D. T2 5.1 - Replication conditions assessment on applications with sediments for flood and erosion protection pilot monitoring (Port of Rotterdam)

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Dr. A.J. Wijdeveld

Ing. M. Wensveen

Deltares / Port of Rotterdam

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SUMMARY

1 INTRODUCTION

The project aim is to increase sediment reuse for erosion and flood protection. Currently, of the 100 - 200 million m^3 a year (40 – 80 mln. tons dry weight (d.w.) a year) of dredged sediments in Europe 99% is dumped at sea and/or managed as waste[1].

Zooming in on North West (Netherlands, Germany, France, Flanders) the yearly dredged amount of sediment is 30 – 50 mln. m^3 a year (or roughly 12 – 20 mln. tons d.w. a year). For Port of Rotterdam alone the dredged volumes fluctuate between 5 and 10 mln. m^3 a year (2 – 4 mln. ton d.w. a year). The SURICATES target to reallocate 500.000 m^3 / 200.000 tons of d.w. sediment from Port of Rotterdam is therefore roughly 5 -10% of the yearly volume for the port. This is an increase with a factor 5 - 10 as compared to the 'business as usual' scenario.

SURICATES target is an increase in the number of sediment reuse projects in NWE to drive sediment reuse to 1.3 Mt/y (1.6 – 3.3%) after 5 years, and 2.3Mt/y (2.9 – 5.8%) after 10 years in the EU. The evaluation of the pilots undertaken for SURICATES help in defining 'lessons learned' and assessing the conditions under which the pilot can be repeated elsewhere. And is further upscaled (in Port of Rotterdam) feasible?

The aim of this report is threefold:

1. To evaluate what part of the pilot was successful and why (not)?
2. What are the conditions under which the reallocation of sediment within the port can be done successfully elsewhere in North West Europe?
3. Is further upscaling of this concept feasible?

1 SedNet, 2004, WP 4 - DREDGED MATERIAL TREATMENT TECHNOLOGIES IN EUROPE, Pol Hakstege,
Aquatic Sediment Expert Centre Ministry of Transport Public Works and Water Management The Netherlands

2 Pilot Port of Rotterdam in more detail

2.1 Location of the reallocation site

The reallocation site is next to the constructed wetland ’Groene Poort’ at WGS84 coordinates (51.93027698 4.21570301). Figure 1 illustrates the area and Figure 2 gives the changes in bathymetry during the pilot at the reallocation site.

Figure 1 Photo of the reallocation site

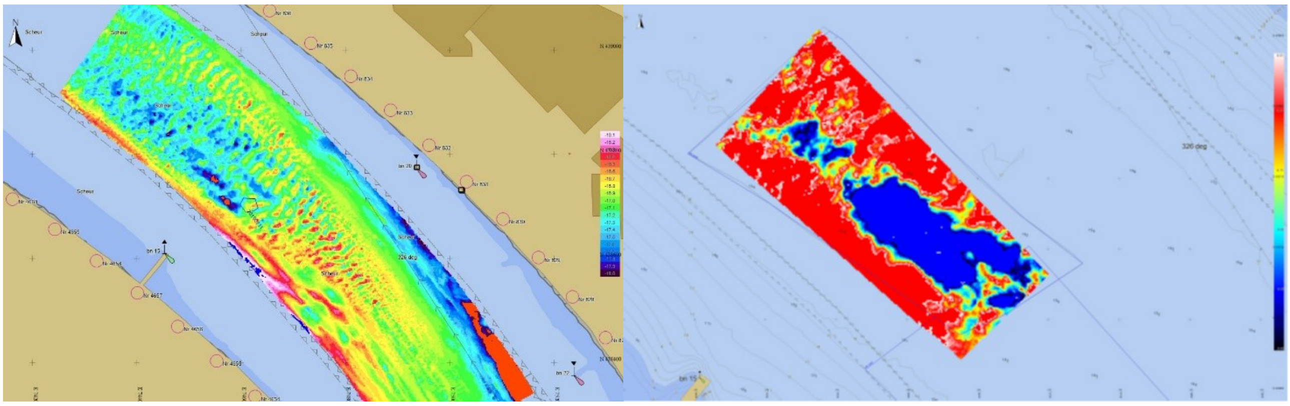

Figure 2 Reallocation site, river bend (left) and detail of target site (right). In red the areas with a shallower water profile after reallocation and in blue the areas with a deeper water profile

The reallocation site is in the tidal influences part of the harbour. Figure 3 illustrates the reallocation area in the context of the marine border (east), the inflow of two rivers and the dredges sites for the pilot.

Figure 3 Global overview of the reallocation site area in relation to the Port of Rotterdam area

2.2 Legal preparations

Beneficial use of sediment in the Netherlands is permitted without license. Instead there is a notification to the minister with the intention to use sediment, clarifying the sediment quality and purpose of the application. Normally getting approval this takes 2 days. Due to PFAS (and the lack of data on PFAS in the sediment used for this pilot) the process took 2 months.

While the presence (or absence) of PFAS in the sediment was an unforeseen factor at the time of preparation the fact that the quality of the sediment on the dredged sites (see Figure 3) are evaluated on a regular base helped in preparing the notification to the minister. But since reallocation within the harbor is not done on a regular base it took several meetings with the authorities to explain the purpose and benefits of the pilot. It helped that the pilot has been discussed and prepare with the authorities over a year in advance so that the final notification was no surprise.

Since the pilot is carried out within a shipping lane the local port authority also needs to be involved and all activities needed for the reallocation, the monitoring and if necessary, measures to mitigate unforeseen impacts need to be submitted, approved and communicated during execution.

Getting approval (or a permit) requires a very clear description on what is being done exactly, how much material is involved, where the material is reallocated, what is the predicted impact, how this impact is monitored and what mitigation measures are possible and what triggers taking them.

2.2.1 Lesson learned

Check the sediment quality standards, involve all authorities and get approval in time. **50% of the work is in the preparations. 50% of the preparation is communication**.

2.3 Selection of the reallocation site

The reallocation site is selected based on **numerical modelling** of the tidal movement of suspended sediments. The targets are:

- The turbidity flume caused by reallocation must reach the sea over a one tide period,
- The predicted impact of siltation within the port must outside the navigation channel,
- The wetland (southern bank of reallocation site) must receive sediment.

Figure 4 illustrated the modelled impact of multiple reallocations over a period of 2 weeks.

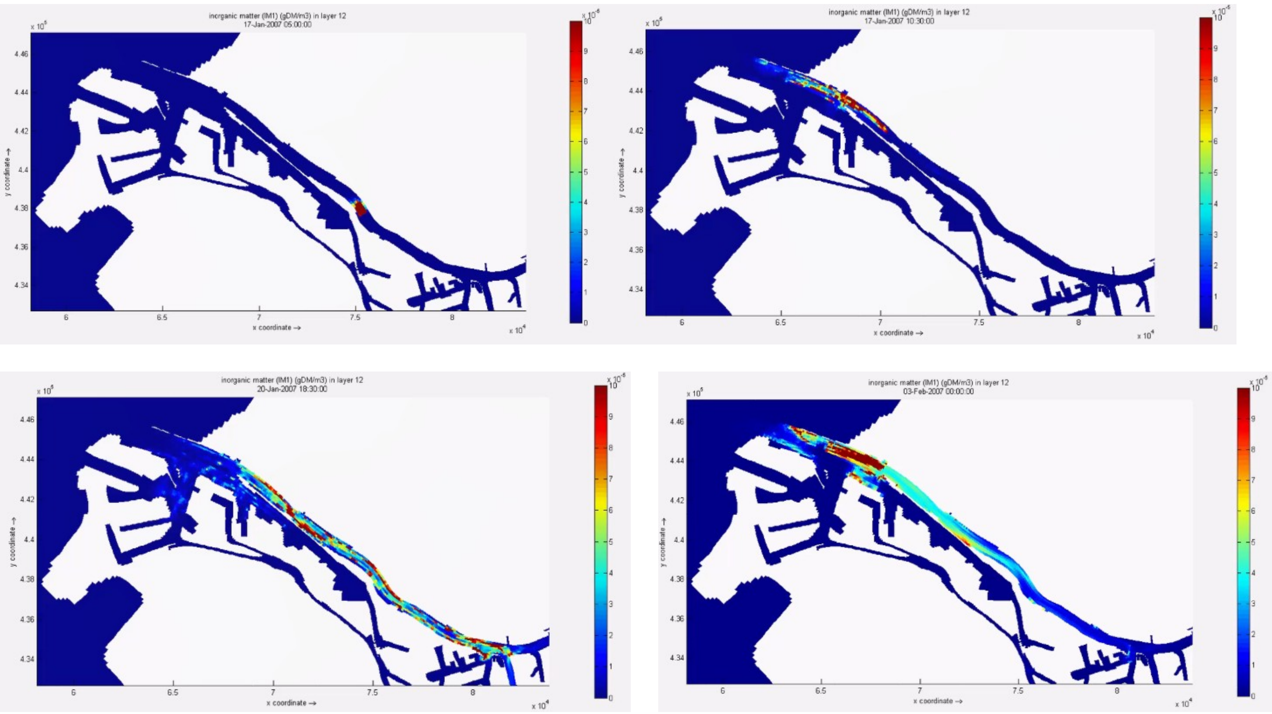

Figure 4 Modelled impact of reallocation. Upper left pattern at initial reallocation, upper right pattern at first outgoing tide, bottom left pattern after multiple reallocations incoming tide, bottom right pattern after multiple reallocations outgoing tide

The resulting siltation (predicted change in the port bathymetry) is given in Figure 5.

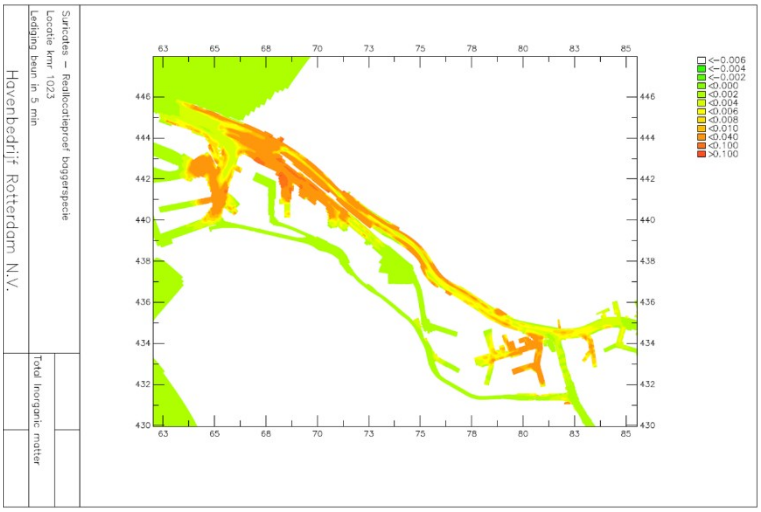

Figure 5 Changes in the port bathymetry in meter due to the reallocation of sediment at the pilot site

2.3.1 Lesson learned

The selection of a suitable pilot reallocation site and the **dimensions of the pilot should be based on the predicted impact on a system scale**.

Numerical models help to **predict the impact** of sediment reallocation. Not only at the local site but especially at a larger (port) scale. Figure 5 shows that not only downstream locations are expected to be impacted, but also upstream locations. This includes desired impacts (river bank siltation) and undesired impacts (navigation channel siltation).

Numerical models can help in **scaling the pilot.** Figure 5 illustrates that the reallocation of 500.000 m^3/200.000 tons of sediment at this location has a predicted impact of 1-4 cm at most in the different parts of the port. The yearly fluctuation in local sedimentation/erosion and the netto sedimentation in the area is on average a tenfold of this impact (during the pilot a sediment bed level change of 1 meter was observed at the river banks; a factor 25 compared to the predicted siltation). Evaluate if a maximum 10% increase of siltation is enough to establish the impact of the pilot.

The scale of the pilot in a port depends on the **risks** (shipping), **the desired impact** (siltation on the river banks and wetlands) and the possibility of **measuring the impact** of the pilot.

In summary: Choosing a pilot site for sediment reallocation in a port requires system knowledge (either by modelling or measurements), a risk evaluation of undesired impacts and an evaluation of the dimensions of the pilot are large enough to have a measurable impact.

2.4 Conditions at the reallocation site

The selection of the reallocation site already imposed boundary conditions with regard to the distance from the sea (one tide transport distance), the amount of sediment (not too much to cause a risk, not too little to not have an measurable impact) and the predicted impact (no extra siltation in the channel, extra deposition on the river banks/wetland).

After selection of the site there is also the practical implementation of the reallocation. First there is the challenge to combine regular dredging maintenance with being at the reallocation side at the turn of the tide. The condition was that most reallocated sediment which was not deposited at the river banks would have to reach the sea within one tide. Therefore, the dredging vessel under contract had **one-hour time window** based on the **48-hour advanced tidal prediction** at the reallocation site (Figure 6).

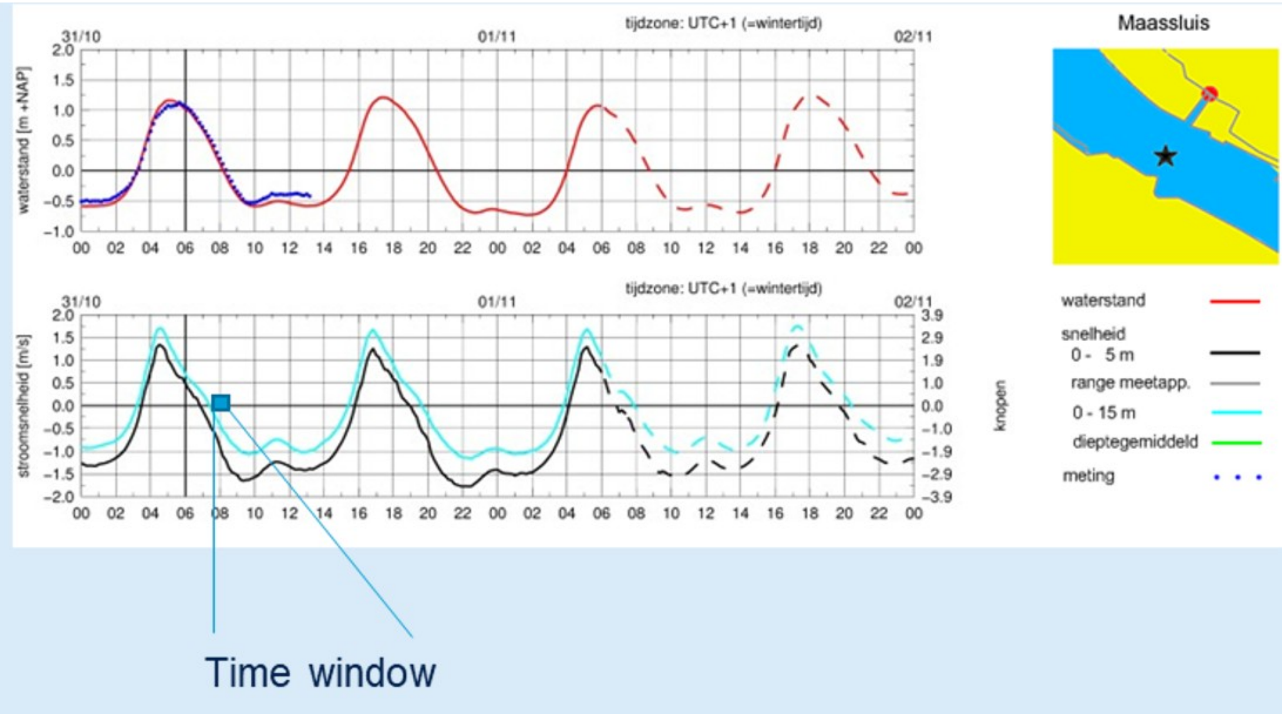

Figure 6 Operational time window for reallocation

The use of a dredging vessel with a draft of 7 m prevented a direct reallocation at the river banks. Discharging the sediment by rainbowing was not permitted. Therefore, the dredging vessel had to discharge the sediment within the shipping channel. This required close cooperation with the **port authorities** on the **exact timeframe** (5 minutes) **and position** of the reallocation area, hence the strict dimensions of the area as shown in Figure 2.

Figure 7 Dredging vessel (Ecodelta) at the reallocation site, full (top) and empty (bottom)

2.4.1 Lesson learned

Contracts with dredgers **must be clear** and **objective**, so that inspection (sediment volume, tidal time window, position of the reallocation site) is possible **meeting the requirements**. (Port) authorities need to be able to rely that the conditions in the permit are met and checked.

2.5 Monitoring

The monitoring results are described in other parts of the project. Here the question is if the monitoring is able to quantify the impact of the pilot (as compared to the natural variation in the system) and if monitoring can provide information to mitigate for unwanted consequences before the consequences become an actual risk. Figure 8 illustrates the nearness of the main flood defence work for the Rotterdam area, the Maeslant storm surge barrier, to the reallocation site.

Figure 8 Passage of Ecodelta through the storm surge barrier 2½ km downstream of the pilot reallocation site, siltation in the closing mechanisms of the doors has to be prevented at all cost

The impact of the sediment reallocation has been monitored based on the following questions:

- The change in bathymetry in the main shipping channel, is there extra siltation?
- The nourishment of the constructed wetland, is sediment entrapped?
- The sedimentation balance, is there an observed increase in the amount of fluvial sediments?
- The turbidity in the channel, how is the sediment transported?

This required a combination of **vessel survey's** (bathymetry at the reallocation side, flow velocity's over the tide, turbidity over the tide, suspended sediment depth profiles over the tide), **sediment samples** (grabs and cores) and **on-site monitoring** (siltation within the wetland).

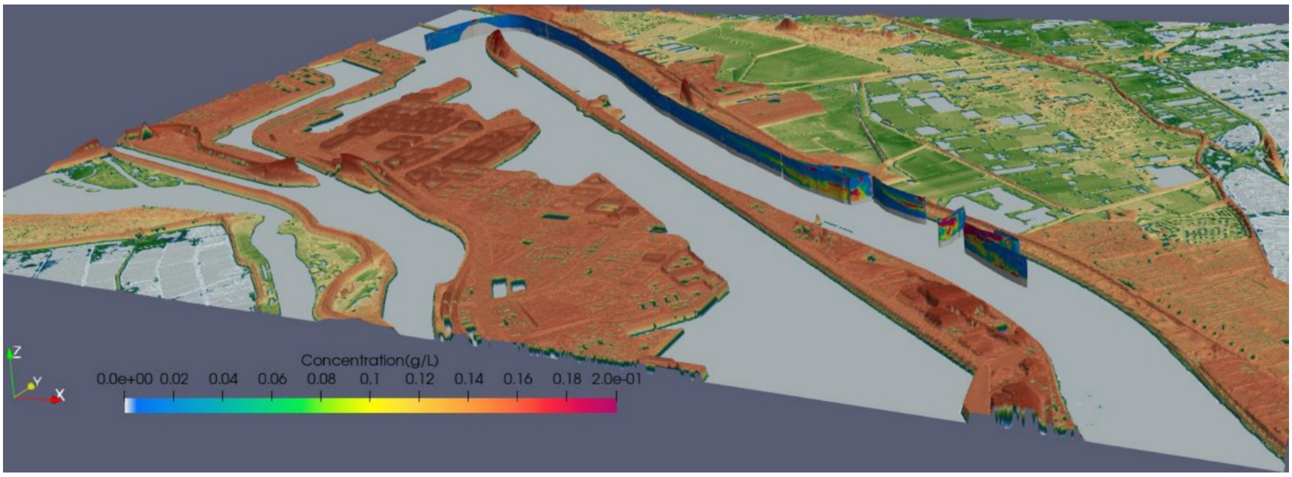

Figure 9 Example of constructed turbidity profiles based on ADCP backscatter – following the reallocation flume downstream

2.5.1 Lesson learned:

Routine monitoring alone only addresses some aspects but lack an overall understanding. The **combination of relative new monitoring techniques** (like ADCP backscatter for turbidity), rare earth element fingerprinting for a sediment origin balance and optical cables for patterns in deposition and erosion) help to **complete the picture** on what happens with the reallocated sediment on a system scale.

2.6 Pilot Port of Rotterdam conclusion

The pilot was a partial success.

2.6.1 On site impact

The monitoring has shown that at the reallocation site (within the navigation channel) a small shift in the reallocation site position was needed to prevent siltation in the northern bend of the channel. After a shift of a few hundred meters downstream the impact of reallocation on the bathymetry was limited. There was a temporal risk due to scour holes, but these filled up over time.

2.6.2 Downstream impact

There was no siltation at the downstream storm surge barrier, the reallocation did not form a thread for the closure of the barrier doors and a permit was given to continue reallocation during the storm season (starting in October). This extension was needed due to a two months late start with the sediment reallocation (due to unforeseen checks on the PFAS levels in the sediment).

2.6.3 System impact

On a system scale, a mass balance could be made based on the core samples taken up- and downstream of the reallocation site and the shift in the composition in rare earth elements in these samples (illustrated in Figure 10). On average the increase in the river sediment fraction in the studied area (40 km) due to the reallocation is +0.2%. This is negligible.

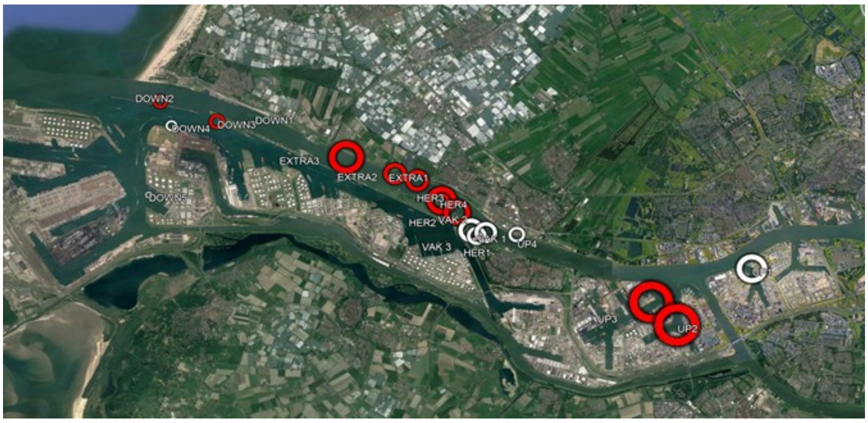

Figure 10 Enrichment (in red) and depletion (in white) of the river sediment fraction at the river banks after 4 months of reallocation (the reallocated sediment comes from the river while most sediment in the area has a marine origin)

2.6.4 River bank and wetland impact

The aim to strengthen the river banks and wetland with extra sediment was not met. This is best illustrated by Figure 11, in which the siltation over a tide is plotted after a reallocation event.

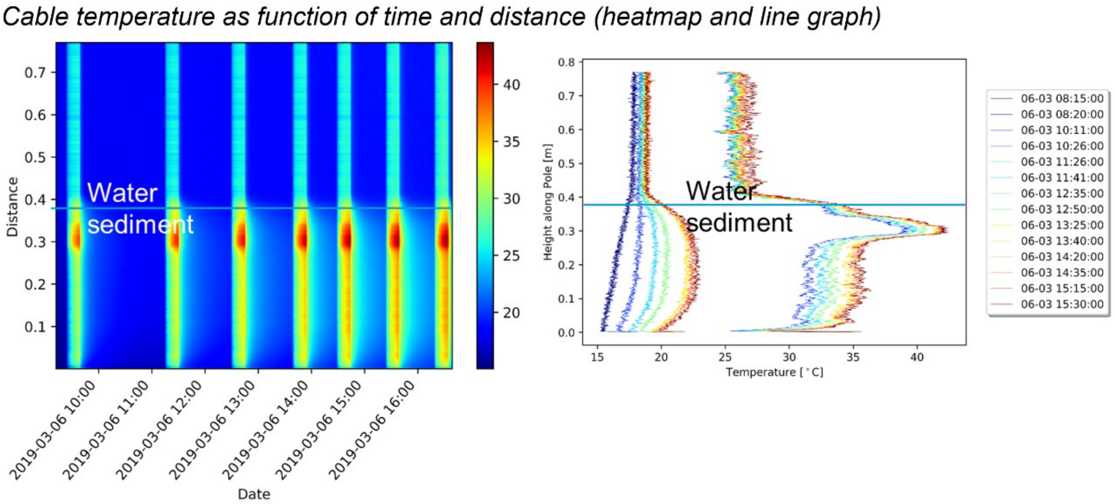

Figure 11 Siltation within the constructed wetland

The maximum flow speed during the tide of 1.5 m/s is too high, resulting in a bottom shear stress able to mobilise the reallocated sediment (see Figure 12).

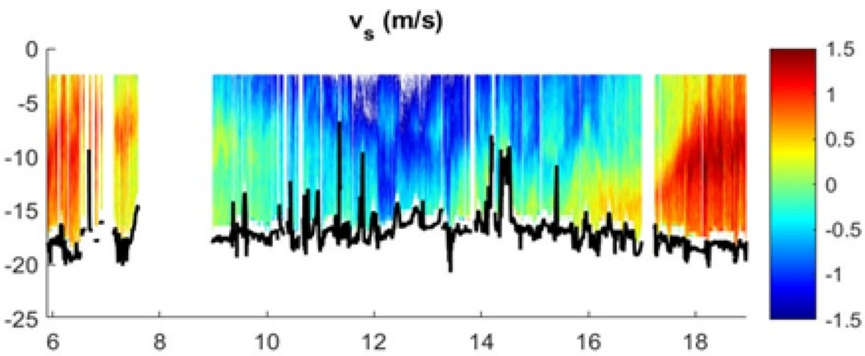

Figure 12 Measured flow velocity's over a 13-hour period

Detailed lab studies on the sediment yield stress (Table 2.1) confirmed that the shear stress after settling was insufficient to prevent erosion (Figure 13).

Table 2.1 Sediment shear stress for the sediment from the dredging sites

Sample Location	Type	Yield Stress 1	Yield Stress 2	Density
VAK 22	Bulk	Newtonian behaviour		1.07
	Water removed	5	23	1.18
VAK 23A,1	Bulk	Newtonian behaviour		1.09
	Water removed	4.5	20	1.18
VAK 23A,2	Bulk	1	3.5	1.14
	Water removed	1	5	1.15
VAK 25	Bulk	Newtonian behaviour		1.15
	Water removed	3.5	18.5	1.28
	Sieved & Water removed	4	18.5	1.20
VAK 31,1	Bulk	Newtonian behaviour		1.13
	Water removed	2.5	10.5	1.24
	Sieved & Water removed	4	17	1.18
VAK 31,2	Bulk	Newtonian behaviour		1.12
	Water removed	2	11	1.29
	Sieved & Water removed	4	13.5	1.17

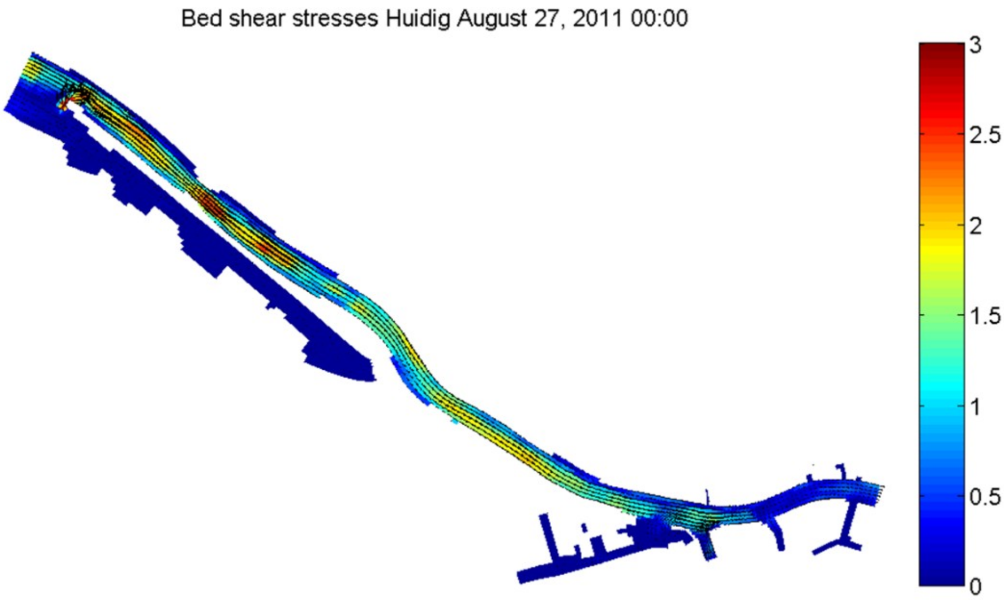

Figure 13 Calculated bed shear stress occurring in the system (at the reallocation site the shear stress of 1 – 2 N/m^{2}exceeds the sediment yield stress

A second reason was the entrance to the construction wetland was insufficient to entrap sediment. The distance between the reallocation by the dredging vessel and the wetland entrance was +/- 10 meters (see Figure 14, top), but even then, the observed turbidity in the top water layer (Figure 14, middle) was not able to enter the wetland (as was foreseen (Figure 14, bottom)).

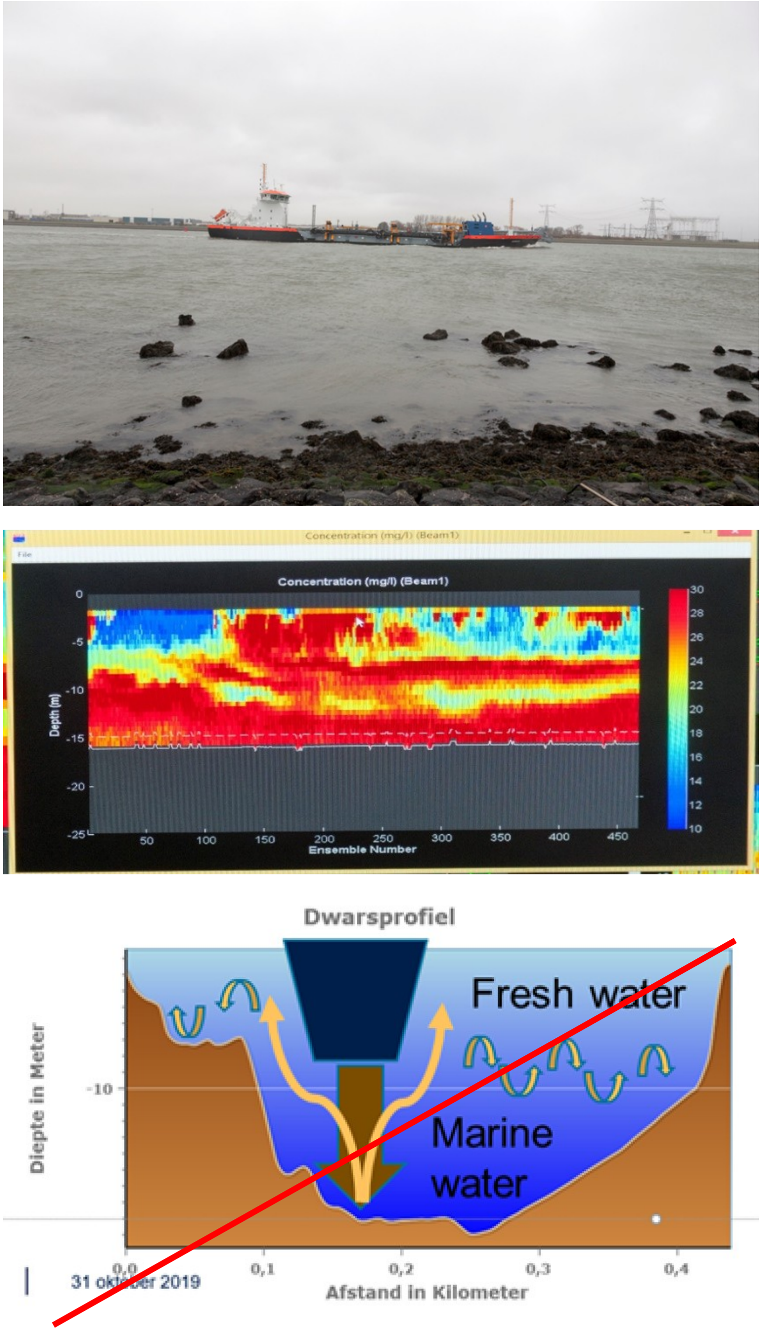

Figure 14 Position dredging vessel next to wetland (top), turbidity in after reallocation (middle) and conceptual model on sediment entrapment (bottom)

2.6.5 Conclusion in relation to SURICATES goals

In summary, the reallocation is a success in the sense that the reallocation does not impact the port sediment balance (an increase of +10% of the yearly sediment volume only has an 0.2% impact on the overall system sediment balance). But the goal for SURICATES, to strengthen the river banks and wetland against erosion and flood protection is not met.

2.6.6 Lesson learned

The pilot was well prepared. Numerical model studies were used (also used for operational management of the port) and a careful site selection was done. By depositing the sediment on the doorstep of a constructed wetland with low flow conditions the expectation was that part of the sediment would be entrapped.

Despite the **failure to capture sediment on the river banks and within the wetland** advice can be given to other ports on the concept of sediment reallocation within the port.

3 Conditions under which reallocation of sediment within the port can be done successfully

3.1 The concept only works when there is a tidal influenced river

The transport of sediment is mainly due to the tidal variation in flow velocities. When expressed as a mass balance (Figure 15), most sediment transport occurs during the outgoing tide.

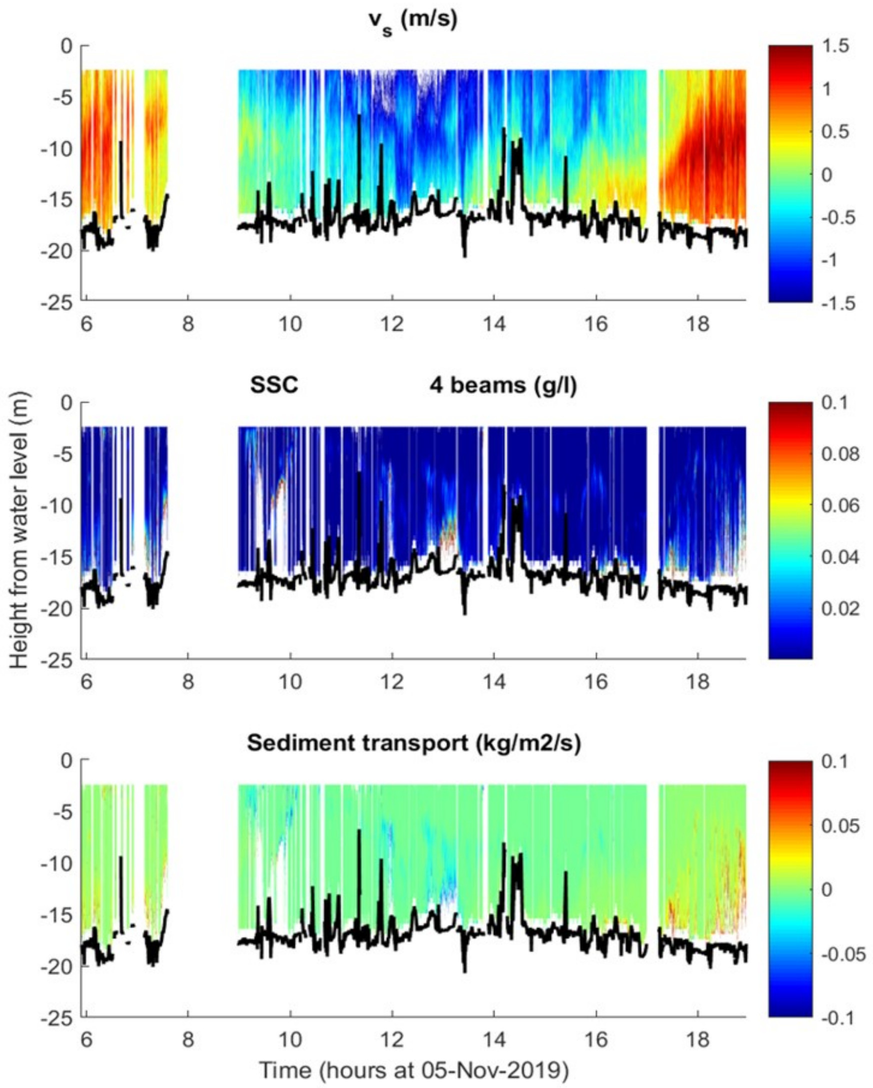

Figure 15 Mass balance of sediment transport based on flow velocity and turbidity

The technical conditions for which reallocation within the port is feasible can be derived based on the river system dynamics (the energy present (or lack thereof) to transport sediment. For Port of Rotterdam the critical sediment yield stress (T_y) of 1 – 2

Pa (or N/m²) for the dredged sediments was exceeded with flow velocity's of >1.5 m/s. Marine sediments with a d_{50} between 10 and 1000 µm often have yield bed shear stresses lower than 1 Pa (see Figure 16).

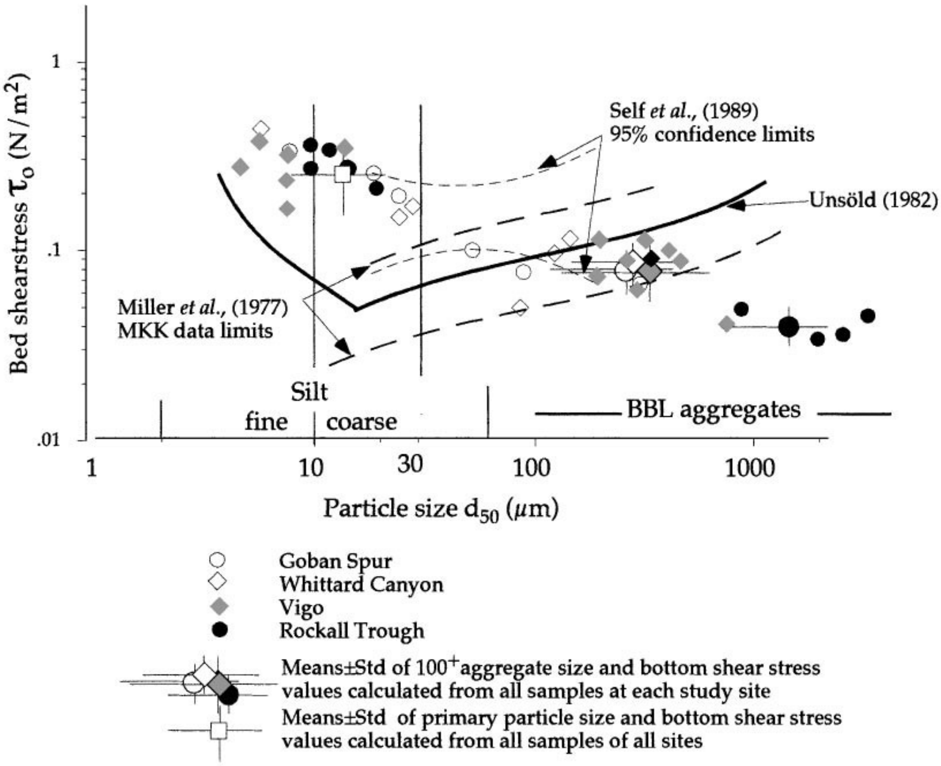

Figure 16 Relation between particle size and bed shear stress (Sediment erosion thresholds and characteristics of resuspended aggregates on the western European margin, Laurenz Thomsen and Giselher Gust, Deep Sea Research Part I: Oceanographic Research Papers, 2000)

Most rivers in low land area's do normally not exceed a flow rate of 1.5 m/s. A tidal influenced river is needed to have enough energy to transport the sediment.

The reverse is true for river bank deposition and wetland entrapment of sediment for flood protection. First, sediment has to be able to enter the area and second the flow velocities should stay below the bed shear stress limit (here a flow velocity of <1.5 m/sec). Consolidation can help to strengthen the sediment (Figure 17), but that also means that flow rates have to stay below the threshold value (here 1.5 m/sec) for a period of weeks to months.

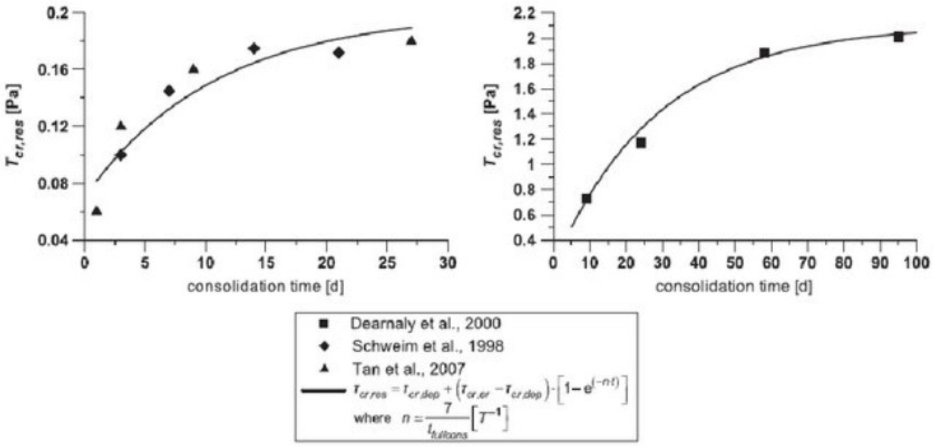

Figure 17 Development of critical shear stress for resuspension over time (Simulating the fate of mechanically eroded masses in the Thermaikos Gulf, Katerina Kombiadou and Yannis N. Krestenitis,, Continental Shelf Research, 2011)

3.2 DEFINE YOUR GOAL CLEARLY

The Port of Rotterdam case illustrated that having two goals (no siltation in the navigation channel and no netto impact on the sediment balance of the harbor and extra sedimentation on the river banks/constructed wetland for erosion and flood protection) have different requirements.

3.2.1 Reallocation without additional sedimentation in the port

The pilot was successful when it came to the goal of no extra sedimentation. That means that for sediment with a grain size with a d_{50} of roughly 100 μm (fine sand, see Figure 18) a tidal flow velocity of 1.5 m/s (outgoing tide) results in a bottom shear stress at or above the sediment yield stress.

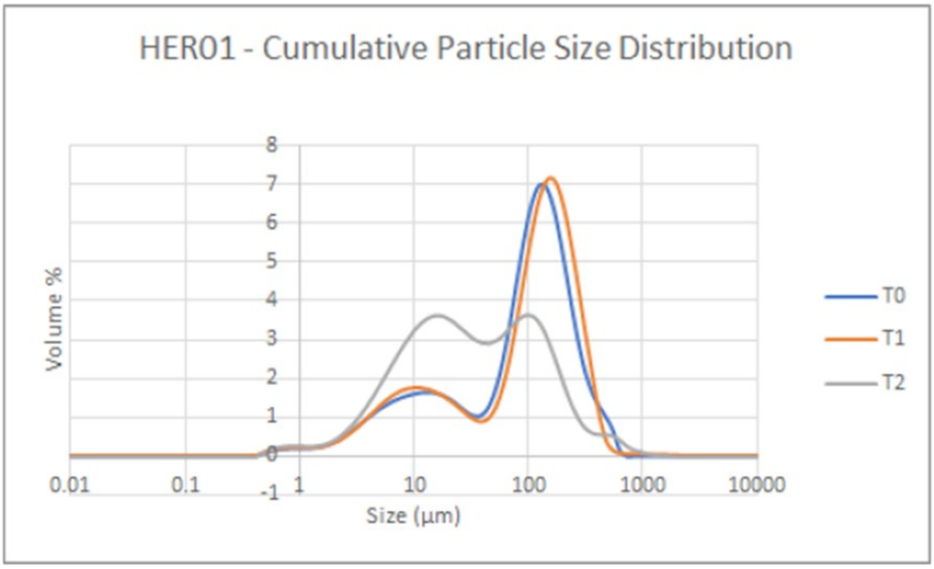

Figure 18 Grain size distribution at the reallocation site during the T0, T1 and T2 monitoring

For other ports these correlations must be checked. Critical parameters:

- Maximum flow velocity at the river bank / the resulting bottom shear stress

- Sediment yield stress (of the source material)
    - This can often be correlated to the grain size distribution and density

3.2.2 Reallocation for river bank strengthening

Reversal of the conditions as stated in paragraph 3.2.1 would yield extra sedimentation.

Based on the provided information (especially Figure 14 on bottom shear stress in combination with the yield stress of the dredged sediment as presented in Table 2.1) the failure to capture sediment on the river banks could have been predicted. What remains unexplained is why the constructed wetland, where flow velocities are much lower, was not able to trap sediment. Here the entrance of suspended sediment into the wetland might have caused the limiting factor.

3.3 Scale on a level that you can manage

Reallocation of sediment within the port carries risks. Since some of these risks are for other stakeholders in the port (more on that in communication) be sure that you can monitor and manage the risks. On the other side, downscaling the reallocation to a level on which you cannot monitor the effects as compared to the normal sedimentation dynamics in the port leads to discussions and often results in not accepting the change in policy on a structural level (as part of the port sediment management strategy).

Based on the experience with the port of Rotterdam pilot reallocation of 10% of the annual amount of dredged sediment seems a minimum to have quantifiable impact. Translated to risks, reallocation of 500.000 m^3 in a 6 months period (due to the storm season a year around reallocation was not allowed) results in roughly 20.000 m^3 a week. Based on weekly surveying and based on an observed trend in unacceptable sedimentation outside the target areas of +3 weeks this means that in case that mitigation measures are to be executed there is a need for roughly 80.000 m^3 of sediment removal. Be certain your dredger under contract can offer that capacity if needed.

In this example the area (40 km) is mapped on a weakly base with a predicted maximum impact of +2 cm a week (see Figure 4 and 5 for the modelled impact over a two-week period). This results in a risk of loss of 8-10 cm of nautical depth before mitigation measures are taken. (Figure 19 illustrates the impact of dredging after the pilot has been finished to reset the system).

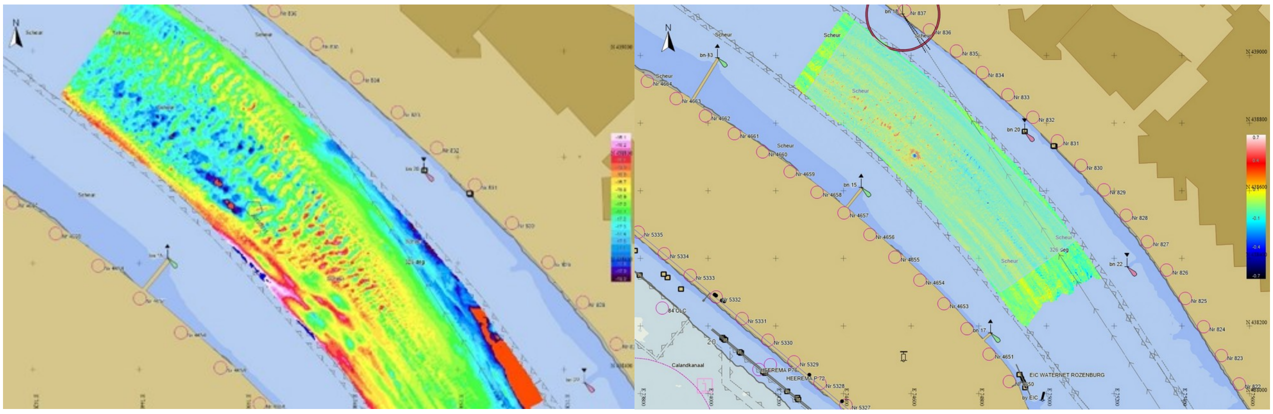

Figure 19 Dynamic changes in bathymetry during the pilot (left) and a 'reset' by dredging after the pilot.

3.4 Costs versus gains

Make a cost/benefit balance, especially if there are different stakeholders involved. Reallocation within the port has the potential to save money in the long term (less travel distance) but requires intensive monitoring (cost) before accepted on a structural port maintenance level. Also consider cost for mitigation measures and who is responsible for taking them. Port of Rotterdam pilot:

Savings on travel distance and time as compared to sea: 5.000 km / 250 hour

There are different methods to express environmental gains like wetland restoration and greenhouse gas emission reduction in benefits. Port of Rotterdam pilot, reduction of greenhouse gas emissions:

CO2: 520.000 kg

NOx: 3.000 kg

3.5 Use both numerical models and monitoring data

The site selection and selection of monitoring locations for sediment sampling has profited from the available numerical models to predict the impact of reallocation of sediment. This is also true for the scale of the pilot needed to have a conceivable impact. The reallocation volume of 500.000 m^3 / 200.000 tons d.w. of sediment resulted in a predicted level of local changes in sedimentation in the range of +1 – 4 cm. While this change was insufficient for evaluation based on routine monitoring (mainly the bathymetry changes on a system scale) the combination with more accurate sediment balance monitoring techniques made it possible to establish the impact of the reallocation against a much larger (factor 10) background sediment mass balance.

3.6 Communication

50% of the work is in the preparation and 50% of the preparation is communication. Even in countries as the Netherlands with extensive dredging and sediment reuse experience, implantation of a new sediment management strategy (even temporarily) raises a lot of questions. A pilot must be clear in the source of the material (clean), the impact (also for shipping and safety), the checkability of the goals in relation to the monitoring strategy and the mitigation measures in case the system behaves differently as compared to expectations. Also, while most contractors will be willing to cooperate, working with nonstandard conditions (time window, area of reallocation, specific source of the dredged material) requires clear instructions and supervision that instructions are indeed clear.

While the reallocation of sediment serves a beneficial use and is part of the EU strategy towards a circular economy, the benefits are long term and for the society and the risks are direct and for the stakeholders. Therefore, trust in the transparency of the process is essential.

3.7 SUMMARY

The technical conditions for which reallocation within the port is feasible can be derived based on the river system dynamics (the energy present (or lack thereof) to transport sediment. For Port of Rotterdam the critical sediment yield stress (T_y) of 1 – 2 Pa (or N/m²) for the dredged sediments was exceeded with flow velocity’s (outgoing tide) of >1.5 m/s.

Define your goals in accordance with the expected feasibility (see technical conditions). Numerical models on the hydrodynamical conditions (or even better morphological models with sediment transport and bottom yield stress) help in defining area’s where reallocation is likely to be successful.

Start early with preparations, know your risks and know how to mitigate the risks, involve all stakeholders in the port and authorities and be specific about cost/benefits and risks/gains (and for who) of the pilot. 50% of the 50% of the work is in the preparation and 50% of the preparation is communication.

4 UPSCALING WITHIN PORT OF ROTTERDAM

Based on the lessons learned and the conditions under which reallocation of sediment within the port can be done successfully, upscaling and incorporation in the port maintenance is feasible. There are two separate tracks to follow:

4.1 USE OF SEDIMENT TO STRENGTHEN RIVER BANKS AND DEVELOP WETLANDS FOR EROSION AND FLOOD PROTECTION

The areas within the port with flow velocities of >1,5 m/s during part of the tide are not suitable for direct placement of dredged sediment. While solutions are possible to strengthen the sediment during placement (like using flocculant additives), it seems not feasible to directly use dredged sediment for river bank protection. Sediment is a suitable source of material for erosion and flood protection in constructed wetlands if flow velocities within the wetland are substantially lower than the critical shear stress level of the dredged sediment. This can be arranged by weirs. As is shown in Figure 17 the critical shear strength of sediment can increase over time (weeks to months) due to consolidation, bioturbation, vegetation and soil ripening. Therefore, a periodical flood (like in the spring) with flow velocity's above the initial critical shear stress level does not have to lead to erosion.

The lesson learned is that placement of sediment on the doorstep of the wetland is not enough. The exchange and settling of suspended sediment with sediment placed in the main channel is insufficient. The sediment must be placed within the wetland. This can be done by rainbowing, small barges, by pipe or even by truck (from the river bank site) of needed.

Figure 20 Filling of pilot site 'Kleirijperij' with dredged sediment

4.2 REALLOCATION WITHOUT ADDITIONAL SEDIMENTATION IN THE PORT

The second goal of the pilot was to establish the conditions under which reallocation of sediment in the port can be done without extra sedimentation (in the main navigation channel). Chapter 3 states the conditions under which, for Port of Rotterdam, upscaling is feasible.

Main criterium: flow velocity during part of the outgoing tide >1.5 m/sec

The original criterium of transport of the reallocated sediment over 1 tide is not essential, if the flow velocity during outgoing tide downstream of the reallocation site exceeds the 1.5 m/s. For Port of Rotterdam the translation of flow velocities to bed shear stress is already incorporated in the numerical models, see Figure 13.

The 'operational hydrodynamic model' (OSR) (Figure 21) can give insight in the flow conditions for the port and can be used to do scenario analyses for reallocation at specific locations.

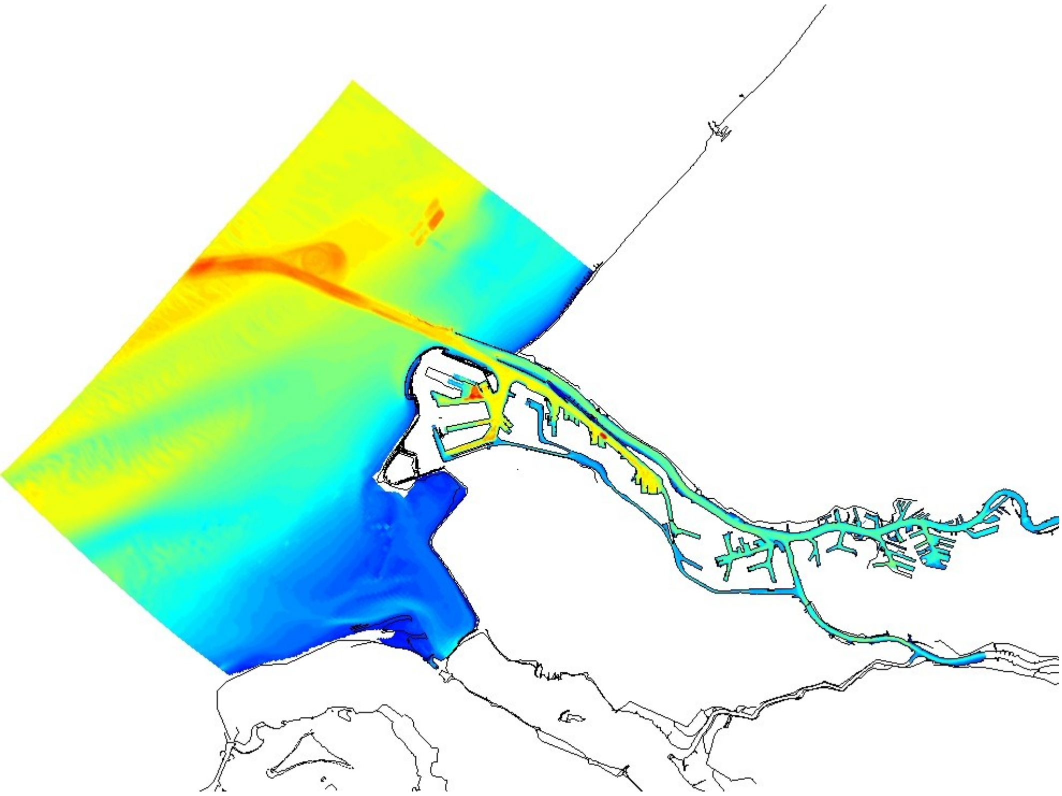

Figure 21 Operational hydrodynamic model Port of Rotterdam

These scenarios can include the definition of time windows for reallocation, the impact of periods of low discharge (tidal induced or river based) or the impact of maintenance dredging (channel depth) on flow velocities.

Confidence by all stakeholders that reallocation of sediment within the port does not lead to risks regarding shipping, flood protection or other port development projects is essential. Monitoring of the impact and a clear mitigation strategy is needed. Therefore, the aim is to upscale from 500.000 m^3 (10%, one-time event) to 2.5 mln. m^3 sediment a year (as part of the adaptation in the port sediment management strategy). This upscaling to 25% of sediment reuse is in line with the long-term ambition as set out in the goals for SURICATES.