

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

Robert J. VOS^{*}, Steef W.M. PETERS^{*}, Reinold PASTERKAMP^{*},
Monique VILLARS^{**}, Martin J. BAPTIST^{**},
Jos M.M. KOKKE^{***}, Erin HOOGENBOOM^{***}

^{*}Free University of Amsterdam, The Netherlands
Institute for Environmental Studies

Robert.Vos@ivm.vu.nl

^{**}WL|Delft Hydraulics, The Netherlands

Nicky.Villars@wldelft.nl

^{***}National Institute for Coastal and Marine Management (RIKZ), The Netherlands

J.M.M.Kokke@rikz.rws.minvenw.nl

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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 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 remote sensing and mathematical models in addition to field measurements to determine the baseline conditions of 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 used for model calibration. Having established the baseline, the model was used to predict 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. It was shown that dumped sediments will be best observable in spring and summer. Therefore, monitoring of the estuary during the tunnel construction with the present methodology is advised.

1 INTRODUCTION

1.1 POTENTIAL ECOSYSTEM IMPACTS

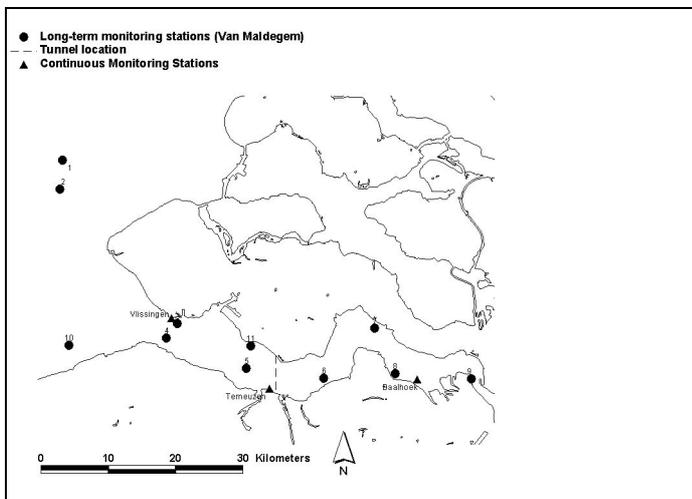


Figure 1. The Western Scheldt estuary with monitoring locations.

Total Suspended Matter (TSM) plays a significant role in chemical, physical and biological processes in Dutch coastal waters. TSM consists of sediments with a particle diameter $< 63 \mu\text{m}$. In the Western Scheldt estuary, the maintenance dredging of the shipping channel and harbors continuously brings sediments into suspension. The Western Scheldt estuary (located in the south of the Netherlands; appr. $51^{\circ}26'N$, $3^{\circ}35'E$ - $51^{\circ}22'N$, $4^{\circ}15'E$, see Figure 1) is a highly dynamic environment, where significant amounts of sediments (under natural conditions) are brought into suspension due to tidal forces and wind induced waves. The estuary is characterized by relatively deep gullies connected to the sea, tidal flats and shallow areas at the side of the estuary.

Currently, a large amount of dredged tunnel material with a high silt percentage is dumped (silt is the inorganic fraction of TSM). Any change in TSM concentrations and TSM 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 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. *burial* of benthic species;
3. increased *siltation* may alter the habitats of benthos;
4. *fluid mud* layers may occur;
5. the *chemicals* present in the tunnel material 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 detectable. However, there is a desire and legal responsibility for the Directorate Zeeland (Directie Zeeland) to monitor the environmental effects of the construction activities. Directie Zeeland has set up a monitoring program and has established three monitoring stations for continuous measurement of suspended matter by using calibrated optical instruments attached to fixed poles (Directie Zeeland, 1999a).

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 al, 2000), the Dutch Coastal zone (Vos et al, 1998a; Vos et al, 2000) and the Frisian lakes (Vos et al, 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 model is an integrator of time and space measurements to get a 'best estimate' of the complete spatial and temporal variability of TSM. In addition, the TSM model was used to predict how, where and when the dumpings of suspended sediments will become distinguishable from a very dynamic natural background of suspended sediments.

2 REMOTE SENSING

2.1 Retrieval of Suspended Particulate Matter

A multi-temporal physical/analytical approach (Dekker and Peters, 1998; Vos et al, 1998b) was developed for conversion of remote sensing data to TSM. 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 were done of the Specific Inherent Optical Properties (SIOP) of the Western Scheldt at 5 stations. 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 (De Haan and Kokke, 1996). A procedure was used (Pasterkamp et al., 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 clearer sea water into the estuary are visible.

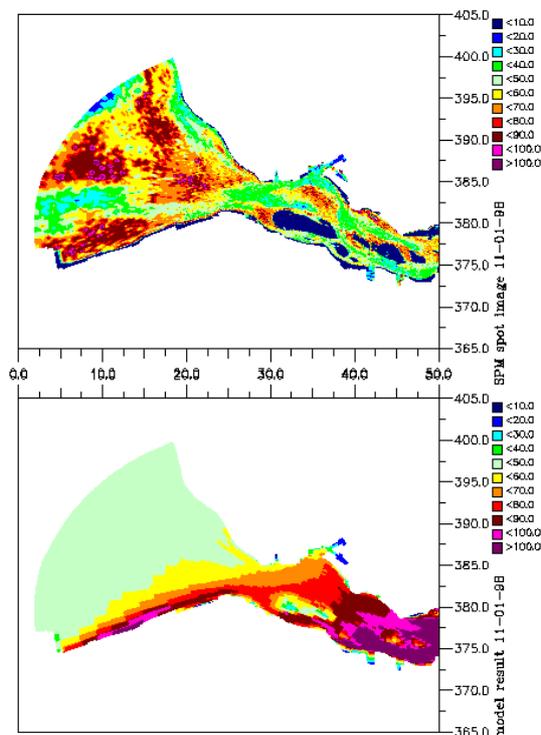


Figure 2. Remote sensing image for 11 January 1998 (top) versus model result (bottom). Inflowing water.

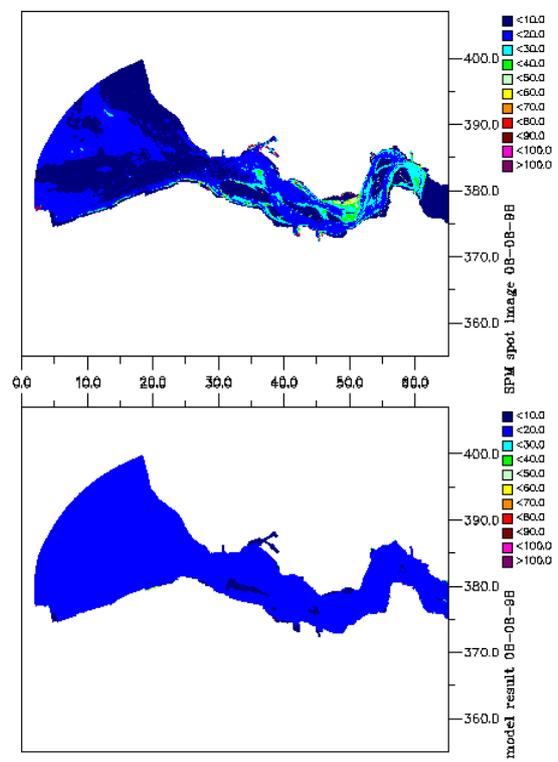


Figure 3. Remote sensing image for 8 August 1998 (top) versus model result (bottom). Inflowing water.

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 built 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 meters 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 reflectances 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.

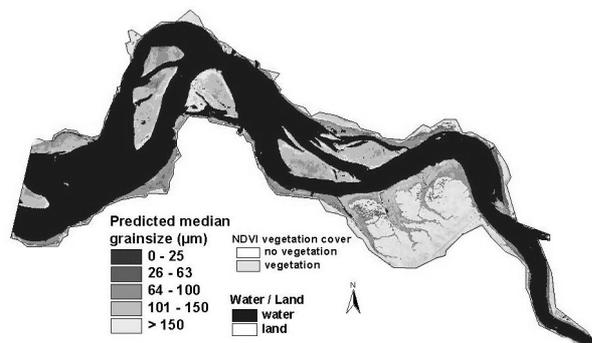


Figure 4. Predicted median grainsize (μm) for the Western Scheldt estuary.

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 ('full grid') 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 computations on the full grid are feasible (they will take about 65 hours on a powerful workstation), they are not practical 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 sediment 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. 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. Dumping data for harbor dredging indicate that significant amounts of silt 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 for the year 1998 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
- Data from 2 continuous monitoring stations at Terneuzen and Baalhoek for the period October-December;
- Mean monthly averages (averaged over 1970-1990) of TSM at 8 locations were used.

In-situ data were kindly supplied to us by Directie Zeeland (1999a, 1999b). The continuous monitoring stations each have one data point every 10 minutes. A SPOT image has a spatial resolution of $20 \times 20 \text{m}^2$. 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 al., 2000).

The agreement with the mean monthly mean averaged TSM data turned out to be satisfactory, except for October 1998. A storm for the period 25-29 October (day numbers 298-302) causes bottom erosion that brings TSM into suspension in the model. This causes the deviation from the observed twenty yearly average. Indeed, observed TSM for the continuous monitoring stations (Directie Zeeland, 1999a) confirm these high values. However, at Baalhoek, for unknown reasons sediments get into suspension one spring-neap cycle after the storm. At Terneuzen and Vlissingen this anomaly was not observed so it must be a local effect. This emphasizes that in-situ measurements are sensitive to local sediment processes and this complicates their use in environmental impact assessment studies. A comparison of model results with the remote sensing results for station Baalhoek is shown in Figure 5. The location of Baalhoek is given in Figure 1. The spring-neap cycle of TSM observed in the continuous data sets of Terneuzen, Vlissingen and Baalhoek was reproduced by the model, although at Baalhoek there is a phase lag of one spring-neap cycle with measurements (Figure 5).

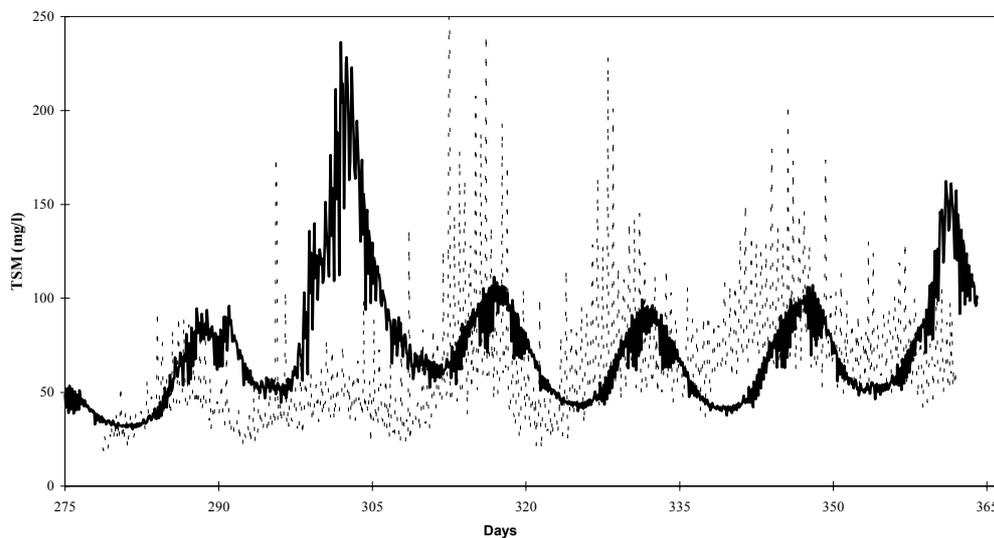


Figure 5. Comparison of model data (solid line) and in-situ data (dashed line) for TSM (mg/l) at Baalhoek

A comparison of model results with remote sensing SPOT maps is shown in Figures 2 and 3. Since the SPOT images cover not the whole estuary only a comparison can be made for part of the estuary, and these figures are for the west and middle part including the dumping site near Terneuzen. The agreement between the average model concentrations and the SPOT images is good since this was an item of the model calibration. The local sediment distribution, however, is not correct for the January image. The resuspension of sediments at the *sea entrance* of the estuary was not correctly modeled. 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. Although this needs further investigation it will hardly affect model predictions of TSM *within* the estuary. For the August image (Figure 3), the overall agreement is good. However, the model underestimates TSM in the curves and near tidal flats. It overestimates the TSM somewhat in the gullies. Although that these model results show less detail than SPOT images they represent correctly the *average seasonal TSM concentrations and the tidal TSM variability*. Accuracy on a detailed spatial scale can probably only be achieved with the full grid, but hereto very large computations are required. Also spatially varying boundary conditions for TSM will be required. Remote sensing images may be used in the future to supply information on these boundary conditions. The model can further be improved by applying a better initialization of bottom sediments at the entrance of the estuary. TSM models coupled with wave dynamics models and having 3D full grid resolution are at present computationally too demanding.

We conclude that the essential characteristics of (the seasonal behavior and tidal variability) of TSM are modeled. Therefore, the model gives be used as a tool for prediction of the spreading of dumped tunnel silt into the estuary, on a *seasonal scale*. The present results are a *best estimate* of the baseline for a complete temporal and spatial 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 m³ 'Boonse Klei' being excavated and dumped over a period of 1.5 years. The Boonse Klei consists primarily of very fine silt (<63 μ) (Rijkswaterstaat, 1998). As a rough estimate, a conversion factor of 1ton per m³ 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 continuous 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.

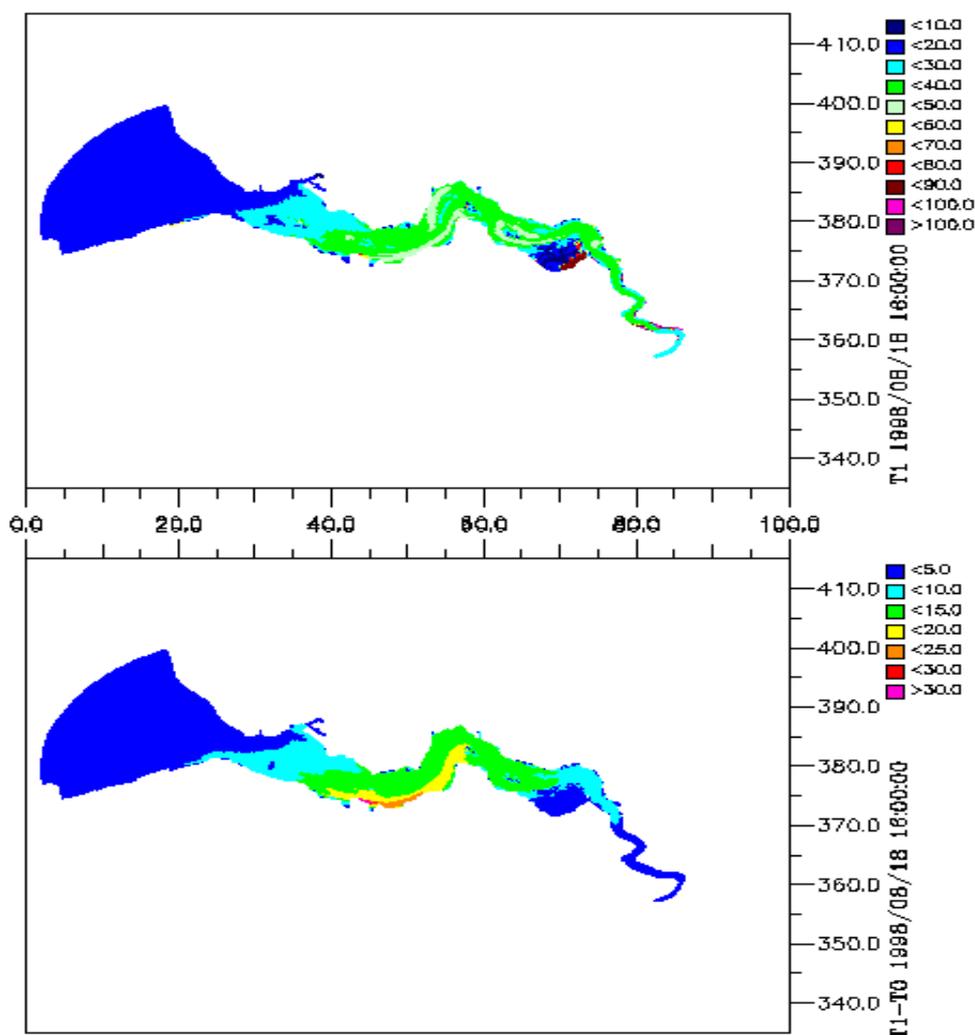


Figure 6. Modeled effect of the dumping of TSM (mg/l) for 18 August. The top figure shows the total amount of TSM, whereas the bottom figure shows only the dumped silt fraction.

On the 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 (see Figure 6, bottom). The natural background concentrations in this area vary from 5-20 mg/l in summer (Directie Zeeland, 1999b) and will increase (for the present scenario) to 20-35 mg/l for this area (see Figure 6, top).

5 CONCLUSIONS

An integrated methodology based on the synergetic use of in-situ data, remote sensing data and model data was used in this study for getting a best estimate of TSM in the Western Scheldt estuary. It is demonstrated that this methodology 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 tunnel silt into the estuary from dumping can be predicted with models. This may optimize future observations of the spreading of tunnel silt into the estuary.

Although the model has certain approximations (grid resolution, boundary conditions, simplified wave dynamics and 2-dimensional approach) it gives a best estimate of the complete spatial and temporal distribution of TSM. Therefore, it can be used as a tool for predicting the spreading of dumped silt into the estuary. It was shown that the predicted effects are quite significant over more than 25km along the estuary in the summer period. 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 m³ 'Boonse Klei' into the estuary over a period of 1.5 years (Rijkswaterstaat, 1998). 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 sediment dumping can probably best be observed for spring and summer periods. In addition, since this is the biologically active period (and since the primary production is light limited) there may be an impact of these sediment dumpings on the ecosystem. Therefore, monitoring of the estuary during the tunnel construction with the present methodology for this period is advised.

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