BASELINE MAPPING OF SEDIMENT DISTRIBUTION IN THE WESTERN SCHELDT ESTUARY PRIOR TO TUNNEL BORING

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ABSTRACT

Large infrastructural construction projects may have a profound impact on the environment and ecology of environmentally sensitive areas. The construction of a tunnel below the Western Scheldt and the associated sediment dumping in the Western Scheldt Estuary may influence the sediment budget and the quality and quantity of pelagic and benthic life in the estuary. For the purpose of monitoring the effects of the dumping, it is essential to know the baseline situation, which (in this case) is an inventory of a) the temporal and spatial dynamics and distribution of suspended matter in the estuary and b) the deposition of sediments on tidal flats. Because of the size of the potentially affected area and the dynamic character of the tidal water system it was decided to use besides field measurements, remote sensing and mathematical models to set a baseline for the sediment distribution. The added value of an integration of modern techniques such as remote sensing and sediment transport modeling together with a sensible use of in-situ measurements was demonstrated. SPOT images rendered accurate synoptic distributions on suspended sediments, and were a valuable data set for model calibration. Having established the baseline, the model predicts the distribution of dumped suspended matter in the Western Scheldt. The deposition of mud on tidal flats was analyzed both with models and from remote sensing. In this study it was shown that effects of the dumping will be observable in spring and summer periods. Therefore, close monitoring of the estuary during the tunnel construction is required.

1 INTRODUCTION

1.1 POTENTIAL ECOSYSTEM IMPACTS

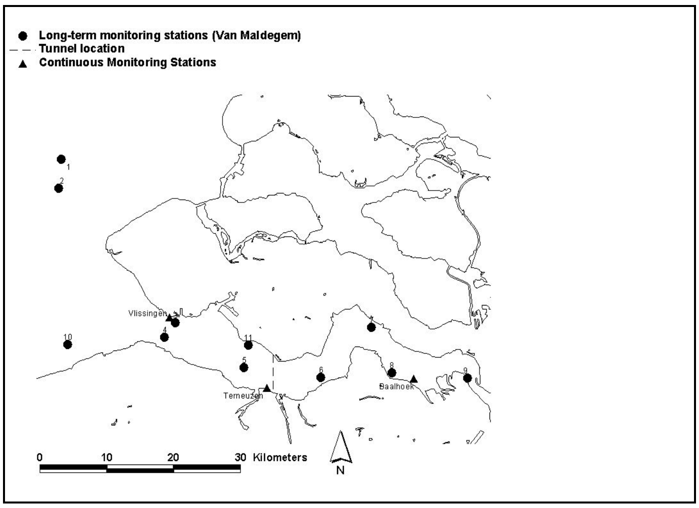

Figure 1. The Western Scheldt estuary with monitoring locations.

Silt plays a significant role in chemical, physical and biological processes in Dutch coastal waters. In the Western Scheldt estuary, the maintenance dredging of the shipping channel and harbors continuously brings extra silt into the water system. The Western Scheldt estuary (located in the south of the Netherlands; appr. 51°26’N, 3°35’E - 51°22’N, 4°15’E, see Figure 1) is a highly dynamic environment, where significant amounts of silt (under natural conditions) are brought into suspension due to tidal shear stress and wind induced waves. that the area is characterized by relatively deep gullies connected to the sea, tidal flats and shallow areas at the side of the estuary (especially in some of the curves and at Saefthinge). Currently, a large amount of dredged tunnel material with a high silt percentage is dumped.

Any change in silt concentrations and silt characteristics may have a potential impact on the ecosystem. The most direct, physical effect of the dumping of the tunnel boring material is an increase in the Total Suspended Matter (TSM) concentration. The increase in TSM can directly and indirectly affect several ecological processes in the water column and in the sediment. Five different potential effects are:
1. *increased TSM concentration* can affect the primary production, the food uptake of benthos and the ability of fish and birds to hunt for their prey;
2. increased sedimentation may *bury* benthic species;
3. increased *siltation* may alter the habitats of benthos;
4. *fluid mud* layers may occur;
5. the chemicals present in the *drilling muds* may impact the ecosystem.

These effects can further affect the habitat suitability for various species. Additionally, dredging activities to deepen the shipping channel to Antwerp Harbor will result in additional dumping of dredged bottom sediment.

1.2 THE NEED FOR AN INTEGRATED DATA-MODEL APPROACH

For monitoring the effects of the dumping, it is essential to know the baseline situation of sediment distribution and variability. The existing monitoring infrastructure (facilities and programs) for the Western Scheldt are not appropriate for following the potential detailed changes resulting from the dumping of the tunnel boring material. There is a need for monitoring information with a detailed spatial and temporal resolution. The existing conditions of turbidity and suspended concentrations in the estuary are highly dynamic due to the significant amount of silt that is naturally brought into suspension due to tidal forces and wind induced waves. Thus it is not certain to what extent the dumping of the tunnel boring material will be 'visible'. However, there is desire and legal responsibility for the Directorate Zeeland to monitor the environmental effects of the construction activities. The Directorate Zeeland has set up a monitoring program and has established three monitoring stations for continuous measurement of suspended matter.

Additionally, the use of optical remote sensing and water quality models was considered for operational monitoring. The synergetic use of remote sensing, in-situ information and modeling to improve knowledge of water quality and ecology has been investigated in recent years using the RESTWAQ (Remote Sensing as Tool for improved knowledge on WAter Quality and ecology) methodology. Through applications to the Southern North Sea (Vos and Schuttelaar, 1997, Gerritsen et all, 2000), the Dutch Coastal zone (Vos et all, 1998a; Vos et all, 2000) and the Frisian lakes (Vos et all. 1998b), RESTWAQ has proved to be a very valuable method to improve knowledge on water quality. This especially holds for TSM and underwater light conditions. The use of the RESTWAQ methodology for monitoring the Western Scheldt estuary was expected to provide a more complete picture of the spatial and temporal developments in the estuary water system. With the methodology, the chance of observing changes in the system will be increased, since not only time-histories of suspended matter at a few locations are obtained, but in addition the spatial changes due to dumping will be observable from remote sensing. The TSM model was used to predict how, where and when the dumpings of suspended systems will become distinguishable from a very dynamic natural background of suspended sediments.

2 REMOTE SENSING

2.1 Retrieval of Suspended Particulate Matter

A physical/analytical approach (Dekker and Peters, 1998)(Vos et al., 1998) was developed for multi-temporal studies of water quality. This approach involves atmospheric and air-water interface correction of satellite images and the use of an optical model to establish the relationship between concentrations and optical measurements by the satellite. Key parameters in this modeling approach are the optical properties of water and the constituents. The analytical method is relatively independent on field observations, which makes it very suitable for retrospective multi-temporal studies of TSM concentrations.

Nine selected SPOT images were processed to TSM maps. In order to fit a Gordon optical model, in-situ measurements at 5 stations were done of the Specific Inherent Optical Properties (SIOP) of the Western Scheldt. Simulations with the Gordon model were performed with the aim to predict in situ-measured sub-surface irradiance reflectance (R(0-)) spectra. By matching R(0-) simulations to observations, the model was optically closed by fitting the backscattering to scattering ratio. Next, the simulation model was used to derive a TSM retrieval algorithm for various SPOT sensors. A sensitivity study was done to examine the robustness of the TSM retrieval algorithm. All SPOT images were corrected for atmospheric influences and for the effects of the air-water interface. A procedure was developed (Pasterkamp et all,

2000) which allows using known reflectance values of dark water bodies to calibrate the atmospheric correction. Some semi-invariant reflectance features were used for extra calibration and validation. As a last step, the atmospherically corrected images were transformed to TSM maps using the TSM retrieval algorithm. All maps were validated using long term averaged TSM measurements and continuous in situ data measurements. The validation proved that the TSM maps correctly described both overall mean concentrations and the local variability.

Two SPOT images for the western part of the estuary are shown in Figures 2 and 3. The SPOT TSM map for 11 January 1998 (Figure 2, top figure) shows high sediment concentrations as a result of sediment erosion from relative shallow (5-8m) areas in front of the estuary, and from tidal flats in the estuary. The wind speed at the beginning of January was high and frequently above 10m/s. The SPOT TSM map in Figure 3 (top figure), is for 8 August 1998. In summer the TSM concentrations are much lower. Still, the gullies that transport the relative cleaner sea water into the estuary are visible.

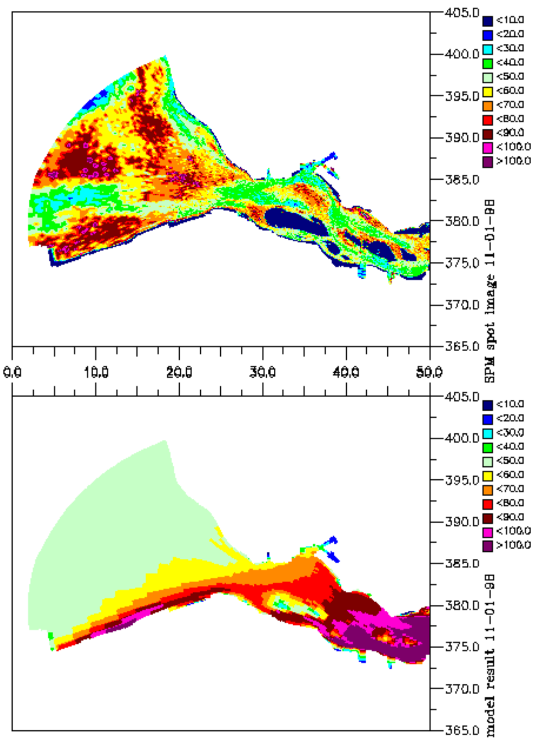

Figure 2. Remote sensing image for 11 January 1998 (top) versus model result (bottom). Inflowing water.

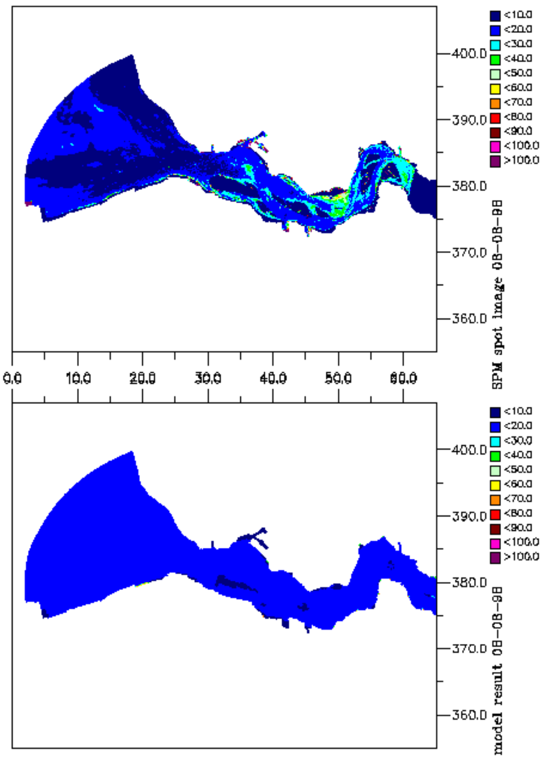

Figure 3. Remote sensing image for 8 August 1998 (top) versus model result (bottom). Inflowing water.

2.2 Classification of Tidal Flats

One SPOT image at low water (7 May, 1996) was selected for classification of tidal flats into areas with fine sediment (silt), and coarse sediment (sand). The fine sediments have a higher reflectance in the green and red band of the SPOT sensor than the coarse sediments. However, this situation is reversed for the near-infrared. An empirical algorithm was build to relate reflectance to median grainsize (Baptist and Peters, 1999). Data for tuning the algorithm were retrieved from extensive campaigns for measuring the sediment composition of the Western Scheldt in 1992 and 1993 (McLaren, 1993; McLaren, 1994). Bottom samples were taken each 500 metres and for some places each 250 meters. For this study the samples that were located in the intertidal areas were selected, leaving 230 samples for further analysis. A multiple linear regression was applied for the McLaren samples and the SPOT reflectance's of the green, red and near-infrared bands. Results of the image classification are shown in Figure 4.

A validation of the resulting image with a separate data set of median grainsize values for a single tidal flat, the Molenplaat, was carried out. This data set contains median grainsize values measured in March, June, September and December on about 100 sample locations.

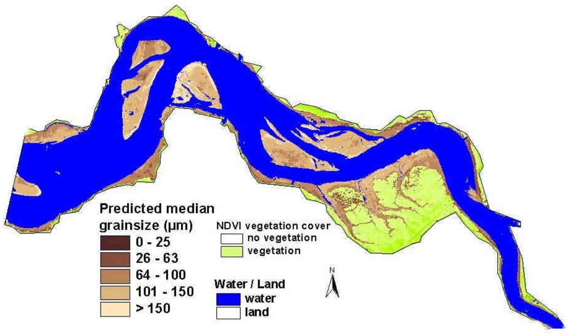

Figure 4. Predicted median grainsize (μm) for the Western Scheldt estuary.

The correlation between the measurements and the prediction was tested for each season and turned out to be rather limited. However, a visual inspection of the classified SPOT image, and the Molenplaat ground truth data set showed that the location of the finer sediments on Molenplaat was correct. It was found that the algorithm (fitted with the McLaren data set) overestimates the grain sizes for this particular location, and this will need further investigation. To further develop this method as an operational tool, first a more reliable classification has to be made. This involves dealing with spatial and temporal variations and whether or not the information from the sediment surface is representative for the bed sediment composition.

3 WATER QUALITY TSM MODEL

A 2-dimensional (vertically averaged) curvi-linear water quality model for suspended matter transport in the Western Scheldt estuary was set up. The model used for this study includes the Western Scheldt up to the Scheldt river near the city of Antwerp. The hydrodynamic computations (Salden, 1999) were done on a grid (SCALWEST-fine) of 76036 segments for one spring-neap cycle of 14.5 days. The water quality suspended matter model used was Delft3D-WAQ (Delft3D, 2000), run with only 1 layer in the vertical (Villars and Vos, 1999). The water quality model was run for the full year 1998, while repeatedly using the hydrodynamic results. The water quality simulations were done with an aggregated grid of 4341 segments in order to reduce computation times. Although larger computations are feasible, they are not practicable since calibration of these complex suspended matter models requires a large amount of test simulations.

Sediment enters the modeled area from the boundaries (boundary conditions at the open sea boundary and river boundary), where the concentrations are specified based on available monitoring data. The model also has an initial amount of sediment in the water column and on the bottom, which must be set at the beginning of a simulation (initial conditions). Sediment loads can be input to the model to simulate dumpings from dredging activities in harbors. Also, the water quality model includes processes such as sedimentation and resuspension that continually redistribute the sediment within the water column. Due to morphologic dynamics and effects of dredging activities silt layers may get exposed and come in contact with the water column. The model does not consider these types of large scale changes in the bottom channels or tidal flats that also serve to redistribute sediment material in the estuary. Dumpings data for harbor dredgings indicate that significant amounts of silt material are dumped and therefore this source of sediment was accurately included in the model. Summarizing, the calculated TSM concentrations in the model at any one time are a function of:

- input of sediment from boundaries, initial conditions, and loads (dumpings of harbor silt)
- advective transport based on the hydrodynamics (tidal water flow)
- dispersive transport (random, chaotic spreading of material)
- sedimentation and resuspension of material to/from the bottom, as affected by the tide induced water flow velocities and wind induced waves.

For the (final) model calibration the following data were used:

- Remote sensing images from SPOT processed to TSM values and converted to the model grid (8 images);
- Data from a continuous monitoring station at Vlissingen for January-December (kindly supplied by Directie Zeeland, 1999);
- Data from 2 continuous monitoring stations at Terneuzen and Baalhoek (kindly supplied by Directie Zeeland, 1999) for the period October-December;
- Twenty yearly monthly mean averages of TSM at 8 locations were used for the calibration.

The continuous monitoring stations each have one data point every 10 minutes. A SPOT image has a spatial resolution of $20m^2$. Thus an enormous amount of data is available from these two data sources, which makes that data reduction methods for a comparison with models are required. The data reduction method focuses on retaining the essential details of the data and using this '*representative*' information for calibration of the model. In order to get reproducible and objective 'best' results from the calibration process, a goodness-of-fit (or cost function) method was used. Such a method is especially required when large data sets, being of different nature, are used (Vos et all, 2000).

The agreement with the twenty yearly monthly mean averages turned out to be satisfactory, except for the period of October 1998. A storm at the beginning of October produces high loads of TSM in suspension in the model which causes a deviation from the observed twenty year average. Indeed, observed TSM for the continuous monitoring stations at Terneuzen and Baalhoek (Directie Zeeland, 1999) confirm these high values. At Baalhoek, for unknown reasons it takes one spring-neap cycle for the silt to get into suspension. At Terneuzen this anomaly was not observed so it must be a local effect. This emphasizes that in-situ data are always sensitive to local sediment processes and this makes it hard to use them in regional environmental impact assessments. The spring-neap cycle of TSM observed in the continuous data was reproduced by the model (see Figure 5). A comparison of model results (for a simulation with, and without the effect of silt from harbors which is dumped into the estuary) with the remote sensing results for station Baalhoek is shown in Figure 5. The location of Baalhoek is given in Figure 1.

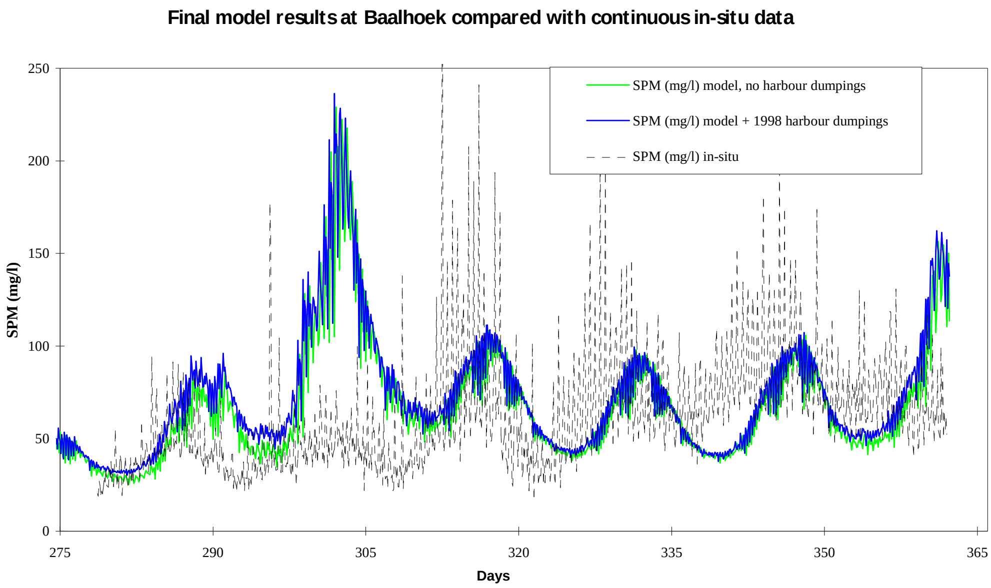

Figure 5. Comparison of model data for TSM (mg/l) and in-situ data at Baalhoek

A comparison of model results with remote sensing SPOT maps is shown in Figures 2 and 3. Unfortunately, since the SPOT images cover not the whole estuary only a comparison can be made for part of the estuary. Clearly, model results show much less detail than SPOT images. This is not only due to the coarse model grid but also due to approximations for uniform boundary conditions for TSM at the model boundaries. The remote sensing image for January (Figure 2) suggests the presence of large amounts of silt at the bottom of the water column near the entrance of the estuary. This may be a consequence of intensive dumpings of silt dredged at the harbor of Zeebrugge. Also a local circulation in the hydrodynamics (that is not observed in the model) may contribute to these high TSM results.

The agreement between model and data can still be improved by applying more realistic boundary conditions and better initialization of bottom sediments at the entrance of the estuary. However, the essential characteristics of the seasonal behavior of TSM are modeled. Therefore, the model can be used as a tool for prediction of the spreading of dumped tunnel silt into the estuary, on *a seasonal scale*.

4 PREDICTIONS OF SPREADING OF DUMPED TUNNEL SILT

With the calibrated water quality model for 1998 it is possible to make predictions for the T1 phase by simulating tunnel material dumping scenarios. The T1 situation is the situation during the dumping of silt from the tunnel boring. In the modeled T1 scenario, 1 Mton (dry weight) tunnel material was discharged at a constant rate into the Western

Scheldt over a period of 1 year (1 January - 31 December). This amount is based on predictions of a total of 1.5 million m^3 'Boomse Klei' being excavated and dumped over a period of 1.5 years. The Boomse Klei consists primarily of very fine silt (<63 μ) (RWS, 1998). As a rough estimate, a conversion factor of 1ton per m^3 is assumed. It is recognized that the amount of the dumped material is a very rough estimate, and a new scenario can be calculated when more precise information on the dumping amounts are known. The chosen scenario provides an indication of the expected increases in TSM concentration, as well as the spreading patterns and the transport of the dumped material.

The results showed that during winter periods, the natural background concentration and the natural variability of TSM in the estuary is very high. Therefore, no effects of dumped material can be observed except very close to the dumping site for this period. *However, during spring and summer significant effects of the dumping may be observable.* Unfortunately, two of the three monitoring stations are located rather far from the dumping site (Vlissingen, Baalhoek) and this reduces the possibilities to detect significant effects considerably. For Baalhoek it was also shown (see Figure 5) that local effects play a role in the TSM behavior, thus making it difficult to demonstrate effects of the tunnel dumping. The Terneuzen station is very close to the dumping site, and therefore gives less information on the spreading of dumped silt.

On contrary, remote sensing is expected to give a good insight in the spreading of dumped material. The effects will be visible as a large plume of sediment that oscillates with tide along the estuary, but only for the *spring and (especially) summer period*. An example is given in Figure 6 for August 2000. These calculations show that a significant increase of 15 mg/l in a distance of 25 km around the dump site may be observable with remote sensing imagery this summer. The natural background concentrations in this area are then about 10-15 mg/l and will increase (for the present scenario) to 30-40 mg/l.

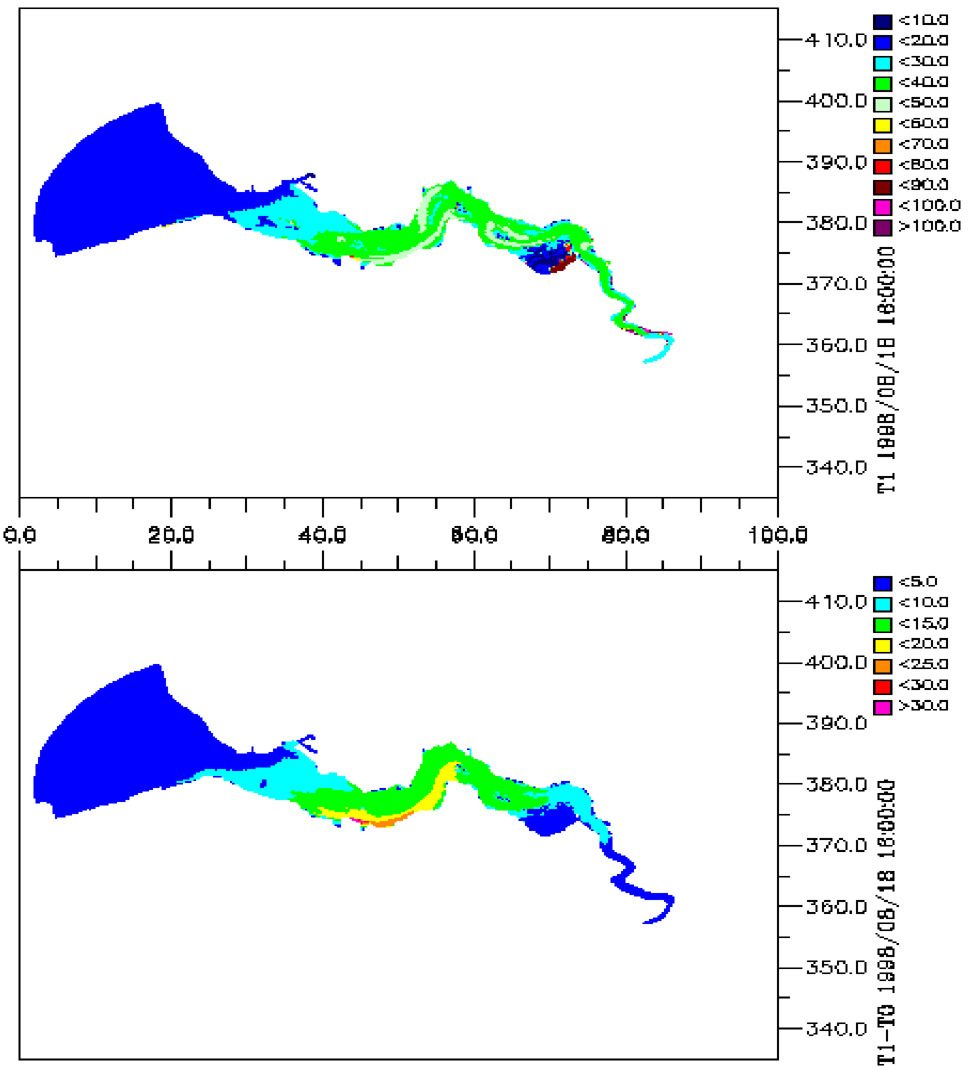

Figure 6. Modeled effect of the dumping of TSM (mg/l) for an arbitrary moment in August. The top figure shows the total amount of TSM, whereas the bottom figure shows the amount of TSM of the dumped silt fraction only.

5 CONCLUSIONS

It is demonstrated in this paper, that the use of an integrated data methodology (based on the synergetic use of in-situ data, remote sensing data and model data) for monitoring the Western Scheldt estuary provides a more complete picture of the spatial and temporal developments in the estuary water system. With such an approach the chance of observing changes in the system will increase since:

1. In addition to the in-situ observations, spatial changes due to dumping will be observable from remote sensing.
2. The spreading of silt into the estuary from dumping can be predicted with models. This may steer future observations of the spreading of tunnel silt into the estuary.

Although the model has certain approximations (boundary conditions, bottom sediments and 2-dimensional approach) it can be used as a tool for predicting the spreading of dumped silt into the estuary. This because the predicted effects are quite significant since they are extending over more than 25km. More detailed modeling is not expected to alter these predictions for spatial scales of that size. Nevertheless, the present predictions are all based on the assumption of a dumping of a total of 1.5 million m^3 'Boomse Klei' into the estuary over a period of 1.5 years. If this amount turns out to be a factor of 2 lower, also the effects will be halved. Therefore, precaution with respect to these predictions is still required.

In this study it was shown that effects of the dumping can only be observed for spring and summer periods. Nevertheless, since this is the biologically active period (and since the primary production is light limited) there may be an impact of these dumpings on the ecosystem. Therefore, close monitoring of the estuary during the tunnel construction is required.

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