Stijn Claeys, Guido Dumon, Jean Lanckneus and Koen Trouw

Mobile Turbidity Measurement as a Tool for Determining Future Volumes of Dredged Material in Access Channels to Estuarine Ports

Abstract

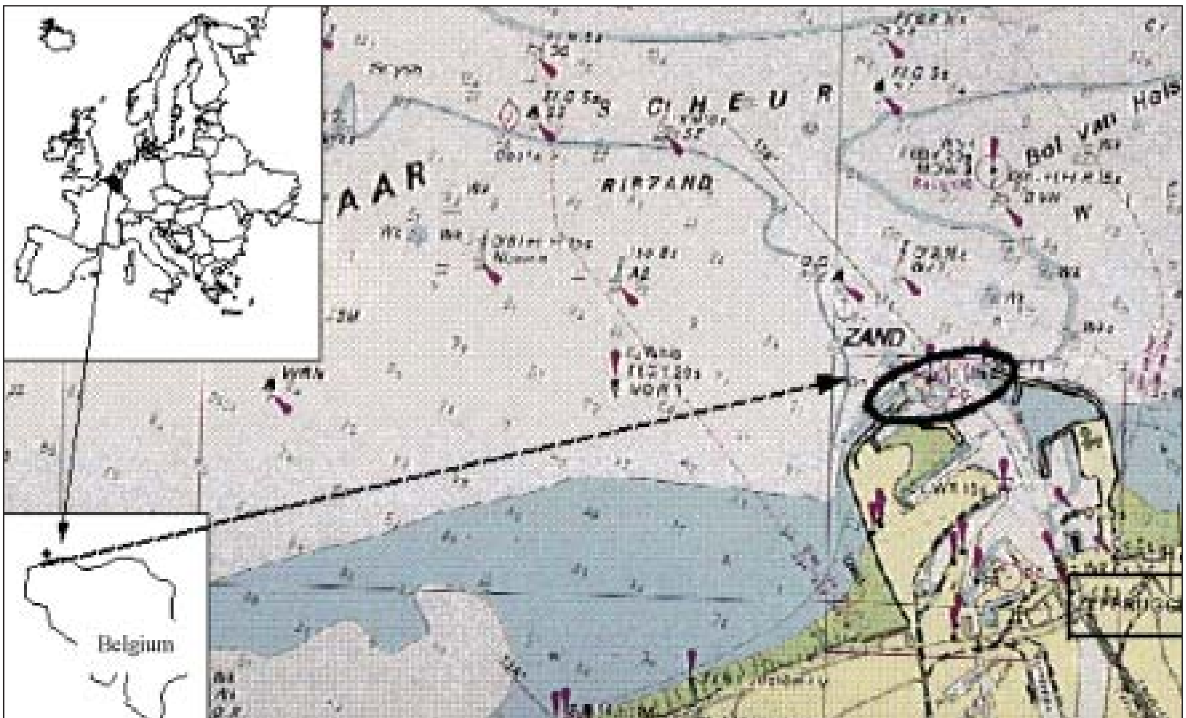
Monitoring the environmental impact of dredging and relocation operations and estimating the turbidity (sediment flux) is becoming increasingly more important. Predicting the natural relocation of dredged material can lead to a better planning of the dredging activities. Of equal importance is the monitoring of the background turbidity in order to assess the relative importance of the turbidity plume created by dredging activities.

Monitoring the sediment flux, caused by the action of tidal currents, waves and wind, with the help of mobile measurements at the entrance of the harbour of Zeebrugge is part of the research project "The ecological monitoring of dredging works in the Belgian coastal harbors", (MOBAG 2000) of the Ministry of the Flemish Community (Waterways and Maritime Affairs Administration, Environment and Infrastructure Department, Coastal Waterways, Oostende, Belgium).

On-line mobile monitoring was performed using an Acoustic Doppler Profiler (model NDP, mounted at the hull of the vessel). The NDP was calibrated with backscatter turbidity sensors (mounted on a computer-controlled towfish). Turbidity and current data were visualised and used to estimate the sediment flux.

During the project 13 hours of measurements took place during neap and spring tides. Data through the water column were collected along a track crossing the entrance of the Outer Harbour of Zeebrugge. The data were corrected off-line for errors. Finally, the sediment flux was calculated from the corrected current and turbidity profiles.

Figure 1. Location of the sediment flux monitoring at the Outer Harbour of Zeebrugge, Belgium.



The recorded profiles made it possible to visualise flow rate and sediment flux. The profiles showed a very complex pattern of in- and outflow of current and suspension material. The amount of sediment that remains in the harbour after completion of a tidal cycle is quite different for a neap and a spring tide. Measurements showed that after a tidal cycle during neap and spring tides, respectively 795 tonnes and 3200 tonnes of sediment remained in the harbour. The obtained results proved as well that the turbidity caused by dredging activities (in the harbour), is merely a short-time local phenomenon and for the most part does not exceed background turbidity.

Introduction

The sediment flux, entering the harbours, is subject to very complex tidal and meteorological influences. The sediment behaviour cannot be completely understood when sensors are used that only provide information from single points. On-line mobile monitoring of the turbidity, current speed and current direction over practically the entire water column makes it possible to visualise the complexity of the sediment flux.

A mobile survey campaign was successfully executed at the Outer Harbour of Zeebrugge during neap and spring tides.

This kind of monitoring campaign is very useful for predicting the amount of sediments coming into the harbours. Therefore dredging campaigns can be better planned.

Description of the Monitoring Campaign

Location and period
Two campaigns, one at spring tide and one at neap tide, were carried out during which measurements took place for an entire tidal cycle.

Profiles were measured along a track located across the axis of the access channel near the entrance of the harbour (Figures 1 and 2). The position of the vessel (determined by DGPS) in relation to the theoretical track was visualised on-line with the help of two navigation computers (location and period: Figures 1 and 2, Table I).

Because of the strong current coming into the harbour, all measurements were performed in the same direction (from southwest to northeast) to prevent the towfish from being dragged under the vessel by the current.

Monitoring method
After evaluation of available current information,

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Guido Dumon received a degree as a Civil Engineer in Chemistry and Engineer in the Environmental Sanitation from the University of Ghent, Belgium. He is presently Senior Engineer at the Coastal Waterways Division of the Ministry of the Flemish Community, Head of the Department of Hydrometeorology and the Environment.

Guido Dumon

Dr Jean Lanckneus received his Doctor of Sciences in Mining and Minerals from the University of Ghent, Belgium in 1987. For 13 years he worked for the Dept of Physical Geography. In 1996 he founded a consultancy company Magelas BVBA, which specialises in survey work and in the practical scientific analysis of sediment fluxes and morphological evolution patterns of the seabed.

Jean Lanckneus

Koen Trouw received his degree as a Civil Engineer at the KU Leuven, Belgium in 1994 and will defend his doctoral work on sand transport as a result of irregular waves at the end of 2001. In 1999 he became project engineer at International Marine and Dredging Consultants (IMDC), where he is involved in morphological modelling of estuaries and coastal seas and the preparation and interpretation of measuring campaigns.

Koen Trouw

Table I. Date of the monitoring campaign, amount of sailed profiles. Information concerning the time of the measurements.

	Date	Hour	1°Low tide	2°Low tide	# Profiles transverse	# Profiles lengthwise
Spring tide	19/04/'00	6u34-20u05	07u10	19u23	21	4
Neap tide	28/04/'00	1u15-16u45	01u40	15u30	36	2

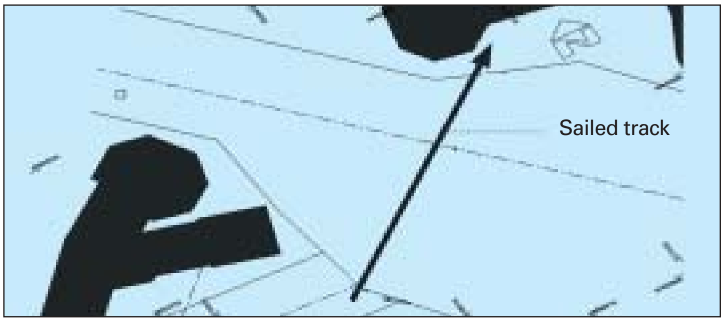


Figure 2. Theoretical track across the entrance of the harbour of Zeebrugge.

Figure 3. Picture of towfish (Navitracker equipped with OBS sensors).

Figure 4. The Acoustic Doppler Profiler, mounted on the hull of the vessel.

two theoretical tracks were defined and visualised on the navigation computer. All instruments were time-stamped with the KART DGPS-time.

Measurements were carried out with the help of a towfish (Figure 3) and a hull-mounted Acoustic Doppler Profiler (type NDP) (Figure 4). The following parameters were recorded:
- by the NDP: intensity, current speed, current direction over practically the entire water column;
- by the towfish equipped with OBS-3 and OBS-5-sensors: turbidity, pressure, position.

To provide on-line data during the survey, the optical backscatter sensors were calibrated with sludge taken from the survey area (harbour). Because the optical backscatter sensors are sensitive to the colour of the sediments the sensors (OBS) were calibrated using oxidised (lighter coloured) sludge. The registered data gave us an idea about the order of magnitude of the turbidity. The "fine-tuning" of the data was done by using the analysed suspended solids-concentration of the water samples. This combination provides an accurate calibration of the optical backscatter sensor.

The vessel mounted Acoustic Doppler Current Profiler measures the current speed and direction below the hull (Figure 5). This is performed by measuring the scattered acoustic signal reflected by particulate matter in the water column together with the Doppler effect. The system determines the vessel's velocity with the ship's navigation system, removes this velocity from the measurements and obtains the current velocity relative to the earth. By combining acoustic and optical information, this instrument can also provide information about the quantity of the particulate matter. This information is obtained from the intensity of the received reflection, also referred to as the backscattering strength or signal amplitude.

Different instruments from different manufacturers are available on the market. The equipment used during the survey was the "VM-NDP" (1.5 MHz) produced by Nortek AS. The NDP was interfaced with a high resolution kinematic DGPS. A vertical resolution of 0.5 m bin (maximum vertical resolution) and a horizontal resolution of 1 profile/ 2 sec were chosen. This configuration can be adapted according to the situation and the

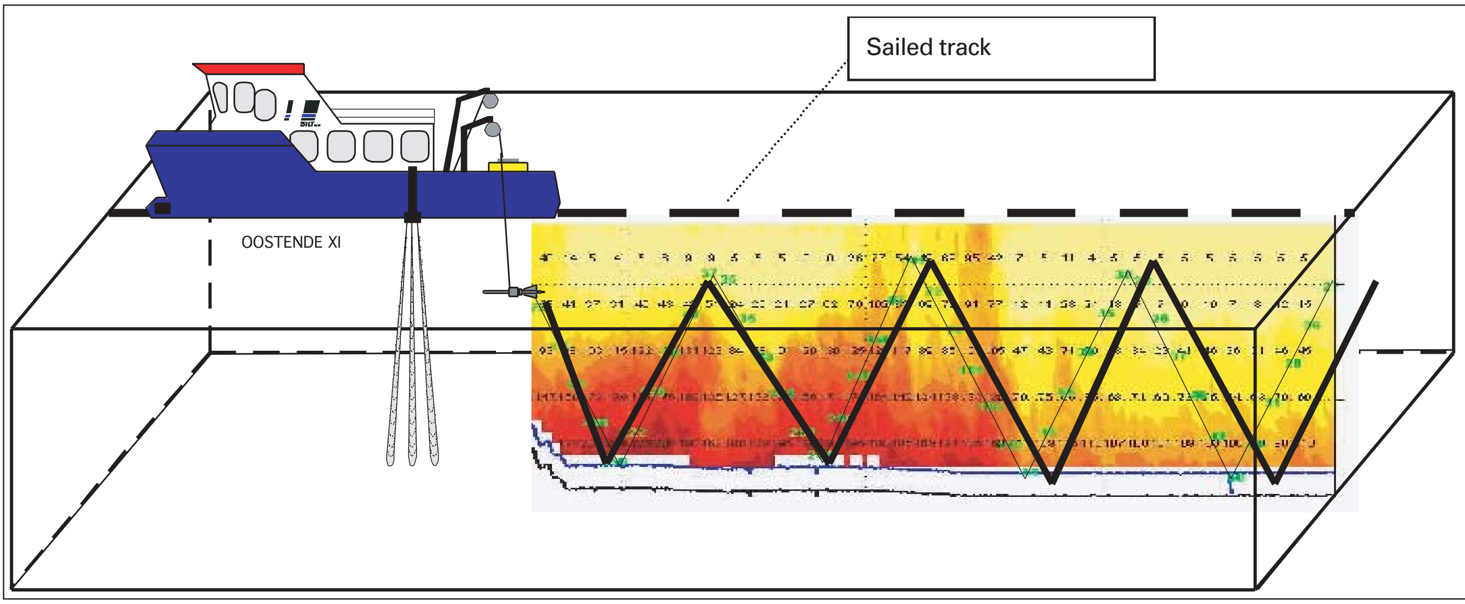


Figure 5. Monitoring method using a hull-mounted Acoustic Doppler Profiler and a towfish equipped with OBS sensors.

desires of the client. The speed of the vessel varied between 1 and 2 knots.

The towfish with OBS sensors, driven by a computer operated winch, automatically undulates in the water column between 2.4 m under the water surface and 1.5 m above the bed.

During the conversion of the acoustical backscatter signal into turbidity, a large number of parameters have to be taken into account. Most of these parameters are known:
- frequency of the acoustical waves;
- angle of the acoustical waves;
- speed of sound: salinity (conductivity, pressure, temperature);
- distance to the bin; and
- concentration (OBS), grain-size.

Collecting and visualising turbidity information, using the in-house developed software package "Sedidec", provides a turbidity profile. This visualisation can be done on-line and semi- on-line (after each sealed track). Also different tracks can be visualised on the same 3D figure. However it is still necessary to control the data for errors (spikes).

Using a hull-mounted NDP has following limitations:
- no information (caused by reflection from the bottom) for the last 3 bins starting from the bottom (= 3 x 0.5= 1.5 m);
- no information for the first cell from the sensor (NDP) = blanking distance;
- acoustical waves are sensitive for air-bubbles (caused by the propeller of passing vessels).

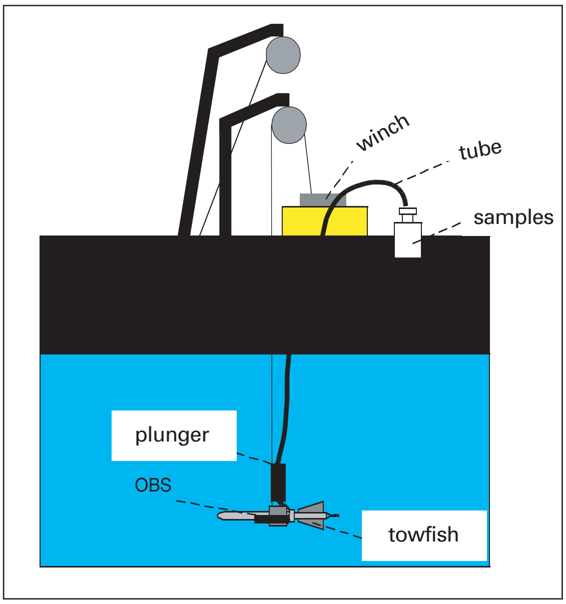


Figure 6. Taking water samples with a plunger.

Data Processing

Correction of the calculated turbidities by in situ sampling

The calculated turbidities were re-calculated using suspended solid data from the samples taken on board. A plunger, mounted on the towfish nearby the OBS-sensor, took these samples (Figure 6). A very good relation between the measured turbidity (OBS) and the analysed samples was found.

Using NDP data for calculating turbidity values is a relatively new technique in which careful calibration of the system is of great importance. DEC believes that

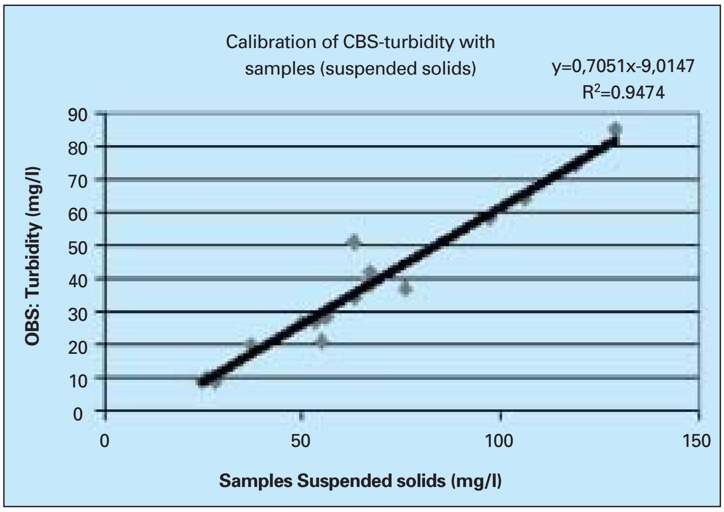


Figure 7. Calibration of OBS turbidity with samples (suspended solids), y = 0.7.51x — 9.0147, r^2 = 0.9474.

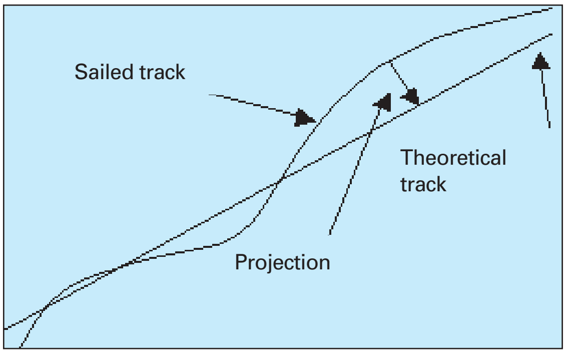


Figure 8. Projection of the sailed track on a theoretical track.

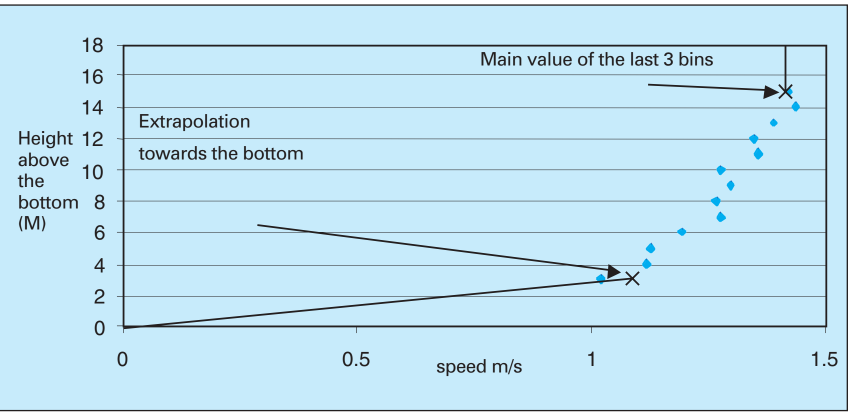


Figure 9. Extrapolation of the speed towards the bottom and the water surface.

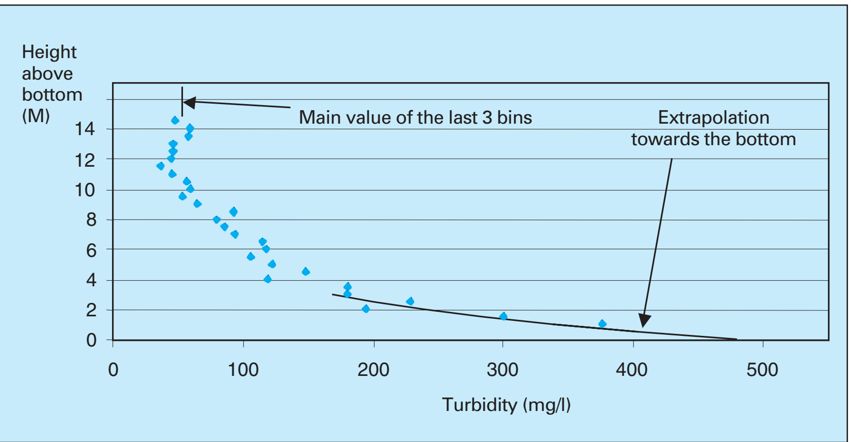


Figure 10. Extrapolation of the turbidity towards the bottom and the water surface.

this technique has a great potential and has put a lot of effort in the assessment of its reliability. The equation, provided by the manufacturer of NDP, was used as a starting point. Its effectiveness was confirmed by DEC after performing a large number of tests. DEC found however that the reliability could greatly be improved by a continuous calibration with an OBS. This additional and continuous calibration could furthermore lead to a simplification of the equation.

DEC performed a large number of measurements in which the value of turbidity deduced from the NDP was compared with the turbidity value measured by OBS. A correlation (r^2) between the turbidity values obtained with the two methods gave in all cases high values varying between 0.60 and 0.93.

At the same time the turbidity measured by the OBS was controlled by measuring the suspended solids in water samples. Correlation coefficients for these turbidity values were also very high and varied typically between 0.90 and 0.95. The correlation coefficients calculated for the measuring campaign described in the paper were 0.75 for the correlation between NDP and OBS and 0.95 for the correlation between OBS and samples (Figure 7).

Current speed and direction deduced from NDP are in agreement with the data obtained from previous measuring campaigns.

Sediment flux

General

A theoretical track was determined by averaging the sailed tracks. This track has the following coordinates: 513270 E and 5689800 N (UTM) and a direction of 54.7 ° N.

The sailed tracks differ very little from this theoretical track. Each bin of the current-profile (also recorded with the NDP) is characterised by a current (speed and direction) vector. To measure the incoming and outgoing sediment flux each current vector had to be projected perpendicularly on the theoretical track (Figure 8). This allows the transformation of the current vector to a vector that is going in or out of the profile.

Currents
As mentioned above, the reflection from the seabed and the blanking distance near the water surface lead to a hiatus in the profile.

The hiatus nearby the seabed was filled by extrapolation assuming that the current speed on the bottom (210 KC) had a value of zero. The hiatus nearby the surface was filled with the mean value of the last three vertical cells (Figure 9).

Turbidity
The turbidity hiatus nearby the seabed was filled up by extrapolation of the turbidity values (of the lowest measured bin) towards the seabed. This extrapolation does not take the sediment-transport over (density flow) the seabed into consideration. This transport can be very important concerning the total sediment flux of the harbour.

The hiatus nearby the surface was filled with the mean value of the last three vertical cells (Figure 10).

The errors caused by air bubbles (propellers of passing vessels) were replaced by a mean value of the surrounding cells. The errors were detected by taking into account the difference between the calculated turbidity and the turbidity measured by the OBS.
The measured turbidity was considered as correct.

Flow and sediment flux
Multiplying the area of a bin (= 12.5 m^2) with its current speed value provides us with the flow rate. Multiplying the flow rate of a bin with its turbidity value gives the sediment flux.

The sediment transport of each profile was multiplied with a time period corresponding to half the period between the preceding and following profile. The total net transport is the sum of all these products during one tidal cycle. The variation in time of the sediment flux and flow rate is visualised in a graph in which every point represents the total sediment or flow passing trough the entrance of the harbour over a period corresponding to half the period between the preceding and following profile.

Discussion

Turbidity profiles
The maximum turbidity measured during spring tide is 2.200 mg/l and during neap tide is 900 mg/l. The mean lowest turbidity measured varied between 30 and 50 mg/l. As it is not possible to understand the sediment behavior from only the turbidity profiles, it is necessary to take into account as well the prevailing current direction and speed.

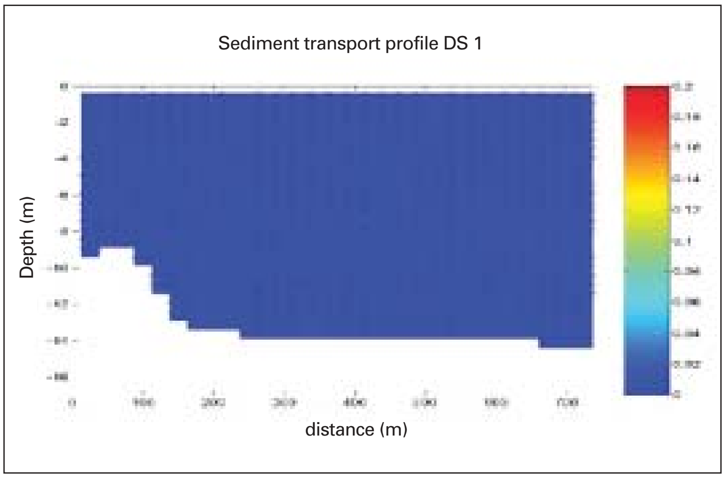


Figure 11. Sediment transport (kg/m^3/s); neap tide cycle; low tide; profile DS 1.

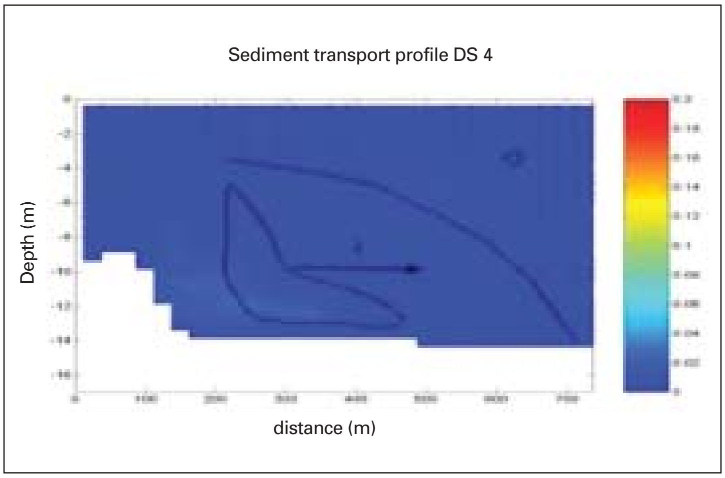


Figure 12. Sediment transport (kg/m^3/s); neap tide cycle; two hours after low tide; profile DS 4.

Sediment flux
The pattern of the sediment flux during spring tide differs little from the one during neap tide, but large differences in magnitude are however found. During low tide a homogeneous sediment flux output takes place as it is visualised in the profile of Figure 11.

One to two hours later, a sediment flux input consisting of a core appears in the western part of the profile (Figure 12) after which it is shifts from west to east over the bottom.
One hour before high tide, the sediment flux profile is divided into an input (east) and an output (west) part; at this time the flux core is expanding itself vertically in the eastern part (Figure 13).

The core of this sediment flux input moves from the eastern part to the western part. On high tide, a core of sediment input is surrounded by sediment output

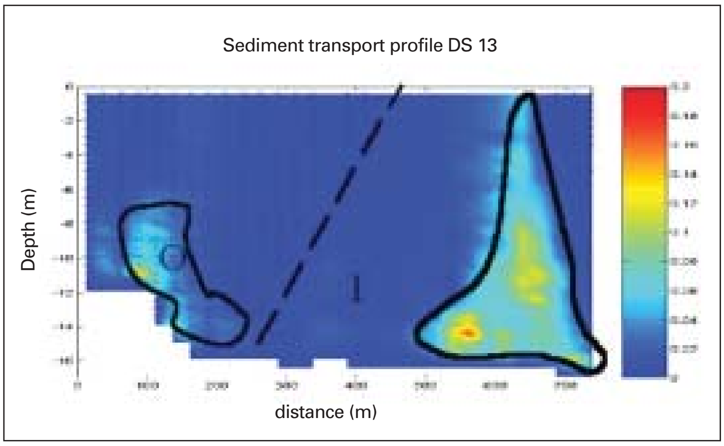


Figure 13. Sediment transport (kg/m³/s); neap tide cycle; one hour before high tide; profile DS 13.

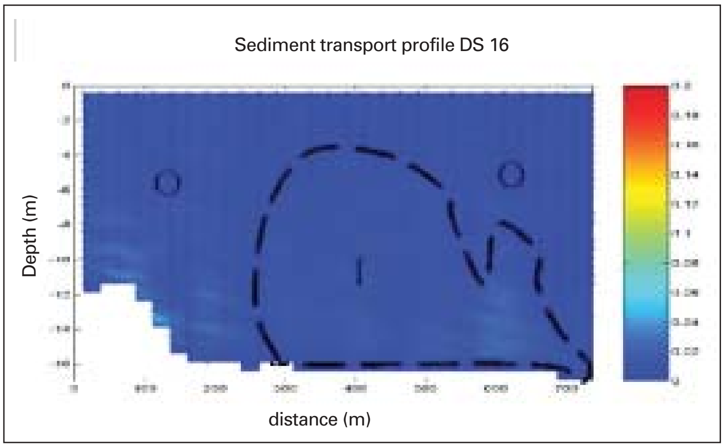


Figure 14. Sediment transport (kg/m³/s); neap tide cycle; high tide; profile DS 16.

(Figure 14). The input still moves from east to west where it disappears. At low tide the pattern repeats itself.

Quantification of the profiles during a spring tide

The monitoring campaign of a tidal cycle during spring tide started at 9h10 (6 hours before high tide) and ended at 21h23 (6 h25 after high tide). Interpolation between the flow profiles gives us the following results: 46 10^6 m^3 water flowed into the harbour and 44 10^6 m^3 flowed out of the harbour.

The current pattern is very complex during this period. An evaluation of the total sediment flux (not taking the bottom transport into consideration) during one tide cycle gives us an estimation of the amount of incoming and outgoing sediment: Sediment input, about 9200 tonne and sediment output, about 6000 tonne.

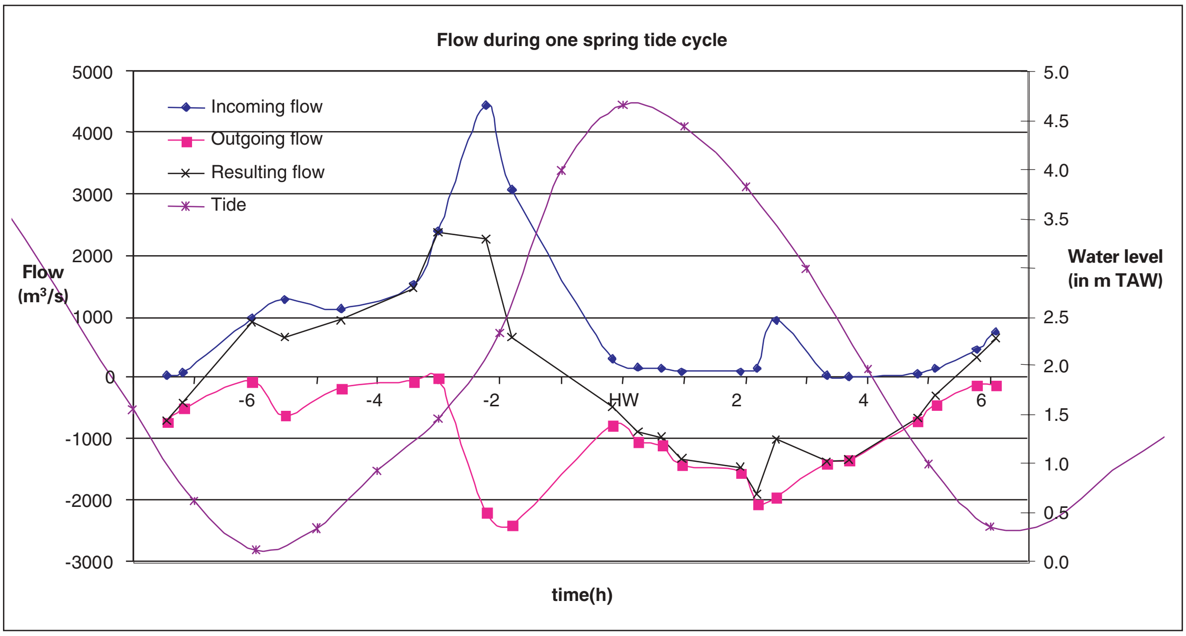
Using these data, it was assumed that a total of 3200 tonne of sediment remained in the harbour. The highest sediment input and the highest flow rate took both place 2 hours before high tide (Figures 15 and 16).

Quantification of the profiles during a neap tide

The monitoring campaign of a tidal cycle during neap tide started at 2h38 (5h30 hours before high tide) and ended at 15h15 (7 h00 after high tide). Interpolation between the flow profiles gives the following results: during these period 33.3 10^6 m^3 water flowed into the harbour and 32.8 10^6 m^3 flowed out. The current pattern is as well very complex during this period.

An evaluation of the total sediment flux (not taking the bottom transport into consideration) during one tide cycle gives us an estimation of the amount of incoming and outgoing sediment: A total sediment input of about

Figure 15. Incoming, outgoing and resulting sediment flux during one spring tide cycle.



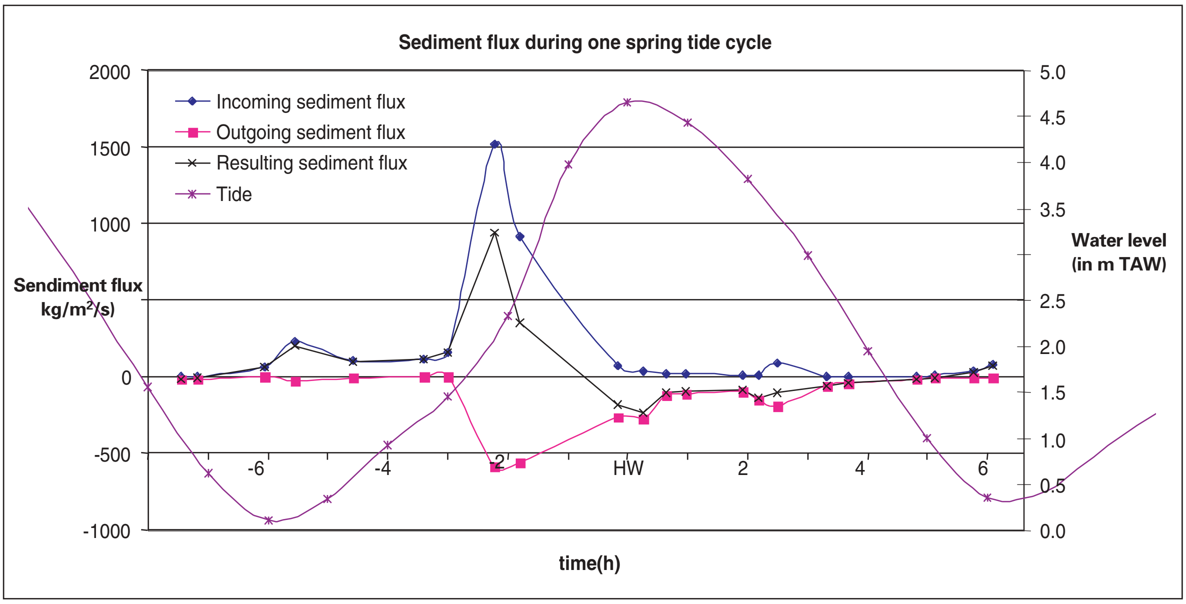


Figure 16. Incoming, outgoing and resulting flow during one spring tide cycle.

2050 tonne and a sediment output of about 1260 tonne took place in one neap tide cycle.

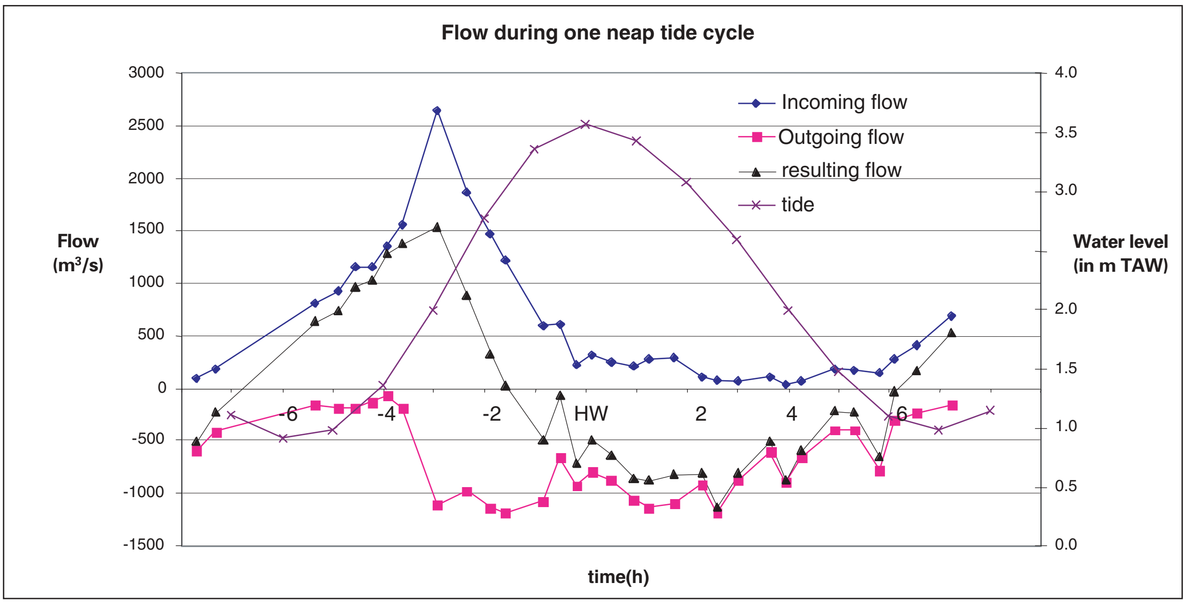
Using these data, it was assumed that a total of 795 tonne of sediment remained in the harbour. The highest sediment input took place 3 hours before high tide (Figures 17 and 18).

Discussion

The 13 hours measurements across the harbour entrance were performed once during a neap tide period and once during a spring tide period. Although the exercise was not repeated, which undoubtedly would have increased the reliability of the results, the authors are confident in the correctness of the produced results. Bonds of reliability were not added to the results, as it is extremely difficult to assess the degree of correctness of, for example, the necessary extrapolations (Figures 9 and 10) applied to the calculations.

However the results of the calculations of the resulting sediment flux coincide well with results of completely different methods. The sedimentation rate in the Central Part of the Outer Harbour was as well assessed by using a gamma-ray backscatter probe. Sedimentation rates were calculated based on measurements carried out nearly every month and this from 1996.

Figure 17. Incoming, outgoing and resulting flow during one neap tide cycle.



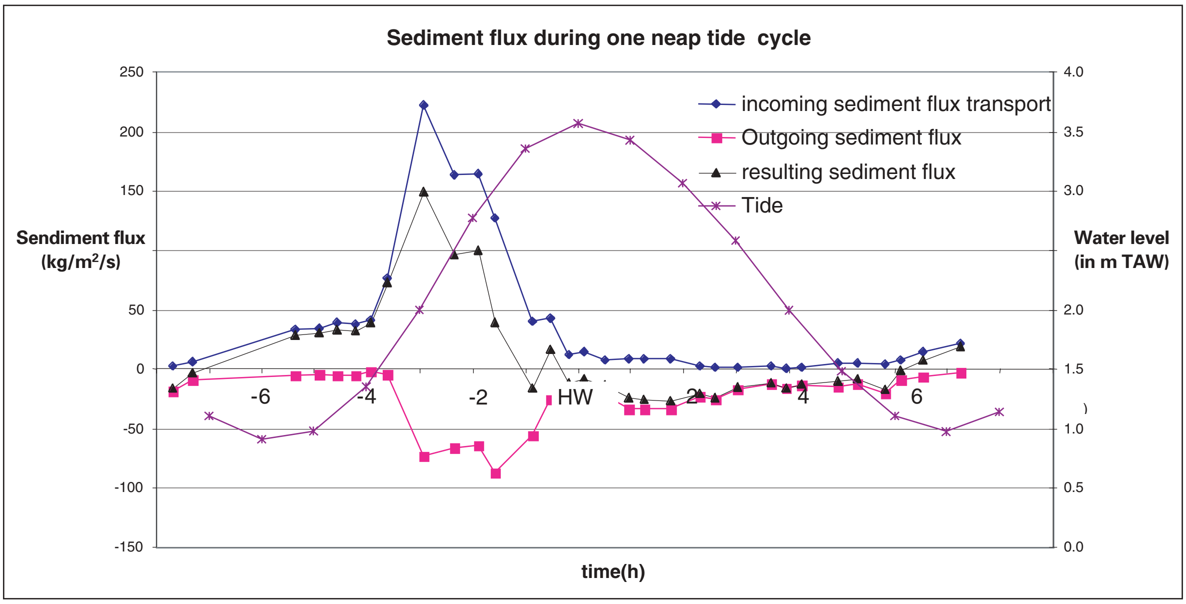


Figure 18. Incoming, outgoing and resulting sediment flux during one neap tide cycle.

The rates give an indication of the net inflow of suspended sediment over a period of ± 30 days. From these calculations it can be derived that during a mean tidal cycle a net sediment inflow of 3500 to 8000 Tonnes Dry Material takes place. These quantities are of the same magnitude as the 3500 tonnes calculated with the NDP for a tidal cycle during spring.

Conclusions

The entrance of the harbour of Zeebrugge is subject to strong variations in current speed and direction caused by the tidal action. During neap and spring tide a similar current pattern occurs, but large differences in the incoming and outgoing flow exist. Incoming and outgoing flows could be measured for one tidal cycle in spring and in neap tide.

A difference of 25% between the (average of the incoming and outgoing flow) flow between neap (33.0 10^6 m^3) and spring tide (45.0 10^6 m^3) is responsible for a large difference in sediment input. Using the data of this survey, calculation gives an evaluation of the net sediment input of 3200 tonne during a tidal cycle at spring tide and a net input of 795 tonne during a tidal cycle at neap tide (four times as much).

This monitoring campaign made it possible to calculate the sediment input during one tide cycle. Important is to know that the monitoring campaigns were performed in good weather conditions. Stationary monitoring, using similar equipment, demonstrated that wind speed and direction have a very big influence on the sediment behaviour. Therefore a monitoring campaign during stormy weather conditions would certainly provide interesting results.

Important to know is that the above-mentioned quantities are the results of a calculation of the measured data for the *suspended solids only*. The extrapolation towards the bottom has not been tested for reality. Combining detailed measurement (with a bottom mounted device) in the 2 m from the bottom will give a better idea of the bottom transport. The "density-flow" over the bottom can be of great important to the total estimation of sediment input in the harbour. Also the calculated data cannot be generalised for each tide cycle, therefore a repetition of this survey is needed.

This survey gives a more detailed image of the complex structure of the sediment flux in the water profile at the entrance of the harbour of Zeebrugge. Knowledge on the sediment fluxes will, together with sounding data of the harbour, allow a better understanding of the sediment behaviour which will result in a better planning of the dredging activities.