Effectiveness of the mud motor near Koehool

Results and interpretion of a tracer study

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1209751-004

Deltares

Title
Effectiveness of the mud motor near Koehool

Client	Project	Reference	Pages
Waddenfonds	1209751-004	1209751-004-ZKS-0001	23

Trefwoorden
Dredge disposal, Intertidal areas, mud engine

Samenvatting
Part of the sediment dredged from the port of Harlingen will be disposed on a new location, in order to promote accretion and development of salt marshes near Koehool. In order to predict the effectiveness of disposal on this new location, a tracer experiment was carried out. Two types of tracer were used: one dispersed from an existing disposal location, and another dispersed from the proposed location. Samples were collected from the area of interest (close to Koehool) and analysed for tracer content. This revealed that approximately 80% of sediment released from the proposed location deposits in the area of interest, whereas 20% of sediment released from the existing location deposits in the area of interest. Results further suggest that the fate of disposed sediment on the short term (days-weeks) is determined by the phasing of disposal within in the tidal cycle (disposal during ebb, flood, high water or low water) but less important over longer periods (weeks - months).

Referenties
Subsidie aanvraag WF221847, toekenning 14-357-MD

Versie	Datum	Auteur	Paraaf	Review	Paraaf	Goedkeuring	Paraaf
1.0	dec. 2016	Bas van Maren	BM	Thijs van Kessel			
2.0	12 jan 2017	Bas van Maren	BM	Thijs van Kessel	TvK	Frank Hoozemans	

State
final

Inhoud

1 Introduction

1.1 Study area

The Dutch port of Harlingen dredges large amounts of fine-grained sediment from its port, which is currently released in the Wadden Sea. In order to make beneficial use of the dredged sediments, it is planned/proposed to dispose this material closer to shore in order to generate land for salt marsh accretion. By releasing the dredged material closer to existing bare mudflats and a small fringe of salt marshes (Figure 1.1), we aim to enhance salt marsh growth by increasing the sediment availability in the tidal channel near the area of interest. Active stimulation of salt marsh growth is a century-long common practice in the Wadden Sea, as the Frisian and Groningen coast has been progressing for centuries by constructing brushwood groynes and in this way creating mild conditions where (fine) sediment can settle. The mud motor project evaluates the effectiveness of a strategy which increases the sediment supply to mud flats, as a less-intrusive alternative for land creation through the use of brushwood groins.

Figure 1.1   Project site, showing development of pioneer marsh vegetation on the tidal flats close to the dike.
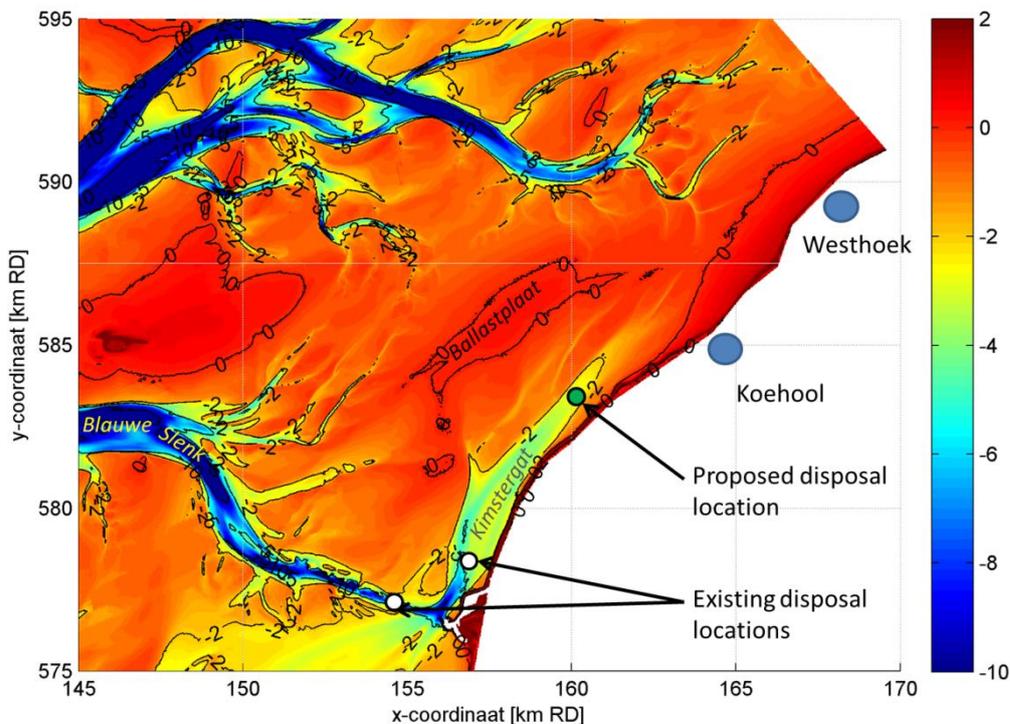
Figure 1.2   Proposed and existing disposal locations plotted on a bathymetric map and names of most important channels and flats.

Approximately 1 million m^3 of fine sediment is dredged in the port of Harlingen annually and released at nearby disposal locations (Figure 1.2). From September 2016 onwards, an amount of approximately 300,000 m^3/yr will be released at a proposed disposal location, for a period of 2 years. The aim is to bring as much sediment as possible to Koehool (Figure 1.2). The new disposal location has been chosen based on the accessibility of the hopper dredger (as the water depth is limited) and the estimated sedimentation footprint assessed by a simple numerical model (Vroom, 2015). The model allows evaluation of the importance of the along-channel disposal location and the proximity to the coast (in the cross-shore direction). This revealed that the amount of sediment depositing close to Koehool is more sensitive to a cross-shore location shift than an along-channel location shift. The optimal location indicated by the model is given in Figure 1.2, marked as the proposed new disposal location.

1.2   Tracer techniques

The effectiveness of the new disposal location can be measured through observations in the water column (suspended sediment concentrations; SSC), the bed (bed level change), and through release of sediment tracers. Evaluating bed level changes with observational techniques is difficult because the expected sedimentation thickness on the mudflat is very small (possibly millimetres or a few centimetres) compared to (1) measuring errors of common altimetry techniques and (2) the natural variation in bed level. The expected impact on SSC near Koehool is even smaller, and therefore a long period is needed in order to detect changes as a result of the dredge sediment release compared to the natural variability. A sediment tracer experiment has several advantages over SSC or bed level measurements to determine the amount of dredged sediment depositing on the mudflat:

- the technique has a much higher accuracy than measuring a sedimentation thickness;
- deposition due to natural processes can be separated from deposition of sediment from the dredger hopper by labelling the dredge material with a sediment tracer;
- the relative importance of multiple disposal locations can be identified through multiple sediment tracer signatures;
- the sedimentation can be followed on multiple time scales (days to months).

Therefore, a sediment tracer experiment was executed in the spring of 2016, using two different colours of sediment tracer to label sediments released from the (proposed) new and existing dredge disposal site. Preparing the tracer experiment involved the following steps:
- selecting the type and amount of sediment tracer
- determining the release method, timing and locations
- defining the sampling methodology

Execution of this experiment involved:
- release of the sediment tracers
- collecting bed samples in the area of interest
- analysing the samples
- interpreting the results

1.3 Aim of the experiment

The sediment tracer experiment aims to give insight into the sedimentation of fine sediment onto the mudflats in the area of interest, both from the (proposed) new disposal location, and from one of the existing disposal locations. To this end, two colours of tracer were used. By using a large amount of sampling locations (~100), not only the amount but also the variability of the sedimentation within the area of interest can be assessed. By making a mass balance, the total amount of sedimentation of each sediment tracer in the area of interest can be compared to the total amount of tracer particles released as a measure of the effectiveness of the disposal location. The evolution of sedimentation patterns over time is assessed by carrying out multiple sampling campaigns (one, two, and 4-5 weeks after release of the tracer).

Summarizing, we aim to answer the following questions with the sediment tracer experiment:
- what is the effectiveness of the (proposed) new and the (existing) old disposal location?
- what is the variability in sedimentation over the area of interest?
- what is the variability in sedimentation over time?

2 Methods

2.1 Tracer characteristics

Deltares commissioned Environmental Tracing Systems Ltd (ETS) to manufacture a fluorescent tracer with a particle size distribution (PSD) and behaviour similar to sediment dredged from the port of Harlingen (Figure 2.1). The PSD of the dredged sediments indicate a d_{50} of 4-9 µm, depending on the measuring equipment. The d_{50} of the two sediment tracers was ~5 µm (measured with a Coulter LS230). After complete mixing each sediment tracer with sediments in the hopper, we expect the tracer particles to be encapsulated in flocs formed by the natural sediments, and thereby behave similarly.
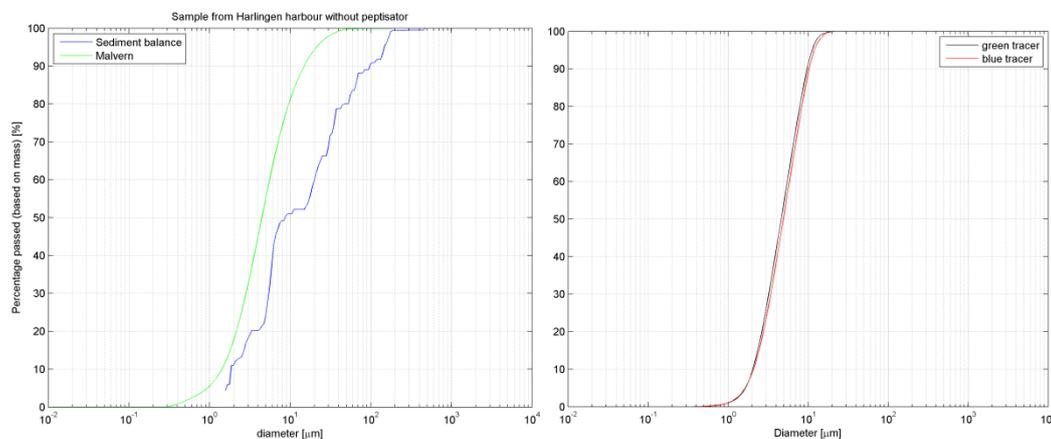

Figure 2.1   Particle size distribution of sample taken from the port of Harlingen (left) and the tracer material (right)

Two different tracer colours were used: a green tracer at the (proposed) new disposal location and a blue tracer at the existing disposal location. For both locations an amount of 100 kg dry weight per tracer colour was used equivalent to ~4 x 10^{14} tracer particles (exact numbers: green 4.0364 x 10^{14}, blue 3.952 x 10^{14}). These numbers are measured by counting the total number of tracer particles within a known dry weight and verified with the particle size distribution data. The amount was chosen based on the expected sedimentation rate and the spreading area and the experience of the sediment tracer expert (ETS), who has 20+ years of experience with tracer experiments in similar systems.

The tracer has a grain density of ~2600 kg/m^3, similar to natural sediment. The particles are composed of a natural mineral and thermoplastic polymer base to which fluorescent dye is added. The impact of the tracer on the environment is described in the Material Safety Data Sheet (MSDS), is classified as environmentally inert, and reports no harm for the environment.

2.2 Tracer release

The sediment tracers were released on the 30th (green tracer, proposed dredge disposal location) and 31st (blue tracer, existing dredge disposal location) of March, 2016. The dry tracer material was first mixed with water to prevent dispersion by wind when adding the tracer to the dredge hopper. Subsequently the tracer material was diluted with a hose, and then mixed in the hopper. To avoid the sediment tracer being spilled or prematurely released through the hopper doors, the dredge hopper (with a volume of 600 m^3) was filled to

approximately 25% before any tracer particles were added. The tracer particles were then mixed into the hopper load as the dredge hopper continued to be filled up to approximately 90% full, in order to avoid any overflow of the tracer particles as it travelled between the dredge site and each disposal location. In total, ~4 x 10^{14} tracer particles were mixed in a hopper volume of 540 m^3. On site, the hopper opened its bottom doors and all sediment inside the hopper is instantaneously released. After disposal, the dredge hopper remained at the disposal location and flushed the dredge hopper completely pumping large quantities of seawater whilst the hopper doors remained open.

Figure 2.2   Adding water to the dry tracer material (left) and diluting the tracer with a hose while adding it to and mixing it in the hopper (right).
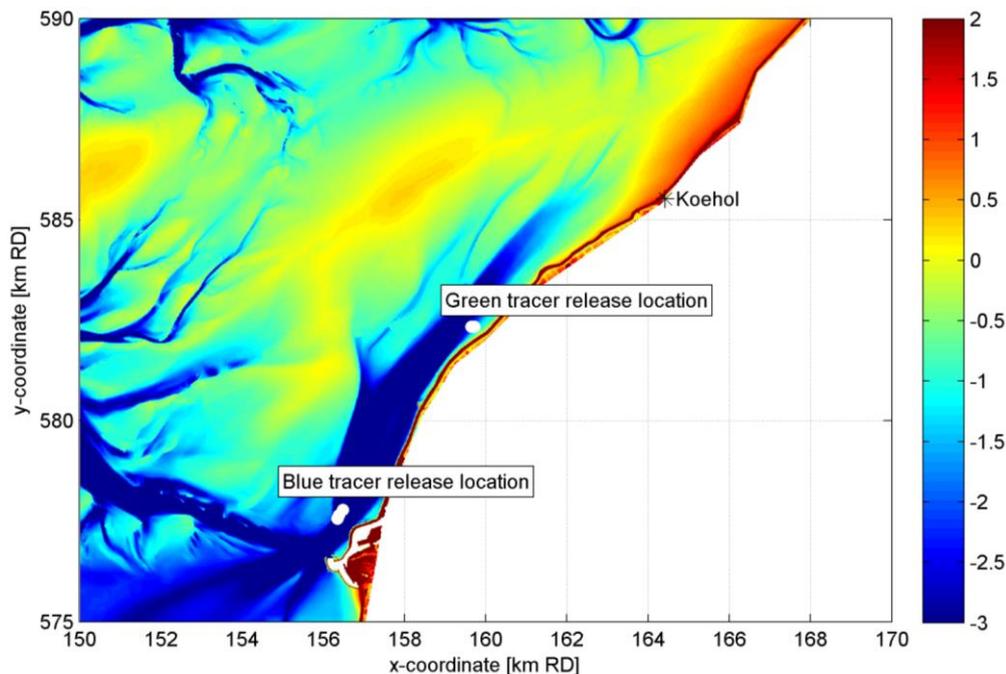

Figure 2.3   Release locations of blue and green tracer.

During release of the green tracer, it was high water at Harlingen, the wind speed was approximately 10 m/s and the prevailing direction was west-south-west. The blue tracer was released during a rising tide, under mild wind conditions (2 m/s from the north).

Longitude	Latitude	Date & time [UTC]	Remark
5.456793	53.227662	2016-03-30 12:12:58	Disposal green tracer
5.457800	53.227619	2016-03-30 12:15:49	Flushing hopper after green disposal
5.407349	53.184826	2016-03-31 08:52:26	Disposal blue tracer
5.407958	53.185605	2016-03-31 08:53:49	Flushing hopper after blue disposal
5.409391	53.186714	2016-03-31 08:56:53	Flushing hopper after blue disposal

Table 2.1   Disposal locations of green and blue sediment tracer. Local time is UTC + 2 hours (incl. daylight saving time).
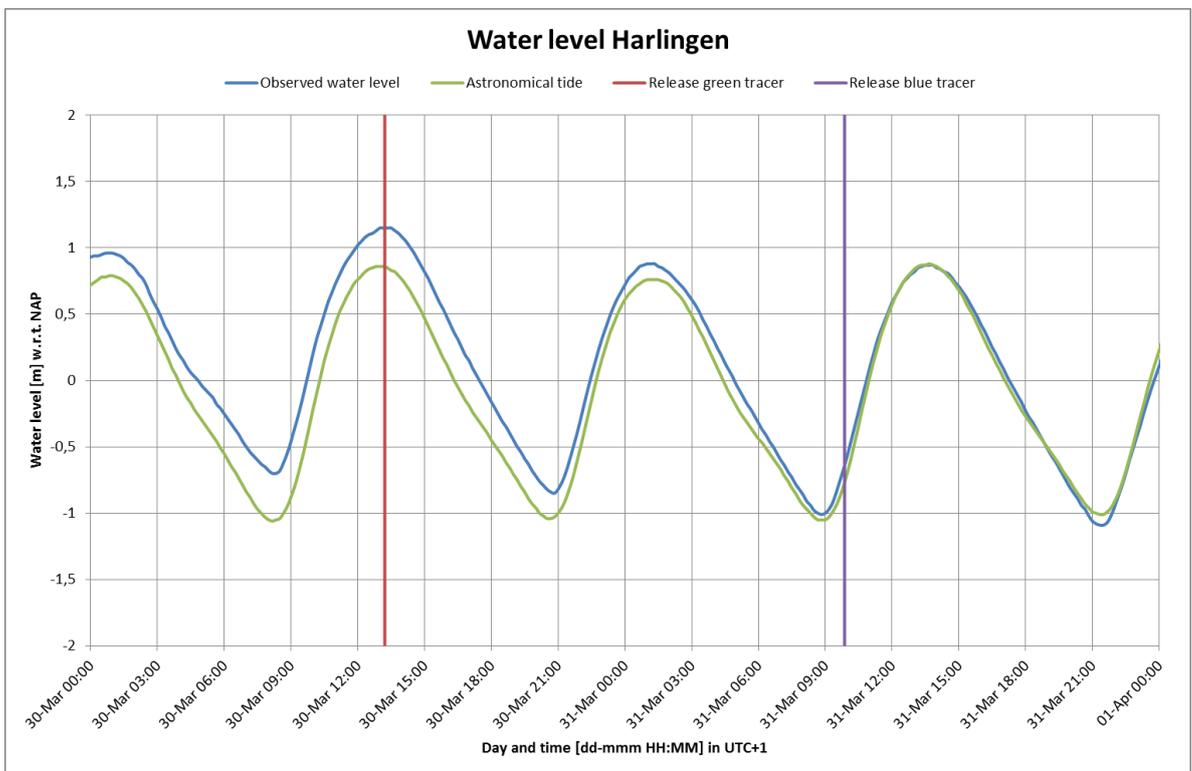

Figure 2.4   Observed water level in Harlingen (blue), astronomical tide (green) and the two releases (vertical lines).
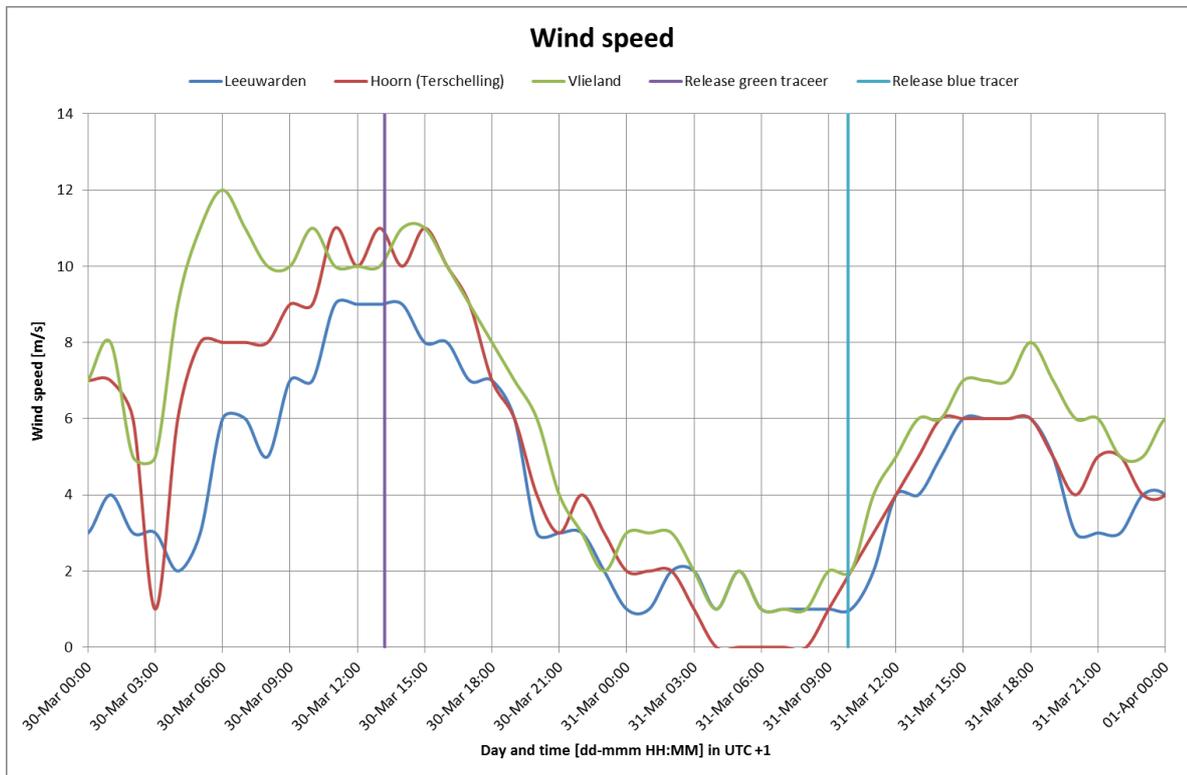
Figure 2.5   Wind speed at 3 nearby stations (Leeuwarden, blue; Hoorn, red; and Vlieland, green) and the two releases (vertical lines).
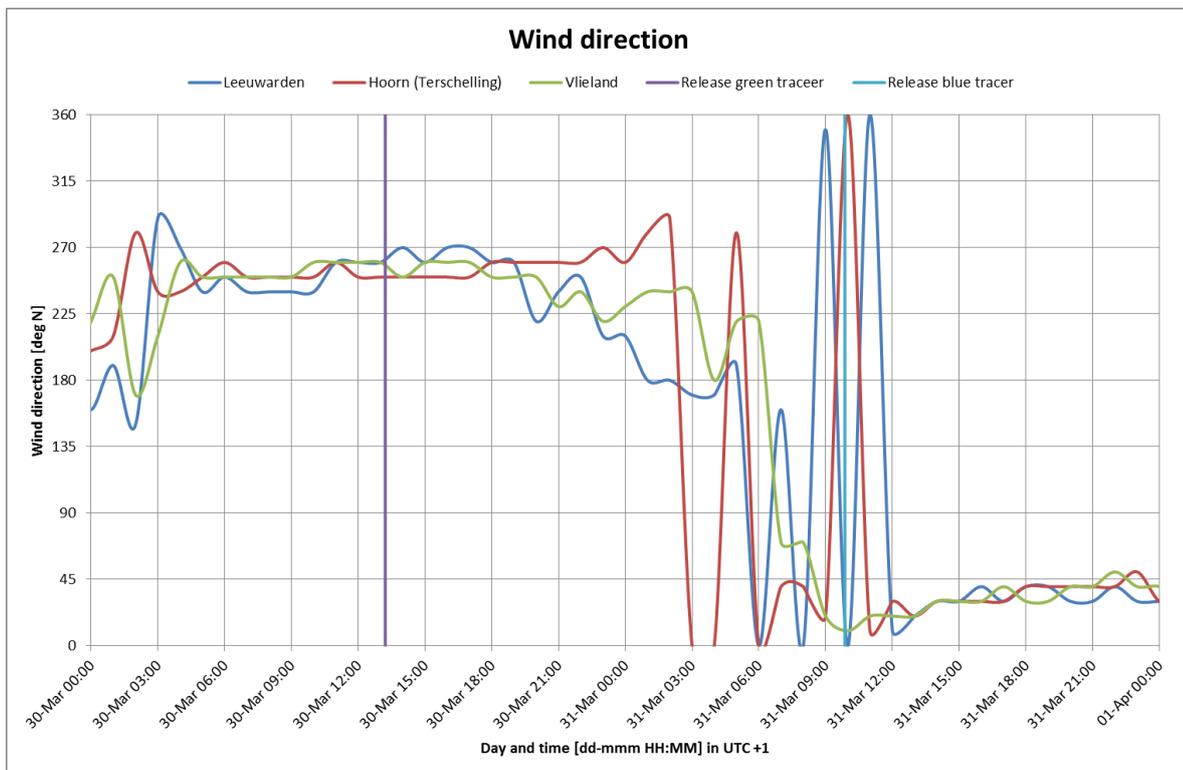

Figure 2.6   Wind direction at 3 nearby stations (Leeuwarden, blue; Hoorn, red; and Vlieland, green) and the two releases (vertical lines).

2.3 Sampling

Samples were collected on foot and by boat. Sampling of the area of interest on foot was challenging, as the tidal flats consist of very soft mud. Sampling the upper tidal flat by boat was also difficult due to the very shallow water depth and short duration of inundation. Timing of the sampling campaign was therefore crucial. Figure 2.7 displays the sampling locations.

The majority of the samples were collected by boat, using a custom-made vacuum sample corer (Figure 2.8). The sample tubes for collection by boat had a diameter of ~4 cm and a minimal length of 50 cm. The long length was chosen to be able to capture both a possible soft unconsolidated top layer and the more consolidated bed underneath to ensure sealing of the vacuum in the sample tube. It was very important to collect the soft (unconsolidated/nepheloid) fluffy layer as this was likely to be the layer with most tracer accumulation.
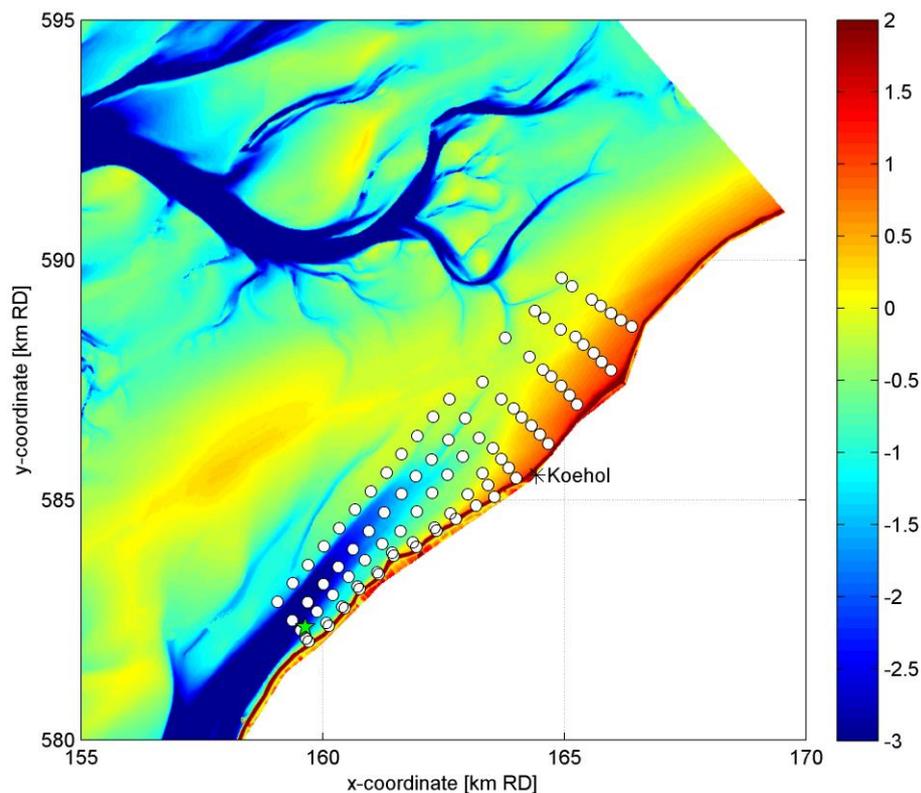

Figure 2.7   Sample locations in the area of interest. The green tracer release location is indicated with a green star. The blue tracer release location lies outside the figure.

Sample locations on the upper tidal flat were collected on foot during low water. To ensure safe walking over the mud flat, snow shoes were used to enlarge the footprint (Figure 2.8). Sample tubes for the sampling campaign on foot had the same diameter (~4 cm) as the tubes used for boat sampling, but where shorter (length of 10 cm). A tube length of 10 cm was chosen based on the bed irregularities of the mudflats which comprised harder more consolidated areas interspersed with pockets of much softer unconsolidated sediment with a very high water content; all samples were taken in these pockets in the mud flats (Figure 2.8). The sample tube was pushed into the mud, making sure the top layer was not disturbed. Then a cap was placed on top of the tube to ensure vacuum, the tube was taken out of the

mud and the bottom cap was placed. A new pair of disposable gloves was used for each sample to prevent cross-contamination of the samples. The samples were kept in an upright position all the time to avoid mixing and disturbance of the surface water-sediment interface.

In between the second and third sampling campaign, on the 18th of April, a total of 7 samples were collected by the Navicula research vessel from NIOZ in the Kimstergat channel in between the port of Harlingen and Koehool (Figure 2.9). These samples were taken with a box corer, and the top layer of the sediment was collected into a plastic bag and delivered to Deltares. In total 3 field sampling campaigns were conducted (see Table 2.2).

During each sampling campaign two samples were also taken by boat in the port of Harlingen (see results section hereafter for the location). Sampling was done in sheltered, rapidly accreting areas of the port.
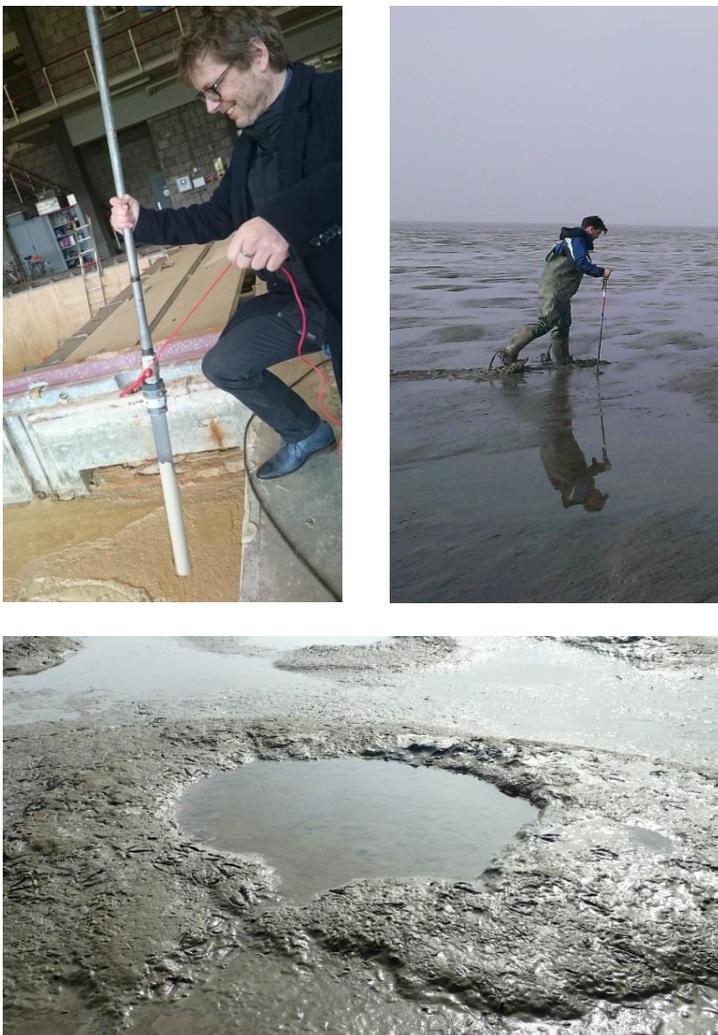

Figure 2.8   Testing the custom-made vacuum sample corer for very soft mud in the lab (top left), walking on the mud flat using snow shoes and ski poles (top right) and humps and troughs (pockets) on the mudflat (bottom).

After sample collection, the long samples tubes from the boat sampling were shortened for shipment to ETS' laboratory in the UK using the following methodology; a small hole was drilled a couple of centimetres above the sediment bed-water interface to let any surface

water drain from the sample. The tube was then shortened while the sample was not disturbed. The shortened samples were packed in a crate and sent.

Table 2.2   Timing of the field campaigns

Campaign	By boat	On Foot	Timing
A	4 and 5 April	4 and 5 April	after 1 week (4-6 days)
B	12 and 13 April	14 and 15 April	after 2 weeks (12-16 days)
Navicula	18 April	-	after 2.5 weeks (18-19 days)
C	3 and 4 May	28 and 29 April	after 4-5 weeks (28-35 days)

Collection of samples by boat and on foot could not always be done simultaneously, as the collection by boat needed to be done during high water during daylight and the collection on foot could only be done during low water during daylight. For the collection by boat the weather conditions were also important, as they could only be conducted during fair weather conditions.
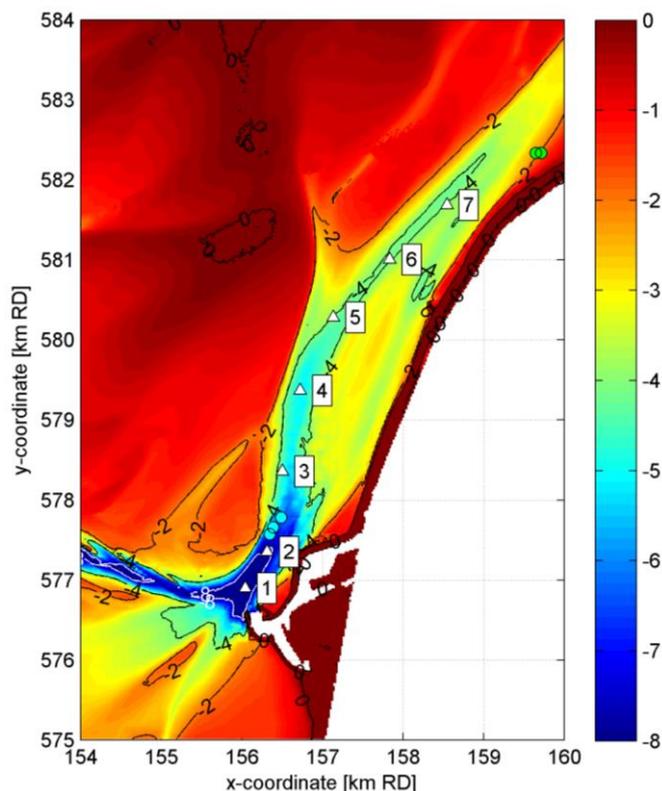

Figure 2.9   Locations of the samples (white triangles) taken during the Navicula cruise on April 18th plotted on top of the bathymetric map of the Kimstergat channel. The blue and green dots indicate the release locations of the blue and green tracers respectively.

After a certain period of time, period vertical mixing of sediments may lead to deep burial of sediments. Sampling is then required to be several dm deep (and to be consistent, such deep cores are then needed for all campaigns). Deeper cores are logistically difficult (in the field and in the laboratory) and therefore sampling was terminated after 4-5 weeks (after which most of the green tracer was recovered, as will be shown later).

2.4 Lab analysis

The samples were analysed in ETS' laboratory in the UK. For the long sample tubes (collected by boat), the top 10 cm were taken and homogenised. For the small sample tubes, the entire sample was homogenised. After weighing the total homogenised sample, a subsample of 2-4 gram was taken and (after weighing) suspended in approximately 50 ml of water. A subsample (of around 0.2-0.5 ml) of the suspension was taken with a pipette, in which all individual tracer particles were counted using a fluorescent optical counting device. This is an equivalent detection limit of counting 1 tracer particle (or more if a higher concentration) in approximately 200-500 million natural sediment particles, based on the particle size distribution data of the native sediment and tracer particles released.

As will be shown in the following chapter, the typical count per subsample is 1-10 tracer particles, with the majority being 1-3 tracers. This amount is too low to generate a statistically reliable map of the tracer distribution. In hindsight the dilution of the sample should have been lower (now the sample was diluted with a factor 1:5000 to 1:20.000), more tracer material should have been dispersed, or duplicate / triplicate tests been executed to ensure the accuracy of the (sub) sampling methodology.

3 Results

3.1 Tracer analysis

The results are shown for the green and blue tracer particle releases separately, after 1, 2 and 4-5 weeks, in Figure 3.1 and Figure 3.2 respectively. The green tracer was released close to the mudflats (see location in Figure 2.3) and the blue tracer close to the port. Over time we observed an increasing amount of tracer in the surveyed area of interest, both for the green and the blue tracer. A larger amount of green tracer was accounted for within the area of interest (in line with expectations, because of the proximity of the release location), but also measured in the box core samples collected in-between both tracer release locations (Table 3.1) and in the port of Harlingen (Figure 3.1 and Figure 3.2). Surprisingly, only green tracer was observed in the port of Harlingen. Despite the close proximity of the blue tracer release location, no blue tracer was observed in the port.

Figure 3.1 *Presence of green tracer 1 week after release (top left), 2 weeks after release (top right) and 4-5 weeks after release (bottom). Colour bar indicates actual counts (maximised at 6 counts). The release locations are shown as blue (see inset) and green stars. Circles denote sampling by boat; squares sampling on foot.*

Blue tracer campaign A
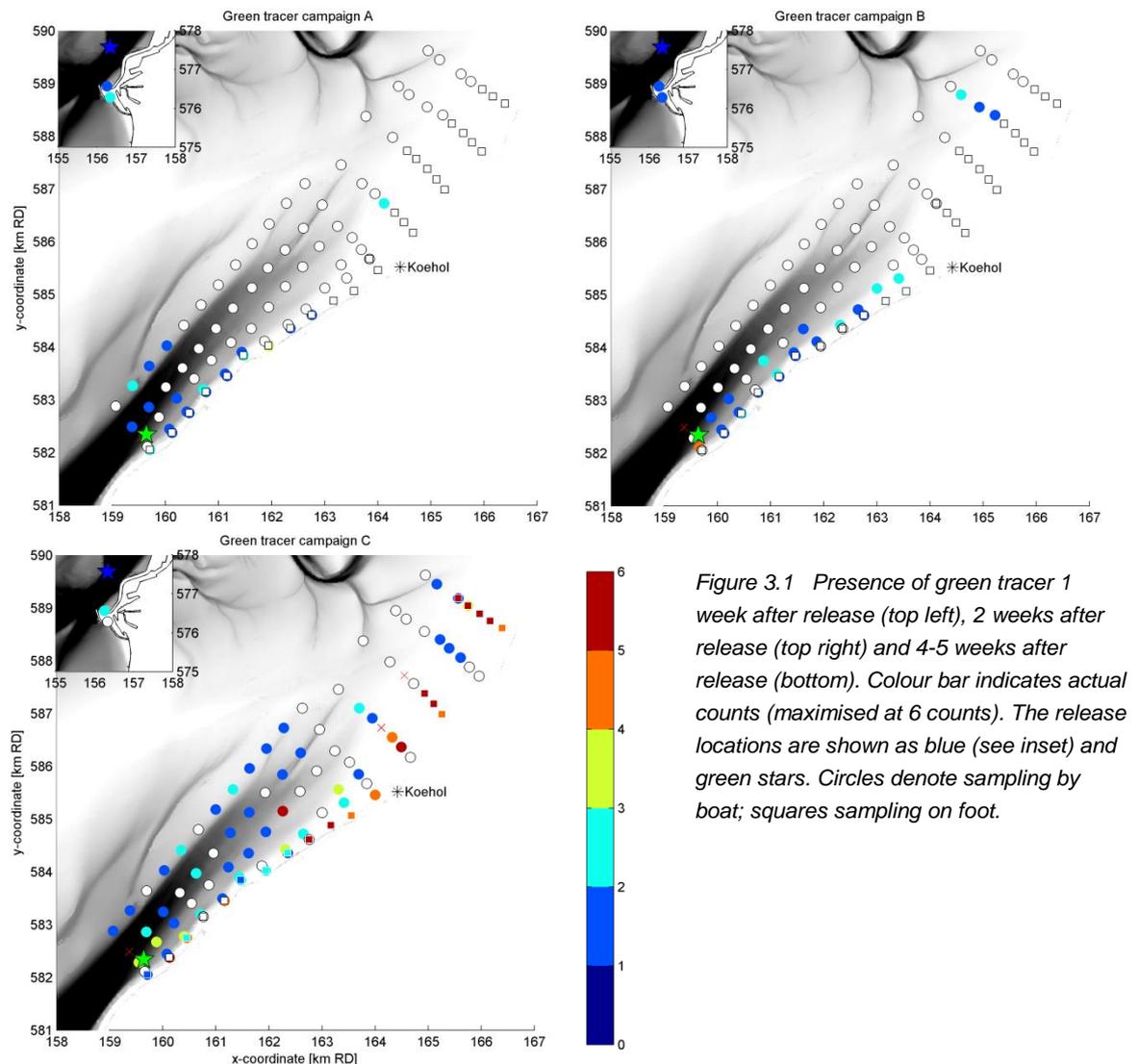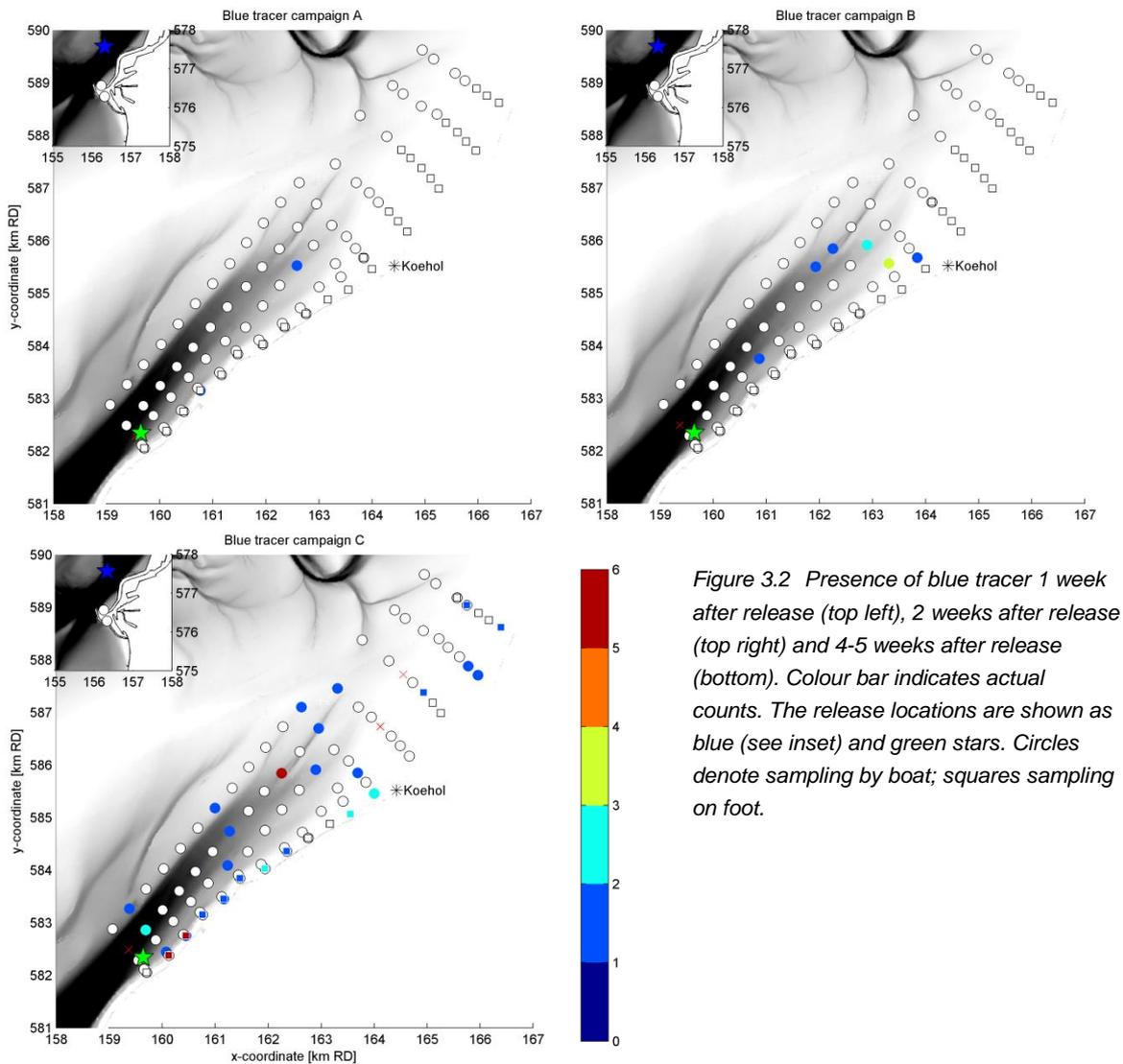

Blue tracer campaign B

Blue tracer campaign C

Figure 3.2 Presence of blue tracer 1 week after release (top left), 2 weeks after release (top right) and 4-5 weeks after release (bottom). Colour bar indicates actual counts. The release locations are shown as blue (see inset) and green stars. Circles denote sampling by boat; squares sampling on foot.

Table 3.1   Tracer counts in the samples collected by the Navicula, 18-19 days after the tracer releases.

Sample number	x [RD] (m)	y [RD] (m)	Blue tracer	Green tracer
1	156040.0	576896.7	1	1
2	156314.5	577351.6	0	2
3	156505.9	578358.4	0	0
4	156726.0	579372.0	0	3
5	157134.5	580284.7	0	2
6	157836.7	581012.0	0	0
7	158544.1	581692.0	0	0

The amount of tracer particles counted in each subsample (Figure 3.1 and Figure 3.2) can be converted into the amount of tracer particles per m^2 (see Box 1), which are then interpolated in space. This total number of tracers in the survey area can be used to assess the

effectiveness of the tracer release (in percentage of the originally released amount of tracer: see Table 3.2). These results suggest that

(1) Initially (in the first 2 weeks) only 10-15% of the green tracer (proposed location) was transported towards and deposited within the surveyed area. Between week 2 and weeks 4-5, this increased to 80%.
(2) The amount of blue tracer (existing location) accounted for within the surveyed area increased more gradually; around 1% was retrieved in the study area after 5 days, around 5% after 2 weeks (~40% of the amount of green tracer), to approximately 20% after weeks 4-5.

Note that over time, the amount of tracers accounted for within the surveyed area (especially the blue tracer) might still increase (as the last sampling campaign showed the largest tracer content).

Box 1. Conversion of tracer particle counts to estimated sedimentation thickness

Per tracer colour, approximately 4×10^{14} individual tracer particles were released with 540 m^3 of hopper sediment. When distributed uniformly, each tracer particle is therefore associated with 1.4×10^{-12} m^3 of the sediment-water mixture in the hopper. We estimate the dry density in the hopper to be 450 kg/m^3. Therefore, each tracer particle is associated with a dry sediment mass $M_{t,o}$ of 0.6×10^{-9} kg.

Of each core, only a subsample is analysed for tracer content (as reported in Figure 3.1 and 3.2). The average dilution F for subsampling differs strongly per core, and therefore the exact conversion of tracer count to sedimentation thickness differs for each individual core. Using a typical dilution value as an example ($F = 15000$), the associated mass per tracer per core $M_{t,c} = 9\ 10^{-6}$ kg ($M_{t,c} = M_{t,o}\ F$). The associated mass per m^2 (M_t) follows from the diameter of the core D as in $M_t = M_{t,c} / (3.14\ (D/2)2)$. With $D = 4.5$ cm, $M_t = 5.7\ 10^{-3}$ kg/m^2.

A rough indication of the effectiveness of the mud engine can be obtained by assuming the measured tracer dispersion after campaign C is representative for long-term deposition rates. In two years' time, 600.000 m^3 of sediment will be released. This would result in a total mass $M = 600.000/540\ M_t = 6.3$ kg.

This sediment mass is then converted to vertical accretion rates using the dry density ρ_{dry}. Using $\rho_{dry} = 500$ kg/m^3 (the average of 470-567 kg/m^3 as reported by Vroom, 2015), the long-term accretion rate $\Delta z = M / \rho_{dry} = 1.26$ cm for every observed tracer. The maximum amount of observed tracer (10) then corresponds to $\Delta z = 12.6$ cm. Any deviations between the observed tracer maps (Figure 3.1 and 3.2) and the accretion rates (Figure 3.3) result from variations in the dilution factor F (which varied per core).

Table 3.2   Estimated percentage of tracer accounted for within the surveyed area of interest.

Sampling Campaign	Time after release	Blue	Green
A	5 days	1	13
B	2 weeks	5	12
C	4-5 weeks	20	80

The results of the tracer measurements can also be used to provide a first estimate of the siltation rate resulting from the new disposal location. As the total number of particles and sediment released from the hopper is known, we can estimate the siltation rate resulting from dredged sediment disposal. Applying the methodology described in Box 1 to the complete surveyed area (using sampling campaign C) yields a map with accretion rates (Figure 3.3) after disposal of 600.000 m^3 of sediment from the hopper (from the existing and proposed disposal location). This map reveals that the highest sedimentation rates of particles released from the new disposal location occurs several kilometres north and south of Koehool, at a depth of 0.5 below to 1 meter above chart datum (NAP).
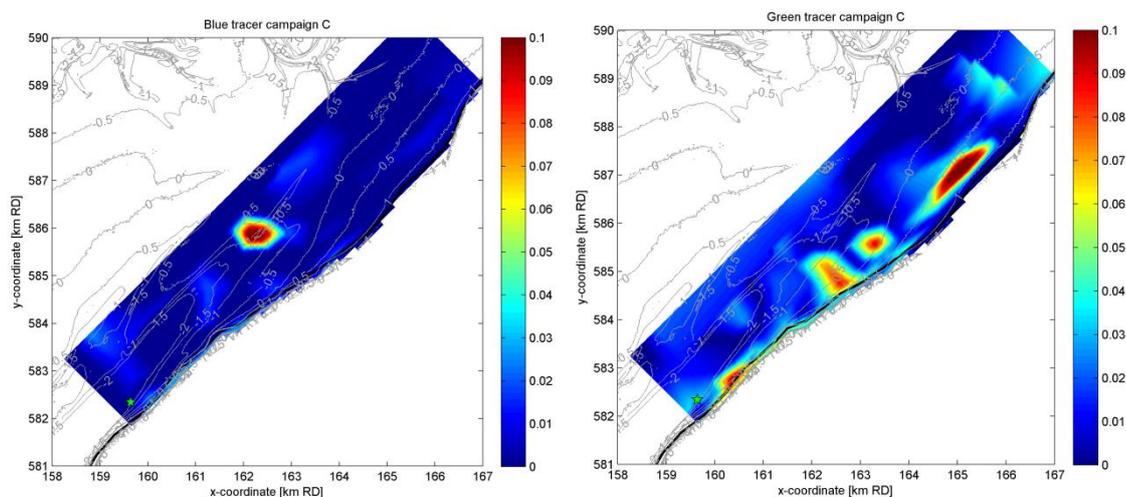

Figure 3.3   *Estimated sediment thickness in [m] for a dredging disposal of 600.000 m^3, computed by interpolating sample results of sampling campaign C in space, and scaling tracer count per subsample to total sample. The proposed release location is shown as a green star.*

3.2   Interpretation

The tracer results suggest that the amount of green tracer accounted for increased slowly within the sampled area of interest. This slow increase in tracer amount can be explained through 2 hypotheses:

1) The disposed sediment placed by the dredger was initially deposited on the bed, and subsequently slowly resuspended from the bed and was transported towards and deposited within the area of interest by the flood currents (& possibly wind-driven circulation and waves).
2) The green tracer was released at HW, and was initially transported southwest-ward by the ebb flow. Subsequent transport (back) to the mudflat through diffusion by tidal currents (& possibly wind-driven circulation and waves) was slow.

Which of these hypotheses is more likely, will be estimated through a closer analysis of the data and previous model results. Important observations are the following.

*   Some of the green tracer was retrieved in-between its disposal location and the port of Harlingen (Table 3.1) and in the port itself (Figure 3.1) suggesting that at least part of the tracer material was dispersed southward (as in Hypothesis 2).
*   Hypothesis 2 is further supported by the computed bed shear stress distribution (Figure 3.4). A typical critical bed shear stress for erosion of the disposed sediments is 0.3 Pa, which is exceeded >80% of time at the green tracer disposal location (situated close to the flats but still in the channel). It is therefore unlikely that the

- disposed fine-grained sediment was still present at the disposal location 2 weeks after disposal.
- The disposal area is part of the sampling area. Even in absence of erosion, some lateral migration of the disposed sediment is to be expected, and the tracer counts should have been higher. The observation of low tracer values in the proximity of the release location shortly after tracer release therefore supports hypothesis 2.
- The green tracer results show a net migration and deposition over time towards the east as it spreads. Such a pattern can be explained by both hypothesis 1 and 2.

Based on these considerations, it is most likely that the majority of the released sediment and tracer remained in suspension after release, was transported south-westward by the ebb currents following the tracer release, and slowly returned to the area of interest (Hypothesis 2).
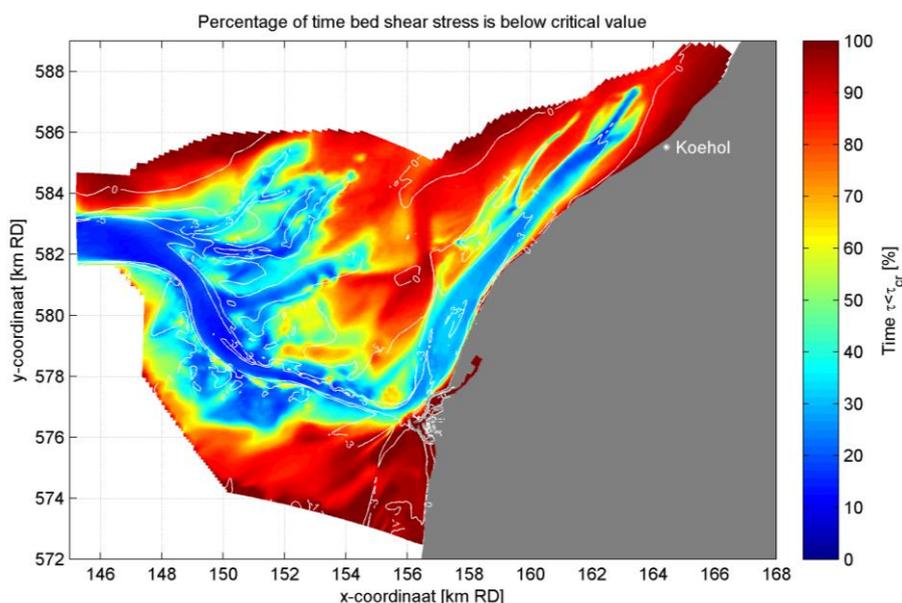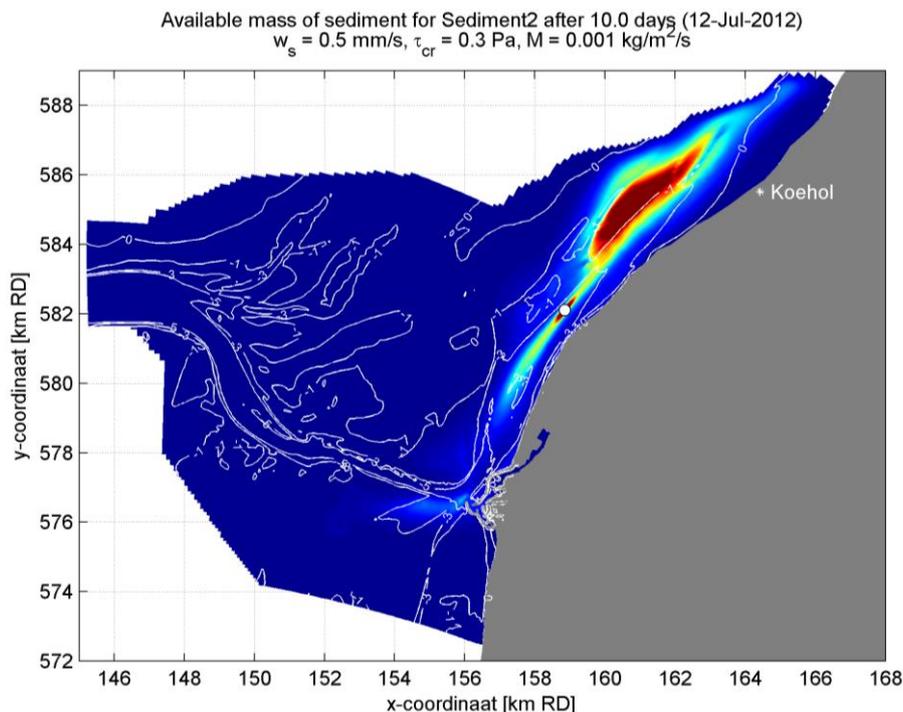

*Figure 3.4   Computed percentage of time that the bed shear stress is **lower** than a typical critical bed shear stress of 0.3 Pa (from Vroom, 2015). In the channel, this critical bed shear stress is exceeded ~80% of time, whereas it is exceeded ~20% of time on the flats.*

The absence of blue tracer particles measured in the port samples is more difficult to explain. The blue tracer was released in the tidal channel in which the computed bed shear stress is exceeded for ~80% of time (Figure 3.4). It may be that the settling rates within the port are so large, that the majority of the blue tracer was already buried by non-tracer sediment before the first samples were collected (samples in the port were taken in a strongly depositional area). Equally surprising is the low counts of blue tracer particles found in Navicula samples (Table 3.1). Even though most of these samples were collected closer to the release of the blue tracer, more green samples were observed.

We also observe that the green tracer deposited mostly on the mud flats and less in the tidal channel (both in the primary study area and in the Navicula samples). Probably, the tidal channel is too energetic for the fine sediment to deposit (Figure 3.4).

The effectiveness of the release location is much larger than earlier predictions with a numerical model (Vroom, 2015) suggest: see also Figuur 3.5. The observations suggest that

sediment deposits in relatively shallower areas than the model indicates (where large amounts of sediment deposited in the channel). This is probably the result of wave-induced resuspension, which was not modelled. In the model, sediment cannot be transported over the flats towards Koehool, because the bed shear stress by currents is too low. In reality, sediment is regularly stirred up by waves, and transported landward by the (weak) tidal currents. Future model simulations of the dredge plume dispersal therefore need to include wave-induced resuspension.

Figuur 3.5   Computed deposition pattern resulting from 10 days continues release of sediment (settling velocity of 0.5 mm/s; critical shear stress of 0.3 Pa) from the location indicated with a white dot. From Vroom (2015).

The model also predicts relatively more deposition north of the Kimstergat tidal channel than the observations confirm. The reasons for this differences are at this point not understood, but possibly also related to resuspension by waves.

3.3   Uncertainties

The presented tracer results are subject to a number of inaccuracies and uncertainties. The main sources of uncertainty are related to

- Laboratory procedures related to measuring mass and volumes which lead to errors between 0.1% or higher, but can compound to several % overall. However, such errors are considered insignificant overall.
- Given the relatively low counts of tracer particles, the potentially largest (random) error arises from sampling and subsampling. Mass balance calculations, summarised in Table 4.2, assume spatial homogeneity in the tracer concentrations between each sample location over a wide area; clearly there is likely to be variability in the tracer counts per unit area as a result of sedimentology, distribution and the ability to collect a representative sample at each sample location. In addition, sub-sampling of the core sample, dilution and subsequent analysis of each sub-sample can result in errors especially when tracer counts range between 0 and 1-3 tracer particles being counted in each subsample especially when the counted particles are diluted out of an

estimated total of several 10's of thousands of tracer particles per the original core sample. Counting 2 instead of 1 or 3 tracer particles can easily result from random sampling and subsampling errors, leading to a factor of 2 difference. However, over large areas and large sample numbers (~100 per sampling campaign) such random errors are likely to cancel or average out.

- The initial amount of tracer particles released per colour (~4 x 10^{14}) is based on a count of tracers per known mass, which is then extrapolated to the complete released tracer mass (100 kg). However, this total amount of tracer particles released has a large influence on the computed percentage of tracer deposited within the surveyed area of interest (Table 3.2) and the computed deposition rate as a result of two years of sediment disposal (Figure 3.3). An error of 10% in the initial amount of tracers leads to an error of 10% in the predicted siltation rates and tracer recovery rate

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4 Conclusions and recommendations

4.1 Conclusions

The main conclusions of the tracer study are that
1) After 5 weeks, approximately 80% of the (green) sediment tracer released at the new disposal location was deposited within the surveyed area. The effectiveness of the proposed disposal location is greater than expected based on earlier numerical model results (Vroom, 2015). This is probably the result of wave-induced resuspension, allowing transport of sediment over the flats.
2) By comparison, approximately 20% of (blue) sediment tracer released from the existing old dredge disposal location was deposited within the surveyed area.
3) Sediment settles preferentially on the flats within 2-3 km southwest and northeast of Koehool. Relatively less sediment settles in the Kimstergat channel because it is too energetic.
4) The total percentage of green tracer particles accounted for within the surveyed area of interest took more than 2 weeks to increase above 10-15%. This can be explained by two hypotheses:
    Hyp. 1: the green tracer was very immobile. Sediment released from the hopper immediately settled and was only slowly resuspended and transported into the study area
    Hyp. 2: the green tracer was very mobile. Since the disposal of the green tracer at the new location occurred at HW, sediment may have been initially transported in the SW direction. The tracer (and disposed sediment) only slowly dispersed over a wide area, and therefore the amount of tracer in the study area slowly increased.
5) Hypothesis 2 is supported by
    • The observation of fines (t racer particles) far away from the study area (in the port of Harlingen and the Navicula samples)
    • The strong current velocities at the release locations (flood flow velocities of ~ 1m/s according to the numerical model – Vroom, 2015). This is further supported by the preferential settling of tracers on the flats.
    There is no direct evidence supporting Hypothesis 1.
6) There are no clear indications for the low retrieval rate of tracer in the Navicula samples and in the port of Harlingen released from the old location. The blue tracer release took place during a rising tide (promoting northward transport) in an area with (according to the model) flood flow velocities >1.2 m/s.
7) In hindsight, the amount of tracer initially released and/or the size of the subsample is considered small. The result is a count of tracer particles in the samples which is too low for detailed statistical analyses of tracer distribution. Consequently, there is considerable uncertainty in the observed pattern, and extrapolations should be interpreted with caution.

4.2 Recommendations

The main recommendations resulting from this study are the following:
- The results of the tracer experiment can be utilized to optimise the dredging release strategies. However, the results of the experiment indicate that the new release location is close to optimal, and no adaptation to dredging strategies is needed.
- No further sampling campaigns are foreseen, because over time sediment will gradually mix deeper into the bed. Differences with the initial tracer distribution is then related to (1) horizontal dispersion and (2) vertical mixing. Since both aspects are unknown, a comparison with earlier sample distribution is difficult.
- A new model will be setup, or existing models adapted, to hindcast the observed tracer behaviour. A major adaptation should be to include wave-induced resupension. Such a model can then be applied to estimate the long-term fate of the dredged sediment.
- In a following study, the samples should not be diluted as much as has been done during this tracer experiment (larger subsamples should have been analysed).

5 References

Vroom, J. (2015). Modelresultaten slibverspreiding t.b.v. slibmotor Koehool. Deltares memo 1209751-000-ZKS-0001, 20 pages.