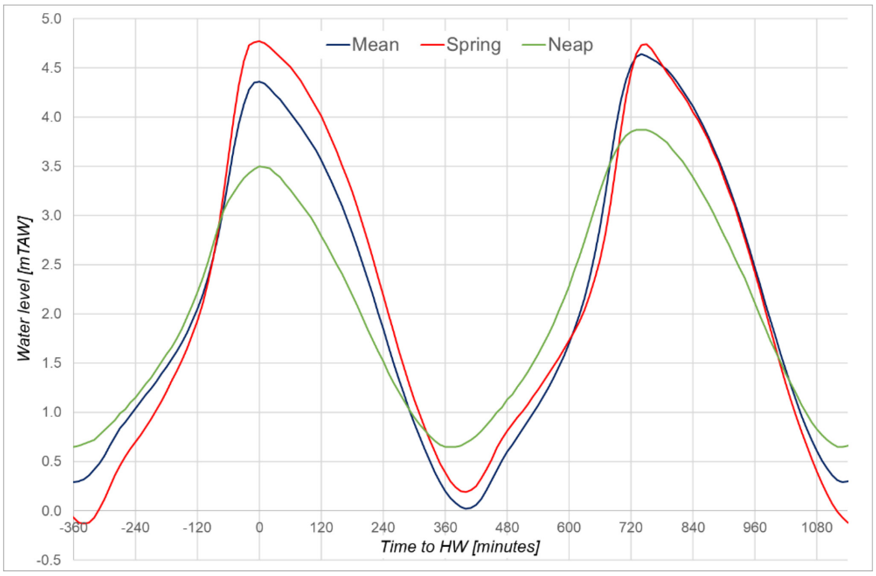

Figure 13 – Down-estuary boundary condition for different scenario's

5.2 Results

For each of the different applied tidal boundary conditions, the averaged suspended sediment concentration over the last 14 days of the simulation was calculated along the estuary[1]. The spatial distribution of the averaged SSC belonging to its respective tidal boundary condition is given in Figure 14. An ETM is formed in the Boven-Zeeschelde near 125 km from Vlissingen for all tidal boundary conditions. The tidal boundary conditions does not affect the position of the ETM. It has an effect on the value of the averaged SSC, with higher values for spring tide conditions and lower values for neap tide conditions. The differences are more pronounced in the Beneden-Zeeschelde (KM-60 – KM-90) and at the location of the ETM (KM-125).

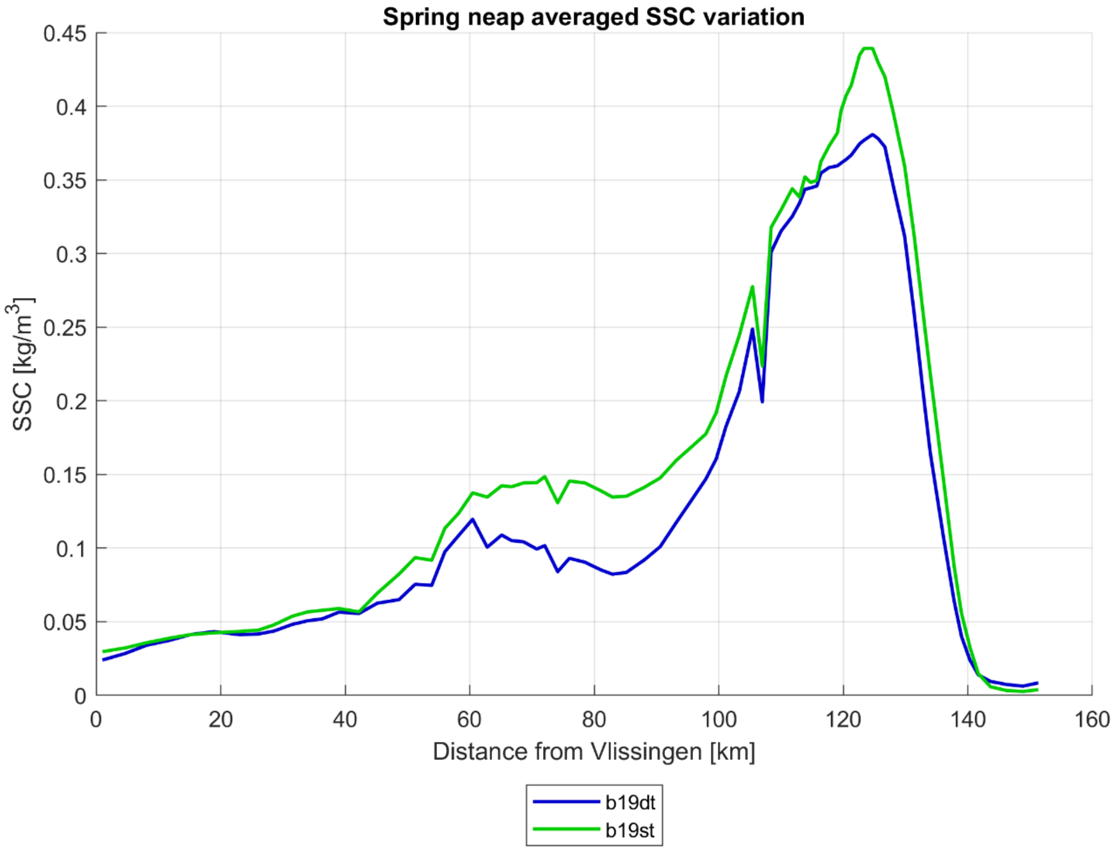

Figure 14 –Averaged SSC variation due to tidal boundary condition (**blue** = neap | **green** = spring tide)

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[1] Although the boundary condition in this set of simulations has no spring-neap variation, temporal variation in SSC is possible due to the non-equilibrium state of the simulations. Therefore it was opted to perform an identical post-processing as the other simulations.

5.3 Discussion

The different tidal boundary conditions result in different hydrodynamic conditions in the estuary: flow velocities will be lower during neap tide compared to mean conditions, while spring tide results in higher flow velocities. This is shown[2] in Figure 15 (dotted lines, right axis). Both for Oosterweel (Beneden-Zeeschelde, ~ KM-75) and Driegoten (Boven-Zeeschelde, ~ KM-100) these differences are more pronounced during flood phase. Higher flow velocities (during spring tide) will induce more erosion of sediment, creating higher sediment concentrations. This pattern is clearly visual at Oosterweel, but for Driegoten sediment concentrations at spring tide are similar to neap tide (Figure 15, full lines, left axis).

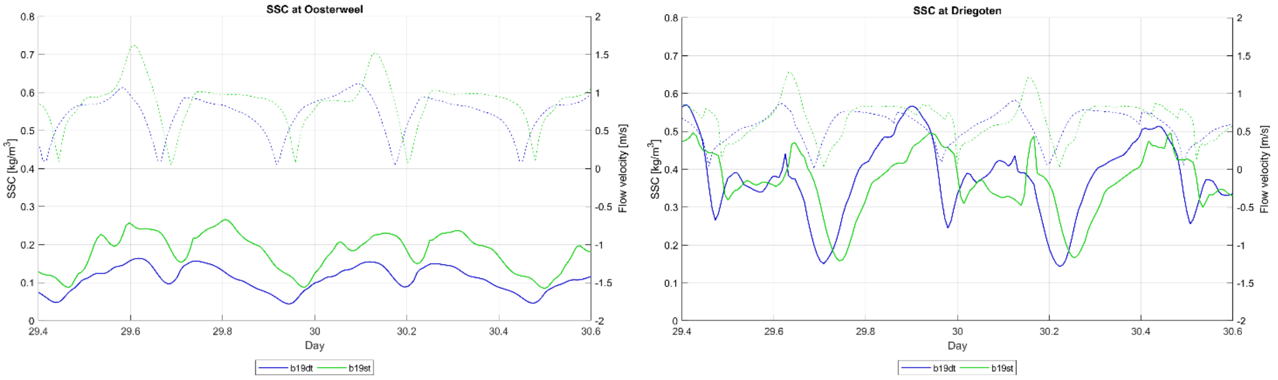

Figure 15 – SSC (-) and flow velocity (--) at Oosterweel (left) and Driegoten (right) for tidal boundary condition scenario’s

For large parts of the estuary the overall (residual) sediment transport patterns are similar for the different water level boundary conditions (Figure 16). However, differences exist in the Beneden-Zeeschelde (KM-55 – KM-90) : during spring tide conditions residual transport is more flood / less ebb-dominant compared to neap tide conditions. These differences are more pronounced than the influence of bathymetric changes between 2011 and 2019 (see Chapter 4).

Near KM-55 residual transport becomes flood-dominant during spring tide, which explains the higher sediment concentrations in the Beneden-Zeeschelde during spring tide. Between KM-80 and KM-90 the residual transport is flood-dominant during spring tide, while it is ebb-dominant during neap tide. However, further up-estuary (KM-90 – KM-120) the residual sediment becomes less flood / more ebb-dominant compared to neap tide conditions. Therefore sediment is trapped at KM-100 for neap tide and KM-90 for spring tide, which could explain why sediment concentrations between KM-100 and KM-120 do not change for different boundary conditions (more sediment in suspension due to higher flow velocities vs. larger spatial part of the estuary were sediment is trapped).

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[2] It should be mentioned that the start of the different scenario’s is not at the identical moment in the tidal cycle, resulting in a phase shift in the presented time series for SSC and flow velocity.

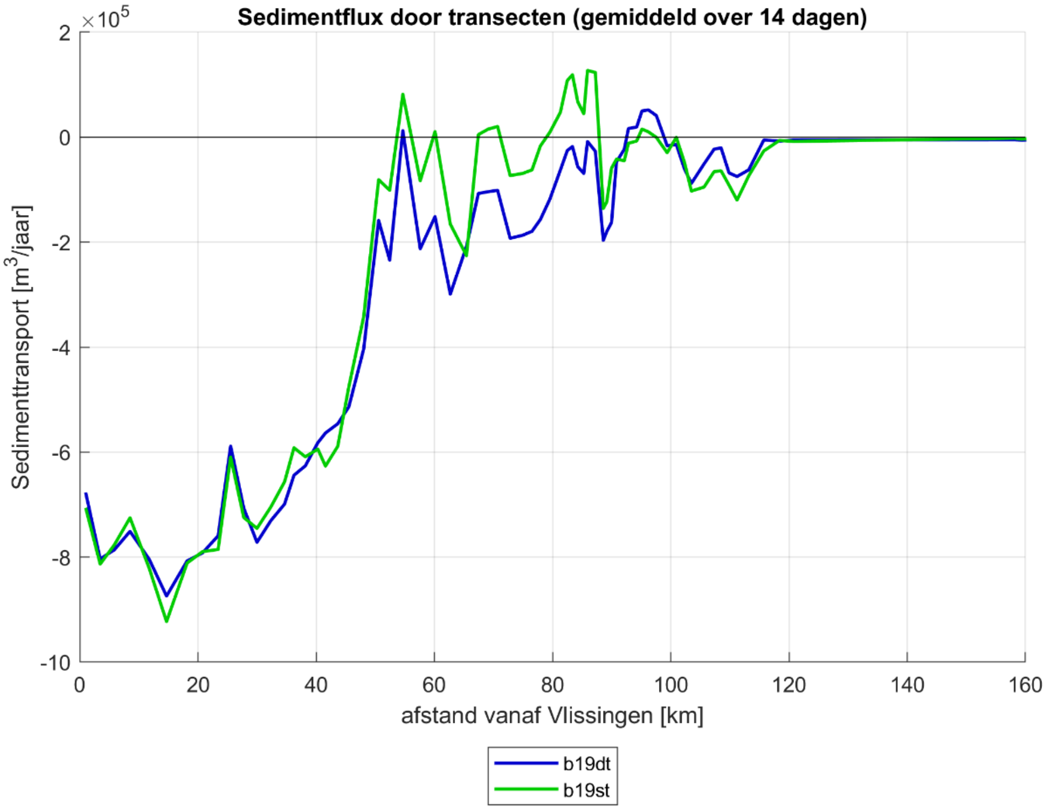

Figure 16 – Averaged sediment flux due to different tidal boundary conditions

6 Conclusions

6.1 Conclusions

In this study, the effect of a variation in fresh water discharge, bathymetry and tidal boundary condition on suspended sediment dynamics in the Schelde-estuary was assessed. Using a numerical model of the Schelde-estuary, including its tidal tributaries, the ETM formation and ETM location was investigated for different scenario's. The spatial distribution of averaged SSC over a spring-neap tidal cycle shows the formation of an ETM within the limits of KM-100 and KM-140 under all different conditions except for the extremely high (P99) discharge.

Under summer conditions (=low discharge) modeled peaks in SSC coincide with observed values. Variations in river discharge causes a difference in the amount of SSC in the ETM and ETM location. Overall, lower river discharges lead to higher SSC in the ETM and a movement of the ETM in up-estuarine direction, whereas during high river discharges sediment is exported out of the ETM causing a decrease of SSC in the ETM and a down-estuarine shift in location. At exceptional high river discharges no clear ETM is formed as SSC is distributed more evenly over the upper parts of the estuary. The export of sediment at high river discharge also leads to higher SSC in parts of the estuary closer to the sea. The ETM gradually moves downstream as river discharges and thus flow velocities increase, with the biggest variation in location from P10 till P50. River discharges higher than P50 have nearly no effect on ETM location. However, for extremely high river discharges (P99), the ETM is washed out and its peak vanishes.

Between 2011 and 2019 some changes in the estuary's bathymetry have occurred. As a result, water volumes have mainly increased in the Boven and Beneden-Zeeschelde. The bathymetric changes lead to changes in hydrodynamics, both with regards to water level and ebb/flood velocities/discharges. In 2019, elevated SSC in the ETM and an upwards shift in ETM location can be discerned compared to 2011. An explanation could be the lower residual down-estuarine transport in 2019 or a net down-estuarine transport that is pushed back by a residual up-estuarine transport at a more down-estuarine location in the Boven-Zeeschelde compared to 2011.

Cyclic boundary conditions were constructed representing neap, mean and spring tide conditions. As the tidal range increases from neap to spring tide, flow velocities increase as well with larger tidal ranges. The effect on the ETM-formation seems rather limited, although differences were found on the SSC profile along the estuary. Spring tide conditions result in higher averaged SSC-values in the Beneden-Zeeschelde. This could be explained by (1) enhanced tidal hydrodynamics, and thus sediment entrainment, and (2) a more flood/less ebb-dominant residual sediment transport in this part of the estuary.

Overall, it can be concluded that the location of the ETM is mainly determined by discharge variations on a seasonal time-scale rather than by spring-neap variations on a fortnightly time-scale. Spring-neap variations do influence the height of the SSC-peak in the ETM, although the impact of discharge variations is again stronger if the highest discharges (P99) are considered.

6.2 Recommendations

Due to computational time, simulations were performed over a period of 45 days. Over this period, SSC-values tend to decrease continuously, indicating no “dynamic equilibrium” is reached during the simulation, even with constant tidal boundary conditions (Figure 17). A longer simulation period may lead to a model that lies closer to its equilibrium state and produce more stable SSC and by extension a more stable ETM making a more quantitative assessment possible.

Further research is needed in order to investigate how changes in bathymetry and water motion between 2011 and 2019 lead to an upwards shift in SSC. The complete “puzzle” of how bathymetric changes affect water levels, tidal range, discharges, flow velocities and ultimately sediment fluxes should be made. For instance, the difference in ebb/flood velocities and the evolution of the velocity around slack, can be assessed to show whether or not the observed increase in tidal range actually leads to an increase in flood velocities or changes in the phasing of the flow velocities around slack, which could lead to an upwards shift of the ETM.

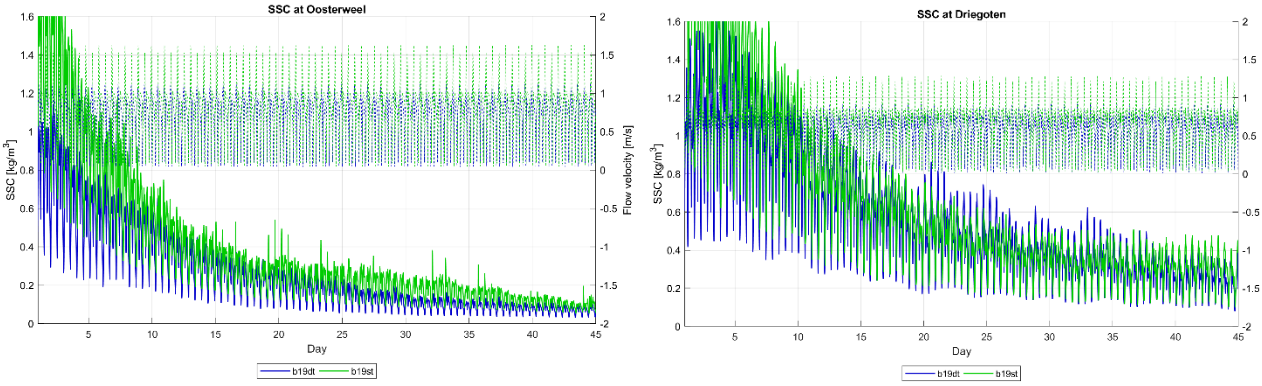

Figure 17 – Long term SSC (-) and flow velocity (--) at Oosterweel (left) and Driegoten (right) for tidal boundary condition scenario’s

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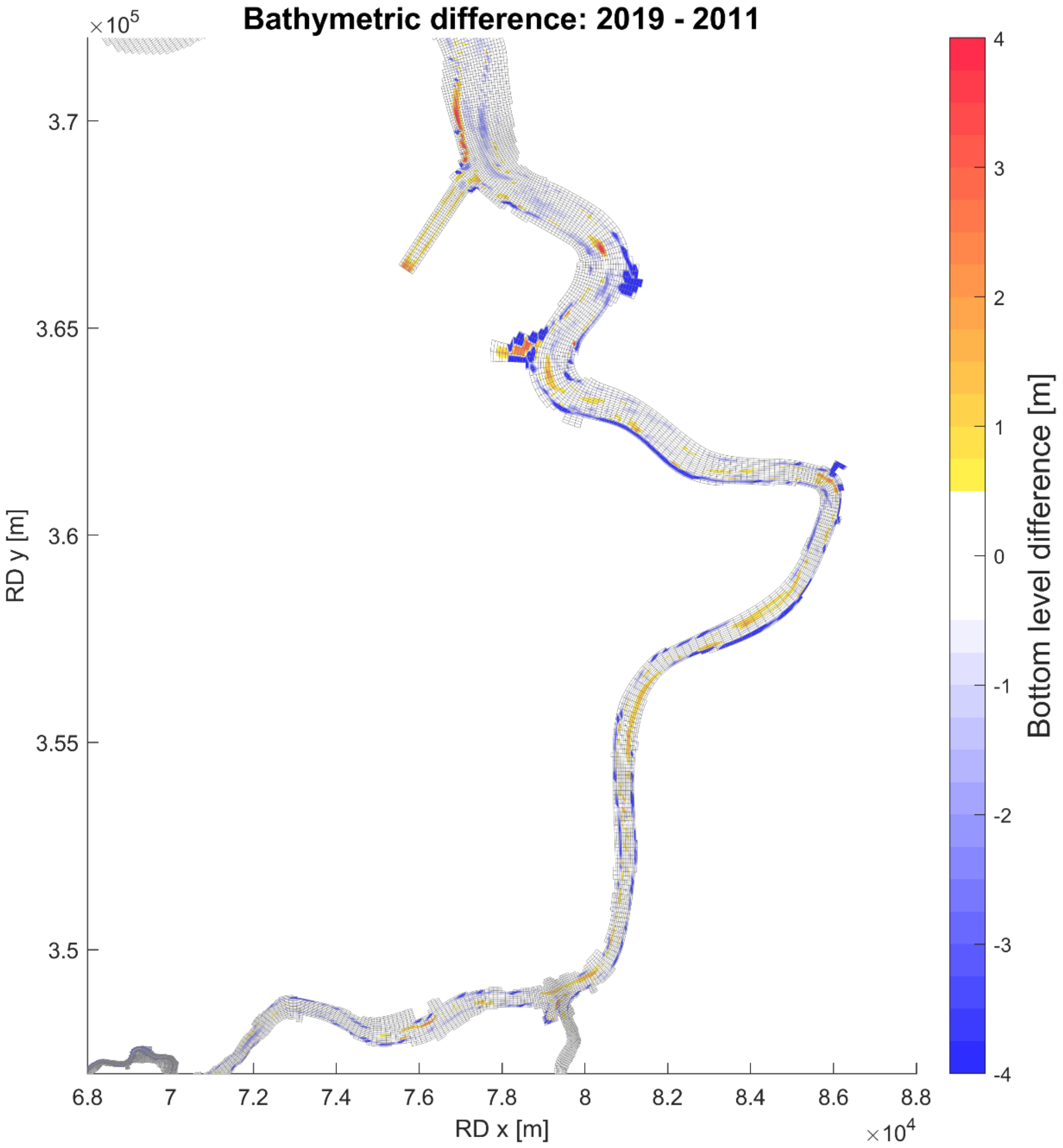
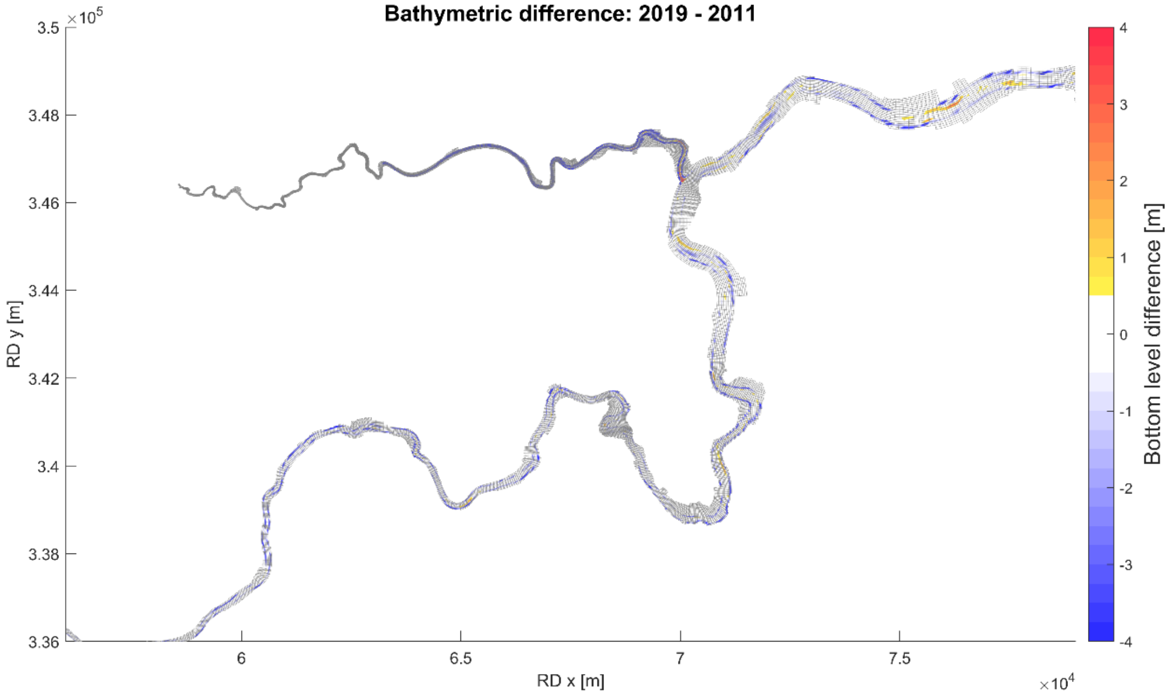
Appendix 1 Morphological changes Zeeschelde

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3.46
3.44
3.42
3.4
3.38
3.36
RD x [m]
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6.5
7
7.5
Bottom level difference [m]
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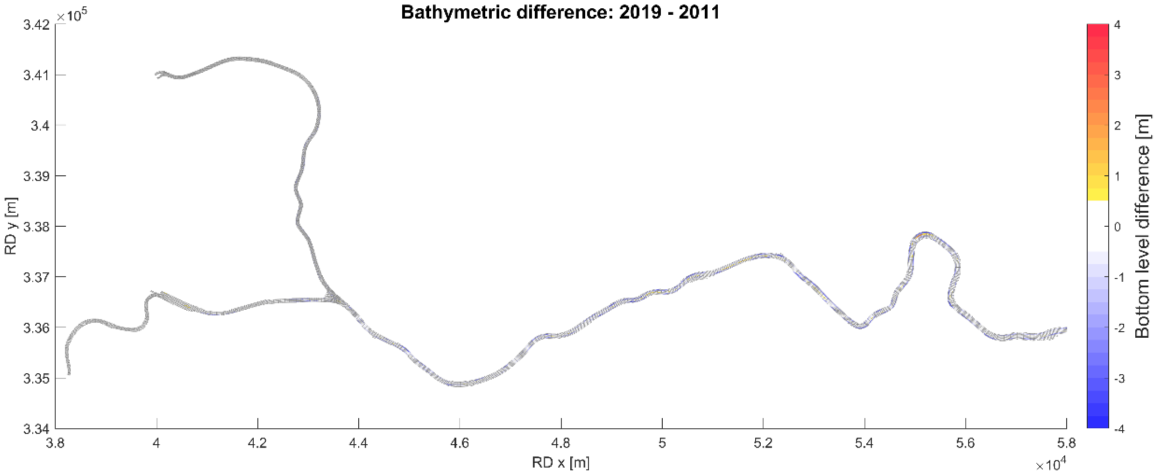
3
2
1
0
-1
-2
-3
-4


Bathymetric difference: 2019 - 2011
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3.4
3.39
3.38
3.37
3.36
3.35
3.34
RD x [m]
×10^4
3.8
4
4.2
4.4
4.6
4.8
5
5.2
5.4
5.6
5.8
Bottom level difference [m]
4
3
2
1
0
-1
-2
-3
-4

DEPARTMENT **MOBILITY & PUBLIC WORKS**
Flanders hydraulics Research

Berchemlei 115, 2140 Antwerp
T +32 (0)3 224 60 35
F +32 (0)3 224 60 36
waterbouwkundiglabo@vlaanderen.be
www.flandershydraulicsresearch.be