E-proceedings of the 36th IAHR World Congress
28 June – 3 July, 2015, The Hague, the Netherlands

MUD DISPOSAL AND SUSPENDED SEDIMENT CONCENTRATION IN THE LOWER SEA SCHELDT – TOWARDS A HYPERTURBID SYSTEM?

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ABSTRACT

In this paper, an analysis of continuous SSC measurements in the Sea Scheldt is presented. Information from different projects that focus on the state of the Scheldt Estuary (Belgium-Netherlands) and the management of dredging and disposal activities, is discussed to increase the insight in the effects of mud disposal and the increasing sediment concentrations (SSC) in the Lower Sea Scheldt.

Keywords: Scheldt estuary; sediment concentration measurements; dredging; mud disposal; water quality

1. INTRODUCTION

Several estuaries in Europe, e.g. the Loire in France and the Ems on the Dutch-German border, have witnessed a transition to a state characterized by very high suspended sediment concentrations, a so-called hyperturbid state. These estuaries underwent a ‘regime shift’ (Winterwerp, 2012; Winterwerp & Wang, 2013; Winterwerp et al. 2013) as the consequence of deepening, narrowing, rectification and reflection at hard upstream boundaries. These man-made changes to the estuaries led to a tidal amplification and an increase of the tidal asymmetry which resulted in an upward transport of mud. This in turn reduced the effective hydraulic resistance. Finally, this reduction closed a feedback loop as it leads to further tidal amplification.

In the Scheldt Estuary, and especially the Sea Scheldt (i.e. the Flemish part of the Scheldt Estuary, see Figure 1), several elements that contribute to the abovementioned feedback loop are identified. These may indicate that the system is, as other estuaries in the past, evolving towards a hyperturbid system.

2. BACKGROUND

2.1 Man-made interventions in the Scheldt estuary

The estuary has been subject to many historical interventions in the past centuries. Jeuken et al. (2007) and Van Braeckel et al. (2012) provide comprehensive overviews. Many interventions indicate that the Scheldt estuary is a heavily modified system, including activities such as land reclamations (22,000 ha in Belgium since 1100 AD, 40,000 ha in the Netherlands since 1650 AD), rectifications in the Upper Sea Scheldt, execution of flood protection plans, building of locks (Boudewijn lock, Kallo lock, Terneuzen, Dendermonde, Upper Sea Scheldt …), ports (Sloehaven), docks (Deurganckdock) and terminals (Europaterminal, Noordzeeterminal), dredging and sand mining (estimated at ca. 150 million m³ in the Western Scheldt since the 1950s), changes in the upstream input discharges, building of bank protections, groynes, …

The Scheldt estuary now is an intensely shipped area, holding the fairway to the ports of Vlissingen and Terneuzen in the Netherlands and Ghent and Antwerp in Belgium (see inset in Figure 1). In the 1970s and 1990s, the main fairway was deepened several times to allow for increasingly larger ships to access the ports. In 1995, the second deepening allowed tide-independent access to the port of Antwerp for ships up to a draught of 11.6 m.

Already in 2001 (DZL & AWZ, 2001) the Long Term Vision (LTV) for the Scheldt estuary provided a framework for sustainable management of the Scheldt estuary in a political context of Dutch-Flemish cooperation. The focus of the LTV was aimed at three principal functions: safety against flooding; navigable access to harbours; and naturalness of the physical and ecological system. The measures, projects and directives for monitoring needed to achieve the estuarine state described in the LTV were described in the Development Plan 2010 for the Scheldt estuary (Proses, 2005). One of the projects was the deepening and widening of the navigation channel to allow for tide-independent navigation up to a draught of 13.1 m.

In the Western Scheldt (the Dutch part of the estuary), 11 sills and a few shoals were deepened in 2010 to a depth of -14.5 m LAT (Lowest Astronomical Tide), for a total capital dredging volume of 7.7 million m³. Parallel to this, a flexible disposal strategy was devised (Consortium Arcadis-Technum, 2007; VNSC, 2009) to contribute to the morphological equilibrium of the multi-channel system (through less disposal in secondary channels, as practiced in the past), to

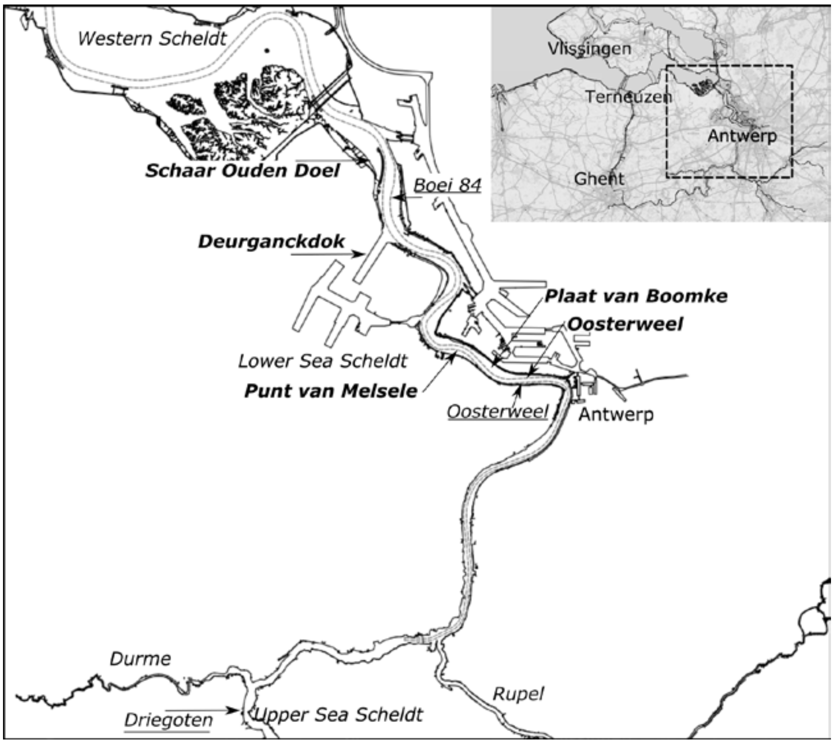

Figure 1: Location map and names of important dredging and disposal locations (bold) and measuring sites (underlined).

contribute to the creation of new ecologically valuable areas near the sand bars (through disposal near sand bars to create low dynamic shallow water and intertidal area), and to conserve existing ecologically valuable areas. This process is monitored closely and reported periodically (Depreiter et al., 2012, 2013; biannual reports, see IMDC, 2014a, 2014b and monthly reports, see e.g. IMDC, 2014c).

In the Sea Scheldt, sills between the Dutch-Flemish border and the Deurganckdock were deepened, a sill at the entrance of the Deurganckdock was removed, and a pivoting area for ships was dredged. The activities took place between 2008 and 2010. In total, about 6.6 million m³ of sediment was dredged.

The Deurganckdock is a tidal dock with a length of 2.7 km, a width of 400 to 450 m. The main construction phase was carried out between 2005 (opening of the dock) and 2007 to early 2008 (extension of the dock). A current deflecting wall was installed at the entrance in 2010-2011 to reduce sedimentation (siltation) in the dock (Roose et al., 2013, Decrop et al., 2013). As of 2011, the maintenance dredging level was deepened to its design level.

2.2 Tidal amplification

During the past century, the tidal range in the estuary has increased significantly (e.g. Kuyper, 2013). The amplification of the tide compared to Vlissingen (near the mouth of the estuary) has increased from a factor 1.2 (1901-1910) near Antwerp (at 78 km from the mouth) to 1.4 (2001-2010) near Tielrode, 30 km further upstream. The most significant breakpoint in the development of high and low water levels, and thus the tidal range, is observed in the 1970s in the eastern part of the Western Scheldt as well as the entire Sea Scheldt. These effects are attributed to the first deepening of the Scheldt. During these works, large amounts of sand were extracted from the estuary. Figure 2 illustrates the peak in total sand volume removed from the estuary in the early 1970s which concurs with the onset of a rapid increase of the tidal range in Antwerp.

2.3 Relevant monitoring programs

In the framework of the Long Term Vision and the Development Plan 2010, the Moneos-T execution plan (Schrijver & Plancke, 2008) was set up for monitoring the effects of the third deepening of the Scheldt. Data analysis and reporting, including the results presented in this paper, is carried out within the framework of the “Monitoring Programme Flexible Disposal” since 2010 (e.g. IMDC, 2014a, 2014b, 2014c) and extensive sedimentation processes monitoring and data analysis “Evaluation of the external effects on the siltation in Deurganckdock” since 2006 (e.g. IMDC, 2014d), both commissioned by the Maritime Access Division of the Flemish Government.

In the Sea Scheldt, the OMES monitoring and research programme was set up after a heavy storm in 1994, to investigate the environmental impact of the Sigma Plan (the flood resilience plan in Flanders) (Meire, 1997). This program is based on periodic (monthly to bimonthly) measurement campaigns, aimed at the functioning of the pelagic ecosystem, mearsuring e.g. the light climate (attenuation of light in the water column and sediment concentrations.

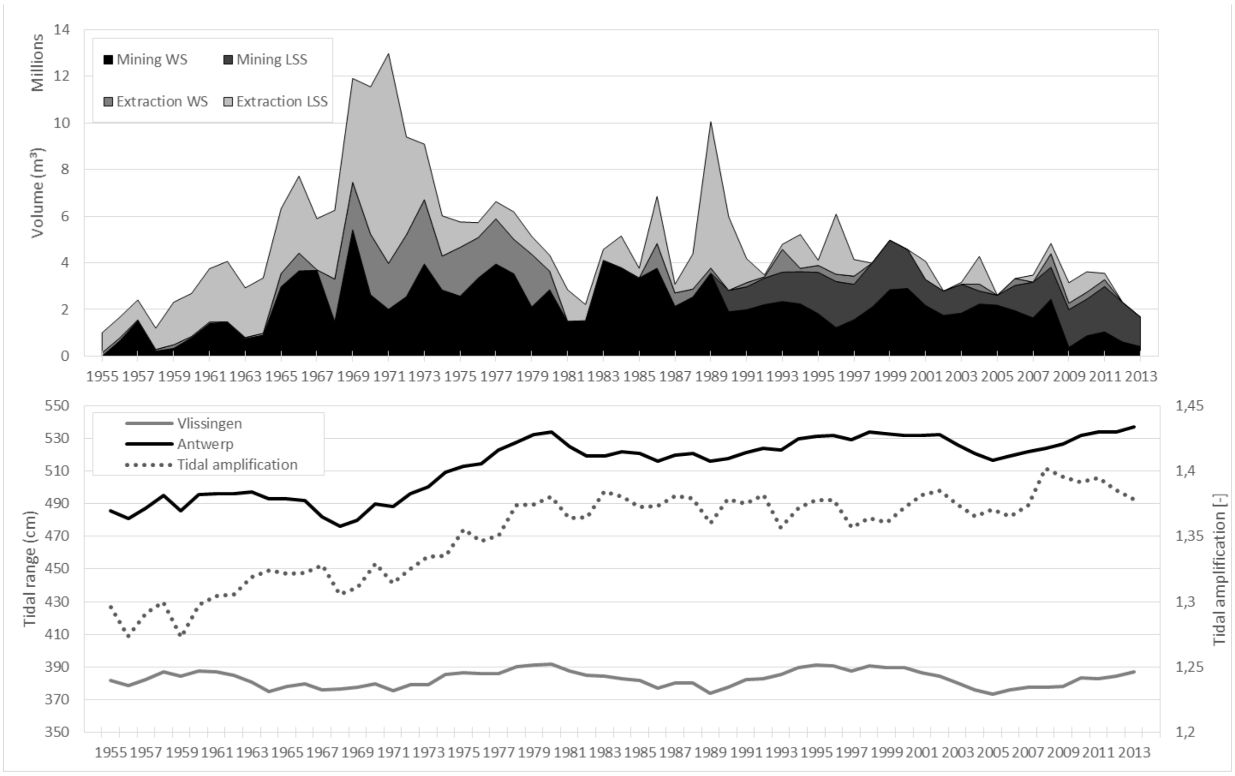

Figure 2: Sand mining and extraction in the Lower Sea Scheldt and Western Scheldt compared to tidal range and amplification between 1955 and 2013. Data from T2009-consortium (2014) and IMDC (2014a).

3. DATA

3.1 Dredging and disposal data

In the Lower Sea Scheldt, dredged mud and sand are (currently) disposed at separate disposal sites. The discrimination between sand and mud is made by the dredger operators per trip, based on the behaviour of the sediment in the ship's hold. Sand is being disposed at the former secondary channel which was closed by a groin in the 1960ies, called "Schaar Ouden Doel", located near the Dutch-Belgian border. This sand is being mined in this location by contractors. Mud disposal sites are situated along shoals west of Antwerp, called "Punt van Melsele" (left bank), "Plaat van Boomke" and "Oosterweel" (two juxtaposed sites on the right bank). In the past, mud had also been disposed at "Schaar Ouden Doel" and other sites.

The dredging and disposal activities in the Lower Sea Scheldt are recorded in the "Bagger Informatie Systeem" (BIS; dredging information system). BIS records consist of ship information, dredged volume, sediment type (sand or mud), dredging and disposal location and other metadata. From this database, the mud disposal volumes through time have been extracted. The volumes (Figure 3) are presented in 'reduced volume' (V'), which is a calculated volume based on a mud density of 2 ton per m^3. Mud disposal volumes varies around ~500.000 m^3 V' per year before 2000. In 2001-2003, volumes between 2 and 3 million m^3 are disposed. Between 2004 and 2008, the mud disposal volume is always lower than 2 million m^3 but higher than before 2001. After 2008, the yearly volume increases up to nearly 5 million m^3 in 2011, to decrease again in 2012-2013, but remaining 3 million m^3 and above any volume recorded before 2011.

These variations, especially the higher values, can be linked to specific interventions. First of all, the high mud disposal volumes in 2001-2003 relate to the deepening and maintenance of sills between Deurganckdock and the Dutch-Belgian border, as preparation to the opening of Deurganckdock. Since 2005, mud is dredged increasingly in Deurganckdock and the sill just north of it ("Drempel van Frederik"), but also the entrances to the Zandvliet- and Berendrecht Lock and the Kallo Lock require more maintenance dredging (Figure 4). In 2011, a peak in the mud dredging volumes occurs mostly due to the deepening of the Deurganckdock and the nearby sill.

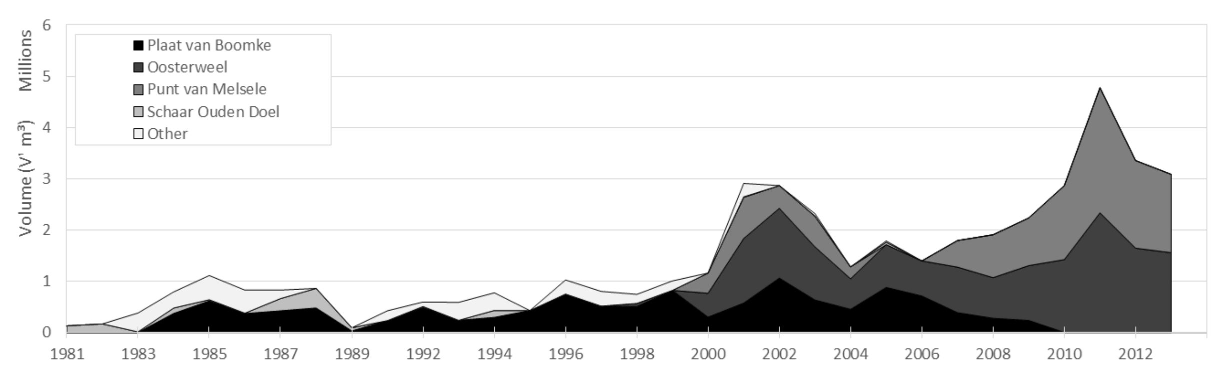

Figure 3: Mud disposal volumes per site in the Lower Sea Scheldt (reduced volume V') from 1980 to 2013. Data from IMDC (2014a).

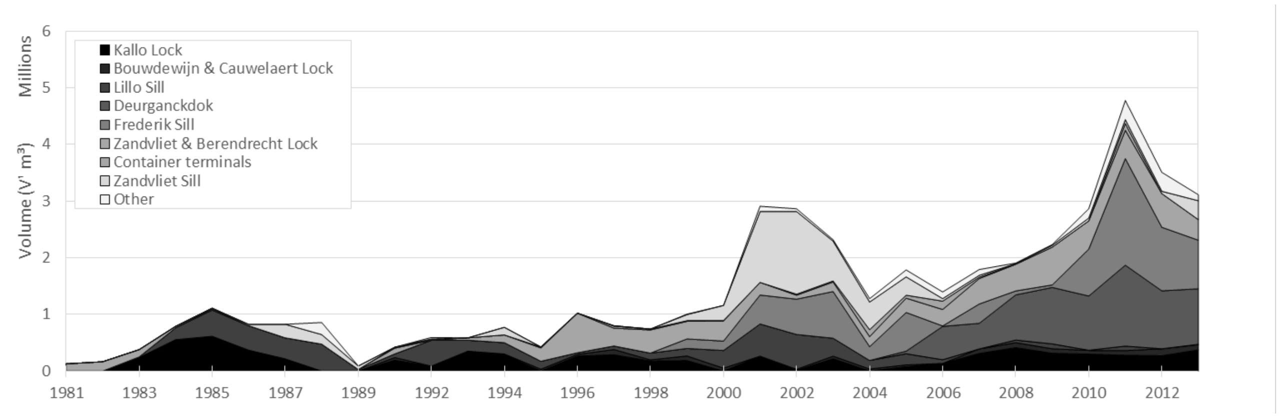

Figure 4: Mud dredging volumes per site in the Lower Sea Scheldt (reduced volume V') from 1980 to 2013. Data from IMDC (2014a).

3.2 Continuous sediment concentration measurements

Continuous turbidity measurements are carried out by Flanders Hydraulics Research at different locations in the Sea Scheldt. Here, we will focus on 3 stations. “Boei 84” is a measuring station near the Dutch-Belgian border. Two turbidity sensors are installed and measure at 0.8 and 3.3 m above the river bed (8.5 m and 6 m below low water level). In the vicinity of the mud disposal sites, the “Oosterweel” station also has two sensors, at 1 m and 4.5 m above the river bed (5.5 m and 2 m below low water level). A third station is further upstream in the Upper Sea Scheldt, “Driegoten”. It has one sensor. Measurement data is reported yearly in the framework of the MONEOS project, e.g. Vereecken et al. (2011) and Vanlierde et al. (2013).

All measurement sensors have been replaced at least once through time. As a consequence, the raw turbidity measurements cannot be compared directly. Through calibration to water samples at discrete times, turbidities are converted to suspended sediment concentrations (SSC, in mg/L), as detailed in the MONEOS report by Flanders Hydraulics Research. To reduce tidal variations and noise in the data, two-day averaging has been applied to the data, resulting in a smoother signal.

Another limitation to the data set is the occurrence of saturation or clipping of the signal, due to the range and/or resolution settings in measurement sensors. The clipping has been eliminated through a correlative model of the 25-percentile value of the SSC signal (within a two-day measurement window) and the average of the same signal, within a year without clipping or saturation. Strong correlations (Oosterweel upper sensor: r=0.98; figure 5) were observed. In years with clipped signals, the same correlation (per sensor) was applied to estimate the average SSC based on the behaviour of the 25-percentile SSC value at each moment (see IMDC, 2014a). Figures 6 and 7 display the continuous and two-day averaged SSC values of the Boei 84 and Oosterweel site. Clipped and ‘restored’ data will be indicated with arrows. Derived statistics are presented in Table 1 and summarized in Table 2. For two sensors with sufficiently long timeseries, 99-percentile trends and values have been determined as well (excluding the years with clipped data).

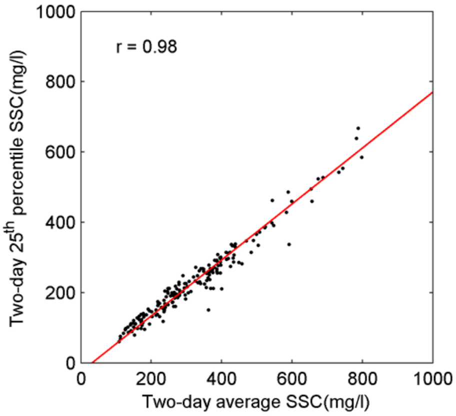

Figure 5: Correlation between bidiurnal 25-percentile and average SSC; Oosterweel upper sensor (IMDC, 2014a).

The data at Oosterweel show a decreasing trend between 2001 and 2005 (11 mg/L) and an increase from 2005 to 2011 (34 mg/L for the upper sensor and 50 mg/L for the low sensor). In 2011-2013, a decrease is observed again (11 mg/L in the upper sensor and 10 mg/L in the lower sensor). The 99th percentile values increase significantly. Measurements upwards of 800 mg/L were increasingly observed in 2013 (3% (upper) and 5% (lower of the time). Before 2007, measurements higher than 800 mg/L never occurred.

At Boei 84, an increase of 13 mg/L was observed during the period 2006-2013. The increase is lower (7 mg/L) in 2011-2013. Here also, the 99th percentile increased significantly (+60 mg/L/year in 2005-2011 and +12 mg/L/year in 2011-2013). 99 percentiles values were higher than at the Oosterweel site, probably because the sensors are closer to the river bed.

Table 1: Statistics derived from continuous SSC measurements: yearly average SSC and standard deviation, 99-percentile SSC and exceedance fraction of 800 mg/L SSC.

Sensor		2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
OOSTERWEEL Upper	Average	133	188	177	113	108	145	177	210	235	244	348	320	327
	Standard dev.	74	98	99	68	63	82	105	112	148	158	160		198
	99th percentile	322	439	426	314	272	375	541	497	668	775	772		962
	% > 800 mg/l	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%		3%
OOSTERWEEL Lower	Average						163	199	248	271		415	350	370
	Standard dev.						90	100	124	159				217
	99th percentile						424	507	576	772				1078
	% > 800 mg/l						0%	0%	0%	1%				5%
BOEI 84 Upper	Average						197	182	209	210	205	212	179	263
	Standard dev.						144	144	166					
	99th percentile						772	742	866					
	% > 800 mg/l						1%	1%	1%					
BOEI 84 Lower	Average						303	293	310	318	352	364	233	377
	Standard dev.						203	214	244	253	266	283		269
	99th percentile						973	975	1128	1177	1227	1234		1258
	% > 800 mg/l						4%	4%	6%	7%	7%	10%		9%
DRIEGOTEN	Average									176	161	377	181	158
	Standard dev.													128
	99th percentile													633
	% > 800 mg/l									2%	0%	16%	0%	0%

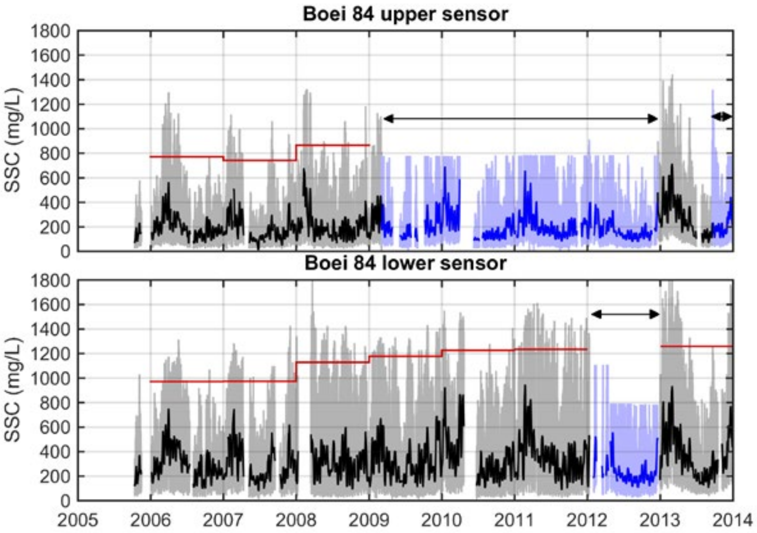

Figure 6: Continuous SSC measurements at Boei 84 site, Lower Sea Scheldt (IMDC, 2014a). Arrows and blue linestyles indicate ranges with saturated data. Light blue and gray are full data range, bold black and blue are two day averages. Red lines represent 99-percentile values.

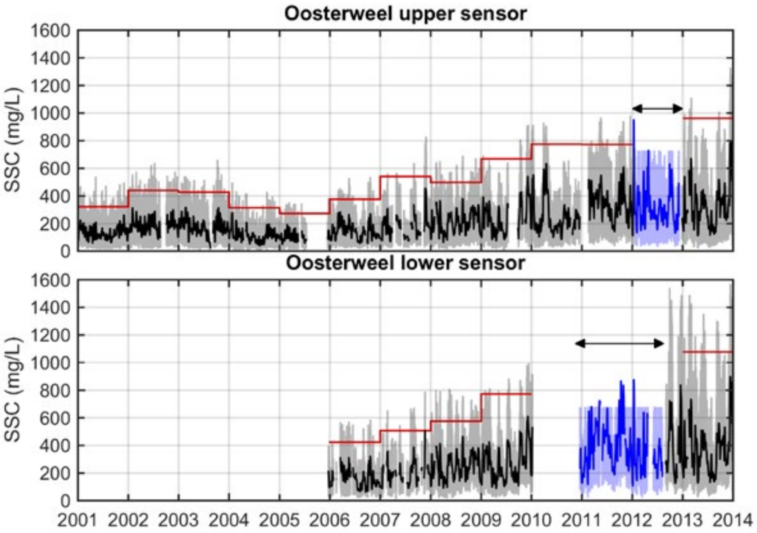

Figure 7 :Continuous SSC measurements at Oosterweel site, Lower Sea Scheldt (IMDC, 2014a). Arrows and blue linestyles indicate ranges with saturated data. Light blue and gray are full data range, bold black and blue are two day averages. Red lines represent 99-percentile values.

Table 2: Summary table showing average trend direction and 99-percentile SSC and 99-percentile values in the Sea Scheldt (Boei 84, Oosterweel, Driegoten stations)

	Trend	**Maximum year SSC average (mg/L)**	**99-percentile trend**	**Maximum year SSC 99-prctile (mg/L)**
B84 Upper	2007-2013 +	2013 (263 mg/L)		
B84 Lower	2007-2013 +	2013 (377 mg/L)	2006-2013 +	2013 (1258 mg/L)
OWL Upper	2005-2013 +	2011 (348 mg/L)	2005-2013 +	2013 (962 mg/L)
OWL Lower	2006-2013 +	2011 (415 mg/L)		
Driegoten		2011 (377 mg/L)		

The data show that the past decade, the average SSC measurements indicate increasing sediment concentrations at Boei 84 and Oosterweel. At the Driegoten site, no trend is observed, but the 2011 year clearly stands out in average SSC. Maximum SSC observations have been observed in 2013 at the Boei 84 and in 2011 in the three other locations. The maximum extreme SSC values (99-percentiles) have been recorded in 2013, following a period of increase since 2005-2006 (Figure 8).

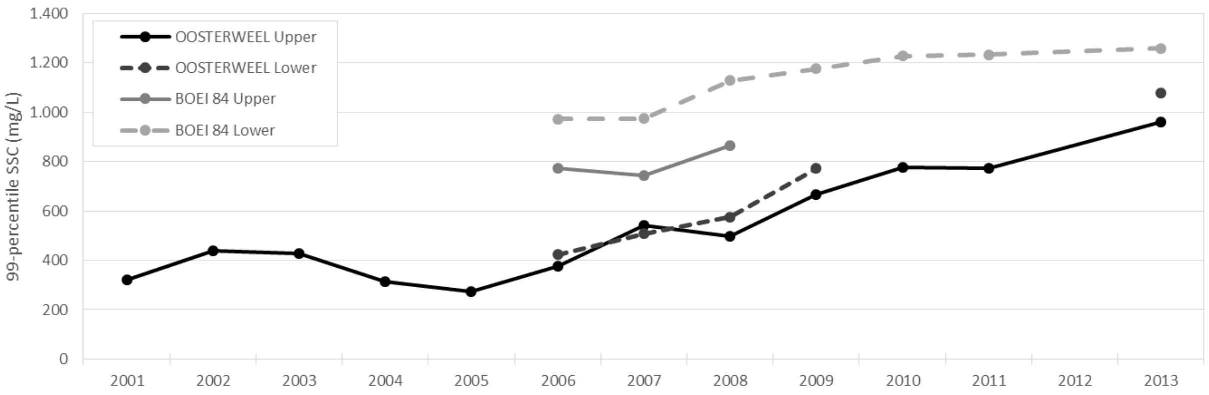

Figure 8: Evolution of the yearly 99-percentile SSC measurements in 4 different sensors.

4. ANALYSIS

4.1 Trends in mud disposal and continuous measurements

In the data description, it is shown that the Oosterweel sensors show peak average SSC in 2011, in parallel to the peak mud disposal in the vicinity (Figure 9). On a longer timescale, a covariation of the timeseries is visible: elevated mud disposal in 2001-2003 corresponds to average SSC values from 130 – 190 mg/L. In 2004-2007, less disposal has taken place, which translates in lower SSC averages. As of 2006, a systematic increase in the mud disposal volumes is observed while a similar trend in the average SSC is observed. In 2012 and 2013, the average SSC is somewhat lower, while the mud disposal volumes are lower as well; both parameters are still higher than in years before 2011. The lower sensor at Oosterweel is less complete but shows similar trends as the top sensor (Figure 10).

This behavior of the SSC signal can be explained by the proximity of the mud disposal locations. Current velocities observed at the Oosterweel lower sensor during spring tide exceed 1 m/s, while at neap time velocities between 50 and 75 cm/s occur (e.g. Taverniers et al., 2012). These velocities are sufficient to resuspend the freshly disposed mud from the Oosterweel disposal locations. Morphological analysis (IMDC, 2013b) indicates that the disposal locations Punt van Melsele and Oosterweel do not show significant accretion but rather deepening. The Plaat van Boomke location has not been used since 2010 as this location did become too shallow. At Oosterweel, there is frequent disposal of sediment, and periods with a high disposal frequency are alternated with periods without sediment disposal. These periods without sediment disposal have a clear effect on the SSC signal at Oosterweel, both in the lower and upper sensors. Figure 12 shows that the SSC signal clearly decreases with the number of days after nearby disposal of sediment ($r = -0.97$, $p < 0.0001$), further corroborating the link between measured SSC at Oosterweel and nearby disposal (Vandenbruwaene et al., 2015).

The measurements at the Boei 84 upper and lower sensors (Figure 11) show an increase in SSC since 2007, although a (visual) correlation with the mud disposal is not present.

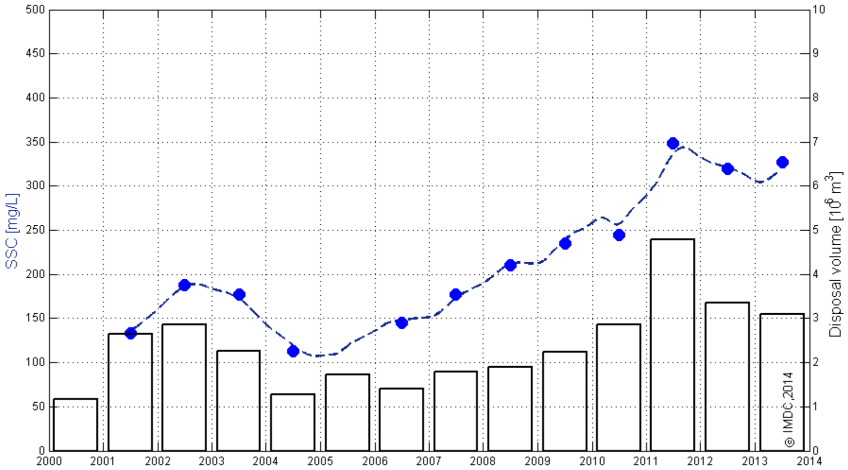

Figure 9: Trend of the yearly mud disposal volume and the year-averaged SSC at Oosterweel top sensor.

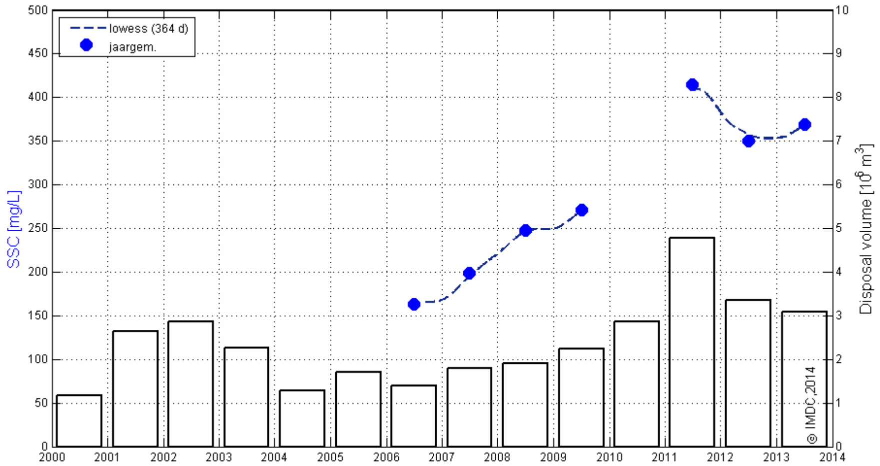

Figure 10: Trend of the yearly mud disposal volume and the year-averaged SSC at Oosterweel lower sensor.

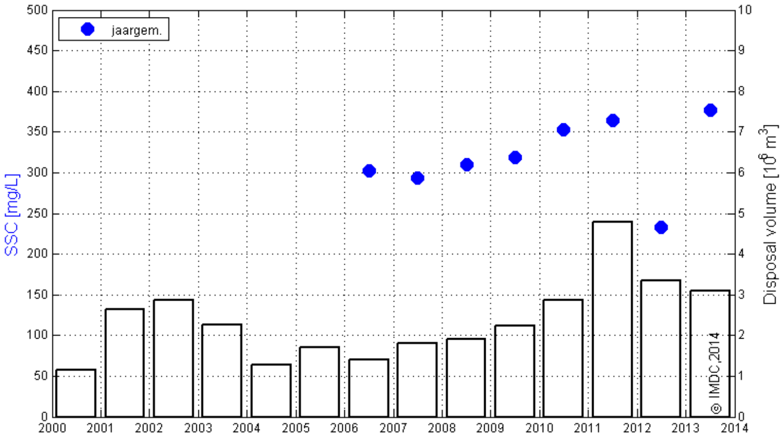

Figure 11: Trend of the yearly mud disposal volume and the year-averaged SSC at Boei 84 lower sensor. The 2012 average SSC is much lower than expected due to missing in the spring season.

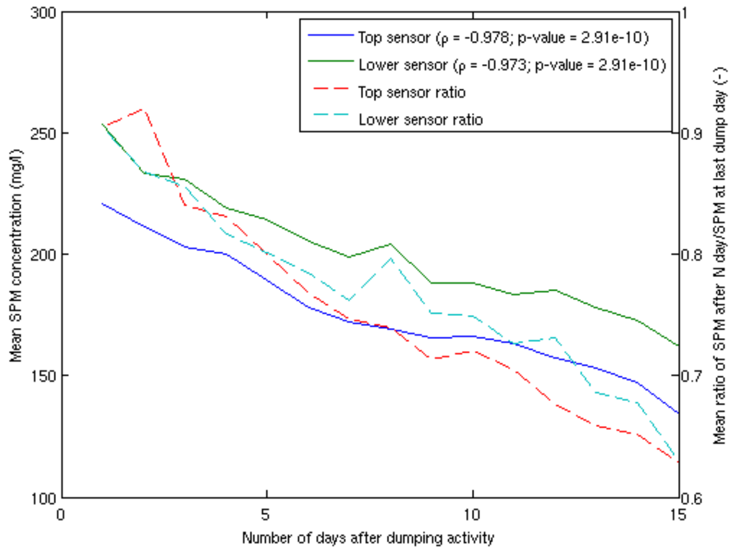

Figure 12: SSC evolution at Oosterweel in the first two weeks after sediment disposal nearby

4.2 Regression analysis

To further elucidate the covarying trends, a multivariate regression analysis has been performed on turbidities measured with RCM9 devices at Oosterweel (top sensor) and Boei 84 (lower sensor) (IMDC, 2013c). For this analysis, it has been chosen not to work with SSC to avoid errors or uncertainty due to calibration between turbidity and SSC. The analysis has been performed on weekly averages because the available mud disposal data is also aggregated at the week level.

The regression models contains following significant terms: a constant term, an autoregressive component (which represents the average turbidity in the previous week; this effect is supported by the relation in Figure 12), tidal components MSF (neap-spring cycle), MM (monthly lunar cycle), SA (yearly cycle, or seasonality) and MF (14 day lunar cycle); the weekly mud disposal volumes and finally a linear trend. Additionally for the Boei 84 lower sensor, the current velocity also significantly contributed to the variation; this was not the case for Oosterweel.

The relative importance of the terms is evaluated through the coefficient of partial determination (Eq. 1, Table 3), defined as

$$r^2_{X_j} = \frac{SSR\ (model) - SSR\ (model\ excl. X_j)}{SSE\ (model\ excl. X_j)} \qquad [1]$$

with $r^2_{X_j}$ the coefficient of partial determination of term X_j, SSR the sum of square of the regression, SSE the sum of the squares of the residuals. The *model* is the complete model, while *model excl.* X_j is the model from which the component or term X_j is omitted.

Table 3: Coefficients of partial determination per component of the regression models

Oosterweel (upper)	$r^2_{X_j}$	**Boei 84 (lower)**	$r^2_{X_j}$
Mud disposal volume	45.1%	Autoregressive component	38.6%
Autoregressive component	45.0%	Neap-spring cycle (MSF)	35.6%
Neap-spring cycle (MSF)	36.0%	Mud disposal volume	34%
Trend	9.6%	Seasonality	15.7%
Monthly lunar cycle (MM)	8.7%	Monthly lunar cycle (MM)	12.1%
Biweekly lunar sycle (MF)	5.0%	Biweekly lunar sycle (MF)	12.0%
Seasonality	3.9%	Current velocity	5.6%
		Trend	2.8%

In the Oosterweel regression model, the mud disposal volumes and the autoregressive components are the strongest terms. The significance of this is that the weekly averaged turbidity strongly depends on the turbidity of the preceding week and the mud disposed in the current week. This observation corroborates the visual interpretation above of the similar trends in SSC and mud disposal volume. Futhermore, it appears that the neap-spring cycle also strongly influences turbidity. This is to be expected as this cycle determines current velocities in the whole system, and thus the potential for erosion and/or resuspension.

The Boei 84 regression model shows that the autoregressive factor and the neap-spring cycle are the strongest factors in the model. The mud disposal volume is a strong third factor in the model. Seasonality and other terms are much weaker in the model. The strong presence of the mud disposal volume in this model is unexpected because the resemblance in trends between SSC and yearly mud disposal was not as striking as in the Oosterweel case.

Both sets of residuals (i.e. the difference between the observations and the model) do not display a trend. A certain amount of variation is still present, however (Figure 13). It is thought that upstream discharge variations and/or suspended sediment loads from the catchments may explain some of these variations as well although they do not show significant trends in the last years.

This analysis confirms that the impact of mud disposal on turbidity (or SSC) in the Lower Sea Scheldt is important. The recent increase in SSC can therefore be related for a large part to the increased mud disposal volumes.

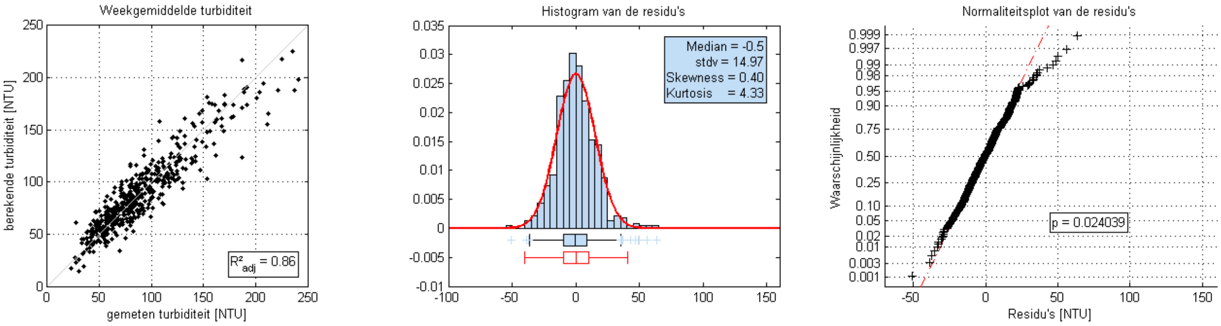

Figure 13: Example of residual analysis of the Oosterweel model. Note the underestimated extreme measured values.

5. DISCUSSION

5.1 Periodic surface sampling and other data sources

The biweekly to monthly sampling and monitoring campaigns in the OMES framework have changed through time, but based on the past years, measurements also indicated that 2011 was a year with higher SSC than preceding years (IMDC, 2013a; Maris et al., 2013; Figure 14). It must be noted however that OMES data has a higher degree of uncertainty due to the independence of tidal phase of the measurements.

Other data sources, also recorded in the framework of the OMES project, corroborate with the 2011 peak SSC data. The light attenuation appeared to be higher on average in 2011 than in 2010 or 2013. Simultaneously, lower algal biomasses and primary production were observed in most stations (Maris et al., 2013).

Vandenbruwaene et al. (2015) also show higher surface SSC values in the OMES dataset in 2011 for the lower Sea Scheldt (in green on Figure 15). In the Western Scheldt, surface SSC was higher in 2010, and in the upper Sea Scheldt in 2009 and 2011. Note the large natural variation in the dataset however.

Flanders Hydraulics Research also performs measurements depending of the tidal phase, at the turning of the tide and at half-tide ebb (Vereecken et al., 2012; Taverniers et al.; 2013a; Vanlierde et al.; 2013, 2014). The highest concentrations are observed at Oosterweel in 2011 and confirm our report above, but so far, no clear temporal trends throughout the Sea Scheldt have been reported.

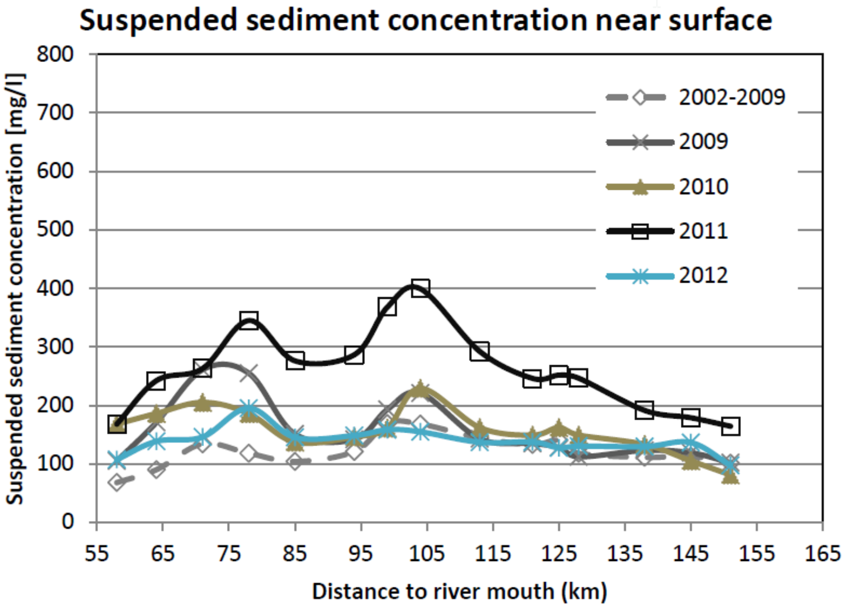

Figure 14: Surface suspended sediment concentrations (source: IMDC, 2013a; Maris et al., 2013).

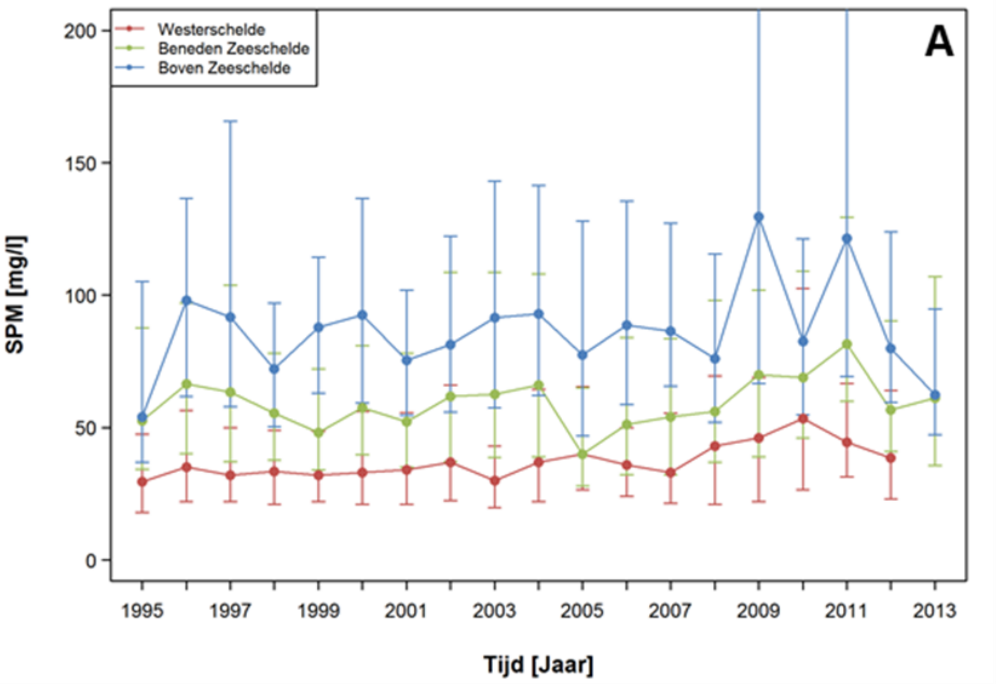

Figure 15: Surface SSC over the period 1995-2013 in the Scheldt estuary. Data from the OMES dataset. Dots represent the median, error bars represent the 25 and 75 percentile.

In the framework of the Long Term Vision research programme, mud dispersion after disposal has been studied to suggest alternative disposal locations (IMDC, 2013b and Van Kessel et al., 2015 (this issue)). This analysis showed that upwards disposal of mud (as is the case now, from the Deurganckdock area to the Oosterweel area) has a strongly increasing effect on SSC (Figure 16). Seaward disposal leads to lower SSC due to increased mixing and dispersion.

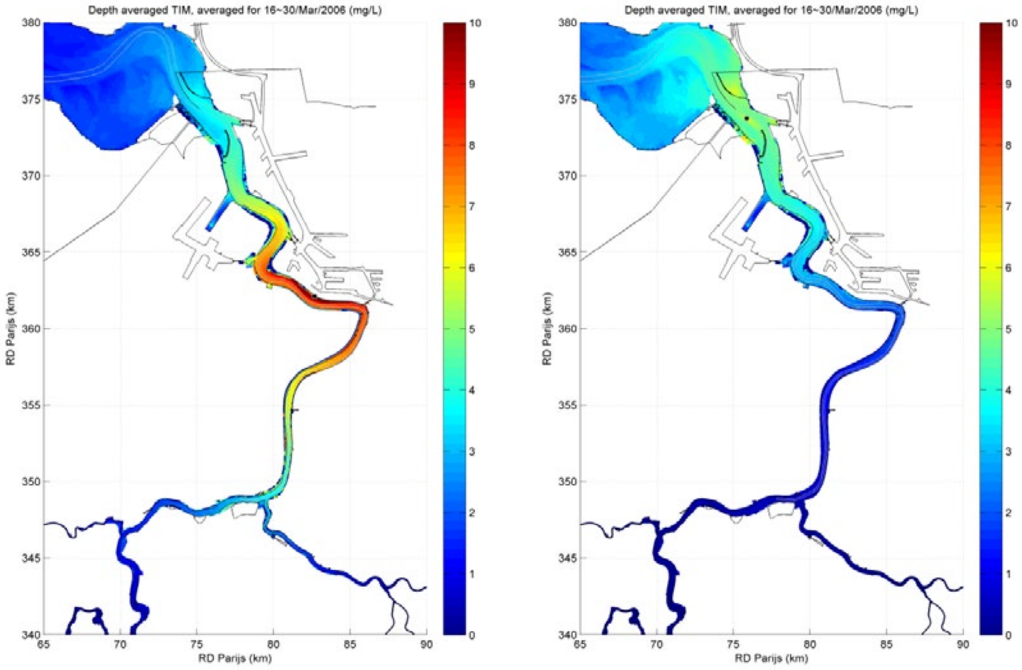

Figure 16: Average suspended sediment concentrations over spring-neap cycle after unit mud disposal at Oosterweel (left image) and Schaar Ouden Doel (right image). (source: IMDC, 2013b).

5.2 Towards a hyperturbid system?

In the Lower Sea Scheldt, processes that make part of the positive feedback loop described by Winterwerp (2012), Winterwerp & Wang (2013), Winterwerp et al. (2013), have been identified. The increase of the tidal amplitude can be explained by the first deepening of the Scheldt estuary during the 1970 that was characterized by large sediment extraction volumes. The increased volume of the estuary undoubtedly led to an increased tidal propagation in the estuary.

In more recent years, increasing suspended sediment concentrations were observed in the continuous SSC measurements. It is proposed that a large part of the variations and increase are explained by the mud disposal increase, in combination with the mud disposal strategy that currently disposes mud against the SSC gradient (towards the sediment concentration maximum, located upwards of Antwerp). A 'recirculation' pattern appears to be invoked by this process: mud disposed at the Oosterweel location is resuspended and caught in mud sedimentation areas. Important sedimentation areas are the Deurganckdock and lock entrances and access channels due to the low dynamical conditions. To prevent disturbance of navigation and accessibility, these areas are regularly dredged which leads to redeposition at the Oosterweel site.

At the moment, the mud disposal strategy mostly effects the Lower Sea Scheldt and the influence seems to be reversible (based on the decreased SSC in 2012 and 2013 in the continuous measurements). The numerical modelling (IMDC, 2013b, Van Kessel et al., 2015) suggests possible alternatives by disposing the dredged mud down the SSC gradient. The speed at which the SSC appears to respond may lead to a quick decline in SSC levels, with positive feedback through less deposition in Deurganckdock and lock entrances.

Although this would not resolve the tidal amplitude increase observed in the past decades, the risk for reduction of the hydraulic drag would be effectively reduced. Another question rises however: at which spatial scale does the hyperturbidity feedback loop act? In other words: over which area do SSC need to be increasing to reduce the effective hydraulic drag to induce further tidal amplitude effects? It is not certain whether the effects observed near Oosterweel would suffice to drive this process.

6. CONCLUSIONS

The Scheldt Estuary has undergone vast changes and interventions, not in the least in the past century. It is known from other estuaries and physical theory that these can lead to amplification of the tidal amplitude. A positive feedback loop has been hypothesized and supported by observations in several estuaries, showing that an increase in tidal amplitude may lead to an increase in sediment concentrations, decrease of hydraulic drag resistance and again in tidal amplitude increase. Estuaries that have undergone such transformations are now characterized by hyperturbid conditions, the presence of fluid mud layers and ultimately, a poor ecological state. High turbidity for instance excludes light penetration in the water column and inhibits thus primary production. Stratified fluid mud layers block oxygen transport through the water column leading to anoxic conditions.

In this paper we addressed the state of the Scheldt estuary. The feeds to the positive feedback loop appear to be present: increase of tidal amplitudes in the past decades, and more recently changes in SSC. Although several datasets and proxies (continuous SSC, light attenuation) point to an increased SSC in the (Lower) Sea Scheldt, other analyses (IMDC, 2014; Vandenbruwaene, 2015) indicate that there are no clear long-term trends after removal of known relations and trends such as the spring-neap cycle.

Although the long-term trend may still not be revealed, our analysis and numerical modelling (IMDC, 2013b, Van Kessel et al., 2015 (this issue)) clearly shows that mud disposal in the Low Sea Scheldt influences a larger area. Increased mud disposal leads to rather immediate elevated SSC values. On the other hand, a decrease of mud disposal also resulted in decreased SSC values.

It is suggested that future sediment management choices will partly determine whether SSC will continue to rise in the Sea Scheldt. The topic of hyperturbidity and regime shift is currently researched to a further extent within the research program “Agenda of the Future” and the “Integrated Plan of the Sea Scheldt”. Ultimately, we recommend to further investigate smart mud disposal and management strategies in the Lower Sea Scheldt to avoid an unwanted regime shift.

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