BAS VAN MAREN AND THIJS VAN KESSEL

LONG-TERM EFFECTS OF MAINTENANCE DREDGING ON TURBIDITY

ABSTRACT

Maintenance dredging is required in many estuaries worldwide to provide access to ports and inland waterways. Sediment is dredged from ports and access channels and disposed of by placing it back at another location in the estuaries. This results in a common belief that maintenance dredging practices lead to enhanced turbidity. Usually numerical methods are utilised to estimate the short-term effects and transport of disposed sediment but they are not designed to estimate the long-term effects of dredging. Quantifying the return flow of sediment from the disposal site to the port is a long-term process and therefore cannot be fully assessed using traditional methods. As such, the quantitative information available to optimise disposal locations for minimum ecological impacts and / or economic impacts is incomplete.

A recently developed dredging module within the open-source modelling platform, Delft3D, is able to capture the two fundamental processes necessary to model the long-term impacts of dredging on turbidity. These two processes are:

- sediment buffering in the seabed and;
- integral modelling of ports and associated dredging requirements.

This model has been applied to three case studies where large amounts of dredging take place: the Ems estuary, the Scheldt estuary, and the Port of Rotterdam. Through these case studies the effects of dredging and disposal locations on long-term turbidity patterns and the return flow of sediment dredged from various ports can be quantified.

INTRODUCTION

During maintenance dredging of ports and waterways, sediment is removed from one part of an estuary or coastal sea and disposed elsewhere. In the short-term, such maintenance dredging leads to increasing concentration levels in the direct vicinity of the dredging and disposal location (e.g., Pennekamp et al., 1996). Over longer timescales and larger spatial scales, the impact of maintenance dredging on the sediment dynamics is much more difficult to quantify (van Kessel and van Maren, 2013) and may blend in with natural occurring sediment plumes (Aarninkhof, 2008). Some of the sediment disposed near placement areas will be transported back into the port or channel it was dredged from. This recirculation rate is often not known but may vary greatly from only a few per cent to nearly 100%.

Above: A new dredging model was applied to study the effects of sediment dredging and disposal on long-term turbidity patterns in the Ems Estuary. (Image: Marieke Eleveld, Deltares)

The aim of this article is to give an overview of recent insights into the long-term effects of maintenance dredging using several case studies in which a new dredging module has been applied. This article will first conceptually describe the impact of dredging on estuarine sediment dynamics and later explain about the dredging module. The article will also highlight three case studies, at the Ems estuary, the Scheldt estuary, and the Port of Rotterdam, in which the module has been applied and finally it will summarise the long-term effects of dredging.

QUANTIFYING HUMAN IMPACTS

Many estuaries are concurrently impacted by human interventions such as port construction, channel deepening, land reclamations, loss of natural shorelines and maintenance dredging. These estuaries experience an upward trend in the suspended sediment concentration (van Maren et al., 2015a). The relative contribution of various human impacts is difficult to quantify based on measurements: decadal time-series registering long-term changes in suspended sediment concentration (SSC) are rare and the changes themselves do not reveal individual human impacts. Maintenance dredging is often considered to be one of the most detrimental factors impacting the estuarine sediment concentrations and hence visibility.

Short-term effects of dredging

Short-term effects of dredging are obvious as can be seen in figures 1 and 2 and are fairly straightforward to predict. Furthermore, the effects can be monitored using commonly available modelling tools such as Delft3D, MIKE, Telemac or ROMS. The main challenges for simulating the short-term impact of sediment disposal are accurate quantification of the source terms – the amount of sediment initially brought in suspension during dredging works (Spearman et al., 2011; Becker et al., 2014); and near field plume behaviour, which was advanced greatly by using Large Eddy Simulation (LES) (de Wit et al., 2015). LES models are very detailed but time-consuming – they highlight detailed ship properties and simulating the interaction of gas, fluids, and solids.

Coupling source terms with conventional far-field sediment transport models allow quantification of the dispersal of the sediments to a larger area. Such models are often designed to accurately represent the hydrodynamics, which determine plume behaviour on tidal timescales. They can, therefore, be applied for the assessment of short-term impact of these dredge plumes on sensitive receptors such as corals or seagrass fields (Doorn-Groen and Foster, 2007). Although these approaches are well-suited to assess the short-term impact of dredge plumes on the environment, they cannot be applied to determine the long-term impact of dredging.

Long-term effects of maintenance dredging

Long-term effects of maintenance dredging on turbidity are strongly influenced by processes not relevant to short-term plume behaviour, such as the interaction between the water column and the bed. In order to more accurately quantify these long-term sediment dynamics, a water-bed module was developed by van Kessel et al. (2011a). Additionally, to guarantee sediment mass conservation in the model on the long-term, sediments released at dispersion sites should not be introduced as an additional source such as in short-term models but ‘dredged’ from depositional areas requiring maintenance such as harbours and navigation channels. A model combining the water-bed exchange and the effect of ports provides a tool to quantify recirculation of disposed sediments and long-term effects of dredging on turbidity.

SEDIMENT LIMITATION

Most natural estuaries (Figure 3a) are characterised by multiple sandy tidal channels, muddy intertidal flats, and vegetated supratidal areas (salt marshes or mangroves). Fine sediment (mud) is brought into the estuary by the river and/or by the sea. This sediment is deposited on the intertidal flats and marshes. On the short-term, some of this sediment is remobilised during floods or storms, but in the long-term sedimentation on the intertidal flats allows the estuary to keep pace with sea level rise.

A great portion of intertidal areas and marsh land have been lost as a result of human interventions – these areas are destroyed or changed to make way for agricultural and residential purposes (Figure 3b). In addition, impacted estuaries often harbour a number of ports which require deepening of access channels and regular maintenance dredging. The loss of intertidal areas implies that fine sediment (mud) transported into the estuary has less space to be deposited, leading to increased suspended sediment concentrations (van Maren et al., 2016). In addition, channel deepening and loss of tidal flats may enhance up-estuary transport of marine sediment and trapping of fluvial transport by increased estuarine circulation and tidal asymmetry. Most of these developments take place concurrently and therefore determining which intervention has the largest impact on the suspended sediment concentration (SSC) is not easy.

It is important to realise that in natural estuaries most sediment is stored on the tidal flats, whereas in impacted estuaries with limited intertidal areas (Figure 3b) most sediment available for transport remains in the channel. Most of this sediment is located in the estuarine turbidity maximum,

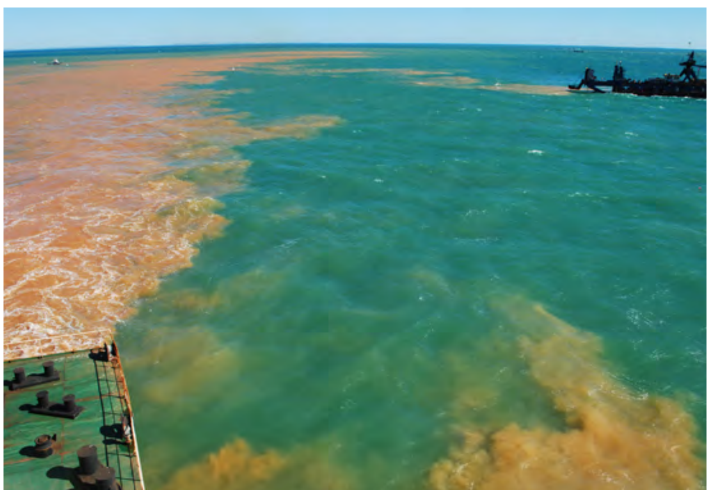

Figure 1. Dredging plume releasing turbid water in clear ambient waters. (Photo: courtesy of EcoShape)

Figure 2. Dredge plumes at sea at the Port of Singapore. (Photo: courtesy of Google Earth)

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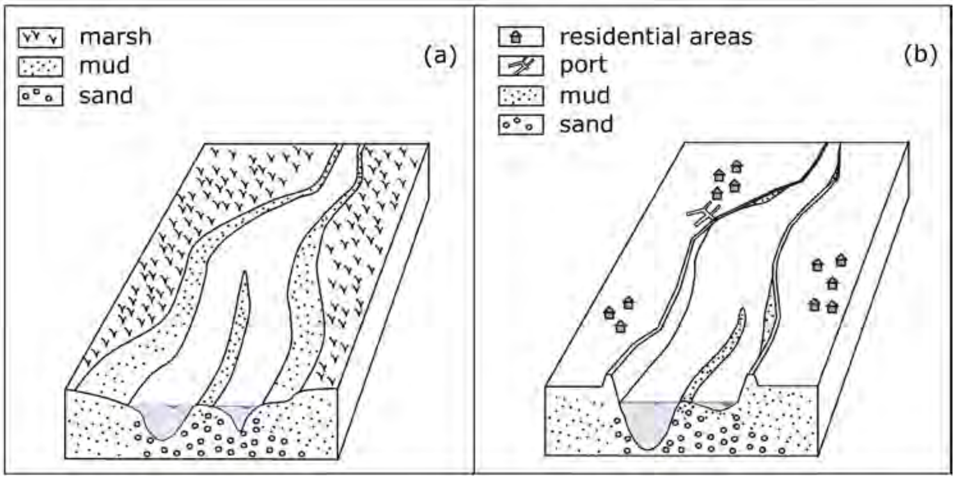

Figure 3. Schematised natural convergent estuary: Left, (a) Consisting of multiple tidal channels, flats and marshes and an impacted estuary. Right, (b) with ports and surrounding residential areas, deeper and more singular tidal channels and embanked shorelines.

where marine upstream-directed sediment transport converges with downstream-directed river sediment. Many estuarine ports and harbour basins are located in the vicinity of such a turbidity maximum (e.g. the ports of Rotterdam, Antwerp and Shanghai). But even in the turbidity maxima of fairly turbid estuaries such as the Ems and Scheldt, which will be elaborated later in this article, the amount of sediment instantaneously in suspension is (much) less than the amount of sediment annually dredged from ports and waterways.

Sediment dredged from a port is disposed elsewhere in an estuary, where it temporally deposits on the bed or leads to locally increased SSC. Within a relatively short time, the disposed sediment is transported back towards the port where it needs to be dredged and disposed again. Take note that this also implies that port siltation leads to a reduction in SSC, only balanced by subsequent sediment disposal.

The impact of processes on suspended sediment concentration conceptually described before can be quantified with a model. It can account for the storage of sediment in and on the bed; dredging and disposal from ports and channels; and an accurate hydrodynamic module that explains the changes in hydraulic conditions relevant for sediment transport.

THE DREDGING MODULE

Dredging and disposal

Ports are an integral part of the model turbid water enters ports and waterways where it settles in response to lower energetic conditions. Siltation rates in ports may be so high that this leads to a significant reduction in the SSC in periods without maintenance dredging (van Maren et al., 2015). Sediment depositing in the modelled ports is therefore removed and placed at the location of the actual disposal area (Figure 4); disposed sediment is not introduced as an additional source term.

This has three important advantages:
- it provides a more accurate reproduction of reality where the sediment concentration near disposal areas increases relative to the situation without dredging;
- port siltation becomes an output parameter with which to calibrate or validate the model;

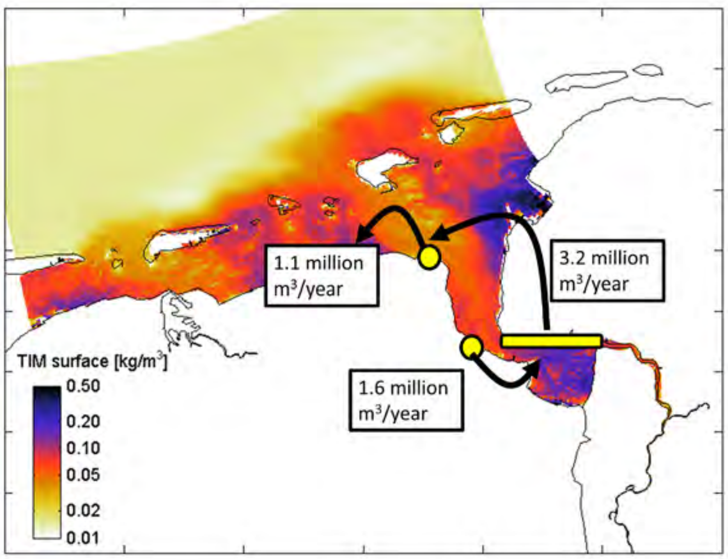

Figure 4: Example of actual port siltation rates and disposal locations in the Ems estuary.

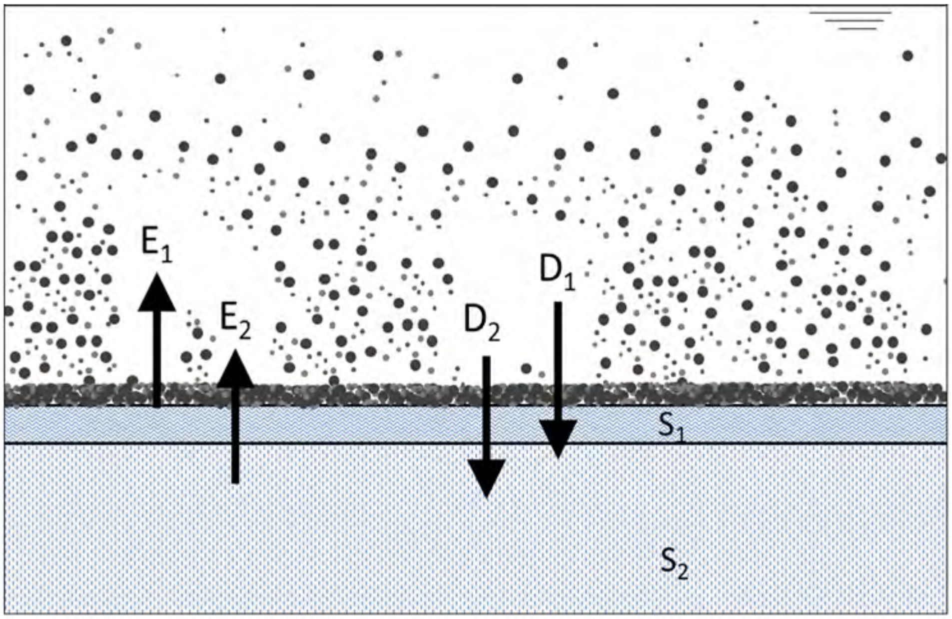

Figure 5. Sketch of the buffer model, depicting the the lower (S_2) and upper (S_1) bed layer, the erosion (E) and deposition (D).

- the effect of disposal scenarios on turbidity changes can be realistically simulated.

The buffer model

The exchange of sediment between the water and the bed is simulated by the so-called buffer model developed by van Kessel et al. (2011a). This model distinguishes two bed layers (Figure 5):

- an upper layer (S_1) which rapidly accumulates and erodes and
- a deeper layer (S_2) in which sediment accumulates gradually and from which it is only eroded during energetic conditions such as spring tides or storms.

The S_2 layer represents a sandy layer in which fine sediment accumulates during calm conditions. When the bed shear stress exceeds a critical value the sandy layer becomes mobile and fine sediment that infiltrated earlier into this layer is slowly released. Most sediment is stored in this S_2 layer.

S_1 represents the thin fluff layer consisting of mud, which rapidly erodes, characteristic for fine-grained estuarine environments. The erosion rates of both layers are determined by user-specified erosion parameters, where the erosion rate of S_1 is typically one order of magnitude greater than that of S_2. The decomposition of the total deposition flux D to the upper and lower layer (D_1 and D_2) can be user-defined, where deposition in layer S_1 is typically 10 to 20 times larger than to S_2, or transport from the upper layer to the lower layer can be simulated as a mixing process (requiring a user-defined diffusion coefficient).

This buffer model has been implemented in software modelling programmes – the Delft3D DELWAQ and Delft3D sediment-online. In Delft3D DELWAQ, the hydrodynamic simulation is decoupled from the sediment transport computations (which are generally much faster), allowing simulation of detailed 3D models on the timescales of years to decades. Over such timescales, the mud distribution in the bed reaches a dynamic equilibrium and can provide a calibration or validation parameter (Figure 6), in addition to port siltation rates and more conventional calibration parameters such as the SSC. Through this approach, the amount of sediment available within the model is limited (as in many estuaries, which is shown in Figure 3).

The buffer model has been developed and applied to three different cases:

- the Ems estuary,
- the Scheldt estuary, and
- the North Sea.

These can be seen in Figure 7. The setup and application of these models have been described in detail by van Kessel et al. (2011a, b) and van Maren et al. (2015a) and will not

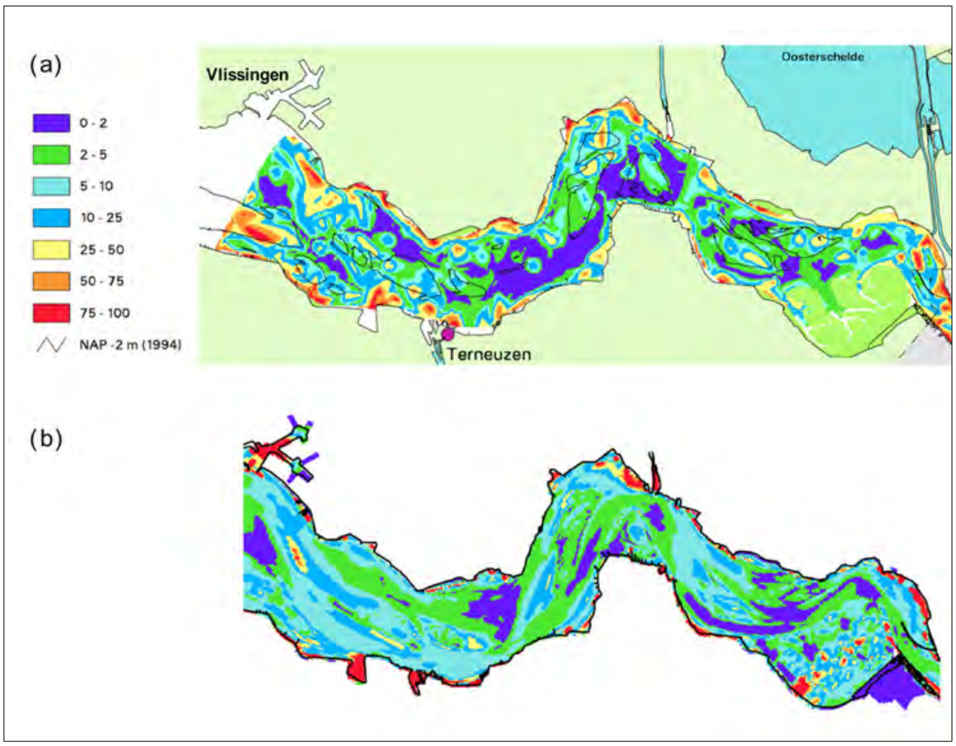

Figure 6. Observed (a) and modelled (b) mud fraction in the bed of the Western Scheldt (van Kessel et al., 2011b).

be elaborated here. The following sections will focus on the computed impacts of dredging on turbidity.

THE EMS ESTUARY: EFFECT OF DREDGING, DEEPENING AND EXTRACTION ON TURBIDITY

The Ems river has a discharge between 30 and 250m³/s, and drains into the Ems estuary along the Dutch-German border. The river is very turbid with occurrences of fluid mud, probably resulting from deepening (Winterwerp et al., 2013; van Maren et al., 2015b). Sediment in the Ems river and estuary is primarily of marine origin. Both the Ems estuary and the Ems river have undergone large anthropogenic changes in the past decades with the construction or extension of three ports, Eemshaven, Delfzijl and Emden, and a large shipyard located at Papenburg. The present-day maintenance depths of the approach channels to the ports are approximately 12m for Eemshaven, 10m for Delfzijl and 11m at Emden. To maintain these depths regular annual maintenance dredging of approximately 8 million m³ (van Maren et al., 2015a) is required.

Observations in the Ems estuary suggest turbidity is increasing at a rate of a few milligrams per litre (mg/l) per year (van Maren et al., 2015a). An increase in turbidity levels in an estuary is often attributed to deepening and port construction because of enhanced maintenance dredging, estuarine circulation and tidal amplification. However, since the increase in tidal range, dredging, and estuarine circulation typically occur simultaneously, their relative contributions cannot be quantified using observational data. The dredging module provides a valuable tool to investigate the relative contribution of deepening and dredging.

The effect of deepening has been investigated by running the calibrated model with a present-day bathymetry and a historic bathymetry from 1985. The change from 1985 to the present leads to an increase in turbidity in the deeper sections of the estuary (Figure 8a). More detailed analysis of the model (van Maren et al., 2015) reveals that stronger estuarine circulation, which has resulted in a stronger near-bed, landward directed flow velocity component, is the main

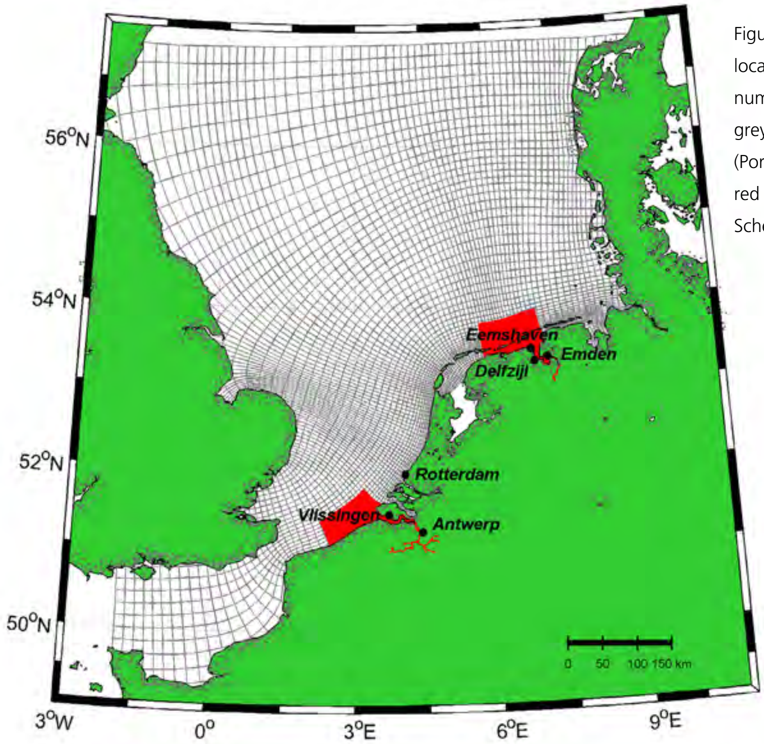

Figure 7. Map with the locations of ports and the numerical model domains: grey for the North Sea (Port of Rotterdam study), red for the Ems and Scheldt studies.

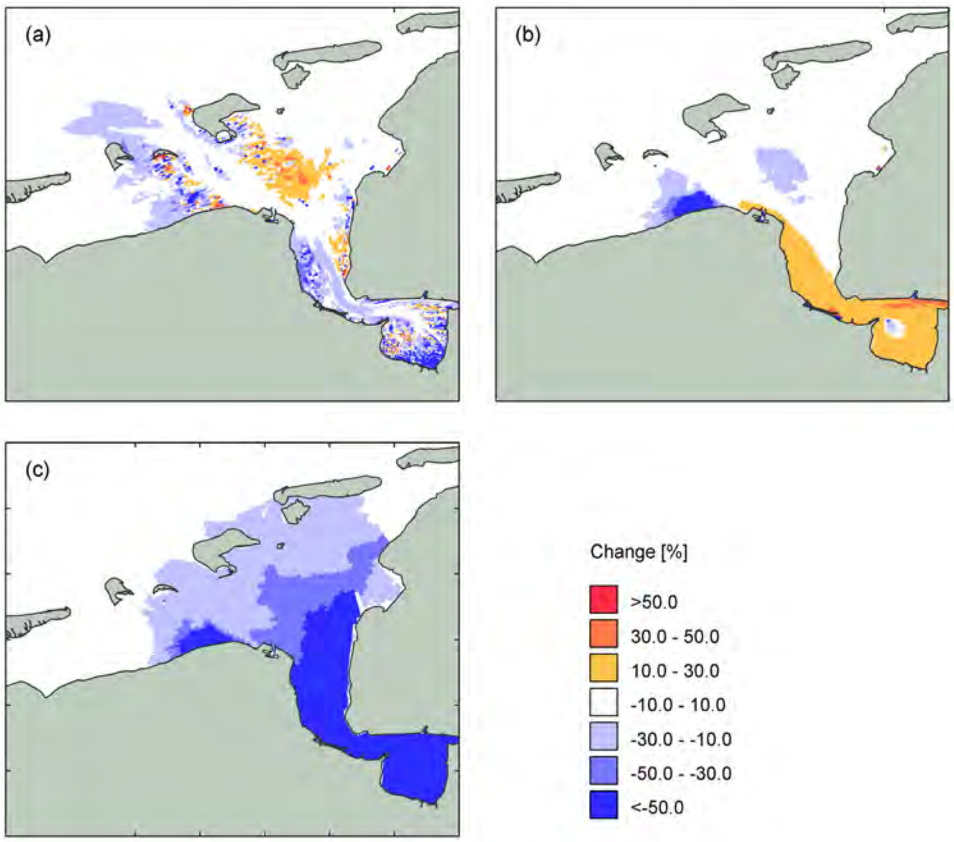

Figure 8. The effect of deepening, dredging, and extraction on yearly averaged SSC. (a) the increase in SSC when returning to the 1985 bathymetry; (b) the increase in SSC when all ports are closed and associated dredging stops; (c) the change in SSC when all sediment depositing in ports is extracted.

driver for this increased turbidity. Hence, a complex 3D hydrodynamic model is needed to model the fate of fine-grained sediment in the Ems estuary.

The largest increase in turbidity is attributed to the extraction of sediment. From 1960-1990, a large amount of sediment – an average of 1.8 million tonnes of mud every year – was extracted from the Port of Emden and its approaches. The model's results suggest that stopping this practice has led to a very large increase in suspended sediment concentration which can be observed in Figure 8b. The effect of regular maintenance dredging has been simulated by closing the ports in the model. This creates a model where there is no deposition in the ports and no need for maintenance dredging. The computed effect on the ports and the resulting maintenance dredging is less than the effect of deepening and the effect of extraction (Figure 8c). The effects of harbour siltation, maintenance dredging and disposal are an increase near the disposal sites, but a decrease elsewhere in the estuary.

The developed model is subsequently applied to investigate the effect of potential alternative disposal sites on turbidity (Figure 9). Turbidity reduces the production of algae, especially in the outer parts of the estuary. The numerical model can be used to assess the impact of seaward disposal of dredged sediment on the reduction of turbidity in the inner estuary and the increase in turbidity in the outer estuary. Since the outer area is most productive, sediment needs to be disposed very far seaward [Figure 9 (c) and (d)] in order to improve the ecological state of the estuary.

THE SCHELDT ESTUARY: DISPOSAL LOCATION AND RECIRCULATION

The Scheldt river has an average fresh water discharge of 100 m^3/s, with minimum and maximum values between 20 and 600 m^3/s (Fettweis et al., 1998). The river drains into the meso-tidal Western Scheldt on the Dutch-Belgian border. Estimates of riverine sediment supply given by Fettweis et al. (1998), vary from 0.75 to 2.2 10^6 ton/year. An additional amount of sediment is supplied by the North Sea which is transported upstream through tidal asymmetry and gravitational circulation.

The sediment near the Port of Antwerp is of both fluvial and marine origin (Verlaan, 2000). Most sediment accumulates in the turbidity maximum, typically located somewhere between the Deurganckdok, a large open container dock located in the Port of Antwerp, and the city of Antwerp, although accumulation is further upstream during very low river discharge. The total amount of mud annually dredged from the various docks in the Port of Antwerp increased from 0.5-1 million m^3 in the 1990s to 3.3 million m^3 between 2009 and 2013. Approximately 1 million m^3 originates from the Deurganckdok, which opened in 2005.

The Scheldt estuary and its tidal river is a classic funnel-shaped estuary. Close to the Port of Antwerp, the estuary has become fairly small, making accommodation space for sediment very limited. This raises three important questions which can be quantified through numerical models:

1. What are the impacts of dredging and disposal locations on estuarine sediment concentrations?
2. What are the sediment recirculation rates of dredged sediment?
3. How can disposal locations be optimised?

The computed recirculation rate of dredged sediment is very high in Antwerp – 70% according to van Kessel et al. (2015). About 45% of the sediment dredged from the Port of Antwerp originated from the Deurganckdok and 25% from the other ports (Figure 10). Recirculation rates of sediment dredged from the Port of Vlissingen, which is located at the mouth of the Scheldt estuary (Figures 6 and 7) are much lower at approximately 15% (Figure 10). Most sediment deposits in this port are directly of marine origin. Strategies to minimise recirculation rates will therefore not be very effective for the Port of Vlissingen but may have great potential for the Port of Antwerp.

Most muddy sediment dredged from the

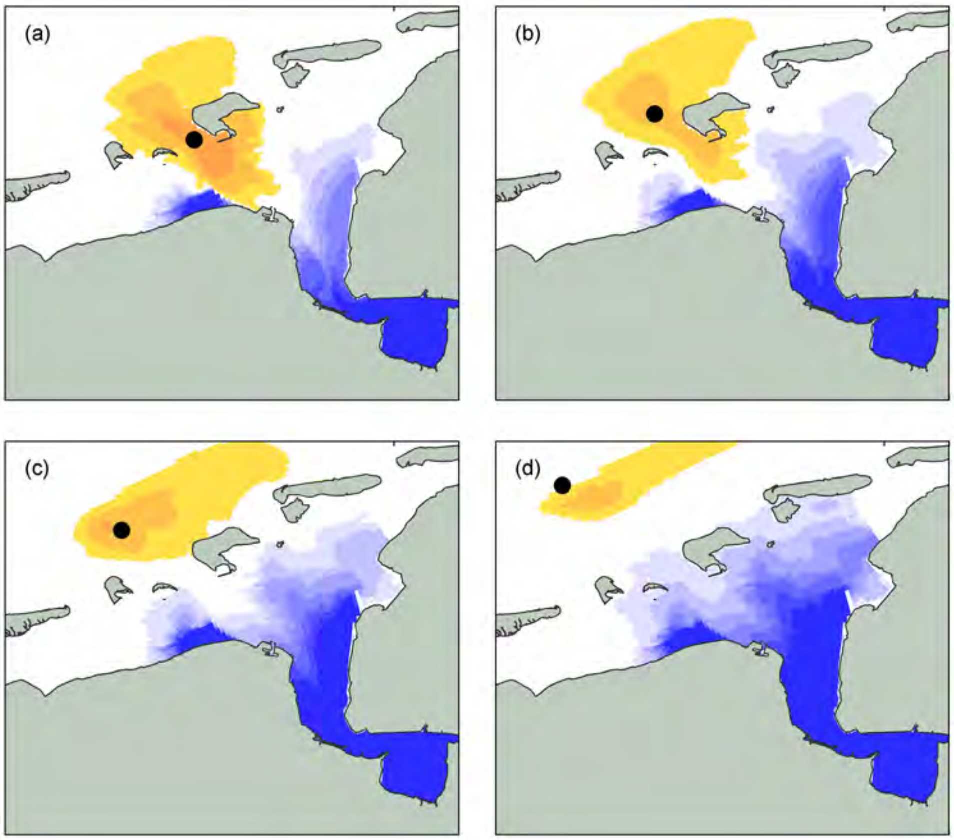

Figure 9. The effect of potential disposal locations on relative change in yearly averaged SSC in percentage and in the same scale as Figure 8. Figures 9(a) - (d) depict the effect of different disposal locations, with the disposal location in each figure denoted with a black dot.

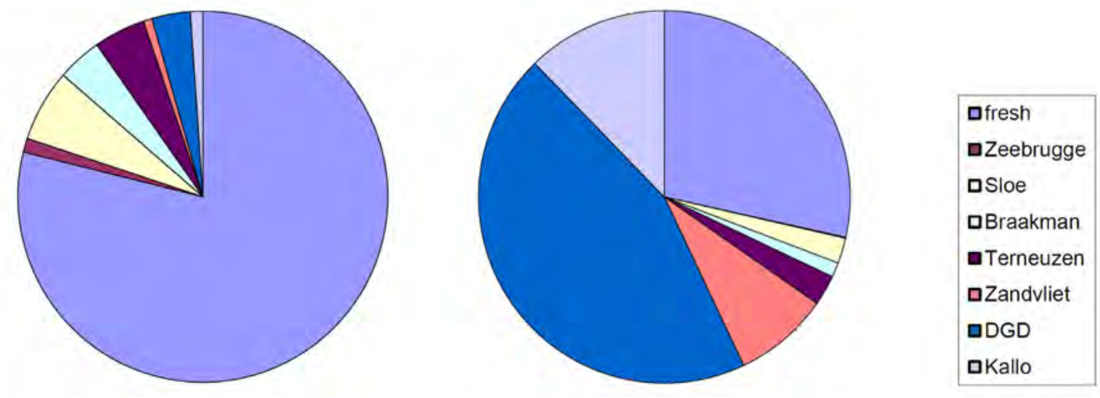

Figure 10. Left, Computed origin of sediment deposits in the Port of Vlissingen at the estuary mouth and right, in the Port of Antwerp's upper estuary. Near Vlissingen only 15% of the dredged material has been previously dredged for the port, contrasting with the Port of Antwerp where 70% of the dredged sediment is recirculated sediment. The remaining sediment is of marine or fluvial origin (labelled fresh).

various docks and locks is disposed close to Antwerp (Figure 11). Simulations with the dredging module in combination with a well-calibrated hydrodynamic and sediment transport model (van Kessel et al., 2011b) reveal that a downstream migration of the disposal location leads to an overall reduction of the sediment concentration in the port area, where the sediment is presently disposed, and in the upstream river of 10-20% (Figure 11). This leads to a similar decrease in the dredging volumes up-estuary of Deurganckdok and a reduction of 7% in Deurganckdok.

The length along the main channel for which an increase in sediment concentration is predicted is smaller at the new location compared to the old location (Figure 11). As the estuary is wider downstream, the absolute increase in sediment concentration near the new location is smaller than the decrease near the old location (20-25 mg/l). However, the relative increase is larger because of lower background sediment concentration (70 mg/l) at the new location compared to that at the old location (130 mg/l).

Which of these disposal sites is most suitable depends on two elements. The first is cost,

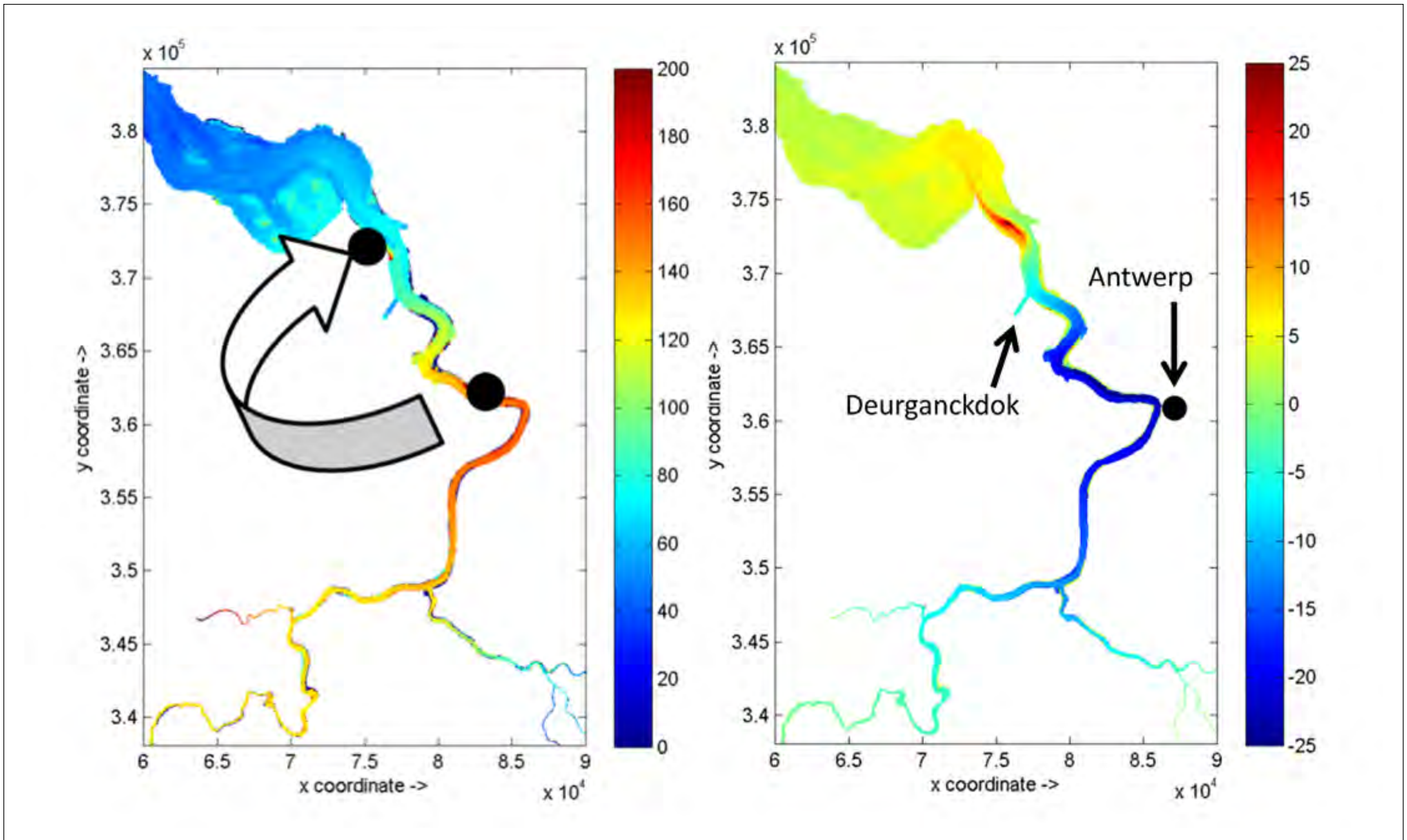

Figure 11. Effect of changing disposal location of sediment deposits in the Port of Antwerp. Left: Yearly average sediment concentration (existing disposal location), including the existing and potential future disposal location. Right: Change in yearly averaged SSC resulting from a change in disposal location.

which is related to the sailing distance of dredge vessels and dredging amount. The second is the environmental impact, which is related to the change in sediment concentration and sensitivity of local ecosystems. A down-estuary relocation of the mud disposal site appears nevertheless to be advantageous.

THE PORT OF ROTTERDAM: LONG-TERM PLUME DISPERSION AND IMPLICATIONS FOR RECIRCULATION OF DREDGED MATERIAL

In recent years, the Port of Rotterdam was expanded through the construction of the Maasvlakte 2 land reclamations. The construction works required large-scale sand mining from the nearby seafloor in the Dutch coastal zone. An extensive study on the long-term effects of the resulting sediment plume dispersion caused by sand mining reveals that the spatial and temporal effect of individual plumes prior to deposition on the sea bed is limited, but the cumulative effect of thousands of plumes is felt at larger spatial and temporal scales. The sandy seabed becomes gradually enriched with fines, resulting in slightly enhanced turbidity levels during and after storms compared to a scenario without sand mining. The effect continues for a few years after the completion of sand mining, after which turbidity returns to its original level.

The duration of these enhanced turbidity levels is determined by the residence of fines in the Dutch coastal zone. It is estimated at four years using concentrations of contaminants adhering to the fines (Laane et al., 1999). In fact, the overall effect is small compared to the natural variability of fine sediment dynamics (van Kessel and Van Maren, 2013) and does not have significant ecological impact. Still the results suggest that rethinking the dispersion strategy for maintenance dredging would be beneficial, because the amount of fine sediment released into the North Sea for maintenance dredging to provide access to the Port of Rotterdam is larger than the capital dredging works described above. Average maintenance dredging in the port and its access channels is 15 million tonnes per year.

The present dredged material disposal strategy is based on short-term tracer and model studies on the return flow of dispersed mud from the release location towards the harbour basins. This yields a return percentage of 12.5% (De Kok, 2004). However, the integral model including the buffering of fines in the seabed in combination with port sediment circulation reveals that in the long-term SSC does substantially increase. Mud dispersion from the continuously used release location results in the gradual enrichment of the sandy seabed with fines in the wide surroundings, thus enhancing background suspended sediment levels. Furthermore, the return percentage of the released mud fraction increases significantly from 12.5% (the existing estimate based on short-term studies) to more than 50% after 10 years (Figure 12). This implies that over 50% of the mud suspended in the Dutch coastal zone nearby Rotterdam has been dredged at least once from its port.

Although further study is required, it is likely that a release location farther offshore beyond the region of freshwater influence of the Rhine may substantially reduce maintenance dredging volumes in the Rotterdam harbour area.

A SYNTHESIS: MODELLING THE LONG-TERM EFFECTS OF DREDGING

The long-term impact of dredging on estuarine SSC is strongly influenced by the amount of available fine sediment. In the examples discussed here, the amount of sediment is fairly limited. Fine-grained sediment is present in the water column, and a small amount of sediment deposits in and on the dominantly sandy seabed. Even in the fairly turbid Ems and Scheldt estuaries, the amount of instantaneously suspended sediment is much lower than the yearly dredging volumes. Sediment is recycled, which has a big impact on the effect of ports on estuarine turbidity.

Many estuaries have been strongly impacted by concurrent human developments such as channel deepening and tidal amplification; port construction and resulting dredging requirements; and loss of intertidal areas. As such developments take place simultaneously and the systems may respond slowly, numerical models in which these effects can be switched on and off individually can be used to determine which of these human impacts has the largest impact on turbidity.

Data is often unavailable for the long periods required to do a thorough study. It is only

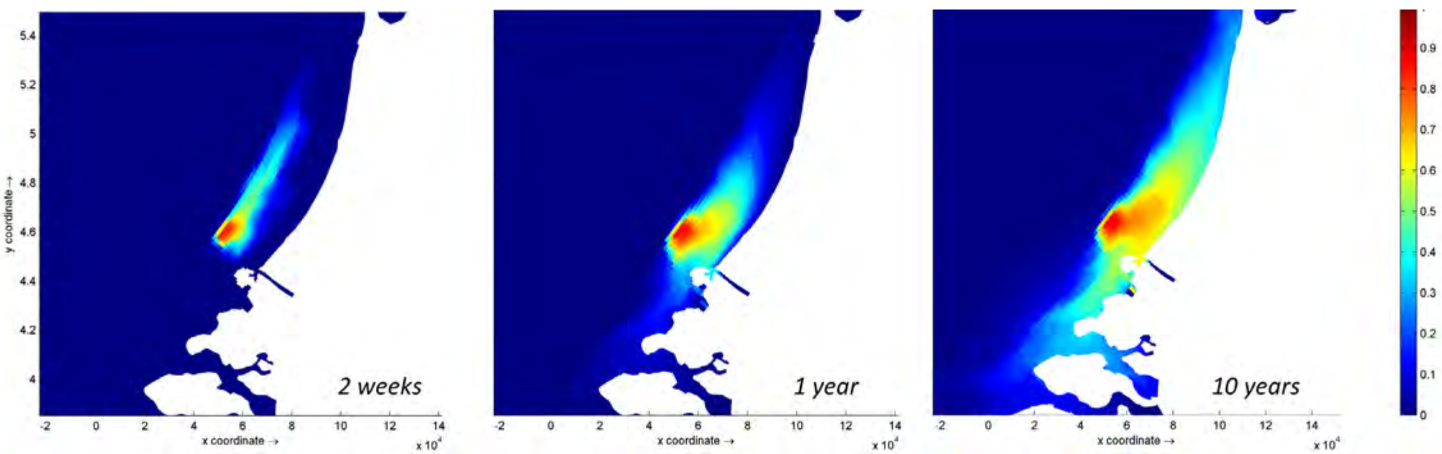

Figure 12. Fraction of dredged mud dispersed continuously from release location within total near-bed SPM concentration (left to right) after 2 weeks, 1 year and 10 years.

documented if the concentration changed but why the concentration changed remains undocumented. Applying the dredging module to the Ems estuary suggests that in that particular system the effect of deepening (and the resulting modified hydrodynamics) was larger than that of dredging and disposal. However, the main reduction in turbidity may be achieved by taking sediment out of the system. Disposing sediment at sea may result in similar reductions in the sediment concentration.

Such quantitative knowledge is needed for policy makers to design and execute measures aimed at reducing the turbidity in the estuary as imposed by the Water Framework Directive. In a convergent, funnel-shaped estuary as the Western Scheldt, the recirculation rate depends on the location within the estuary. The recirculation rate is low near the seaward entrance of the estuary, but increases in the landward direction. The example of the Port of Rotterdam illustrates the importance of considering long timescales for cumulative plume impact assessments and sediment recirculation studies. What may appear to be optimal in the short-term may not be so in the long-term. Given the importance of sediment recirculation, opportunities exist to optimise the dredging location.

The approach brought forward here differs from the approach commonly adopted in numerical modelling of the impact of dredging:

First, most dredge plume assessments are simulated for a short period and disposed sediment is added to the system (and not dredged from a modelled port). Such an approach will by definition lead to an increase in the sediment concentration and is not suitable to assess the long-term effects of dredging on turbidity.

Secondly, many studies aiming at longer timescales and accounting for ambient SSC are erosion-rate limited. The model discussed here is supply-limited, with a finite amount of available sediment and with an erosion rate depending on the amount of sediment on the bed. Erosion-rate limited models assume large sediment availability at the bed. Such a model is calibrated by varying the erosion parameters of the prescribed bed layer until the modelled concentrations approach a realistic value or preferably, measurements. Such models are usually erosional in the energetic areas and not in equilibrium or depositional (as most estuaries are). Furthermore, sediment dredged from a port and disposed in an estuary will become part of a bed that already has an infinite amount (within modelled timescales) of sediment available at the bed. As a result, disposed sediment will not increase the sediment resuspension rates relative to the background conditions. These models will therefore always underestimate the effect of dredging and disposal on turbidity and will underestimate recirculation rates.

Dredging strategies can be optimised for economic or environmental purposes, and estuarine turbidity improved to enhance ecological functioning.

A methodology has been provided here to compare:

1. Dredging requirements and therefore economic costs to sediment concentration impacts and consequently environmental impacts
2. Whether a decrease in turbidity in one part of the estuary is sufficiently beneficial to allow an increase in turbidity elsewhere in the estuary.

CONCLUSIONS

The amount of fine-grained sediment annually depositing in or the residual transport through estuaries by natural processes is often smaller than the annual dredging requirements. A large amount of the sediment dredged from ports then recirculates – sediment is continuously dredged from a port, disposed in the estuary and ultimately transported back to the port. In the long-term, this may lead to an increase in SSC levels. The long-term response in SSC and the return flow to the ports depend on sediment transport mechanisms and may greatly vary per system. The recirculation rate (and thereby human impacts on the system) increase with increasing dredging volumes and decreasing natural sediment transport rates. In estuaries with a large residual transport rate or accommodation space where fine sediments can settle, the recirculation rate is much lower as disposed sediment is rapidly taken out of the system.

In systems with a large recirculation rate, dredging strategies can be optimised. Measures can be devised aimed at a reduction in estuarine sediment concentration or dredging costs or preferably, both.

Such strategies can be optimised using a numerical model which accounts for buffering of fines in the seabed; an integral dredging and disposal routine; and detailed hydrodynamic sediment transport processes. It should be able to run sufficiently long, from a few years to approximately 10 years, to achieve dynamic equilibrium.

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