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RESTWES

REmote Sensing as a Tool for Integrated Monitoring of the WEstern Scheldt

RESTWES project team

BELEIDSCOMMISSIE REMOTE SENSING

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NRSP-2 report 00-09
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This report describes a project carried out in the framework of the National Remote Sensing Programme (NRSP-2) under responsibility of the Netherlands Remote Sensing Board (BCRS)

Executive Summary

In the RESTWES project the baseline conditions (T0) with respect to suspended particulate matter (SPM) in the Western Scheldt estuary prior to discharge of tunnel boring material 'Boomse Klei' from the Western Scheldt tunnel construction was characterised. Use was made of data from in situ measurements, remote sensing and water quality modelling. Strengths and weaknesses of the individual information sources for describing SPM in the Western Scheldt were identified, the added value of integration of innovative techniques such as remote sensing and sediment transport modelling together with a sensible use of in-situ measurements was demonstrated. Based on SPM data of the year 1998 from the three sources of information important characteristics of SPM were assessed, including the dynamic behaviour as well as the spatial variability. Important processes affecting SPM concentrations are identified, such as the spring-neap tidal cycle.

Long-term (20 years of data) monthly averaged in situ data indicate seasonal trends in SPM concentration which occur over the whole estuary: high winter concentrations and low summer concentrations. There is a gradient in concentrations over the length of the Western Scheldt, with lowest concentrations in the east at the mouth of the estuary, and highest concentrations near the Belgian border. Continuous 1998 in situ data from measurement locations near Vlissingen, Terneuzen and Baalhoek indicate a consistent 14.5 day spring-neap cycle, with an additional 12+ hour cycle caused by the tidal period. Additional patterns in the data occur due to storm events (high wind), and possibly other local conditions (e.g. dumping of dredged sediment or local bottom sediment erosion).

Remote sensing images offer 'snapshots' of the estuary, showing a level of spatial detail which is not available in either in-situ data or modelled results. Using measured inherent optical properties of Western Scheldt sediment a number of 1998 SPOT satellite images of the area were interpreted, resulting in 9 SPM maps of the Western Scheldt, showing synoptic distributions on suspended sediments. SPM concentrations can be mapped in steps of 3 mg/l at the lowest concentration range with errors (roughly estimated) from approximately 5% up to 33%.

The dynamic water quality model is the only information source which can give information on SPM at all times at all locations in the Western Scheldt. The water quality model integrates the main trends, patterns and causal effects that are analysed in the in-situ and RS data. Integration of in-situ and remote sensing data with the water quality model has been realised using the method of a cost function. Seasonal patterns, spring-neap cycle, discharges of sediment from harbour dredging activities and wind effects are all incorporated. The model gives a mass conservative spatial representation of SPM and can calculate transport of material. Modelling enables both fore- and hindcasting. Due to restrictions in data of inputs, boundaries and forcings, the present model application is limited in its ability to simulate detailed patterns in SPM concentration as seen in the remote sensing, and very short term variations in SPM concentrations as seen in the continuous in-situ data. Predictions for the T1 situation (during tunnel construction) were made assuming a discharge of 1 million tons of fine silt at a constant rate over a year at one location (near Terneuzen) added to the baseline situation of 1998. The concentration increase may most likely be best 'visible' in the summer months, when background concentrations and natural variability are low over the estuary. The water quality model can also provide information on the transport of discharged tunnel sediment. Analysis of the modelled sediment transport with the model showed that approximately 75% of the total amount of discharged sediment is transported out to the North Sea, and 20% is deposited in the Western Scheldt.

A SPOT image at low water was selected for classification of tidal flats with respect to grain size of the sediment, using sediment composition data from extensive in situ measuring campaigns in the Western Scheldt in 1992 and 1993. Validation of the resulting image was done with a separate data set of median grain size values for a single tidal flat, the Molenplaat. The resulting maps are certainly valuable in a qualitative sense, but the classification method will have to be improved and further developed into an operational tool.

A so-called 'blue print' for operational monitoring of total suspended sediment during tunnel construction was drawn up, in case the RESTWES methodology will be adopted to monitor silt distribution during tunnel construction. The preservation of the organisational structure of the RESTWES project is recommended, but also alternative options for the future were identified. Improvements with respect to data management and (data) communication were indicated (e.g. the use of Internet). Setting up a (local) central point for data collection was advised. Furthermore the application of the Information Cycle approach is strongly recommended to identify information needs, to define a wellfounded monitoring strategy and to give the RESTWES approach a firmly-embedded position.

Samenvatting

In het RESTWES project werd de uitgangssituatie (T0) met betrekking tot de concentratie van totaal zwevend stof (suspended particulate matter, SPM) in de Westerschelde voorafgaand aan de bouw/boring van de Westerschelde tunnel en de daarmee gepaard gaande verspreiding van boorspecie ('Boomse klei') vastgelegd. Daarbij werd gebruik gemaakt van informatie afkomstig van zowel historische als actuele in situ metingen, van remote sensing data en van gemodelleerde gegevens. De sterke en zwakke punten van elk van de informatiebronnen kwamen aan de orde, de meerwaarde van remote sensing en modelleren in combinatie met het gebruik van in situ gegevens werd gedemonstreerd. Op basis van gegevens over het jaar 1998 werden de belangrijkste karakteristieken van zwevend stof in de Westerschelde, zoals het dynamisch gedrag en de ruimtelijke variabiliteit, vastgesteld.
Langjarige maandgemiddelde in situ gegevens geven seizoentrends in de concentratie van zwevend stof aan, die in het gehele estuarium voorkomen: hoge winterconcentraties en (relatief) lage zomerconcentraties. Daarbij is er een gradiënt van hoge concentraties aan de Belgische zijde naar lagere concentraties aan de zeezijde van de Westerschelde. Continu metingen afkomstig van de vaste meetlocaties bij Vlissingen, Terneuzen en Baalhoek geven variaties aan die consistent zijn met de springtij-doodtij cyclus en de getijdeperiode. Extra effecten worden in de data geïntroduceerd door stormen en mogelijke lokale effecten, zoals baggerstortingen of lokale bodem erosie.
Het overzicht en ruimtelijk detail dat remote sensing beelden bieden kan noch door in situ data noch via modellering worden geëvenaard. Een negental SPOT beelden uit 1998 werd onder gebruikmaking van gemeten optische eigenschappen van Westerschelde-sediment omgezet in SPM-kaarten, die een synoptisch beeld geven van de verdeling van slib in het estuarium. De concentratie kan in stappen van 3mg/l worden bepaald met een geschatte mogelijke fout van 5% tot 33%.
Het dynamische waterkwaliteitsmodel is de enige informatiebron die in staat is SPM concentraties te berekenen op elk gewenst tijdstip en op elke locatie. Dit maakt zowel reconstructie als ook voorspelling van slibverspreiding mogelijk. Het waterkwaliteitsmodel integreert de belangrijkste trends, patronen en effecten, die uit in situ en remote sensing data naar voren komen. De integratie van in situ en remote sensing data in de modelomgeving geschiedt met gebruikmaking van de zgn. 'cost function'. Seizoenspatronen, springtij-doodtij cyclus, baggerstortingen, en windeffecten kunnen worden meegenomen. Het model is massa-conserverend, geeft een ruimtelijke representatie van zwevend stof en is in staat transport van materiaal te berekenen. Op dit moment geeft het model globale informatie met een ruimtelijk detail dat onderdoet voor dat van de SPOT beelden, terwijl korte termijn variaties, die zeer goed zichtbaar zijn in de continue in situ metingen niet kunnen worden gereproduceerd.
Op basis van de uitgangssituatie van 1998 met daarbovenop de aanname dat 1 miljoen ton fijne boorspecie per jaar met een constant tempo wordt verspreid via een pijpleiding op een locatie nabij Terneuzen is met behulp van het gekalibreerde model een voorspelling gemaakt t.a.v. de slibverspreiding in de periode van tunnelbouw. Gezien het gegeven dat achtergrondconcentraties en natuurlijke variabiliteit in de zomer het laagst zijn is de kans in die periode het grootst dat een concentratieverhoging 'zichtbaar' zal zijn.
Ook t.a.v. het voor ecologie (en economie) belangrijke vraagpunt "Waar gaat de boorspecie naar toe?" kan het model behulpzaam zijn via het berekenen van slibtransport. Analyse van de modelresultaten geeft aan dat 75% van de boorspecie richting Noordzee wordt getransporteerd en 20% in de Westerschelde sedimenteert.
Een laagwater SPOT beeld werd gebruikt om een korrelgrootte classificatie op de droogvallende platen uit te voeren, gebruik makend van informatie omtrent korrelgrootteverdeling afkomstig van veldmetingen van enkele jaren oud. De resultaten daarvan zijn in kwalitatief opzicht zeker bruikbaar, de methode is echter nog niet betrouwbaar en robuust, zodat verdere ontwikkeling geboden is.
Op basis van o.a. een analyse van het RESTWES project is een blauwdruk gemaakt t.a.v. de organisatie- en data-infrastructuur zoals die bij integratie van de RESTWES methodologie in het operationele monitoring programma t.a.v. de effecten van verspreiding van boorspecie ingericht zou kunnen worden. Aanbevolen wordt van start te gaan met de organisatiestructuur van RESTWES; wel worden enkele alternatieven daarvoor gegeven. Verder worden verbeteringen t.a.v. datamanagement en (data)communicatie aangegeven (Internet) en wordt de inrichting van een centraal punt voor data-inwinning (in Zeeland) aanbevolen. Om goed zicht op de informatiebehoefte te krijgen, een optimaal toegesneden monitoring strategie te kunnen formuleren en de RESTWES methode een stevige positie te geven kan toepassing/gebruik van de Informatie Cyclus (Meetstrategie 2000+) een uitstekend hulpmiddel zijn.

Contents

Beleidscommissie Remote Sensing

Programmabureau BCRS

Meetkundige Dienst

Aan
Geadresseerde

Contactpersoon J.M. Keizer	Doorkiesnummer 015-2691384
Datum 10 oktober 2000	Bijlage(n) 1x
Ons kenmerk -	Uw kenmerk -
Onderwerp BCRS-rapport 00-09	

Bijgaand ontvangt u het BCRS-rapport no. 00-09, getiteld: "RESTWES REmote Sensing as a Tool for Integrated Monitoring of the WEstern Scheldt".

Deze rapportage van het BCRS-project no. 2.1/DE-05 werd opgesteld door het RESTWES project team.

Het project werd uitgevoerd met financiële ondersteuning van de Beleidscommissie Remote Sensing (BCRS).

Met vriendelijke groet,

b/a

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1 General Introduction

1.1 Background

Currently, the Western Scheldt estuary is the focus of much infrastructural activity with potential impacts on water quality and ecology: Specifically, construction of a tunnel under the estuary, linking Terneuzen in Zeeuwsch-Vlaanderen and Ellewoutsdijk in Midden-Zeeland is beginning (mid 1999). As a result, an estimated 1.5 million m^3 of fine material will be dumped in the estuary over a period of several years, potentially affecting Suspended Particulate Matter (SPM)* concentrations (turbidity) and the composition of the bed sediment in tidal flats. This can further affect the habitat suitability for various species. Additionally, dredging activities to deepen the shipping channel to Antwerp Harbour will result in additional dumping of dredged bottom sediment.

The existing monitoring infrastructure (facilities and programmes) 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. 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 is busy setting up a monitoring program and has established two monitoring stations for continuous measurement of turbidity and fluorescence.

Additionally, the use of optical remote sensing and water quality models is being considered for operational monitoring. The interlinked use of remote sensing, in-situ information and modelling 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, the Dutch Coastal zone and the Frisian lakes, RESTWAQ has proved to be a very valuable method to improve knowledge on water quality (especially SPM and light climate). The use of the RESTWAQ methodology for monitoring the Western Scheldt estuary is 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, and resolution of any spatial changes due to dumping will be much higher.

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* *Many different terms are used to indicate particulate matter: Suspended Particulate Matter (SPM), Total Suspended Matter (TSM), seston, silt, etc. In this report, the term Suspended Particulate Matter is used, and is defined as inorganic and organic material that is <63 μ.*

Potential effects from the sediment dumping can be separated into *direct* and *indirect* effects. Expected *direct* effects of the sediment dumping are: increase in sediment concentrations in water (turbidity), changes to flows and bed sediment composition and changes to location/area of tidal flats and channels.

Indirect effects of the sediment dumping are expected on: sedimentation in harbours, dredging activities, sand mining, and ecology.

1.2 Project Objectives

The goals of the project can be summarized as follows:

- to demonstrate the added value of integrated use of in-situ measurements, optical remote sensing data and a water quality model, using the RESTWAQ concept, for assessment of the suspended sediment conditions in the Western Scheldt estuary prior to the dumping of tunnel boring material (T0 situation). This RESTWAQ component of the complete monitoring process will at first be set-up as a prototype due to its innovative character;
- to describe the perspectives for an implementation of the RESTWAQ procedure for monitoring the effects of dumping of the tunnel boring material (T1/T2 phase).

This project, RESTWES (REmote Sensing as Tool for improved management of the WEstern Scheldt) should result in an adequate description of the baseline (T0) situation in the estuary before dumping of the tunnel boring material. The year 1998 has been selected as the 'baseline'. The project should clearly demonstrate the surplus value of the combined use of remote sensing, in-situ and model information for this application.
An additional goal has been to extend the RESTWAQ methodology by also classifying tidal flats using remote sensing data. In this component of the project, classification of sand, fine sediment or vegetated areas will be linked to the ecological conditions of the estuary (habitat evaluation).
Also the evaluation of perspectives for implementation and operationalization within Rijkswaterstaat was planned. The involvement of end users in this demonstration project is a good first step in view of efficient knowledge transfer. Additionally, a 'blueprint for operational monitoring' defining all the steps and procedures necessary for implementing the methodology was to be prepared.

1.3 General Procedure

The following main steps are identified in RESTWES:

1. Acquisition of relevant remote sensing and in situ data over 1998, the period which was chosen to be indicative for the T0 situation in the Western Scheldt.
2. Measurement of optical properties of suspended matter in the Western Scheldt, development of an optical model, and processing of remote sensing images to produce SPM concentration maps;
3. Set-up and initial calibration of a dynamic water quality model for the Western Scheldt.
4. Integration of RS with data from water quality models and in-situ measurement using cost functions, for final calibration of the water quality model;
5. Definition of baseline (T0) conditions of SPM in the Western Scheldt and production of a number of information products illustrating baseline conditions;

6. Prediction of T1 conditions of SPM in the Western Scheldt for a dumping scenario of 1 million tons of tunnel silt over 1 year.
7. Classification of tidal flat composition and habitat evaluation for a selected key species (e.g. the Cockle) in the Western Scheldt Estuary for the baseline conditions (see Baptist and Peters, 1999);
8. Specification of the implementation procedures for application of the RESTWAQ methodology (in an operational system) for the Western Scheldt Estuary ('blueprint').

While this project is seen as a demonstration of the added value of combined use of in-situ and remotely sensed information and modelling of total suspended sediment in the Western Scheldt (using the RESTWAQ methodology), it is hoped that in a following phase the procedure will be extended for use in operational monitoring once the dumping of the tunnel material has commenced.

1.4 The RESTWES project team

The RESTWES study is being conducted by the following team of people

Institute/name	role
RWS-RIKZ:	
Dirk van Maldegem	in situ data acquisition
Ben de Winder	system knowledge, advise
Roger Salden	hydrodynamic modelling
Erin Hoogenboom	management data acquisition, remote sensing
Ricardo Catalan	blue print, reporting
Jos Kokke	overall project management, reporting, editing
WL|Delft Hydraulics:	
Monique Villars	project management, data assimilation, reporting
Robert Vos	water quality modelling, data assimilation, reporting
Martin Baptist	tidal flat classification / assessment of ecological effects
IvM:	
Reinold Pasterkamp	remote sensing data processing, optical modelling, reporting
Steef Peters	remote sensing data processing, optical modelling, reporting
Machteld Rijkeboer	assessment of inherent optical properties
RWS-DZ	
Rob Termaat	representative of end user
Cees-Jan Meeuse	representative of end user
RWS-MD	
Harry Landa	operationalisation of remote sensing
KNMI:	
Hans Roozekrans	meteorological data

1.5 This report

The work on the RESTWES project was subdivided in work packages and resulted in 5 separate reports/documents describing both activities and results of those (sometimes integrated) workpackages:

Hoogenboom, H.J., RESTWES, 1999, Integrated Monitoring of sediment in the Western Scheldt; Part 1: Data acquisition, RIKZ draft report.

Villars, M. and R.J. Vos, 1999, RESTWES, Remote Sensing as a Tool for integrated monitoring of the WEstern Scheldt, WL|Delft Hydraulics report no. Z2472

Baptist, M.J. and S.W.M. Peters, 1999, RESTWES Ecology: Use of remote sensing for classification of intertidal areas, and preliminary ecological assessment of tunnel boring material in the Western Scheldt, WL|DelftHydraulics, Report Z2472.30

Pasterkamp, R.., S.W.M. Peters, M. Rijkeboer and A.G. Dekker, 1999, RESTWES: Retrieval of total suspended matter concentrations from SPOT images, Institute for Environmental Studies, Free University Amsterdam, report W-99/33

Catalan, R.L., RESTWES BLUE PRINT document, 1999, internal RIKZ report, in press.

The present document has come about in a process of selection and editing of those documents. Chapters 2-4 describe the work that has been conducted by WL|Delft Hydraulics and IvM on the main component of the RESTWES project, i.e. analysis of SPM in the water phase of the Western Scheldt through an integration of 3 components information sources, namely: in-situ data, remote sensing data and water quality modelling. See Villars & Vos (1999) for the most extensive version of this work. In Chapter 2, the main activities and results for each of these components are presented. In Chapter 3, comparison of results from the different information sources is made. In Chapter 4, the results of model predictions for a T1 scenario are given. Chapter 5 addresses the use of remote sensing for classification of tidal flats and for assessing the potential ecological impacts of the tunnel material dumping and can be viewed as an edited version of Baptist & Peters (1999). In Chapter 6 the perspectives and implications of implementation of the RESTWES results in a (semi-)operational monitoring system are highlighted, using the information from the so called Blue Print document (Catalan, 1999). Finally Chapter 7 presents conclusions of the RESTWES project and recommendations for the T1 monitoring.

1.6 Acknowledgements

The financial support of both the Netherlands Remote Sensing Board (BCRS) and Meetstrategie 2000+ is gratefully acknowledged. Pieter Blokland (formerly Meetstrategie 2000+) took the initiative to link the application of the RESTWAQ concept to the monitoring of the effects of spreading of tunnel boring material in the Western Scheldt estuary. Thanks to Frans de Bruyckere and Saskia Huijs of the Zeeland Directorate of Rijkswaterstaat (the anticipated end user of project results) for the great many critical questions you asked before we could convince you that RESTWES might work in the Western Scheldt. Their role was taken over by Cees-Jan Meeuse and Rob Termaat. Ben de Winder (RIKZ), thank you for stimulating discussions and for clarifying the intricate situation regarding responsibilities, liabilities and competences of authorities and companies. Dirk van Maldegem produced both readily available historical and actual in situ data and hidden information on harbour dumpings. Dick de Jong's critical review of the chapter on ecological effects was greatly appreciated. Finally Harry Landa's suggestions helped establish the blue print for (semi)operational monitoring of suspended sediment in the Western Scheldt.

2 Material: Acquired data and water quality model

2.1 In-situ data

2.1.1 Introduction

An overview of available in-situ data for RESTWES has been made by RIKZ (Hoogenboom, 1999). In-situ data of concern for RESTWES consist of continuous monitoring, and project based data of suspended particulate matter and turbidity. These data form one of the main information sources about suspended sediment conditions in the Western Scheldt. Tidal cycle data (water levels) and wind data corresponding to the in-situ measurements are crucial for interpretation of the in-situ measurements and these are also available.

The SPM in-situ values are also necessary for input and calibration of the water quality model, and for validating the processed remote sensing images (conversion of reflectance signal to a concentration).

In this chapter, the available SPM in-situ data is reviewed and a short analysis made of the important trends and patterns which can be seen in the data. Available wind data is also presented, and potential relations between wind and in-situ SPM concentrations are discussed.

2.1.2 SPM data

A number of sources of in-situ SPM data in the Western Scheldt (see the general location map in Figure 2.1) is available (Hoogenboom, 1999):

- Continuous monitoring stations (Vlissingen, Terneuzen and Baalhoek)
- Project oriented monitoring data (e.g. van Maldegem, ECOFLAT, Life Westerschelde, GEM, MATURE, Borgerhout)
- Rijkswaterstaat MWTL network

These data are not all readily (digitally) available (especially project oriented data), and data cover different time periods, frequencies, and locations. After a review of available data, the following 2 data sets have shown to be the most useful for illustrating important suspended sediment trends and processes, and calibrating and validating the water quality model and the remote sensing processing:

1. Project data from van Maldegem (1992): Long-term monthly averaged SPM concentrations are available at 9 locations in the Western Scheldt for the period 1970-1990, see Figures 2.2 and 2.3.
2. Continuous monitoring data from 3 fixed stations: Vlissingen, Terneuzen and Baalhoek.

Figure 2.1 General location map Western Scheldt (1970-1990).

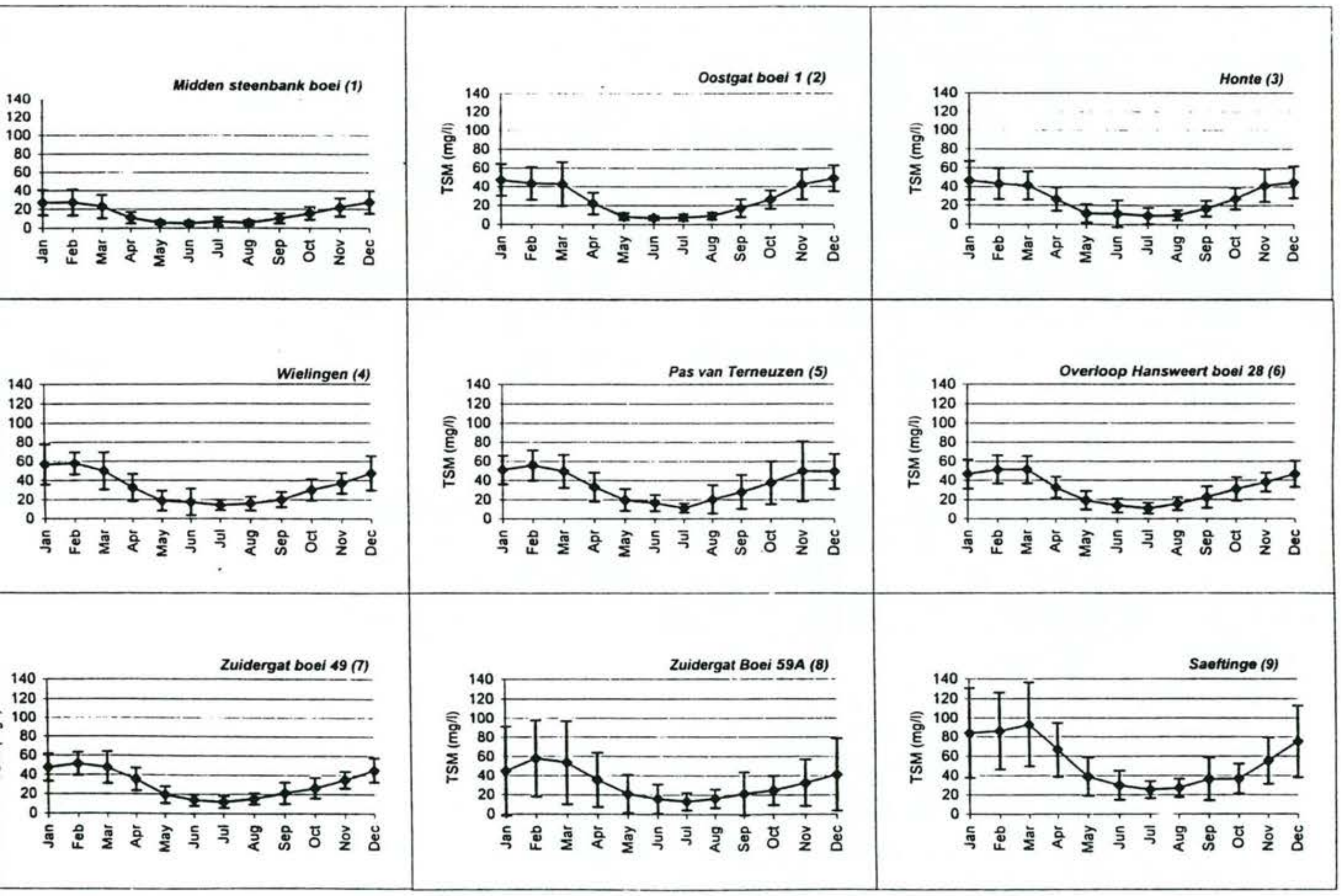

Figure 2.2 Monthly averaged SPM concentrations (1970-1990) at 9 locations in the Western Scheldt.

2.1.3 Continuous monitoring stations

Fixed monitoring stations at locations Vlissingen, Terneuzen and Baalhoek recorded on a continuous basis (every 10 minutes) during all or parts of 1998. All stations monitor turbidity (as optical backscattering, OBS) and fluorescence, which must be converted to obtain SPM concentrations in mg/l. The stations have been established and are operated for Directorate Zeeland by RIKZ. Locations are shown in Figure 2.3.

The station at Vlissingen was an existing station and was operating for all of 1998, measuring at one depth of -4.5 m NAP. In November and December, a technical problem with the instrument prevented measurements of high signals, corresponding to concentrations above ~70 mg/l.

The stations at Baalhoek and Terneuzen were established specifically for monitoring SPM conditions in the Western Scheldt prior to dumping of tunnel material. The station Baalhoek was operational starting on 1 October 1998, measuring at one depth of -4.5 m NAP. The station Teurneuzen measures at 3 fixed depths of -4, -11, and -17 m NAP and was operational starting on 26 October 1998.

The locations for these two stations were chosen because there was a previously existing monitoring station (meetpaal) at each point, and thus measuring instruments could be installed relatively easily. The monitoring station at Terneuzen, located at 'steiger DOW', is at the location for dumping the tunnel material, and is actually within the region selected for discharge of the tunnel material by pipeline (Figure 2.4). The monitoring station Baalhoek is approximately 50 km upstream from the dumping location, near Saeftinghe, a region of great ecological importance.

Data from the 3 stations for all of 1998 are presented in Figure 2.5. Data for Terneuzen are from the shallowest depth (-4.5 NAP). Averaging of the data of these plots resulted in one data point every 2 hours.

In 1998, stations Terneuzen and Baalhoek were only operational in the period October - December, and the data for this period are presented in Figure 2.6 (one date point every 2 hours). Detailed data for the station Baalhoek for the month of October only are given in Figure 2.7 (one data point every 10 minutes).

A comparison of data from different depths for Station Terneuzen for months October and November is given in Figure 2.8. In October, data were not available at depth -17m NAP.

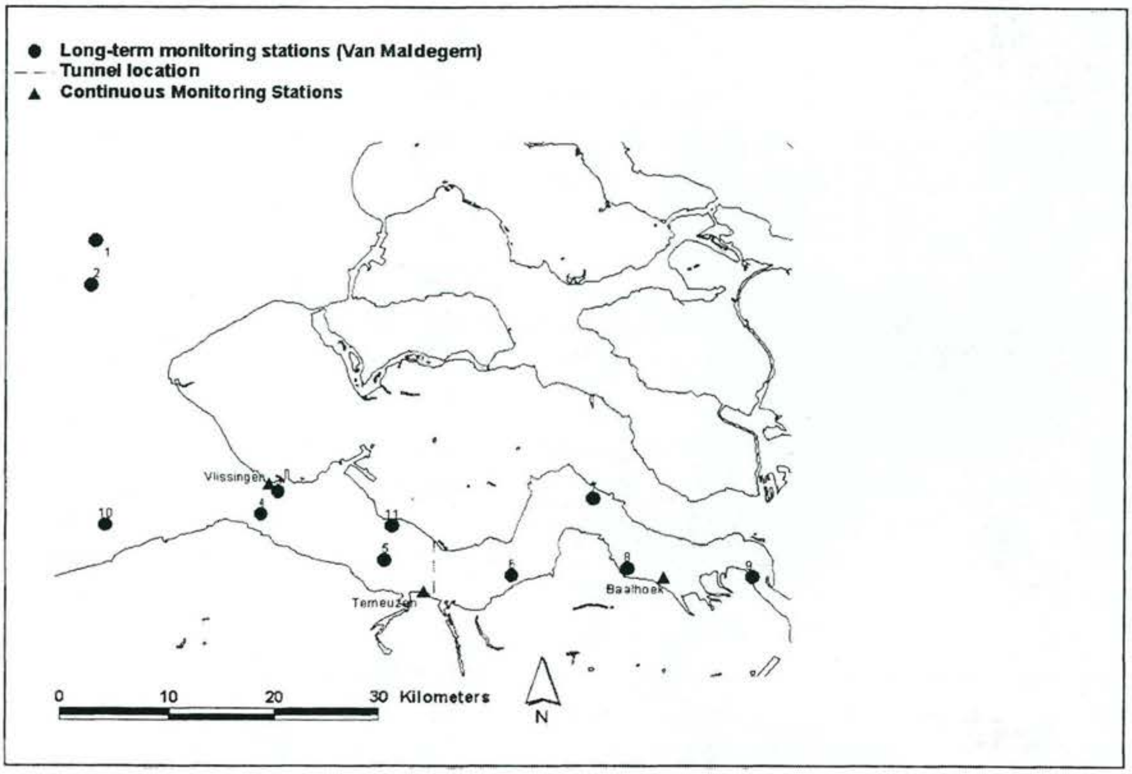

Figure 2.3 Location of continuous monitoring stations together with Van Maldegem stations

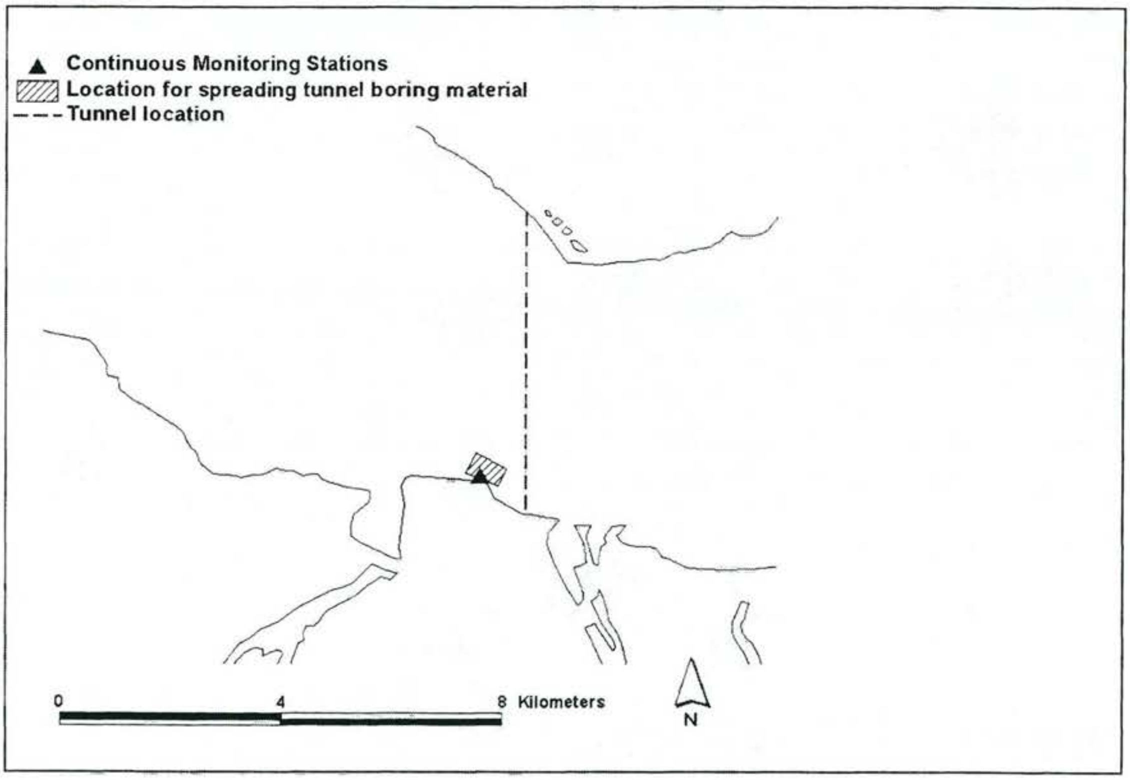

Figure 2.4 Location of continuous monitoring station Terneuzen with respect to the tunnel material 'dumping' location (discharge will most likely be via pipeline)

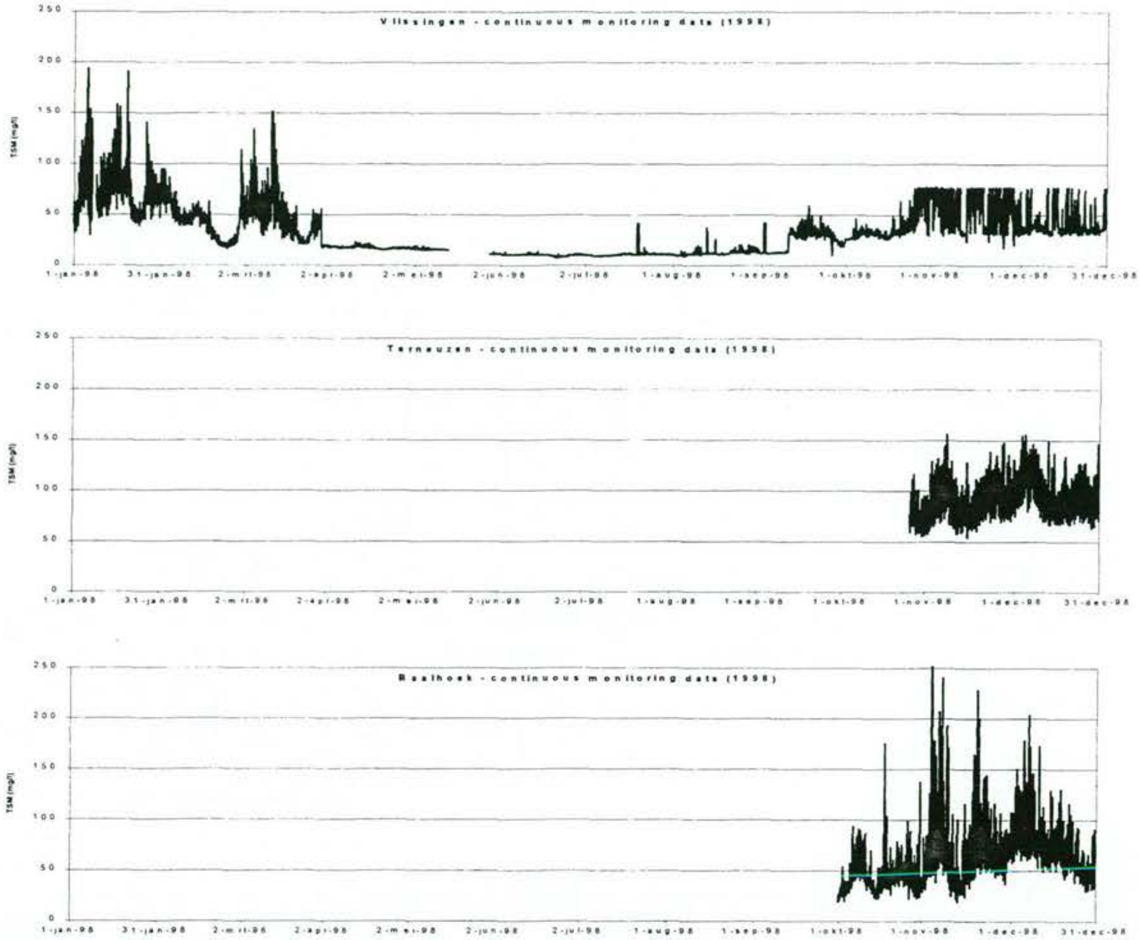

Figure 2.5 Continuous monitoring data of SPM (mg/l) in 1998 (data very 2 hours)

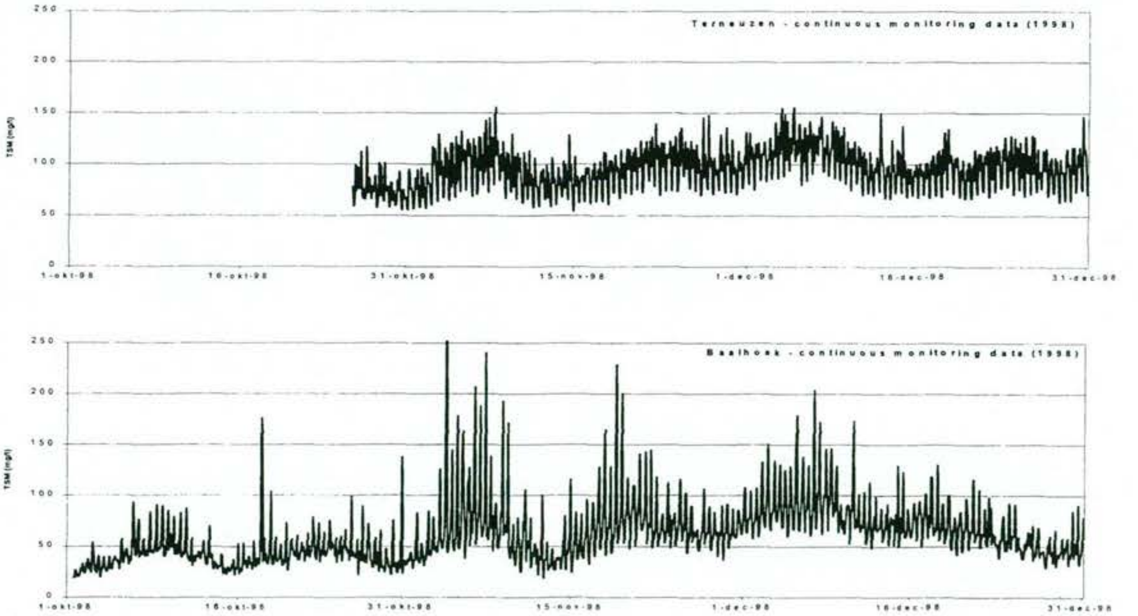

Figure 2.6 Continuous monitoring data at stations Terneuzen and Baalhoek (October - December, 1998; one data point every 2 hours). Here the concentration variation over the spring-neap cycle of ~14.5 days can clearly be seen.

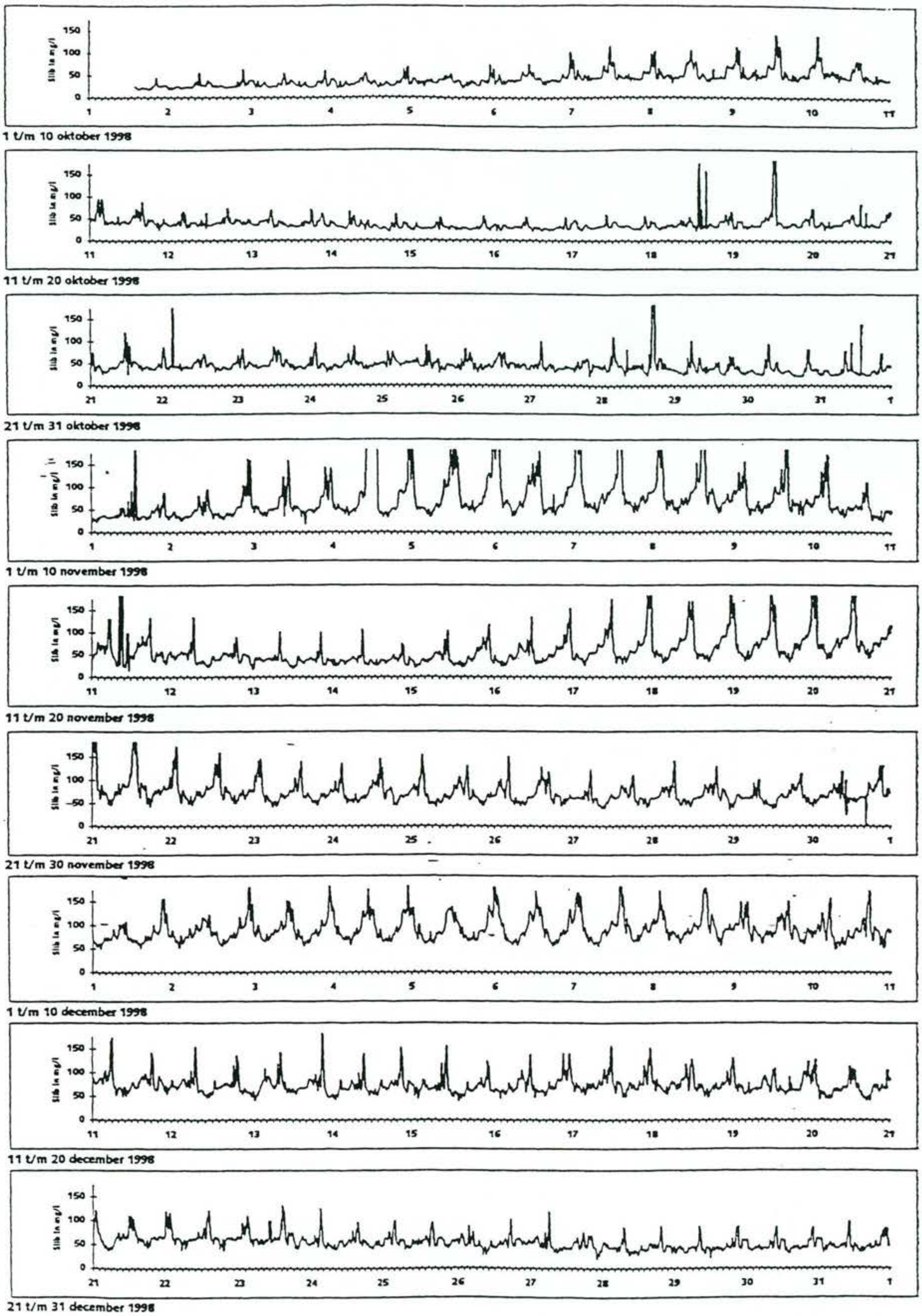

Figure 2.7 Continuous SPM concentrations at Station Baalhoek (October - December, 1998). Here the concentration variation over the tidal cycle can clearly be seen (data every 10 minutes).

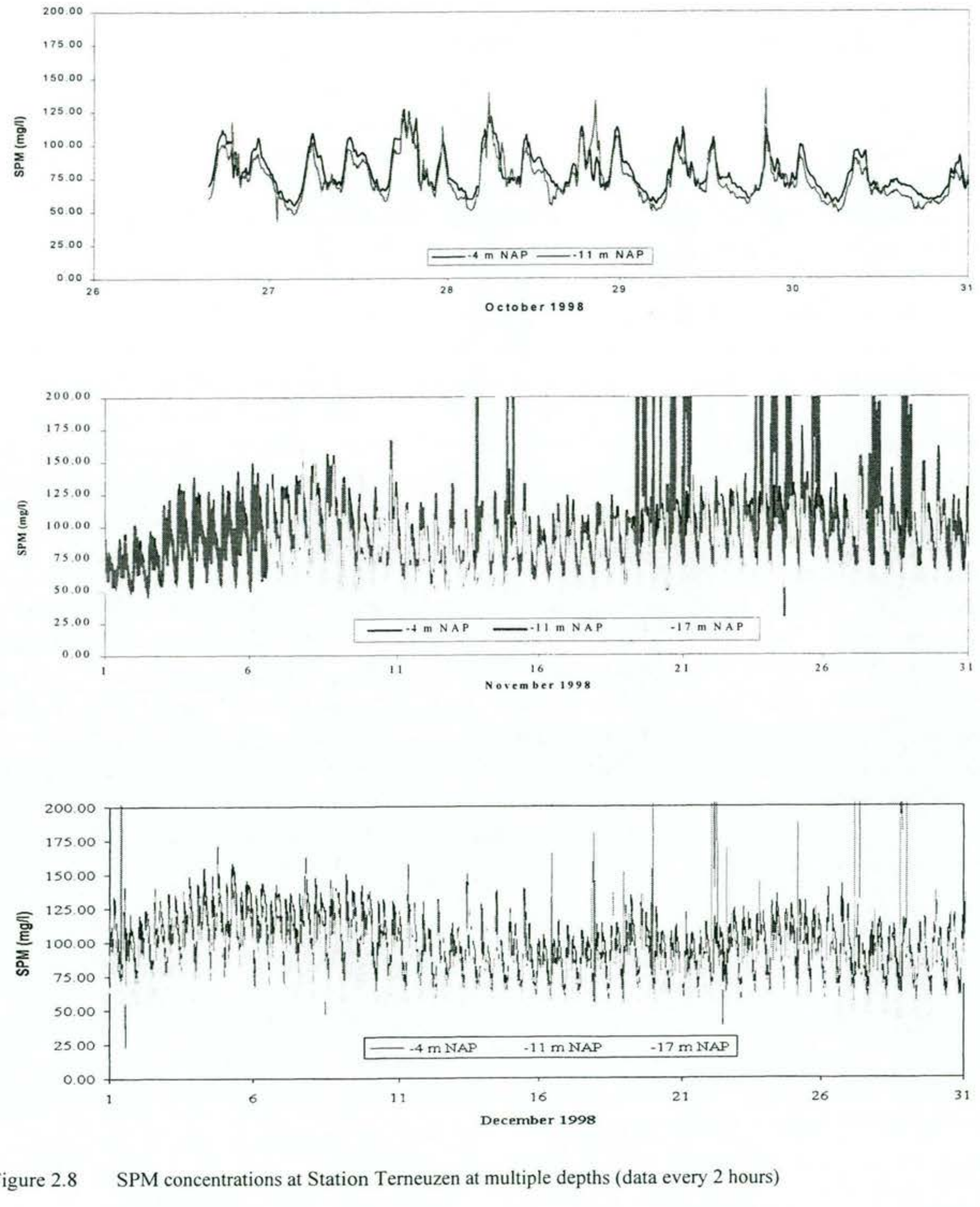

Figure 2.8 SPM concentrations at Station Terneuzen at multiple depths (data every 2 hours)

2.1.4 Trends and patterns in the in-situ data

The selected data sets for SPM measurements show several important trends and patterns in the in-situ data over different time scales:

1. Seasonal cycle over 1 year.

Long-term monthly averaged data (1970-1990) of SPM concentrations in the surface water at 9 locations in the Western Scheldt estuary show a clear seasonal cycle, with lowest concentrations in the summer months June and July (Figure 2.2). Highest concentrations are seen in December and January. At station Vlissingen, for example, winter concentrations are approximately 50 (± 20) mg/l, while summer concentrations are approximately 15 (± 10) mg/l. Other stations essenntially show the same pattern, with different concentration ranges and different degrees of variability over the months. The continuous monitoring data at Vlissingen show the same seasonal trend (Figure 2.5), though the recording instrument had some disturbance in November-December and could not register any signal corresponding to values above ~70- mg/l.

2. Spring -Neap cycle of 14 days.

The variation in SPM concentrations over the spring-neap tidal cycle can most clearly be seen in the continuous measurements at Terneuzen and Baalhoek in the period October-December 1998 (Figure 2.6). These data show concentrations of SPM which have a cycle over approximately 14.5 days, with highest concentrations at spring tide, and lowest concentrations at neap tide. The concentration range in the cycle is small compared to some of the higher frequency peaks which occur, but is consistent through the measured period.

3. Tidal cycle of appr.12.5 hours

Due to the tidal cycle of approximately 12.5 hours, there are SPM concentration peaks corresponding to low water levels (or flood tides), and concentration dips corresponding to high water levels. The result is clear peaks in concentration occurring approximately every 12.5 hours, evenly interspersed with dips in concentration. Tidal cycle peaks are extremely regular and clear to see in e.g. the continuous monitoring data from station Baalhoek (Figure 2.7). In Figure 2.9 the relation between suspended particulate matter concentration and water level is shown for 11 November 1998. This figure illustrates that peak concentrations (0:00 and ~13:00) correspond to rising water (incoming tide), while low concentrations (04:00 and 17:00) correspond most closely with high water.

4. Variation in SPM concentration with Depth

At continuous monitoring station Terneuzen, measurements are made at 3 depths: -4, -11, and -17 m NAP. A comparison of SPM concentrations at different depths over the period October - December 1998 shows that concentrations are very similar (Figure 2.8). In all three months, data from the 2 upper depths are essentially the same. November and December data show that the bottom concentrations (-17 NAP) are somewhat lower. On the whole, it can be concluded that the system is well mixed.

5. Wind effects

Wind has a strong effect on SPM concentrations via waves, and thus wind data for 1998 were also analyzed (see section 2.2.3). Wind waves can create a bottom stress on the tidal flats which causes resuspension of the bottom sediment. It can be seen that periods of high SPM concentrations correspond to periods of high wind. Storm periods in January and March (i.e. wind >10 m/s) correspond to high SPM concentrations seen in the continuous data at Vlissingen. High concentrations at Baalhoek in the first half of November are perhaps due to the wind storm in the period 23-31 October. The wind in October does not seem to affect the concentrations at Terneuzen, though unfortunately continuous monitoring data start only at 26 October.

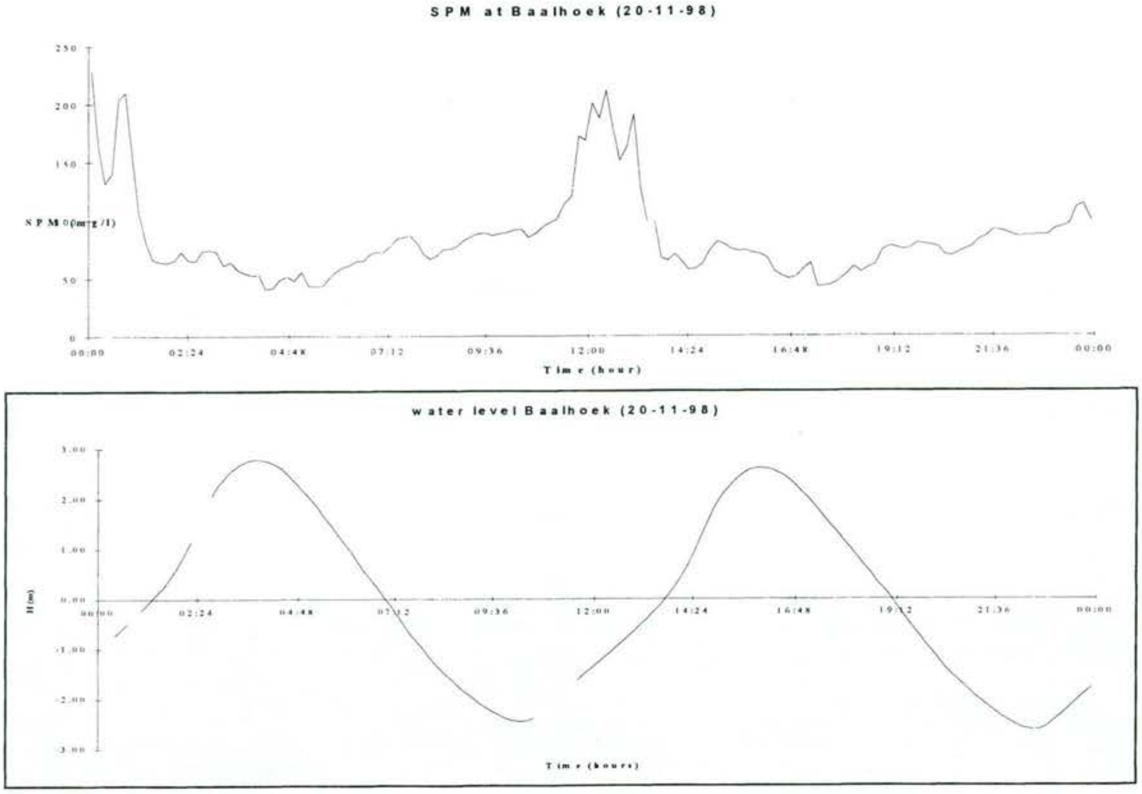

Figure 2.9 SPM concentration and water level, 20-11-98

2.1.5 Wind data

Because wind can have a significant effect on suspended matter transport (sedimentation and resuspension), some analysis of wind data was made. Wind data from the KNMI are available from Vlissingen on an hourly basis, and from Baalhoek every 10 minutes. Data from Vlissingen are used as input to the water quality model, after they are averaged to daily wind speeds (Figure 2.10). The daily average wind speed is calculated as a quadratic average†. Three 'storm' periods of high wind (daily average >10 m/s) can be seen in begin January, begin March and end October-begin November.

To check if there is much spatial difference in the wind over the area of the estuary, a comparison of wind speed as measured at Vlissingen and Baalhoek was made for the period of 21-31 October, 1998, Figure 2.11. The data show that there is no significant difference in wind speed between Vlissingen and Baalhoek. Peak gust and low wind speeds occur at the same time, with similar values. Thus there is no problem in using the Vlissingen data for the whole model area.

The daily averaged values obviously show less variability and less extreme values than the higher frequency data. During the selected period in October, daily averaged values are between 8-17 m/s, while some of the higher frequency wind data measure speeds as high as 23 m/s and as low as 5 m/s. This is not expected to have a significant effect in the model calculation.

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† *Daily average wind speed calculation from 24 hourly values:*

$$W_{daily\ ave} = \frac{\sqrt{w_1^2 + w_2^2 + \ldots + w_{24}^2}}{24}$$

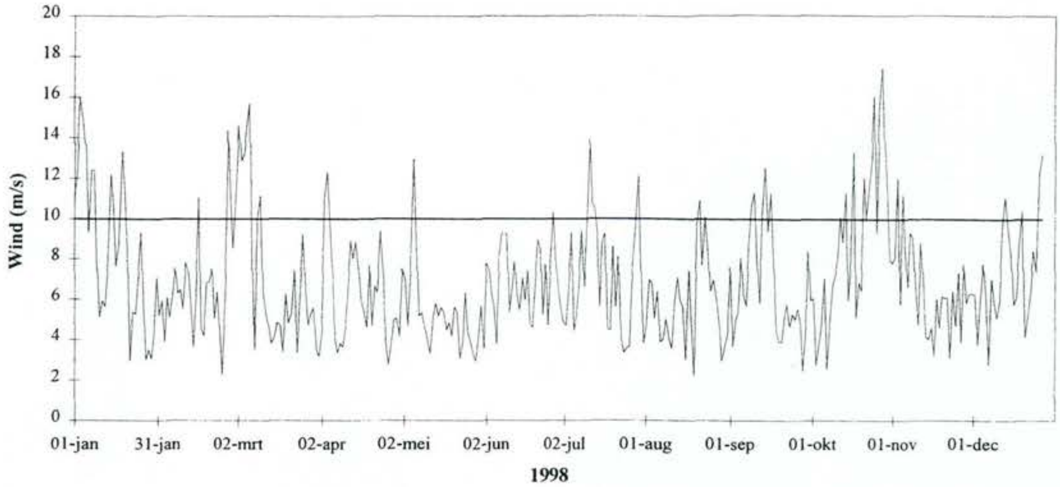


Figure 2.10 Daily average wind speed at Vlissingen. 'Storm' periods of high wind (daily average >10 m/s) can be seen in begin January, begin March and end October-begin November.

Figure 2.11 Wind data at Vlissingen (daily average and hourly) and Baalhoek (10 minutes), 21-31 October, 1998

2.2 Remote Sensing data

2.2.1 Introduction

The information in this chapter is derived from the report of Pasterkamp et al. (1999), which was drawn up in the framework of the RESTWES project and describes the work done by the Institute of Environmental Studies (Vrije Universiteit of Amsterdam) with respect to the inventory of the temporal and spatial dynamics and distribution of suspended matter in the Western Scheldt estuary before construction of the Westerschelde tunnel using remote sensing. The resulting SPM rastermaps were subsequently transformed to the curvilinear hydrodynamic model grid for direct comparison with model results.

2.2.2 Selection of remote sensing data

A number of satellites/sensors are potentially available for assessment of water quality, and specifically for mapping/monitoring of SPM: NOAA/AVHRR, SeaWifs, LandSat, and SPOT. It was decided to use remote sensing images from the SPOT satellite for a number of factors, including image resolution (pixel size), availability/frequency, and cost. NOAA and SeaWifs have a resolution of approximately 1 x 1 km, which is not detailed enough for analysis of water quality in a region like the Western Scheldt. Other limitations of NOAA are saturation of the signal at about 20 mg/l (Vos and Schuttelaar, 1995; van Raaphorst et. al. 1998). Nevertheless previous RESTWAQ studies of the North Sea and Dutch coastal zone have used NOAA (Vos et al., 1995-1998), because for these regions the resolution was appropriate.

Both LandSat and Spot have higher resolution than NOAA, 30 x 30 m and 20 x 20 m, respectively. The single LandSat 5 Satellite has a return period of 17 days, which is insufficient to provide many clear images of the region (data from LandSat 7 only became available since April 1999). The LandSat5 images are about 3 times cheaper than SPOT, but are of lower quality (Vos et al., RESTWAQ-2, PART II, 1998). There are several SPOT satellites, and possible suitable SPOT images are available nearly on a daily basis. Eventually, images were procured from 3 SPOT satellites (SPOT1, SPOT2 and SPOT4), some specific separate processing for each satellite being necessary in order to make intercomparison possible (see section 2.2.3).

Fourteen remote sensing images of the Western Scheldt estuary from the SPOT satellite were purchased, covering the period May 1996- November 1998 (Table 2.1). The images can be classified in categories of tidal water level:

- high water;
- mean water; or
- low water

and tidal phase:

- incoming water or 'flood';
- outgoing water or 'ebb';
- water that is at its minimum or maximum direction (reversing direction) or 'slack';

Additionally, images are given a quality ranking, based on the extent to which the image is cloud-free, and the sun elevation (sun angle). In general, the lower sun elevation, the poorer the remote sensing image, because less reflected light reaches the satellite sensor.

Table 2.1. SPOT RS images and their properties

Year	Month	Day	W (m/s)	Wdir	Tide	Direction flow	H(m)	Side	Sun elev.	Quality
1996	may	7	?	?	low	slack	-2.3	E	52.9	++
1997	august	12	?	?	mean	?	-0.5	E	53.2	++
1998	january	11	8	180	high	incoming	0.75	W	15.6	++
1998	april	2	4		low	slack	-2.1	W	42.2	0
1998	may	10	5	90	mean	incoming	-0.3	W	55.3	++
1998	may	10	5	90	mean	incoming	0.4	E	53.6	++
1998	june	1	4	240	low	outgoing	-1	W	58.3	+
1998	july	20	1	240	high	slack	2	E+0.8W	58.7	++
1998	august	6	9	260	high	incoming	1.1	W	53.3	++
1998	august	8	4	260	mean	incoming	-0.5	W+0.5E	52.1	++
1998	august	10	5	100	low	incoming	-0.9	W	53.6	++
1998	oktober	1	1	40	high	outgoing	1	E+0.5W	34.5	0
1998	november	17	5	250	high	incoming	0.7	W+E	18.9	+
1998	november	20	5	120	low	incoming	-0.8	W+E	18.2	0
H was determined at Terneuzen using tidal analysis program										

Of the 14 available images, a selection of 9 images was made for processing based on image characteristics. Images were selected for processing (Table 2.2) based primarily on the quality (++ Quality = Category I), as well as their spatial coverage of the region, and the time when the image was made. The images were selected so that they covered different seasons in the year, as well as different periods within a tidal cycle. Two images were selected in Category II because they provided additional information, not present in Category I:

- the image of May 1996 is of high quality and contains information on the area where effects of dumpings might be found in the future;
- the image of October 1998 contains information on a tidal phase of outgoing flow. In the first category the type 'outgoing flow' is unfortunately not present.

Table 2.2 Remote sensing images selected for processing

Category I										
Year	Month	Day	W (m/s)	Wind dir	Tide	Direction flow	H(m)	Side	Sun elev.	Quality
1998	january	11	8	180	high	incoming	0.75	W	15.6	++
1998	may	10	5	90	mean	incoming	-0.3	W	55.3	++
1998	may	10	5	90	mean	incoming	0.4	E	53.6	++
1998	july	20	1	240	high	slack	2	E+0.8W	58.7	++
1998	august	6	9	260	high	incoming	1.1	W	53.3	++
1998	august	8	4	260	mean	incoming	-0.5	W+0.5E	52.1	++
1998	august	10	5	100	low	incoming	-0.9	W	53.6	++
Category II										
Year	Month	Day	W (m/s)	Wdir	Tide	Direction flow	H(m)	Side	Sun elev.	Quality
1996	may	7	?	?	low	slack	-2.3	E	52.9	++
1998	october	1	1	40	high	outgoing	1	E+0.5W	34.5	0

In addition to SPOT images, a few NOAA/AVHRR images procured from the KNMI. These remote sensing images were also processed to test their usefulness for analysis of SPM patterns at the sea side of the Western Scheldt.

A total of 16 NOAA/AVHRR images was selected and calibrated using the results from a simple SPM model according to the RESTWAQ non-linear extrapolation method (Vos et al., RESTWAQ-2, PART I, 1998). The images were analysed on SPM patterns, and a comparison was made for the image of 14 February 1998 with that of SPOT from the Dali-catalogue of SPOT-Toulouse (this image was not purchased for the project because of some cloud cover).

2.2.3 Description of remote sensing images

General Description of SPOT RS images

Remote Sensing false colour composites were analysed on their general characteristics. The general conclusions of this inspection was as follows:

1. There is a clear correlation between the observed SPM patterns in the images and depth (at relatively low depth often higher reflections are observed in the images‡). A map of average water depth for the estuary (for the model) is given in Figure 3.2.
2. There is a correlation between the observed SPM patterns and the tidal phase. At slack water (e.g. 20 July) the SPM patterns are absent indicating low SPM concentrations. For incoming and outgoing water, (some) erosion at tidal flats can be observed and concentrations are probably higher than for slack.
3. In winter, there is a clear triangle of relatively high SPM at the Vlakte van Raan, at the mouth of the Western Scheldt. This feature can be seen on 11 January, 10 and 14 February from the Dali Catalogue. A reprint of the false colour composite of 14 February§ from the Dali Catalogue is given in Figure 2.14). This region of higher concentrations might be related to SPM that is washed out from the bottom from dumpings during the winter period (de Bie and Benijts, 1994). Until now, this the water quality of this area has hardly been sampled. However, so much silt was not expected since the bottom sediment in this area is mostly sand (1-10% silt).
4. The outflow of silt from the Belgium part of the Scheldt into the Dutch part is clearly recognisable, and can in some cases be related to the tidal phase. Reflections tend to be higher eastward in the Western Scheldt indicating higher SPM concentrations. An example is given in the false colour composite, Figure 2.12.

‡ A high reflectance corresponds with a higher SPM concentration for cloud-free, atmospherically corrected images, and assuming the absence of bottom reflection. Bottom reflectance occurs in the Western Scheldt estuary only near or at tidal flats (depth < 1-2 m).

§ This image was not purchased because of extensive cloud cover and haziness in the estuary. The image is however, excellent for the North sea.

5. The area below *Plaat van Baarland* is turbid in all images (this location is not sampled by the local authorities, co-ordinates are roughly (3°54', 51°22')). This was not expected since this area has a bottom with only a few-% silt (Van Essen and Hartholt, 1999), except for one small spot where the silt fraction is high (25%-50%). A detailed map of this area shows a complex bottom topography with various small flats (Hydrografische kaart, 1997).
6. At Breskens the water column is more turbid than at Vlissingen.

Figure 2.12 Black and white representation of a False Colour composite of SPOT of tpart of the Western Scheldt for 10 May 1998 (incoming water, rising tide). The influx of SPM form the Belgian part of the Scheldt can be seen.

The false color images were analyzed for patterns and features of SPM. A general description, and an overview of some important features for each image is given in Table 2.3.

Table 2.3. Description of SPM patterns in SPOT RS images

Year	Month / day	Remarks
1996	May 7	1. Silt follows river gully, river curves are clean. 2. River silt goes beyond Saefthinge 3. Interesting structures at tidal flats. At Doel the 'Leidam' is visible.
1997	August 12	1 River gully is relatively clean but silt is observed at curves of gully because of erosion. 2 Silt erodes from tidal flats, high concentration below Plaat van Baarland. 3 Also estuary gully is clean. There is remarkably no silt visible at 'Lage and Hoge Springer' whereas this area is known to be turbid, and has a bottom with a high silt content.
1998	January 11	This image corresponds very nicely with the depth contours of the Western Scheldt area since at relatively shallow areas the turbidity is higher: 1. Honte is deep and relatively clear; 2. Schaar van Spijker is shallow and relatively turbid; 3. Lage and Hoge Springer is shallow and bottom has high silt content: area is relatively turbid 4. High reflectance at Hooge Platen and Middelplaat with erosion at west side since water flows into the estuary; 5. Vlakte van Raan is relatively turbid. However, a gully ('insteek') below Kaloo with somewhat larger depth is visible as a somewhat less turbid area; 6. The Oostgat and Deurlo gullies can be discriminated as relatively clear water 7. Arera below Everingen is turbid. Bottom sediment maps shows only sand here? Origin of this silt may be: • This is a shallow area in general; • Silt erodes from Boeregat which has a very high silt content in the bottom; 8. The concentrations at MP2 (continuous OBS measurements) of the Kust2000 in-situ campaign are 1.5 times higher than those at MP1 (the OBS signals were not calibrated unfortunately). This is in agreement with Remote Sensing;
1998	April 2	1. A gradient left of Oostgat is again clearly present; 2. Silt at Schaar van Spijkerplaat increases; 3. A dumping of dry silt at Breskens of 0.4 kton (total in one day), is clearly visible; the ferry just passes this silt patch of dumped material. The ebb tide is retrieved correctly from the movement of the patch; 4. Silt at Lage Springer is clearly visible; 5. High silt below Everingen-Baarland.
1998	May 10 (West)	1. Silt erodes from Hoge platen, Schaar van Spijkerplaat is turbid, lot of silt below Plaat van Baarland; 2. Silt does not follow gully, gully is relatively clean. 3. There is at sea a remarkable green spot visible at Vlakte van Raan in the false colour composite. The image shows a lot of remarkable stripes probably smearing of material due to wind at the surface. According to RIKZ (L. Peperzak) there was a *Phaeocystis* bloom at this site during this period.
1998	May 10 (East)	1. The Scheldt river discharge is high 2. Silt follows gully but also is in curves, river silt till Saefthinge 3. High silt below Baarland, silt at Middelplaat. 4. Middelgat area is clear. This area is known as a sedimentation area. 5. A minimum silt content near Hansweert is clearly visible. 6. Schaar van Waarde is turbid.

		7. Above Plaat van Valkenisse the area is clear (sand area);
1998	June 1	1. High Silt below Hooge Platen, some silt North of Hooge Platen, erosion West of Middelplaat silt below Baarland again. Some silt west of Molenplaat. 2. Outgoing flow gives laminary type of silt structures
1998	July 20	1. No patterns or gradients in the image, probably clear waters, but river silt from Belgium Schedlt till Saefthinge very well visible 2. High water, small flow velocities give loss of silt gradients
1998	August 6	1. High silt at Hooge Platen and Middelplaat (high water, erosion, waves?) 2. High silt North of Hooge Platen and silt below Baarland 3. Stripe of silt North of Belgian coastline (from Paardenmarkt?), but relatively low silt in Scheur van Wielingen.
1998	August 8	1. High silt at Hooge Platen and Middelplaat (high water, erosion, waves?) 2. silt below Baarland, low silt in gullies except North of Hooge Platen 3. High silt at Sea 4. As usual at Breskens the water column is more than turbid than at Vlissingen.
1998	August 10	Like 8 August.
1998	Oktober 1	1. High water, outgoing tide. High concentrations visible at tidal flats (especially south of Molenplaat and Rug van Baarland). Water flows over these tidal flats and takes sediment with it. 2. Some details: Ships go out at such tides, this is clearly visible. Two ferries visible at Kruiningenpolder-Terneuzen (10h41m) that are close together according to their schedule. At Plaat van Valkenisse cover of pioneer vegetation is visible. Zimmermangeul north of Valkenisse is visible (close to the coast). Area is known to have peat.
1998	November 17	1. Belgium Scheldt is uniform till Saefthinge . There are no gradients in river, possibly due to low sun angle? 2. Colour differences between west and east side of the image.
1998	November 20	1. Not much gradients in estuary due to low sun angle. 2. Almost completely green estuary? Sea silt is still blue.

Description of NOAA/AVHRR images

The following NOAA/AVHRR daily images were processed:

Reference	Date	Time	Tide	Water Level
N0214134	*14-2-'98*	*13:49*	*incoming water*	*-0.50m*
N0319124	19-3-'98	12:47	incoming water	-1.1m
N0429065	29-4-'98	6:56	?	?
N0512125	12-5-'98	12:54	incoming water	+0.7m
N0514141	14-5-'98	14:13	incoming water	+0.7m
N0517065	17-5-'98	6:59	high water	+2.5m
N0517133	17-5-'98	13:59	low water	-2.0m
N0517164	17-5-'98	16:47	outgoing water	-0.2m
N0610141	1-6-'98	14:15		
N0610063	10-6-'98	6:31		
N0726061	26-7-'98	6:18		
N0802165	2-8-'98	16:51	high water	+2.0m
N0808063	*8-8-'98*	*6:31*	*incoming water*	*-1.1m*
N0830163	30-8-'98	16:34	high water	+2.3m
N0923131	23-9-'98	13:19	incoming water	-0.8m
N1110142	24-9-'98	8:21	outgoing water	-0.8m

For 14-2-98 and 8-8-98 (italic) also SPOT images were available (i.e. for 14-2 only a Dali print is available). For images up to 14-5-'98, Kust2000 OBS data (continuous) are also available.

The non-linear scaling procedure of Vos (RESTWAQ-2, 1998; page A1-A3) was applied in order to partially overcome the problem of saturation. Non-linear scaling was done on basis of a preliminary model run with sea boundary conditions for SPM of about 50 mg/l for February 1998. After some trial and error, scaling parameters C* =30.0 mg/l (crossing point of linear and non-linear curves), and δ=50.0 mg/l (half-saturation value) were applied. For summer images this does not lead to different results.

SPM patterns

The most prominent feature in the NOAA/AVHRR images is the concentration gradient along the (sea) model boundary. This gradient shows a decreasing concentration from Belgium to Walcheren, most often with a steep decrease in SPM at Oostgat. This information might be useful for set up of model boundaries. An example is given in Figure 2.13. Also a second gradient from the Belgium coast across the Scheur van Wielingen is seen. This leads to an image with a triangle of higher SPM concentrations at Vlakte van Raan. SPOT images also show this pattern (see Figure 2.14).

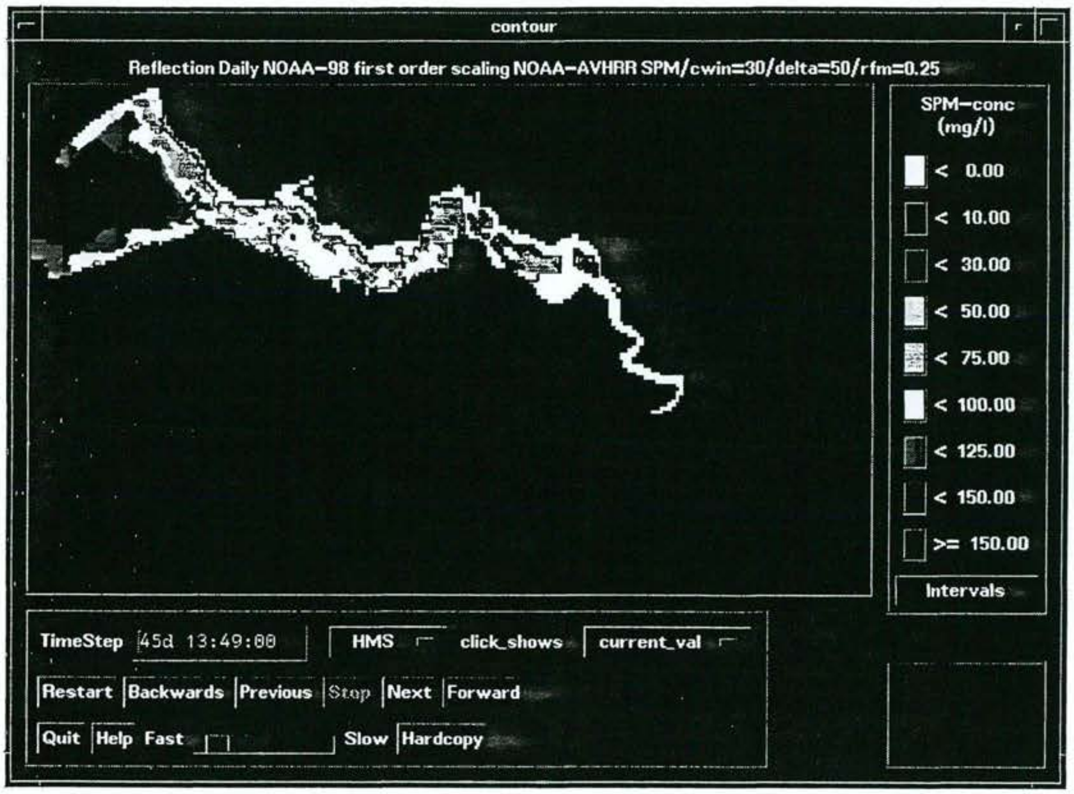


Figure 2.13 NOAA image of 14 February 1998, 13:49 (incoming water -0.50m), rescaled with model result and non-linear extrapolation method to overcome saturation effect.

Figure 2.14 False Colour SPOT image of 14 February 1998 from Dali Catalogue (~ 11.00 hours; low water). A triangle of relatively high SPM concentration, typical for all winter images is visible at Vlakte van Raan at the mouth of the Western Scheldt.

In some of the NOAA/AVHRR images (not shown here) the tide could be recognised:

- High water reveals relatively low concentrations in the estuary, and relatively high concentrations outside the estuary ;
- Outgoing water reveals relatively high concentrations flowing out of the estuary along Scheur van Wielingen and the Belgian coast;
- Incoming water is in general rather unclear in patterns, but the ebb flow is always recognised at Oostgat;
- However, for most of the images occurence of tidal characteristics could not be confirmed neither be falsified.

In two images, SPM spots were clearly visible that *might* indicate dumping of SPM from the Belgium harbours at the dumpings sites R4 (Raan, image of 30-8-'98) and Paardemarkt (image of 17-5-'98).

Conclusions and recommendations for use of NOAA/AVHRR images

Atmospheric correction procedures that do not suffer from saturation are required for sue of NOAA/AVHRR images. Saturation of SPM with the current KNMI atmospheric correction procedure (Vos et al., 1998, RESTWAQ-2, Part I, Appendix A3) occurs and this prevents a detailed analysis of SPM patterns. With this respect, the current SeaWiFS sensor might offer more possibilities since it does not saturate at the sensor. Also use of the SeaWiFS atmospheric correction algorithms for NOAA/AVHRR sensors might offer possibilities for enlarging the amount of RS information for the sea entrance of the Western Scheldt estuary. This relatively large entrance area possibly reflects the effects of intensive dumpings from the area of Zeebrugge (De Bie and Benij ts, 1994) and a collection of SeaWiFS, NOAA/AVHRR and SPOT images might be very useful for monitoring this area.

2.2.4 Processing of remote sensing images

Processing of SPOT level 1 products to suspended matter maps

The selected remote sensing images were processed to SPM maps according to the methodology developed and outlined by Dekker et al., (1998) and RESTWAQ2 (Vos et al. 1998, Part II - Friesland). A full description of the processing is given in Peters et al., (1999). Essentially two steps (information flows) are required for the determination of SPM from remote sensing images, see Figure 2.15.

1) Algorithm development:
In the first step, a mathematical relationship between measured water concentrations and a satellite measured quantity is developed (bio-optical model). In this case, the relevant satellite parameter is the subsurface irradiance reflectance (R(0-)) in the SPOT band 2.

2) Processing satellite observations to apparent reflectances, R(0-) and finally to SPM.
This step involves calibration of the satellite observations, atmospheric correction and application of the (inverse) algorithm derived in step 1.

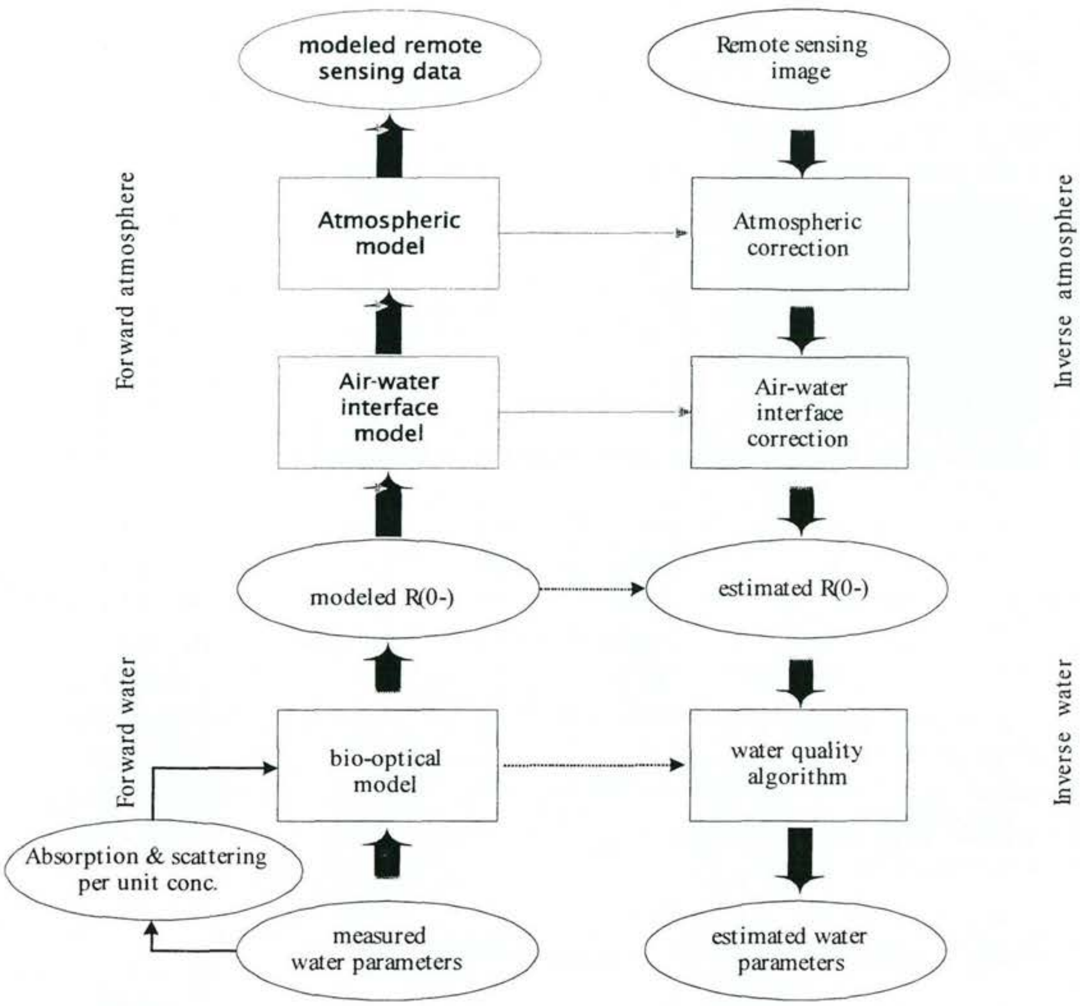


Figure 2.15 The forward and inverse model for remote sensing of water quality. To establish algorithms only the "forward water" and the "inverse water" sections are relevant; to carry out a sensitivity analysis of the operational method or in order to derive specifications for a dedicated remote sensing instrument, it is necessary to go through all the steps from "forward water" via "forward atmosphere" to "inverse atmosphere" to "inverse water". Once the method is operational it is only necessary to run through the modules "inverse atmosphere" and "inverse water"

The relationship between the water quality parameters and the radiance measured at the sensor is also displayed in Figure 2.15 (after Hoogenboom et al., (1998)). For more specific information on atmospheric correction and air-water interface correction the reader is referred to Pasterkamp et al. (1999).

1) Algorithm development (forward modelling):

Because of the (semi-)operational character of this project, use was made of the standard Gordon model for underwater light transport. In this model, the water quality parameters are linked to the R(0-) via the inherent optical properties (IOP) of the water. The inherent optical properties of the water are given by the total absorption (a) and backscattering (b_b) of the water, both depending on wavelength (λ) and expressed in (m^{-1}). The inherent optical properties are physically related to the subsurface irradiance reflectance R(0-) which is the key parameter linking the properties to the remotely sensed irradiance data (Equation 1).

$$R(0-) = r\frac{b_b}{a+b_b} \qquad \text{Equation 1}$$

Where:

$R(0\text{-})$	is the irradiance reflectance just below the water surface, (dimensionless, i.e. the fraction of solar radiance per sterradial that is reflected by the water column, excluding the surface reflection) for a given wavelength;
r	is a coefficient depending on geographic latitude and longitude and the volume scattering function.

The use of this model implies knowledge of the IOP of the water. Here it is assumed that the IOP are the sum of the IOP of the distinctive components in the water (including pure water itself), see Equation 2.

$$a(\lambda) = \sum_i a_i(\lambda) \qquad \text{Equation 2}$$
$$b_b(\lambda) = \sum_i b_{bi}(\lambda)$$

Where:

a_i	is the absorption due to component i;
b_{bi}	is the backscattering due to component i.

Following the law of Lambert-Beer it is then assumed that the IOP of a certain component are a linear function of the concentration of that component. This introduces the *specific* inherent optical properties (SIOP) of a component, see Equation 3. To typographically distinguish the IOP from SIOP the latter is indicated by an asterisk (*).

$$a_i(\lambda) = a_i^*(\lambda)\cdot c_i \qquad \text{Equation 3}$$
$$b_{bi}(\lambda) = b_{bi}^*(\lambda)\cdot c_i$$

Where:

a_i^*	is the specific absorption of component i;
b_{bi}^*	is the specific backscattering of component i;
c_i	is the concentration of component i.

Combining Equations 1 to 3 will link the concentrations of all the components to the subsurface irradiance reflectance, provided r and the SIOP of all the components are known. Because little is known about the SIOP's of the Western Scheldt system, a measurement campaign was conducted (10 March 1999) for in-situ measurement of R(0-) spectra and collection of five samples for laboratory analysis of SIOP's.

The parameterization of the Gordon model requires some estimations for parameters that cannot be measured with the current laboratory set-up, such as the ratio between backscattered and forward scattered light (B) and the shape factor r. In this case, use was made of in situ-measured R(0-) spectra in order to estimate these two parameters.

Mean values found were B = 0.042 and r = 0.38; these values were used for the subsequent modelling. All estimated and measured parameters were entered into the bio-optical model which then was used to simulate a data set containing R(0-) values integrated over the SPOT spectral bands as a function of SPM concentrations. For these simulations it was assumed that:

- CHL = constant = 15 ug / l
- CDOM = constant = 1.73 (λ 440)
- SIOP's are the mean value of the 5 in-situ measurements.

A number of boundary conditions forced the use of only band 2 of SPOT for SPM retrieval. One of them was that simulated and measured R(0-) values matched best in this wavelength range. Another is that this spectral band is less sensitive than band 1 to errors in the atmospheric correction and errors in e.g. the CDOM concentration. SPOT band 3 observations have proved to be unreliable at low R(0-) levels.

From the set of simulations, an algorithm for the relationship between $R(0-)_{band2}$ and SPM was derived for each type of SPOT sensor separately (SPOT1, 2 and 4, HRV1 and 2).

2) Processing satellite observations to apparent reflectances, R(0-) and finally to SPM
The (forward modelling) relationships developed (above) were inverted and used to retrieve SPM maps from $R(0-)_{band2}$ maps. The procedure to derive R(0-) maps is part of the 2^{nd} information flow and is discussed below.

After selection of 9 SPOT images for processing, a number of preparatory steps were taken:

1. SPOT spectral sensitivity curves were collected (SPOT1,2 and 4; of all three systems HRV1 and HRV2) for use in the forward modelling step.
2. All images were geo-referenced using the topographical map 1:50.000 towards the "Rijksdriehoek" coordinate system: image resolution of 20 m was maintained.
3. Next all selected images were corrected for atmospheric influences. For this the atmospherical correction code 'MODTRAN 3' was used, run in LOWTRAN 16 streams mode. Use was made of the Toolkit software package (de Haan et al., 1998). For operational use a prototype "fast and more robust" shell was built for specific processing of SPOT images (relying on a number of underlying Toolkit executables).

For the multi-temporal atmospheric correction, first all images were scanned for reference targets. Specifically dark water bodies of which some knowledge of temporal variability exists were selected, such as "Veerse Meer" and parts of the "Oosterschelde". These targets are used to pinpoint the atmospheric correction by simulating R(0-) values (at estimated concentrations) and matching satellite observed R(0-) with simulated values. This procedure ensures also that no negative values for R(0-) occur.

Supportive to this calibration of the atmospheric correction, targets were sought for that were relatively bright and invariant in time. At two locations (an aluminum factory and a industrial site) such targets were found. However, further analysis showed that, probably due to shadowing effects, there was at some occasions still significant temporal variation.

The total procedure commenced with the selection of a "reference image" (8 August 1998) which was processed to an optimum result. Criteria for quality check were: match with simulated dark water body R(0-) values, realistic values for the atmospheric parameters (horizontal visibility, atmosphere and aerosol type), and realistic values for the retrieved R(0-) and SPM values.

Next all images were processed, using simulated R(0-) values for the dark water bodies as reference as well as the R_{app} values of the bright targets from the reference image. All results were quality checked using the above mentioned criteria except that in this stage SPM validation was done only in a very general sense.

As a last decisive quality check, the SPM maps were validated using all available in-situ data: both the 20 year monthly averaged values and the continuous monitoring data from stations Vlissingen, Terneuzen and Baalhoek. Some validation results are presented below in Figures 2.16 and 2.17. Full validation results are given in Peters et al., 1999. In all cases, the SPM maps agreed very well with the in-situ data and can be considered final products. SPM maps as originally processed in ENVI software were then translated to ARCVIEW files for final presentation and exchange purposes, examples of which are given in Figure 2.18 for 11 January 1998.

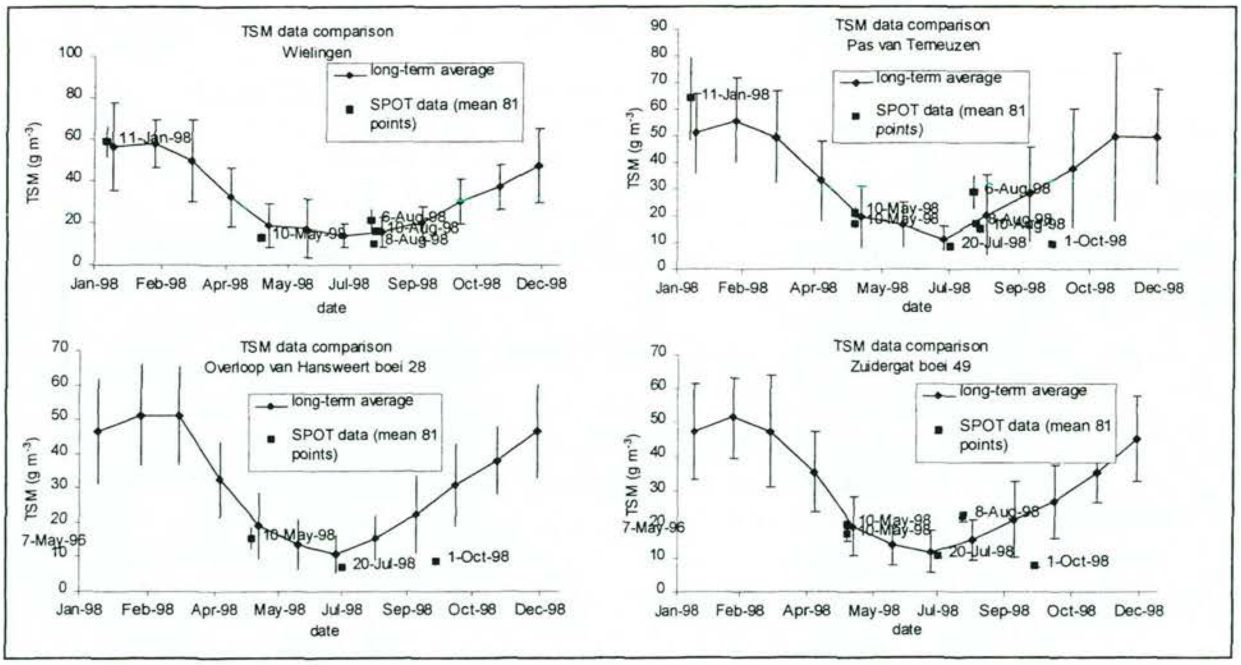


Figure 2.16 Comparison of retrieved TSM concentrations (pink squares) with long term averages (blue diamonds) for several locations in the Western Scheldt estuary. The retrieved concentration is averaged over a region of 180 x 180 m^2, and the standard deviation is indicated with error-bars. Complete validation results are given in Peters et al., 1999.

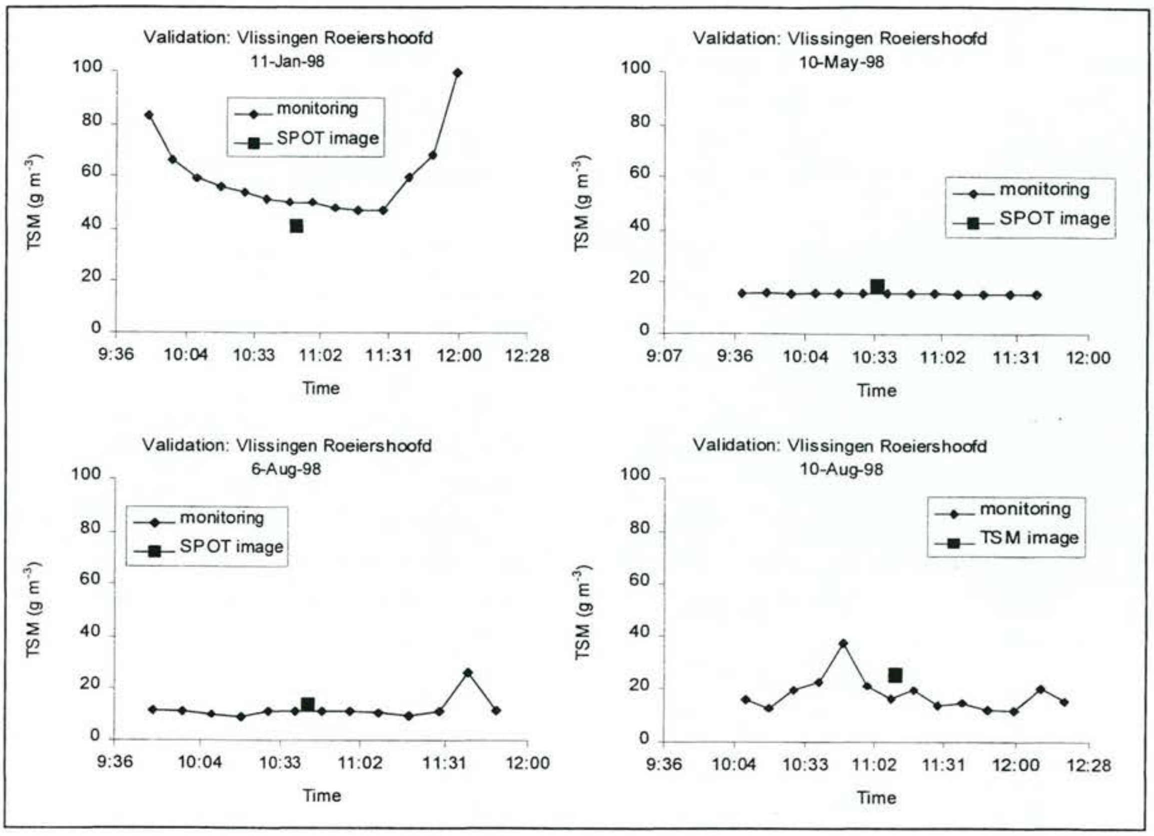


Figure 2.17 Comparison of some remote sensing results with continuous in-situ data at Vlissingen at the day and time of the satellite overpasses. Complete validation results are given in Peters et al., 1999.

Conversion of SPM maps from SPOT to SPM products at the SCALWEST model grid

The SPM maps prepared as described in section 2.2.3 are presented at a very fine rectangular grid of 20*20m (a raster). However, for direct comparison with model results, it is required that these SPM maps are also transformed to the curvilinear model grid of SCALWEST-fine, as given in Figure 4.1. Conversion of SPOT products (in ENVI binary format) to the aggregated curvilinear SCALWEST grid can be done in two ways:

1. Exact averaging of all SPOT pixel values over the SCALWEST curvilinear grid cells;
2. By selecting the SPOT pixel value at the middle of the SCALWEST grid cell;

Since the first procedure required more than 20 computation hours on a powerful (Silicon Graphics Origin 2000) workstation, the second procedure was selected. For purposes of comparing the remote sensing and modelling results and incorporating remote sensing in a final model calibration, this procedure is more than sufficient.

For 11 January 1998, an example is given in Figure 2.18 of the remote sensing SPM product (ArcView). The complete series of SPM maps, derived from the 9 selected SPOT-images is presented in Pasterkamp et al. (1999). In Figure 2.19, a representation of the same data as converted to the SCALWEST model grid is presented. In Figure 2.20, the same data is presented on an *aggregated* model grid, where 16 original grid cells (4 x 4) are aggregated to one aggregated grid. The aggregated SCALWEST model grid is relevant since this was the grid on which the model results were obtained (see section 2.3). The remote sensing result as given in Figure 2.20 can be used for direct model comparison and model calibration only.

For presentation of the remote sensing result, the original SPOT maps presented in ArcView are preferred.

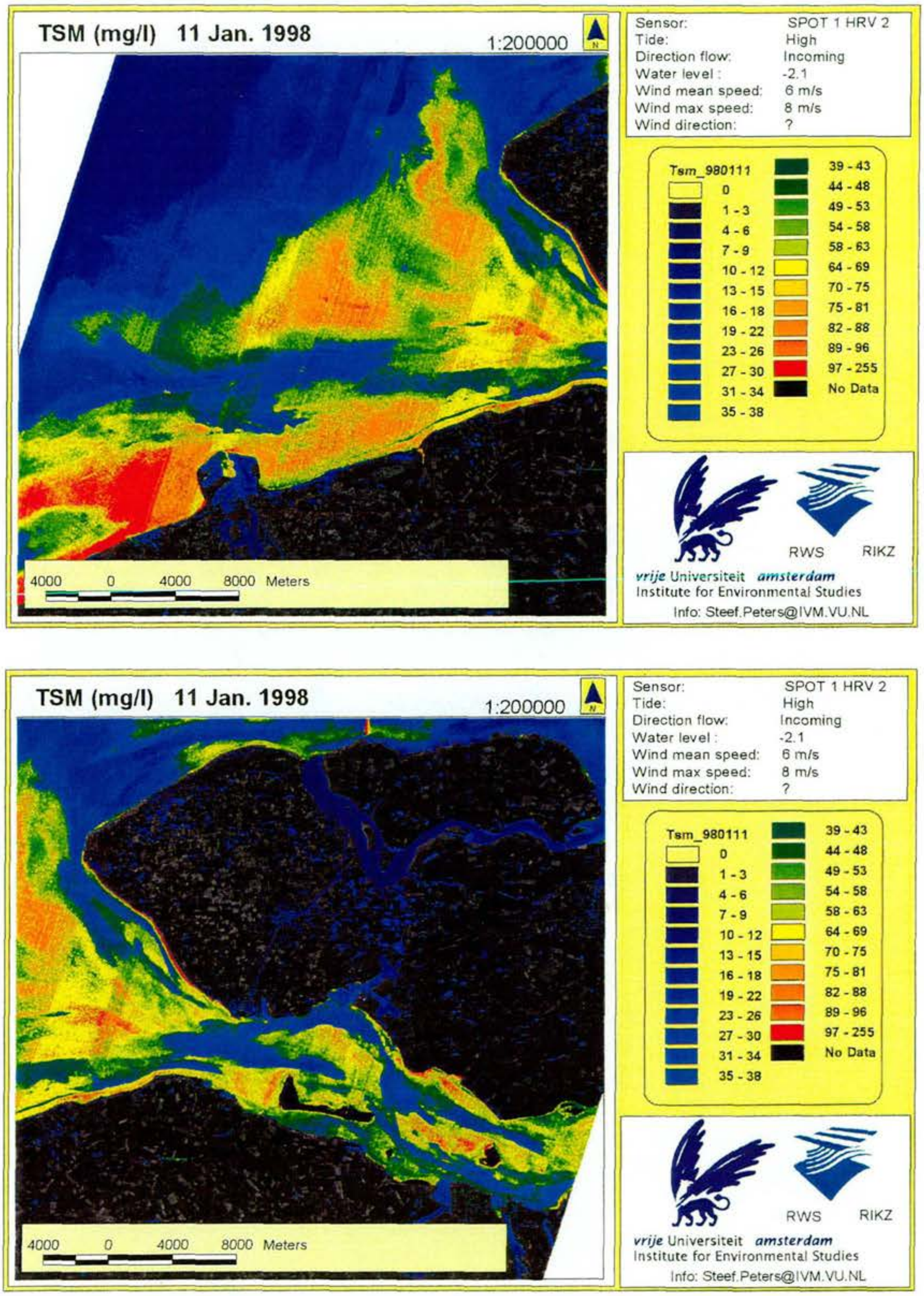


Figure 2.18 Maps of SPM (mg/l) for 11 January 1998 (presented in ARCVIEW)

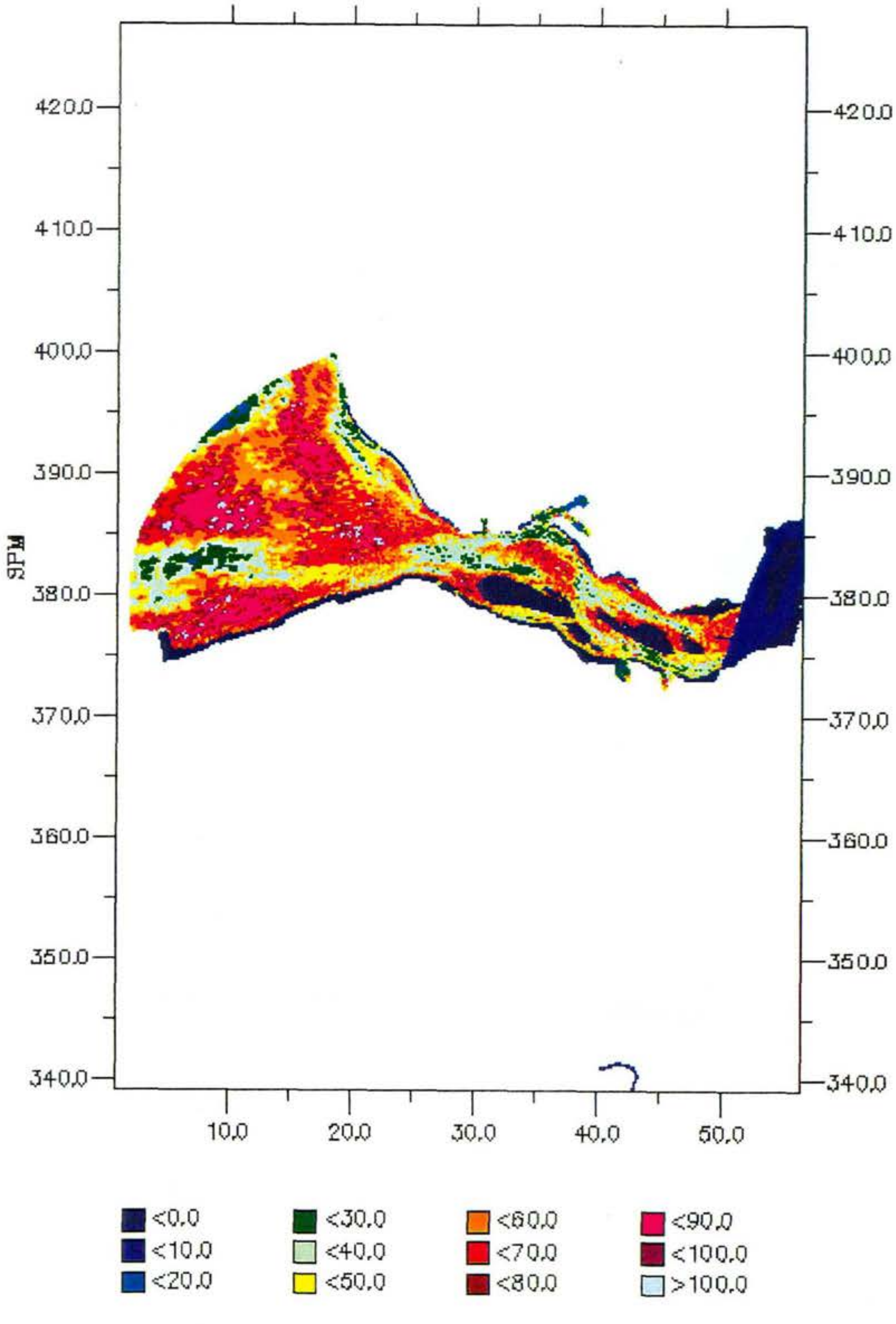


Figure 2.19 Remote Sensing SPM map (mg/l) for 11 January 1998 converted to the curvilinear SCALWEST model grid (no aggregation)

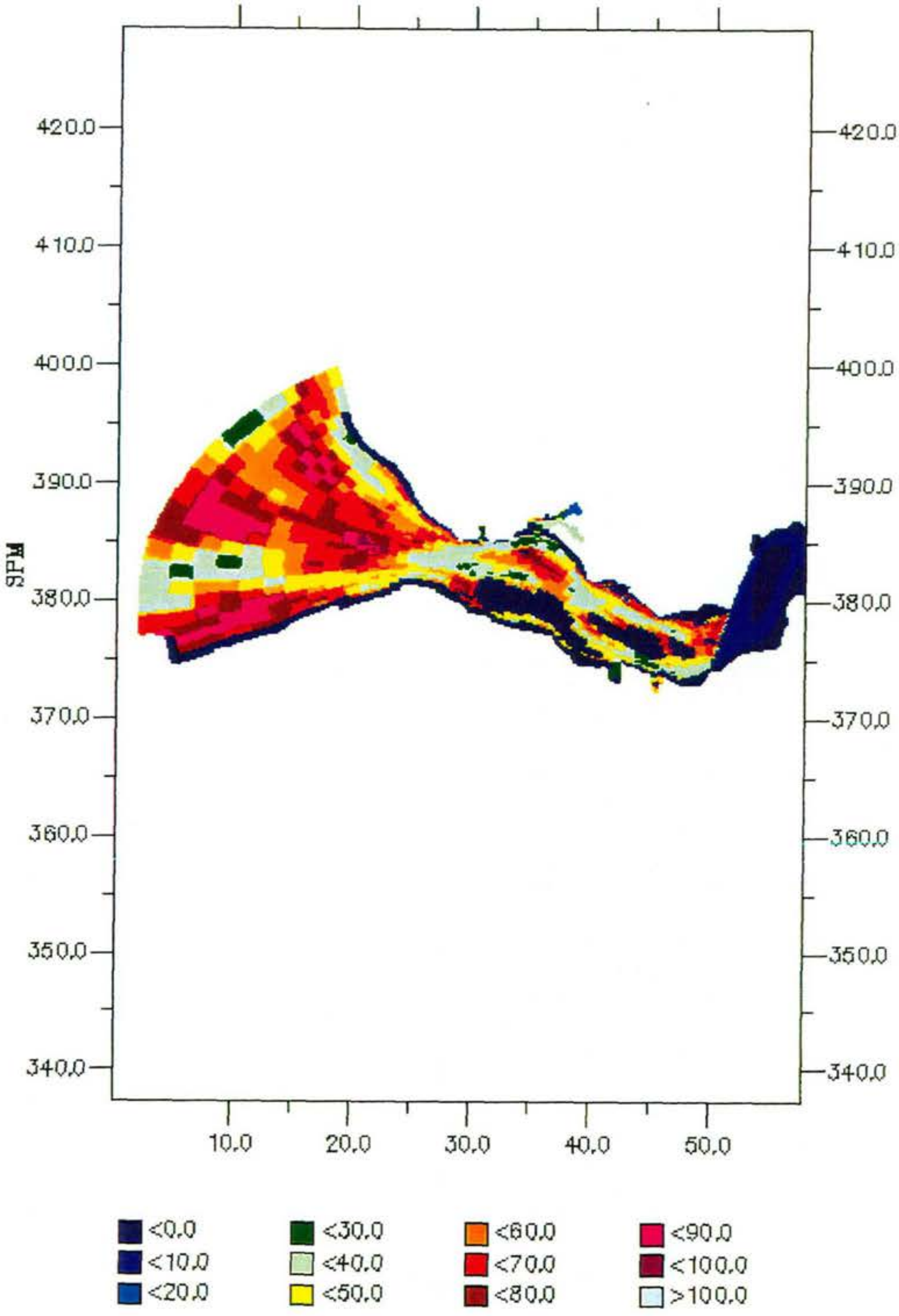


Figure 2.20 Remote Sensing SPM map (mg/l) for 11 January 1998 converted to the curvilinear aggregated SCALWEST model grid

2.3 Water Quality Model

2.3.1 Introduction

A 2-dimensional (vertically averaged) curvi-linear water quality model for suspended matter transport in the Western Scheldt estuary was set up, with the modelled region and the model grid as shown in Figure 2.21 (with RijksDriehoek co-ordinate grid). The model used is Delft3D-WAQ, run with only 1 layer in the vertical (also known as 'DELWAQ'). The model was run for the full year 1998.

An important input for this particular model is the bathymetry. The average water depth (a fingerprint of the bathymetry) is given in Figure 2.22. From this figure it follows that the area is characterised 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). The model used for this study includes the Western Scheldt up to the Scheldt river near the city of Antwerp.

The water quality model for suspended matter requires results from a hydrodynamic model for the water flows, which determines the advective transport of sediment. The model also needs input data for wind; wind creates water waves which in turn can 'stir up' sediment from the bottom.

Sediment enters the modelled 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 harbours. Also, the water quality model includes processes such as sedimentation and resuspension which continuously 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 harbour dredgings from 1997 (Tables 2.4-2.5) indicate that significant amounts of silt material are dumped and that this source of sediment should be included in the model. This will be further addressed in section 2.3.3.

Summarising, the calculated SPM concentrations in the model at any one time are a function of:

- input of sediment from boundaries, initial conditions, and loads (dumpings of harbour 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

The text box below summarises the inputs required for running the model.

What does the Water Quality model need as Input?

The Western Scheldt water quality model needs several types of information as input in order make a calculation:

- Results from a hydrodynamic model (water flow). This is provided by the 2-D (depth averaged) curvi-linear SCALWEST-fine model of RWS-RIKZ (WAQUA). The hydrodynamic model is run for a period of 14.5 days corresponding to approximately a spring-neap tidal period. The hydrodynamic results are used repeatedly to allow a water quality calculation of 1 year (see also section 2.3.2)
- Wind data for the whole year, as daily average wind speed: This is provided by the KNMI from measurement station Vlissingen (see also section 2.1.5).
- Boundary conditions of SPM concentration, for both the sea boundary, and the river boundary. The boundary conditions, which also have to be specified for the whole year, are extremely important in the model calculation and have a large influence on the calculated SPM concentrations. The boundary conditions used in the model are taken from the long-term monthly averaged concentrations (see also section 2.3.3).
- Initial conditions for SPM concentrations (in the water column) and bottom sediment thickness (see also section 2.3.3).
- Point source inputs of SPM: known point source inputs of sediment are specified as loads to the model, and must be defined with respect to the amount, the location and the date dumped. Dredged harbour sediment is an important input at the present (T0) situation (see also section 2.3.3). In the future (T1 situation), spreading of the tunnel boring material will be an important point source input.

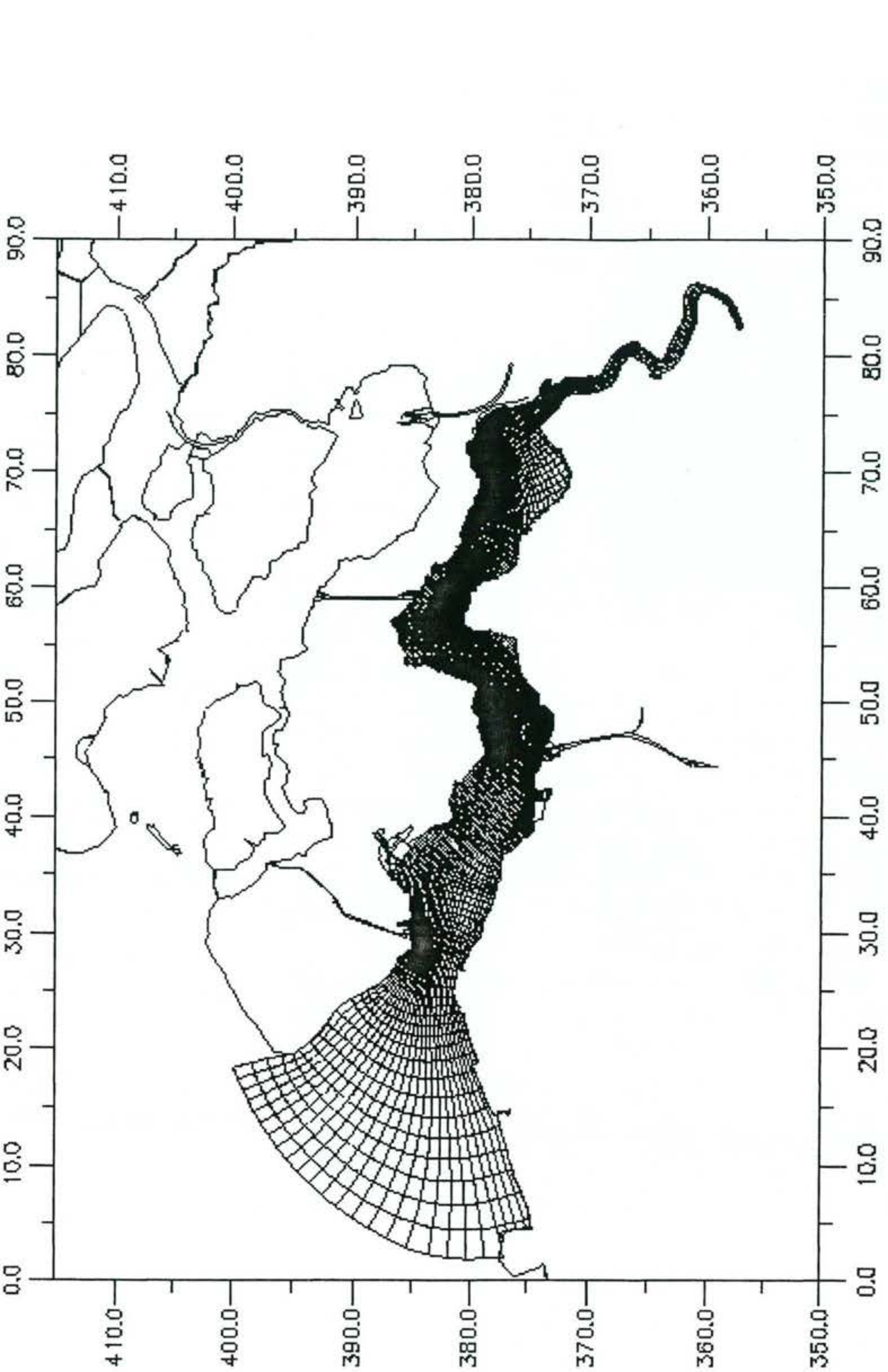


Figure 2.21 RESTWES model grid of the Western Scheldt (aggregated)

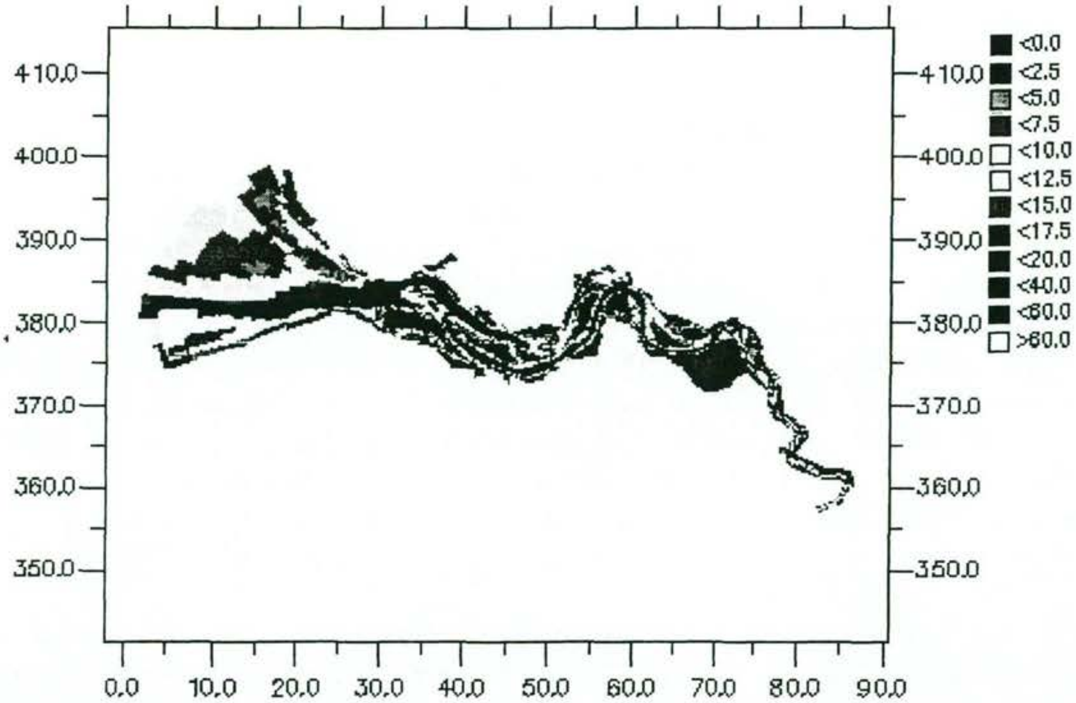


Figure 2.22 Average water depth of the SCALWEST fine model (total water depth averaged over 1 spring-neap cycle of 14.5 days).

Use of measurements for the modelling

In-situ data are used in the model for:

1. forcing function (e.g. boundary conditions);
2. model calibration and sensitivity analysis.

Sea boundary conditions were initialised with values inferred from twenty yearly monthly mean averages of SPM (given in section 2.1). For the (final) model calibration the following data were used:

- Remote sensing images from SPOT processed to SPM values and converted to the model grid (9 images);
- Data from 3 continuous monitoring stations (Vlissingen, Terneuzen and Baalhoek);
- Twenty yearly monthly mean averages of SPM at 8 locations were used for the calibration.

The initial calibration of the model was based solely on the continuous in-situ data from Terneuzen and Baalhoek. The model calibration is further described in sections 4.4 and in Appendix B.

This chapter further has the following sections:

2.3.2 Hydrodynamic modelling and coupling to water quality model

2.3.3 Set up of the water quality model;

2.3.4 Model calibration

2.3.2 Hydrodynamic modelling and coupling to water quality

The hydrodynamic modelling was conducted by RWS-RIKZ. The 2D curvilinear SCALWEST-fine model (2D-WAQUA) of RWS-RIKZ was run for 2 cases:

1. A 14 day period with calm winds. Boundary conditions for the Scheldt were forced with measured time series of water levels at the sea boundary for a spring-neap period with calm winds. The water level after 14.5 days is almost equal to that at the start of the simulation (i.e. a 'cyclic' simulation of water levels). The effect of the spring-neap variation is important for sediment modelling since it induces a variation of the bottom shear stress.
2. A 1 day period with higher wind speed (8 m/s) from the West. Boundary conditions for the Scheldt were forced with measured time series of water levels at the sea boundary of the model for a period of 1 day for such winds. This period comprises an average tide for high winds from West. The water level after 1 day is almost equal to that at the start of the simulation (almost 'cyclic' simulation of water levels). The simulation was done for a period two days after spring tide.

The results from the hydrodynamic model were coupled to Delft3D-WAQ using a specialised coupling programme for SIMONA and Delft3D-WAQ. The conversion was confirmed to be mass conserving.

The first case was further used for the water quality model since:

1. It incorporates the spring-neap variation, and the second case does not do this;
2. It was found that the change in flow for the second case was not much. Changes were mainly induced for SPM due to the fact that solely a spring period is modelled (which is not realistic). Wind effects on salinity turned out to be small.

There remains one serious problem with the present hydrodynamics: a spring-neap cycle of 14.5 days is used in the model, but in reality it should be 14.75 days. This difference causes the model simulation to get out of phase with the continuous SPM in-situ measurements. This problem was partially solved for stations Baalhoek and Ternuezen by shifting the in-situ data over 8 days during comparison model results with in-situ data, since these time-series start end October and last only two months. For Vlissingen data this was not possible, and no shift was applied. There are also problems in comparing model results with remote sensing data: In order to compare model and remote sensing results at a specific moment in time, the model results had to be shifted, so that the correct day and time in the spring-neap cycle were found (e.g. 3 days after spring tide, 4 hours after high tide.). For comparison of the Remote Sensing data and the model data, the model result closest to the remote sensing data in time, and within one meter difference of water level at Terneuzen were selected This brings the results to a comparable tidal phase, however, the forcing functions in the model (e.g. wind) are then also shifted, so the comparison is not ideal.

For any future modelling simulations (e.g. for operational monitoring during the T1 phase) it is recommended re-run the hydrodynamic calculation and use a 29.5 days spring-neap period ('synodal' period) with nearly exactly 28 'lunar' days (24 hours 50 minutes).

2.3.3 Water Quality Model: Set-up and processes

This section describes the set-up of the water quality model, covering the main points of:
1. Model grid for water quality;
2. Substances modelled;
3. Boundary conditions;
4. Inputs from harbour dredgings;
5. Model processes

More details on model set-up and processes are given in Appendix A.

Water quality model grid

The computational grid for the hydrodynamic model (SCALWEST-fine) consists of 76036 segments. Because calculation of water quality for one year on this grid would cost an excessive amount of computer calculation time, an aggregation of the model grid was made. With an aggregation of 4*4 grid cells, the resulting grid for water quality calculations consists of 4341 segments. All model computations were conducted using this aggregated grid (Figure 2.21).

Substances modelled

The substance of interest in the study is Suspended Particulate Matter (SPM), which is the total amount of fine suspended material (< 63 μm). In the water quality model for the T0-scenarios (no dumped material from tunnel silt), SPM is composed of 3 different sediment fractions:
1. (IM1, mg/l); This fraction is for sea silt
2. (IM2, mg/l); This fraction is for river silt
3. (IM3, mg/l); This is a heavy silt fraction

In the model approach, these 3 fractions are summed to obtain SPM (i.e. SPM = IM1 + 1M2 + 1M3). All three fractions exist in both the water column and in the bottom sediment layers. The bottom sediment consists of two layers, S1 and S2. In the simulations, the organic fraction of SPM (phytoplankton and detritus) is not explicitly simulated, but is implicitly included in the above 3 fractions.

In the T1 scenario, the dumped tunnel material is modelled as an additional, but separate fraction, and thus can be analyzed separately from the background SPM conditions.

Boundary Conditions

Boundary conditions of SPM concentrations are one of the most important input data for the water quality model (see Text Box). The concentrations SPM must be specified at both the sea and the river boundary over the entire period of the model calculation. At the boundaries, the concentrations have been defined using average values from Breskens/Vlissingen (sea-side) and from Saefthinge from the twenty yearly mean SPM values of Van Maldegem (1992), Figure 2.23.

These values are spatially uniform (i.e. the same over the all the boundary grid cells) but time-varying per month. At each of the boundaries, a different sediment fraction is specified:

- sea silt (IM1) at the sea boundary
- river silt (IM2) at the river boundary

We note, that similar to the PROMISE modelling study (Brummelhuis et al.1999, Gerritsen et al. 1999) in this study the source terms of sediments (boundaries + dumpings) are of utmost importance for the accuracy of the calculated result.

The current definition of the model boundaries has certain limitations:

- The model boundaries are spatially uniform, and have a constant value over a whole month. In practice, concentrations at the sea-boundary are not spatially uniform, but show strong correlation with depth, especially in winter periods (see e.g. Figure 2.18), and over time.
- The boundary conditions with respect to both flow and concentrations are simplified at the river boundary. In the model (hydrodynamic) calculation, the Scheldt river discharge was constant at 100 m^3/s . In actuality, it varies between extremes of 20 m^3/s and 600 m^3/s with 100m^3/s being the average value. Also concentrations vary heavily in the river Scheldt (Fettweiss et al., 1997).

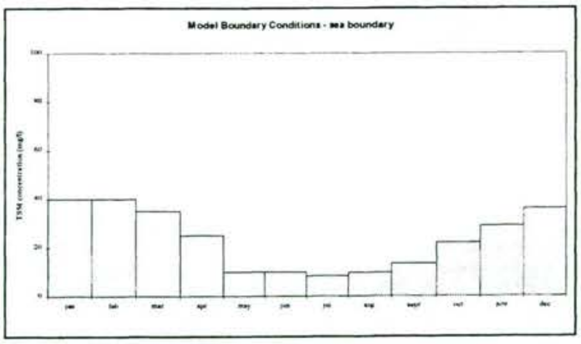
For the definition of the main SPM conditions in 1998 and assessment of the effect of tunnel material, which was the purpose of the present model, these points are not expected to cause significant problems. Nevertheless it might be necessary to adjust the boundary conditions for possible future refinement of the model.

Model initial conditions

The amount of silt in the model at the beginning of the simulation (i.e. the *initial conditions)* has to be specified, for both the water column and the bottom sediment. Particularly the amount of silt in the bottom sediment is important as this is a large reservoir of material that can be eroded and resuspended into the water column (see section 4.3.7 - model processes). For the initial conditions, both the amount (thickness) of the bottom sediment, and the composition (relative amounts of the 3 sediment fractions) have to be specified.

In the model, there are two bottom sediment layers, S1 and S2. The upper layer (S1) is more easily eroded than the lower layer (S2). In the initial conditions, the upper layer S1 exists only on the tidal flats (depth < 2m) and consists of the river silt and sea silt fractions (see Figure 2.25).

The lower layer S2 exists over the whole model area. The initial composition of this bottom layer is an important model parameter and different variations were checked during the calibration phase (see also Table 2.6). For best results, the initial conditions for S2 are a composition consisting primarily of the heavier silt fraction (IM3) which is 95% of the total mass of the bottom S2 layer.



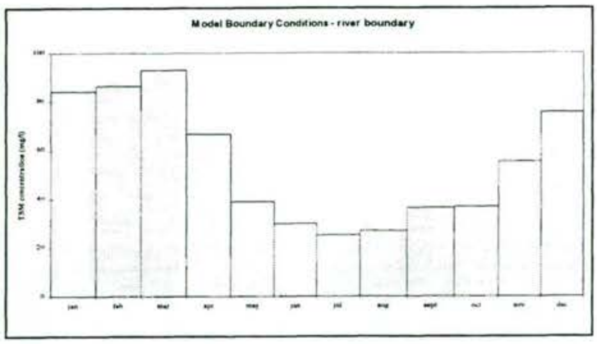


Figure 2.23a Monthly averaged concentrations of SPM inferred from twenty year monthly averages of van Maldegem used for model boundary conditions. Sea boundary: from stations Vlissingen and Scheur van Wielingen.

Figure 2.23b Monthly averaged concentrations of SPM inferred from twenty year monthly averages of van Maldegem used for model boundary conditions. River boundary: from station Saeftinge.

Inputs from harbour dredgings

Point source inputs of SPM are an important model input (Text Box). The main point source inputs of silt are from dumpings of dredged material, specifically from harbour dredging activities. Another possible source of silt is from morphological changes and dredging activities in which silt becomes resuspended in the water column. As stated in section 2.3.1, the model does not include these possible silt inputs.

In this section, the dumpings from dredging activities in Dutch and Belgian Harbours are discussed. The dumpings from dredging of Dutch harbours are within the modelled area and are included as model inputs. Most dumpings from dredging of Belgian harbours are just outside of the model area near the sea boundary, and these dumpings are not included explicitly as model inputs. The effect of the dumpings are included implicitly to a certain extent, as boundary concentrations.

Dutch harbours

Available data on loads from dumping of dredged harbour material indicates that these dumpings are quite significant. The main dumping locations are Terneuzen, Breskens, Vlissingen, Perkpolder and Walsoorden. Specific coordinates for these locations and model grid cell numbers are given in (Villars and Vos, 1999, Appendix A. A summary of total amount (kilotons) of dumped dry silt for 1997 and 1998 are given in Table 2.4. All data has been obtained from RIKZ-Middelburg (van Maldegem).

The 1998 data for the Dutch harbour dumpings became available at a final stage of the project. This data was provided as wet volume of dumped material, per dumping location and dredging location. A conversion of wet volume to the modelled parameter, i.e. SPM as mass dry silt was made (Villars and Vos, 1999, Appendix A). The details of 1998 dumpings are given in Table 2.5.

Table 2.4 Dumped amounts of dry silt from dredging in Dutch harbours (ktons)

Dumping Location	1997	1998
Terneuzen	401	155
Breskens	197	109
Vlissingen	1140	80
Perkpolder	50	--
Walsoorden	9	--
Kruiningen	59	--
Baahoek	-	4
Total	1878 Ktons	385 Ktons

Table 2.5 Dumped amounts of dry silt for from dredging of Dutch harbours in 1998 (ktons)

Dump locations	Dry weight silt per location (Ktons)	dredge location	Start date	End date
Baalhoek	3.7	PerkPolder	8-apr-98	9-apr-98
Breskens	9.0	Handels/jachthaven	1-dec-98	4-dec-98
	57.6	Handels/jachthaven	2-feb-98	1-apr-98
	5.4	Handels/jachthaven	23-sep-98	29-sep-98
	4.4	Handels/jachthaven	8-jun-98	17-jun-98
	6.8	westbuitenhaven	13-jan-98	14-jan-98
	5.6	westbuitenhaven	3-apr-98	7-apr-98
	8.7	westbuitenhaven	4-jun-98	15-jun-98
	11.7	westbuitenhaven	15-sep-98	17-sep-98
Terneuzen	11.9	Oostbuitenhaven	8-sep-98	15-sep-98
	72.1	Oostbuitenhaven	5-jan-98	22-jan-98
	1.7	Westbuitenhaven	9-apr-98	10-apr-98
	3.0	Westbuitenhaven	17-aug-98	3-sep-98
	53.2	Westbuitenhaven	2-oct-98	15-oct-98
	13.5	Westbuitenhaven	23-dec-98	24-dec-98
Vlissingen- total	80.2	various locations	5-dec-98	24-dec-98
TOTAL	348.5			

Data for 1998 were added to the model as loads of dry silt (fraction IM2). Loads are assumed to be mixed very rapidly into the water column, and therefore are added to the water phase, not the bottom sediment layer.

It is notable that the 1998 data show amounts of silt 5 times less than those of 1997. Since the procedures followed for converting the 1997 data could not be checked, there is at the moment more confidence in the 1998 data. Nevertheless, the large difference between the two years indicate that procedures for data processing, including conversion of wet weight volumes to dry weight silt must be clearly documented, and the general procedures for the data processing need to be further operationalized. The data were very difficult to obtain in a digitized manner, and additionally needed significant processing to obtain the aggregated data as presented in Table 2.4 and 2.5. Furthermore, there were some discrepancies between the data obtained for all of 1998 and those previously made available for 4th quarter 1998 by van Maldegem.

Belgian harbours

Data on dumping of dredged material from Belgium harbours (MUMM, 1998) show that these amounts may be significant. Probably these are the largest dumpings from dredging activities around Europe (Gerritsen et al., 1999). For 1-4-1997 till 31-3-1998 an amount of 14.9 Mton dry matter was dumped (MUMM, 1998) at a few locations near the mouth of the Western Scheldt (near the model boundary). Given average silt-fractions for the Belgian dumpings documented by De Bie and Benijts (1994) (~50%) this might roughly be 7 Mton silt, although uncertainties are significant in this number since the actual silt fractions are not known.

From the Belgian dumpings only the dumping at Paardemarkt is within the model grid. It amounts roughly 4 Mton, but is treated in the present model as part of the silt at the model boundary, like for all Belgian dumpings.

Model processes

The model includes a set of processes that are considered to be important for the SPM content of the Western Scheldt estuary. Specifically, four processes are responsible for the distribution and fate of SPM which enters the Western Scheldt from the boundaries, from dumpings, or from the initial conditions:

1. Settling of sediments;
2. Erosion from tidal flats by flow and wind induced waves;
3. Erosion from gullies by tidal flow;
4. Erosion from gullies by wind induced waves

The processes as relevant to the Western Scheldt are described generally below and further details are given in Appendix A. Complete formulations are given in the DELWAQ Technical Reference Manual (WL|Delft Hydraulics, 1997).

Process 1: Settling of sediments

Settling of silt from the water column to the bed sediment is one of the most important model processes. Sedimentation can occur when the water flow velocities (represented as shear stress, tau) are below a critical value (tau-critical for sedimentation). The model includes three fractions of sediment, each having a different value of tau-critical.

The sedimentation rate (flux) is a function of the settling velocities, and each of the three silt fractions has a different settling velocity. Settling velocities for the sea fraction and river fraction are concentration dependent, while the third silt fraction is modelled with a constant settling velocity of 100 m/day, and a high critical shear stress for sedimentation of 4.0 Pa. Both these values were varied somewhat during the model set up, but it was concluded that the amplitude for spring-neap variation at Terneuzen was best represented with the values given here. This gives a spring-neap cycle variation of SPM.

Process 2: Erosion from tidal flats by flow and wind induced waves

In the model, there are two bottom sediment layers, S1 and S2. The upper layer (S1) is more easily eroded than the lower layer (S2). The erosion of each layer is controlled by the model parameter for critical shear stress of erosion (tau-critical for erosion), see Figure 2.24:
Tau-critical erosion (S1) = 0.6 - 1.5 Pa (seasonally variable)
Tau-critical erosion (S2) = 4.0 - 5.0 Pa (seasonally variable)

If the shear stress is greater than the critical values, material in the sediment layer will come into resuspension. Material from the lower sediment layer (S2) will only be eroded if all the material in the upper layer (S1) is gone. The shear stress is caused by a combination of water flow (velocity) and wind induced waves.

On the tidal flats, the upper sediment layer (S1) is present throughout the whole year. The model parameters for erosion have been set so that the upper sediment layer (S1) is stable on the tidal flats under conditions of no wind (no waves). The resulting bottom thickness for the top layer was used as initial condition for all later runs and is given in Figure 2.25. Here the tidal flats can clearly be seen. On the tidal flats, the upper layer (S1) is never fully eroded during the winter seasons, so the second layer (S2) is never exposed (and never eroded). The seasonably variable value of critical shear stress for erosion in S1 is chosen to simulate the effect of stabilisation of the tidal flats by biological influences (diatoms) during the spring-summer period.

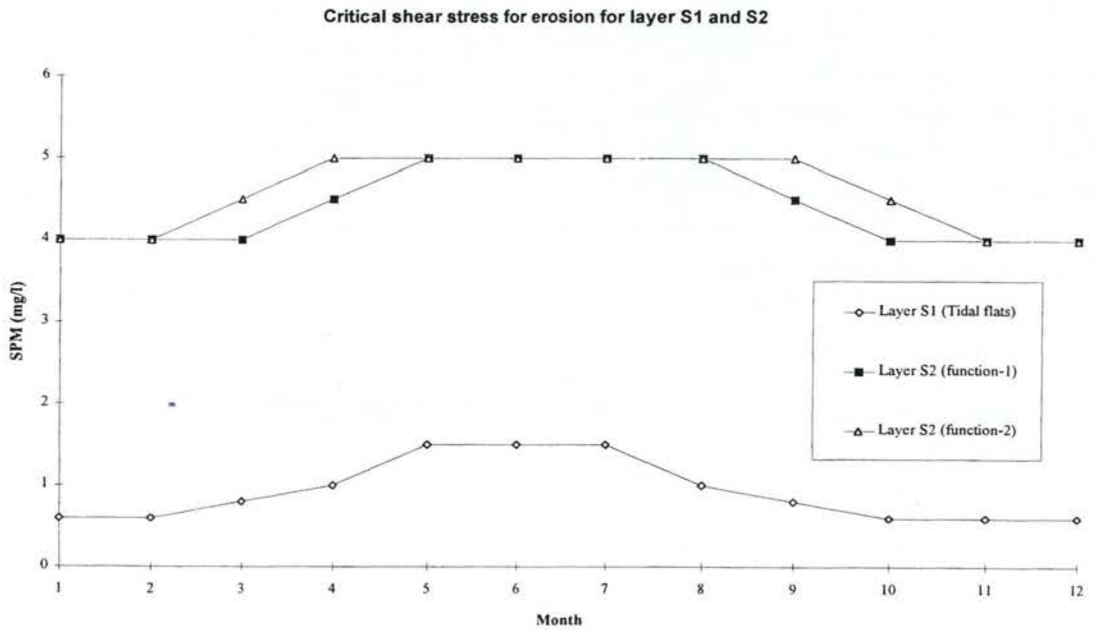


Figure 2.24 Critical shear stress for erosion in sediment layers S1 and S2

In the areas outside the tidal flats, a second bottom layer (S2) with much higher critical shear stresses for erosion was used. This upper sediment layer (S1) has no sediment outside the tidal flats.

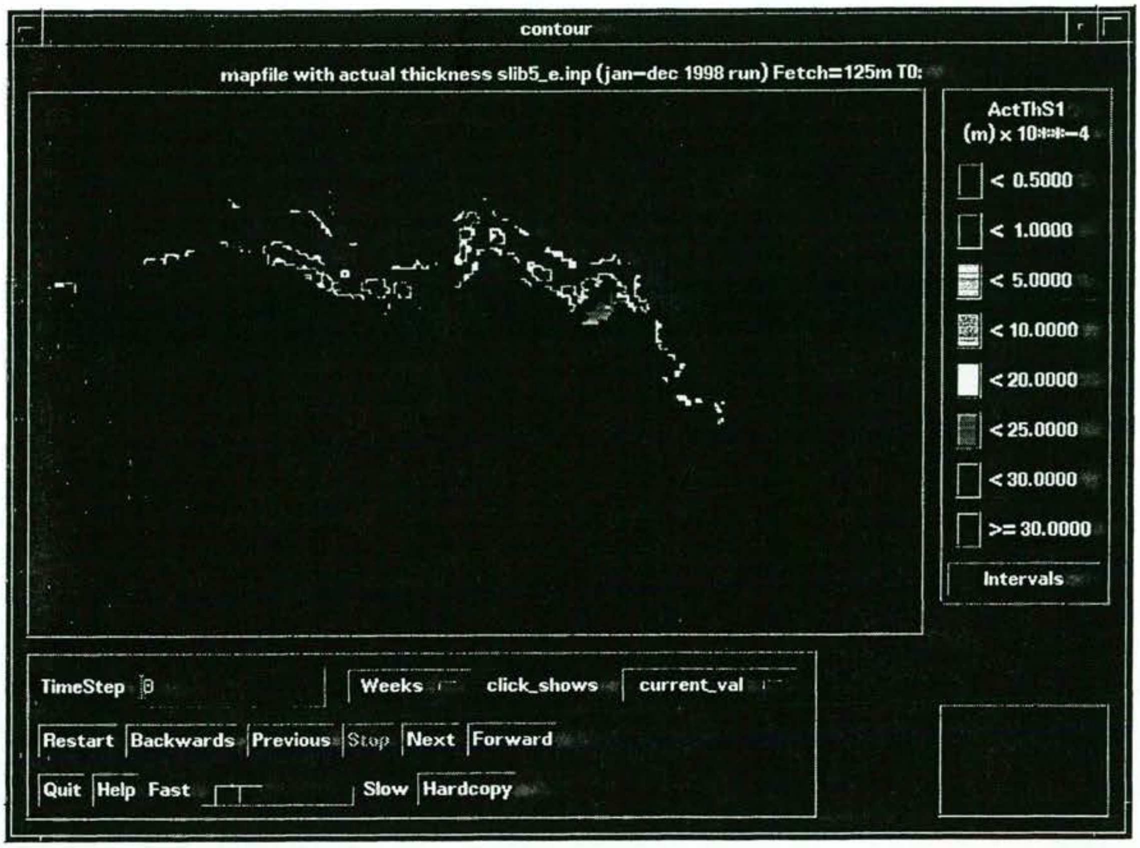


Figure 2.25 Initial thickness of the bottom sediment layer (thickness of two sediment fractions) used for 1-1-1998. The tidal flats can clearly be seen here.

The shear stress created by wind is calculated according to Bijker (in DELWAQ Technical Reference Manual, WL|Delft Hydraulics, 1997), and is a function of the wind speed, water depth and fetch (length of open water in the direction of the wind), see Villars and Vos, 1999, Appendix A. On tidal flats (i.e. shallow water depths), capillary waves (T < 1 sec) can be important in causing resuspension of sediment. Fetch on tidal flats (where average water depth is < 2.0 m) is set to 125 m. With this parameterization, capillary waves are generated (T~0.5 sec, H~45 cm) which can cause erosion during storm periods with wind speeds greater than 10 m/s.

Process 3: Erosion from gullies by tidal flow

Gullies may release some sediment at high shear stresses caused by tidal flow. This process is modelled primarily with the second sediment layer (S2) which has a high critical shear stress for erosion. The critical shear stress for erosion of S2 was set at 4.0-5.0 Pa (seasonal variation). With this value, erosion from the second sediment layer occurs only during spring tide, when highest flow velocities are present. As a result, a distinct difference in SPM concentration is found between spring and neap tides (which have much different shear stress due to flow). The difference in bed shear stress between a spring and neap period is shown in Figures 2.26a and 2.26b for the tidally averaged neap and spring tide respectively .

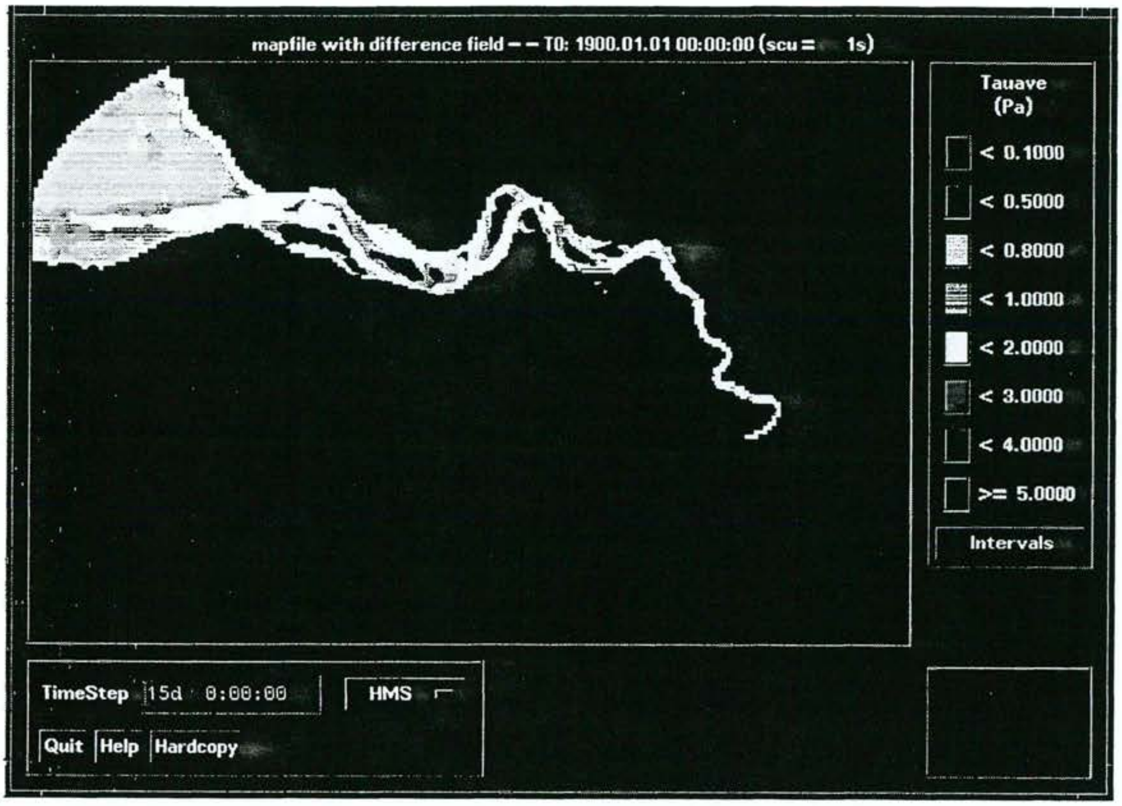


Figure 2.26a The *average* bed shear stress over 7 model days without wind for the *neap period*

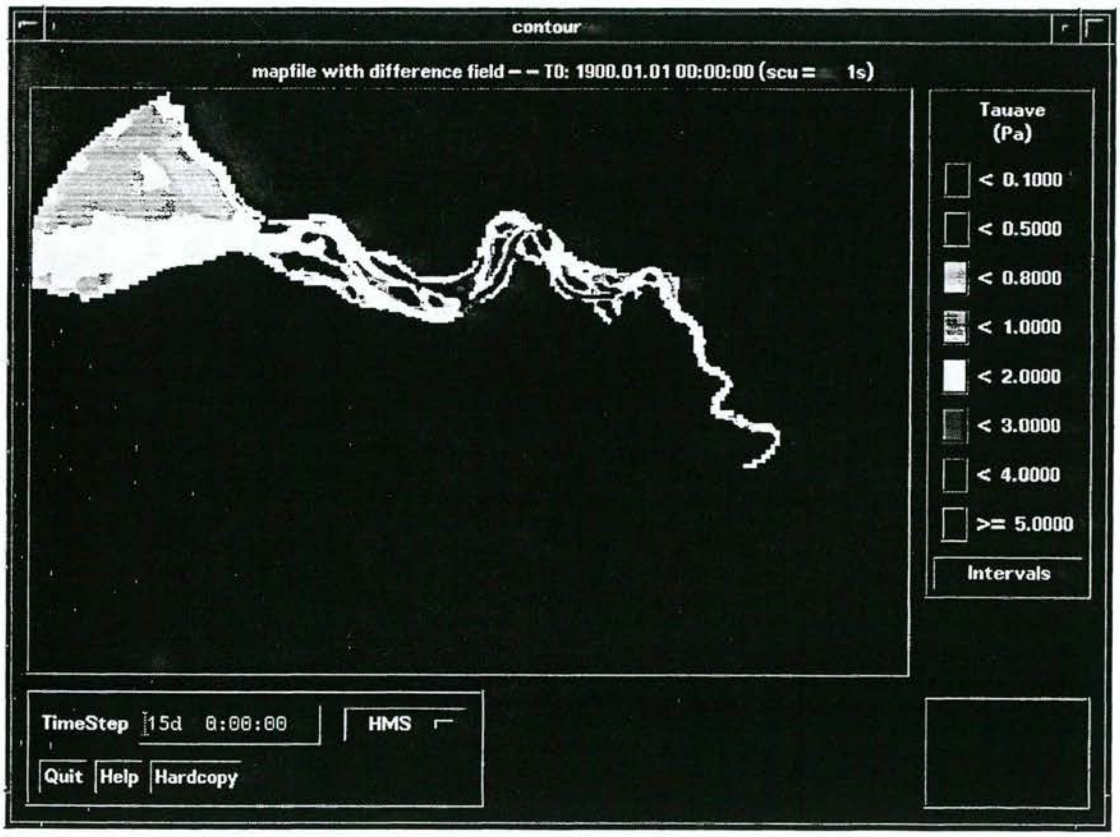


Figure 2.26b The average bed shear stress over 4 model days without wind for the *spring period*

Process 4: Erosion from gullies by wind induced waves

In contrast with the tidal flats, capillary waves do not contribute to erosion in the gullies. In the gullies, waves with longer periods (T~ 2.5s, H~ 1m) are important for erosion. Waves with a long fetch (~5-10km) can very well erode the shallow sides of the gullies (depth<2.5m) at high wind speeds.

In the model, the fetch is set at 6 km for computational segments with a (tidally averaged) water depth greater than 2.0 m in order to generate erosion effects in the gullies. This results in extra erosion during periods of high wind, e.g. January, begin March, and end October. For segments with an (average) water depth less than 2.0 m (i.e. all tidal flats), a fetch of 125m is retained.

Model limitations

The model set-up as described above includes the main inputs and processes which are considered important on the spatial and temporal scale at which the Western Scheldt is being studied, i.e. the entire Western Scheldt for a period of 1 year. At different (smaller) spatial and temporal scales of concern, some of the following processes could also be important:

1. *Stratification:* Both the hydrodynamic and the water quality model are depth averaged, and stratification was not modelled. Stratification may have an important effect on bed shear stresses and settling of sediment (Gerritsen et al., 1999). However, stratification is only expected to affect the Belgium part of the Scheldt. It may also affect the turbidity maximum in that area, though Buchard and Baumert (1998) suggest that the main mechanism for the turbidity maximum is the tidal asymmetry, which is included in the 2D model. Analysis of the continuous in-situ data from Terneuzen show that concentrations are similar at different depths, thus the use of a depth averaged model seems to be appropriate.
2. *Fluid Mud Layers:* Fluid mud or 'luthocline' is a suspension of silt with very high concentrations of more than 10 grams per liter. This process is not included in the current model. It may play an important role at tidal flats, where water can be stagnant, and/or be at very high silt concentrations. Fluid mud layers may also be formed when large amounts of silt are dumped, either from harbour dredging or from the tunnel. If fluid mud layers are formed on the tidal flats, silt may flow off the tidal flats as fluffy layers on the bed.
3. *Secondary flow:* secondary flow (included in 3 D models) might generate additional erosion by flow in curves like 'Schor van Baalhoek'. It is not modelled, but might be an additional explanation for the 12 hour frequency observed in the Baalhoek data (Section 2.1).
4. *Wave induced currents at tidal flats:* breaking waves at the sides of tidal flats can induce local currents. This process is not modelled.

One factor which could be important for providing more detailed spatial results is:
Detailed variations in flow and SPM concentrations for boundaries: model boundaries have a constant influx of water as specified in the hydrodynamic model. The constant influx of water is combined with constant monthly averaged concentrations (from 20 yearly means) of SPM data. For the Scheldt river, the flow is yearly averaged (100 m^3/s). For the sea boundary, the boundary concentrations are spatially averaged (although monthly varying), and must partially also include the effect of silt dumpings from Belgium harbours on the Western Scheldt. Due to these simplifications in defining the model boundaries, the calculated SPM concentrations can never

have large changes in time near the model boundaries. By the sea boundary, the calculated SPM calculations will also be spatially homogeneous as compared to remote sensing data.

2.3.4 Model calibration

In section 4.3 the set-up of the water quality model is described. The model was set up by initialisation of some of the model parameters in test models. The results of these test models were often derived from *qualitative comparison with a single data set (either the Terneuzen set or the Baalhoek set of continuous data)*. Remote sensing data were not used, and no validation was done for the spring and summer period.

After the first model set-up, a proper calibration for SPM was conducted, using *all available data simultaneously*. These calibration data are:

1. Continuous in-situ data for SPM (mg/l) at Baalhoek, Terneuzen and Vlissingen (described in Chapter 2).
2. Twenty year monthly mean averages for SPM for 8 locations (described in Section 2.1).
3. 9 processed images from remote sensing, transformed to the aggregated SCALWEST model grid (see section 3.3.2).

A proper and objective calibration for such large amounts of data is hardly possible by visual inspection, thus quantitative methods for model calibration, such as a cost function, are preferred. Various cost functions were developed and tested successfully by Vos and Ten Brummelhuis (1997) and Ten Brummelhuis et al. (1999) in the PROMISE project for the North Sea, and in the RESTWAQ-2 project (1998, PART I) for the Dutch coastal zone. The formal methodology is described in Vos and Ten Brummelhuis (1997). A simplified version of this methodology was applied in this study as described generally below, and in more detail in Villars and Vos, 1999, Appendix B.

Cost functions for data-model integration

A cost function (or Goodness-of-Fit criteria) calculates the difference between model results and measurements ('observables'), while taking into account the uncertainty in the measurements. If the model result is within the uncertainty range of the measured data, data and model are said to be in agreement and no difference is counted. The greater the difference between model and data, the larger the resulting value of the cost function.

Three separate cost function were used to compare the model with the available data sets and calculate the differences between model and data. The three cost functions were developed to compare the model with the key features of the different data sets.
In a final step, a total cost function value was calculated as the sum of the three individual cost function results (normalized sum).

When a cost function is calculated for several different model simulations (calibration runs), the simulation with the lowest cost function value is the best one (i.e. is the simulation which best matches all the data). Equations for the cost functions are given in Villars and Vos, 1999, Appendix B.

Use of remote sensing data in a cost function

To compare model results with remote sensing data, the model result ideally has to be at the exact date and time of the remote sensing image. For comparison of the Remote Sensing data and the model data, the model result closest to the remote sensing data in time, and within one meter difference of water level at Terneuzen were selected and compared to the remote sensing data. The absolute date of model results could not be used because the model hydrodynamics are slightly out of phase. Thus a time 'shift' in the model results are needed in order to make a comparison with a specific time (see also Section 2.3.2).

The cost function for the model and remote sensing data, focuses on the gradient in SPM concentrations from West to East in the Western Scheldt. To quantify this gradient along the axis of the estuary, the region is divided into 9 zones (Figure 2.27). For the cost function, both the model data and remote sensing data are aggregated for the 9 zones. Only averaged concentrations per zone are compared. The uncertainty in the remote sensing data is taken to be 10% of the SPM concentration. This estimate was estimated from the accuracy of processing of the level 1 SPOT images (section 2.2.3).

Use of in-situ data in a cost function

Two different cost functions were defined for use with the monthly averaged data and the continuous in-situ data.

The model concentrations of SPM and in-situ data were monthly averaged before the difference between the model and the data was calculated. For the continuous in-situ data, this leads to reduction of much of the information in the cost function. However, it was found that use of daily averages did not give very different results. Nevertheless, the cost function is not sensitive for a difference in the oscillations of spring-neap tide and lunar tide. Such cost-functions still need to be developed in the future. This can be done by explicitly using the amplitude and phase of these oscillations in the cost functions (beside the SPM concentrations), obtained from a Fourier analysis of modelled and observed time-series of SPM.

The calculation of the cost function requires a value for the uncertainty (S) in the in-situ data. For the twenty year monthly averaged data, the uncertainties were set equal to the monthly standard deviations. For the continuous in-situ data, the uncertainties were taken to be 20% of the observed averages.

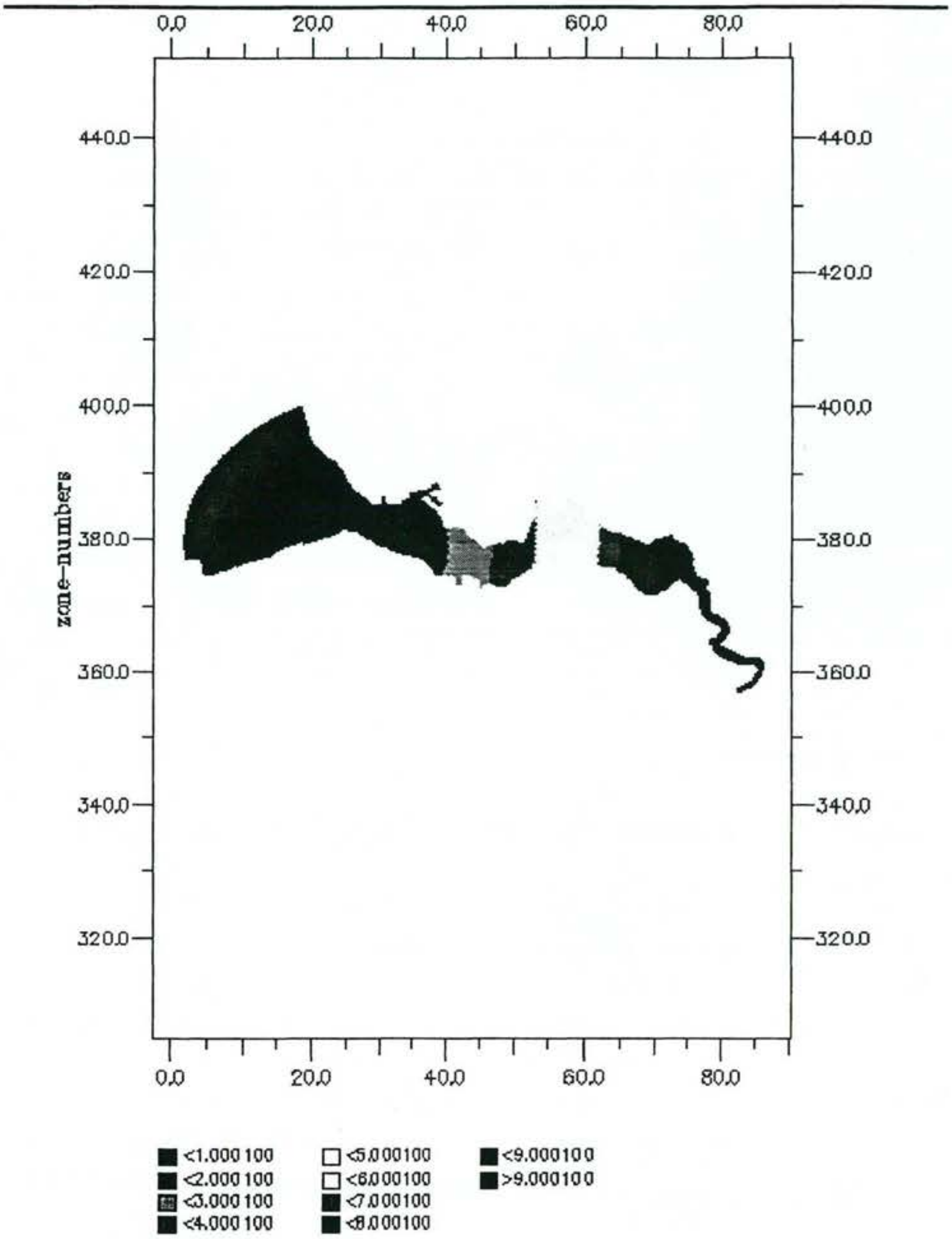


Figure 2.27 Definition of zones used in the remote sensing cost function for comparison of Remote Sensing SPM data with model results. Only averaged concentrations per zone are compared. (<1.000100 = zone 1; < 2.000100 = zone 2; etc.)

Total Cost function

Each cost function results in a cost function value which is indicative of how well the model compares with a particular data set (the lower the cost function value, the better the comparison). Furthermore, a total cost function was calculated as the sum of the 3 individual cost functions (these were first normalized, since they are not of the same order of magnitude). The total cost function was used to determine the best model calibration.

Calibration parameters

The main model processes and process parameters have been described in section 2.3.3 and Villars and Vos, 1999, Appendix A. An overview of process parameters and their final settings is given in Table 2.6. After the model set-up, 11 calibration simulations were done with variations of the parameters. Parameters that were optimised during the model calibration are shown in *italic*. For other parameters, the parameter values were determined during model set-up and remained fixed.

A description of the different calibration simulations and an analysis of results using the cost function is described in Appendix B. The best model calibration run was selected on basis of the cost function, i.e. the simulation with the lowest cost function result.

Table 2.6 Final values for model parameters and inputs. The parameters which were varied during the model calibration tests are given in italic. Other values were determined during the model set-up and remained fixed through the calibration.

Parameter	Description	Unit	Final value
ZResDM	*Erosion rate for layers 1 and 2*	*g/m2/s*	*17280*
TauCRS1DM	Critical shear stress layer 1	Pa	Function, Fig A.3
TauCRS2DM	*Critical shear stress layer 2*	*Pa*	*Function 2, Fig A.8*
Fetch for H< 2m	Fetch for waves for depth < 2m	m	125
Fetch for H> 2m	Fetch for waves for depth > 2m	m	6000
TauCSIM1	Critical shear stress sedimentation IM1	Pa	0.1
TauCSIM2	Critical shear stress sedimentation IM2	Pa	0.1
TauCSIM3	Critical shear stress sedimentation IM3	Pa	4
Manning	Manning coefficient for Chezy form.	-	0.026
VSedIM1	Settling velocity IM1	m/day	Function, Fig A.1
VSedIM2	*Settling velocity IM2*	*m/day*	*Function, Fig A.1*
VSedIM3	Settling velocity IM3	m/day	100
Bottom-comp.S1	Initial bottom for layer S1 at start	-	Figure 4.5
Bottom-comp.S2	*Ratio of (IM3/DM) in layer 2 at start*	*%*	*95*
Sea Boundary IM1	*Concentrations of IM1 at sea boundary*	*mg/l*	*Function, Figure 4.3a*
River Boundary IM2	Concentrations of IM2 at Antwerp	mg/l	Function, Figure 4.3b
Dumpings	*Amounts for Dutch harbour dumpings*	*Mton*	*1998 dumpings, Table 4.2*

Conclusions about model set-up and calibration

A dynamic water quality model for SPM has been set up for the Western Scheldt estuary. It was calibrated on in-situ data and remote sensing data simultaneously, taking into account estimates (a band width) for errors in the data. During the final model calibration 5 model parameters were varied, and the effect of adding dumpings of harbour silt was tested. The best model result will serve as a basis for a T1-scenario simulation (dumping of silt for 1999 from Tunnel boring).

The cost function is crucial for objectively analysing model results with respect to 3 different data sets of the Western Scheldt. The continuous measurements, the monthly averaged measurements and the remote sensing all provide a different 'truth' of the SPM conditions in the Western Scheldt. It was observed during the calibration, that the model results which compared very well with one set of data (e.g. continuous SPM measurements at Terneuzen), did not compare well with the longterm monthly averaged concentrations, or the remote sensing. Pitfalls occur if the model calibration focuses on one local station only. *For the optimal model calibration, there is a need of various data sources, from various techniques and from various locations.*

The best model result therefore, is the one that *on the whole* has the best comparison with all the data. *The cost function is the only method for objectively making this assessment.* Because the model is optimized on different information sources, when the model result is compared to measurements at one specific location, or to a remote sensing image at one specific moment in time the results will never be perfect.

An additional difficulty in comparing model and remote sensing results at a specific time is due to the out-of-phase spring-neap cycle in the model (see section 2.3.2). In order to compare model and remote sensing results at a specific moment in time, the model results had to be shifted, so that the correct day and time in the spring-neap cycle were found (e.g. 3 days after spring tide, 4 hours after high tide.). This brings the results to the same tidal phase, however, the forcing functions in the model (e.g. wind) are then also shifted, so the comparison is not ideal.

The model and data analysis suggests that the continuous monitoring station Terneuzen is situated at a position where the total SPM might be dominated by a local source of SPM. This will need further investigation. Note that the 12 hour frequency peaks in SPM observed at Baalhoek also indicate that at this station there is a large effect of local SPM fluctuations.

3 Assessment of the base line conditions / T0 situation 1998

3.1 Introduction

In this chapter, several model results are presented, and a comparison is made with continuous in-situ data from 3 stations, twenty year monthly mean averages for 8 stations (Van Maldegem, 1992), and remote sensing data.

Only results for 1998 are presented, representing the T0-situation (the present natural situation, including harbour dumpings but excluding the dumpings of tunnel silt). Results are discussed with respect to:

- visual agreement;
- the characteristic differences between modelled suspended particulate matter and measurements;
- recommendations for reduction of observed differences;
- the (relative) value of the different sources of information for assessment of a T0 situation: in-situ, remote sensing and modelling.

3.2 Model results per location, comparison with continuous in-situ data

One method of presenting model results is to show a time line of calculated SPM concentrations at a particular location(s). In Figures 3.1-3.3, the results of the final calibrated model are presented for locations Terneuzen, Baalhoek and Vlissingen, with the continuous in-situ data for comparison. Model results are presented both with and without dumpings from dredged harbour silt for 1998.

Discussion

- The model can represent the seasonal variation of SPM, as seen at Vlissingen; at the other locations continuous in-situ data is only available in October - December;
- The model can represent the spring-neap variation of SPM well at all stations;
- For summer, both model and data for Vlissingen do not show a spring-neap variation;
- The model represents reasonably well the effect of wind speed on SPM at Vlissingen (for wind data see Chapter 2). However, the model can not explain the sudden drop in SPM for the beginning of February. It might follow from the wind direction which is not taken into account in this SPM model;
- The model does not predict correctly the 12 hour frequency peaks of SPM in November 1999 observed for Baalhoek;
- The SPM variations in the data for winter periods (Jan-March, Nov-Dec), are larger than for the model. SPM drops back to a low level at Vlissingen at the end of March, but the model reaches this lower SPM level one month later.

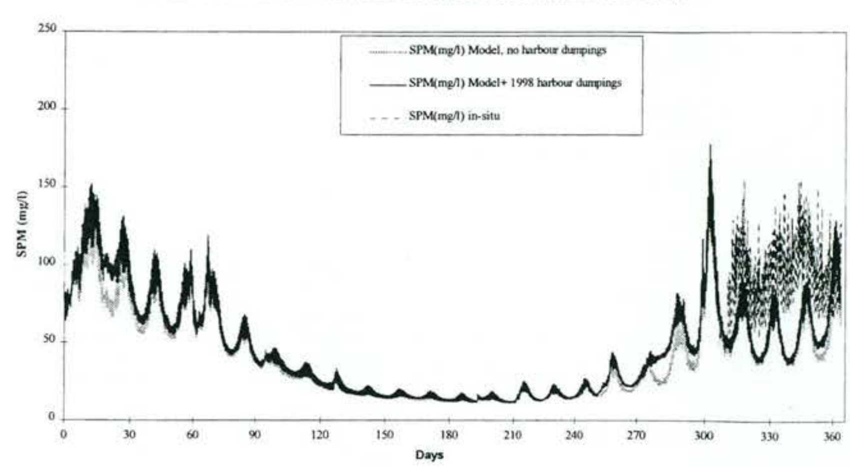


Figure 3.1a Model results for SPM concentration at Terneuzen, complete year 1998.

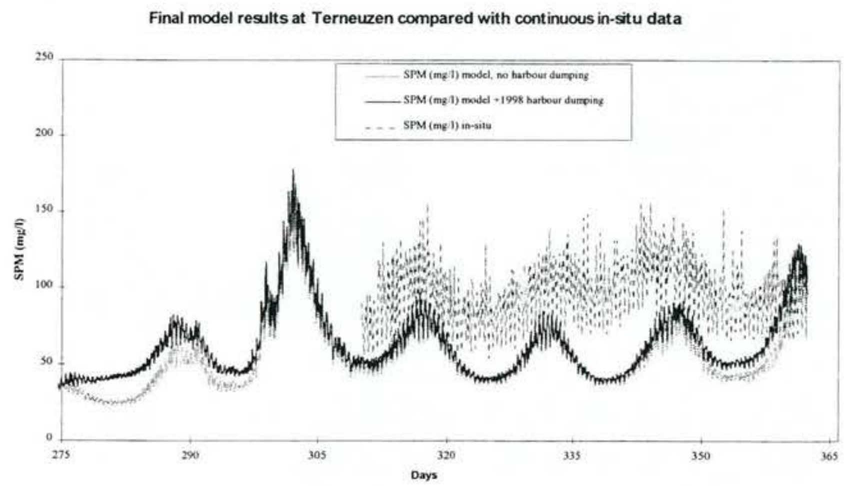


Figure 3.1b Model results for SPM concentration at Terneuzen, October-December1998 (day 275 = 2October) as compared to the in situ measured data at the same location.

Conclusion

The optimised model can very well explain the spring-neap cycle in the data, and the general seasonal behaviour of SPM. However, all more chaotic behaviour in the continuous SPM data, especially those at the tidal time scale, can not be modelled at present.

There is a time-shift in the model which is due to an error in the synodal period (in the hydrodynamic model). This period was chosen to be 29 days in the model, whereas it must be 29.5 days. This time-shift required a relative shift of the data before they could be compared with each other.

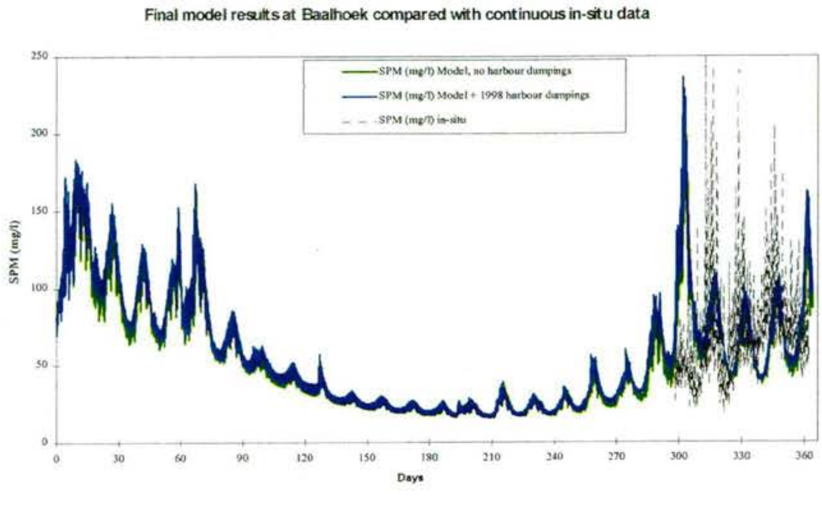


Figure 3.2a Final model results for SPM concentration at Baalhoek, with and without 1998 harbour dumpings.

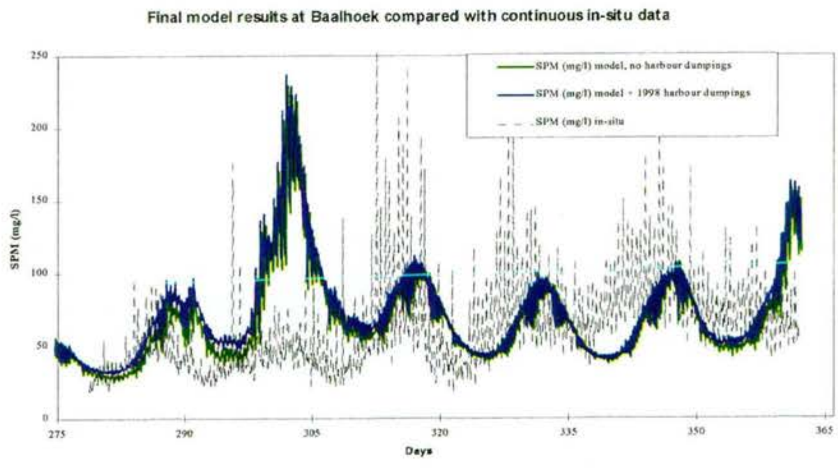


Figure 3.2b Model results for SPM concentration Baalhoek, October-December1998 (day 275 =2 October).

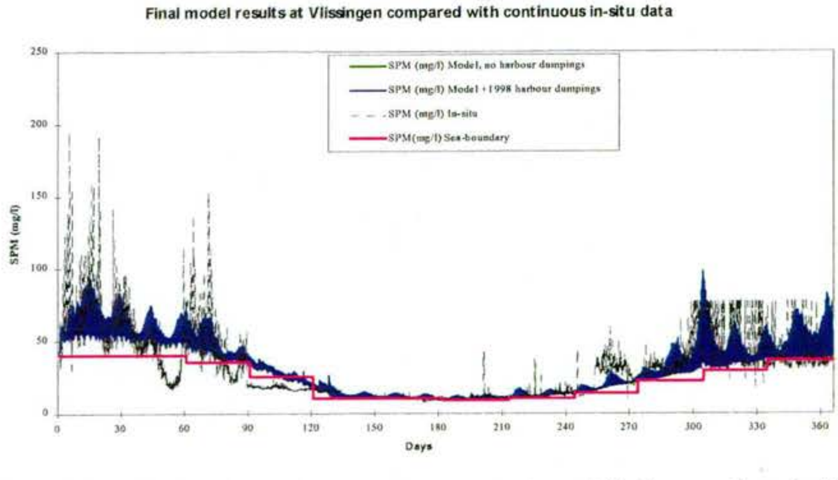


Figure 3.3 Final model results for SPM concentration at Vlissingen, with and without 1998 harbour dumpings.

3.3 Model results per location, comparison with monthly average data

In Figures 3.4a-h, the final calibrated model is compared to the monthly averaged in-situ data of Van Maldegem at 8 locations. Model results include dumpings from dredged harbour silt for 1998. At the selected locations, the model results have been averaged over each month, and thus are directly comparable to the van Maldegem data.

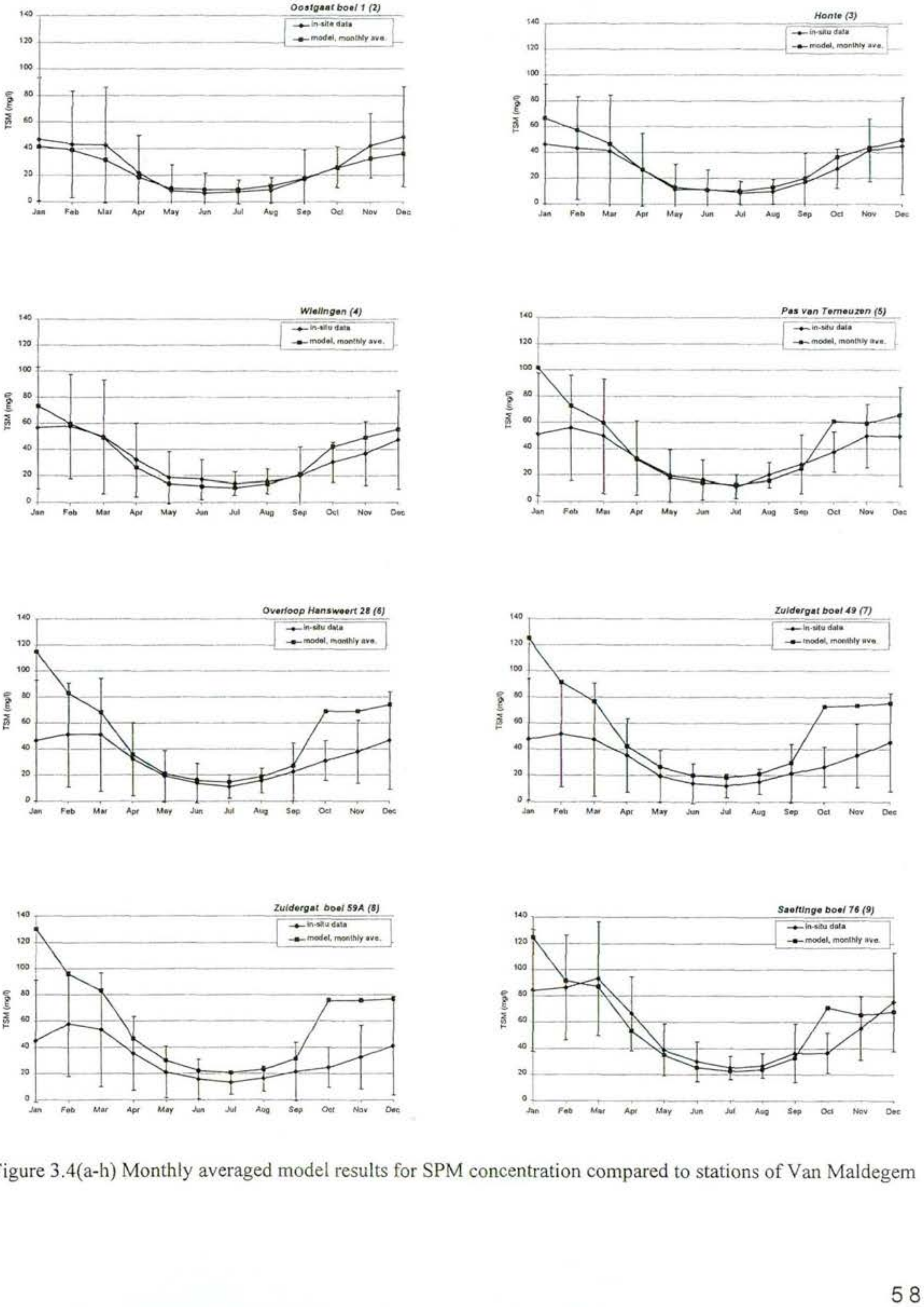


Figure 3.4(a-h) Monthly averaged model results for SPM concentration compared to stations of Van Maldegem

Discussion

On the whole, the model compares very well with the longterm monthly average SPM concentrations, and is within the standard deviation range for almost all months at all locations. The comparison is best in the months April - September, while in the winter and fall months there are some differences.

In January, the model has high concentrations compared to the measurements. The high model concentrations are due to the storm conditions (wind > 10 m/s) that prevail during much of January 1998. The continuous measurements at Vlissingen also show high concentrations during January, with occasional peaks of nearly 200 mg/l. Also in October and November, the model results are high at some stations. In this period, there are also storm conditions. In the model, the high wind causes resuspension of bottom sediment (from wind induced waves), resulting in the high calculated SPM concentrations.

During the months April - September, the modelled results are very close to the longterm monthly averaged SPM concentrations. Only at Zuidergat (stations 7 and 8), the modelled concentrations are a bit high, but still within the standard deviation. At Saeftinghe, (station 9), the modelled concentrations are slightly low, but within the standard deviation.

3.4 Synoptic model results through the year

Model results can also be shown synoptically, i.e. as a map of SPM concentrations for the whole area at a specific moment in time. In order to show the variation of SPM concentration throughout the year, model results are presented at 4 different times: February, May, July and October (Figures 3.5 and 3.6). Each result is during the spring period of the tidal cycle during rising water. The model results are given on the 4*4 aggregated model grid.

These model results show some of the important spatial features in SPM concentrations:

- In all maps there is a gradient of increasing SPM concentrations moving from west to east.
- There is a strong seasonal pattern in SPM concentrations. Concentrations are high (>50 mg/l) in most of the Western Scheldt in the winter (February) and fall (November), and concentrations in most of the estuary are low during the spring-summer period (as seen in May and August). This seasonal pattern is the same as seen in the in-situ data at Vlissingen (continuous) and the longterm monthly averaged data.

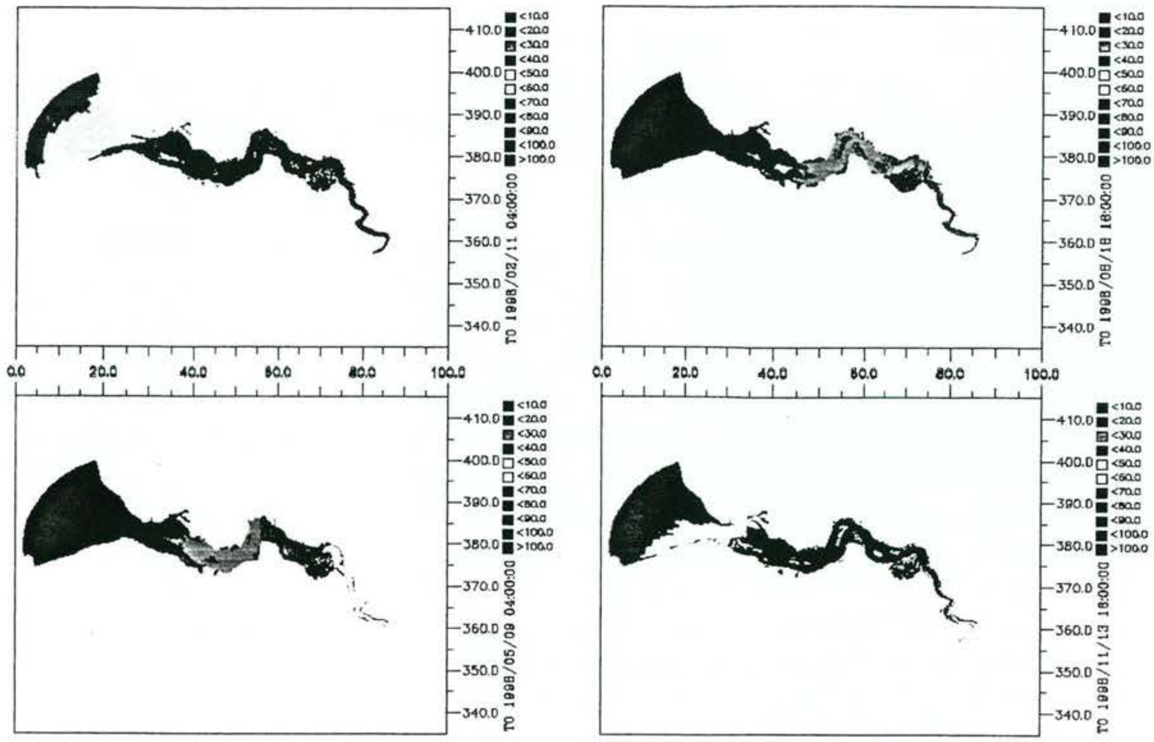


Figure 3.5 (left) Model results for SPM on 11 February 1998 (top) and 9 May 1998 (bottom). Both times are during spring tide, high water

Figure 3.6 (right) Model results for SPM on 18 August 1998 (top) and 13 November 1998 (bottom). Both times are during spring tide, high water.

3.5 Synoptic model results and comparison with remote sensing

An integration of the remote sensing data with the model has been caried out during the calibration phase by using the cost function. In this section selected final model results are presented together with the interpreted remote sensing data shown to allow visual comparison. The remote sensing maps are presented on the full non-aggregated SCALWEST model grid. The model results are given on the 4*4 aggregated model grid. Only results for 11 January 1998 and 20 July 1998 are given in this report. For a complete overview of synoptic model results and corresponding remote sensing maps the reader is referred to Villars and Vos (1999).

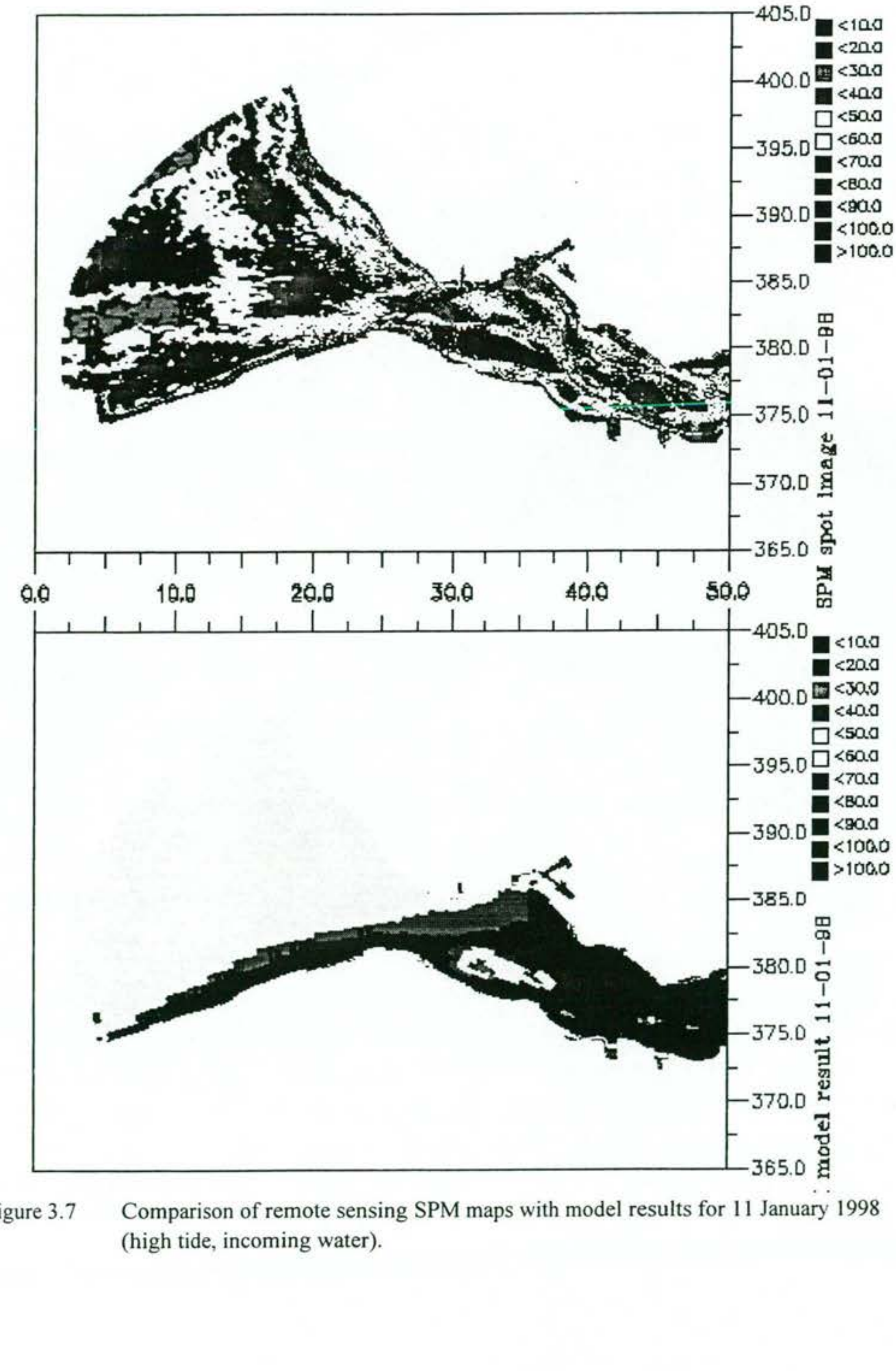


Figure 3.7 Comparison of remote sensing SPM maps with model results for 11 January 1998 (high tide, incoming water).

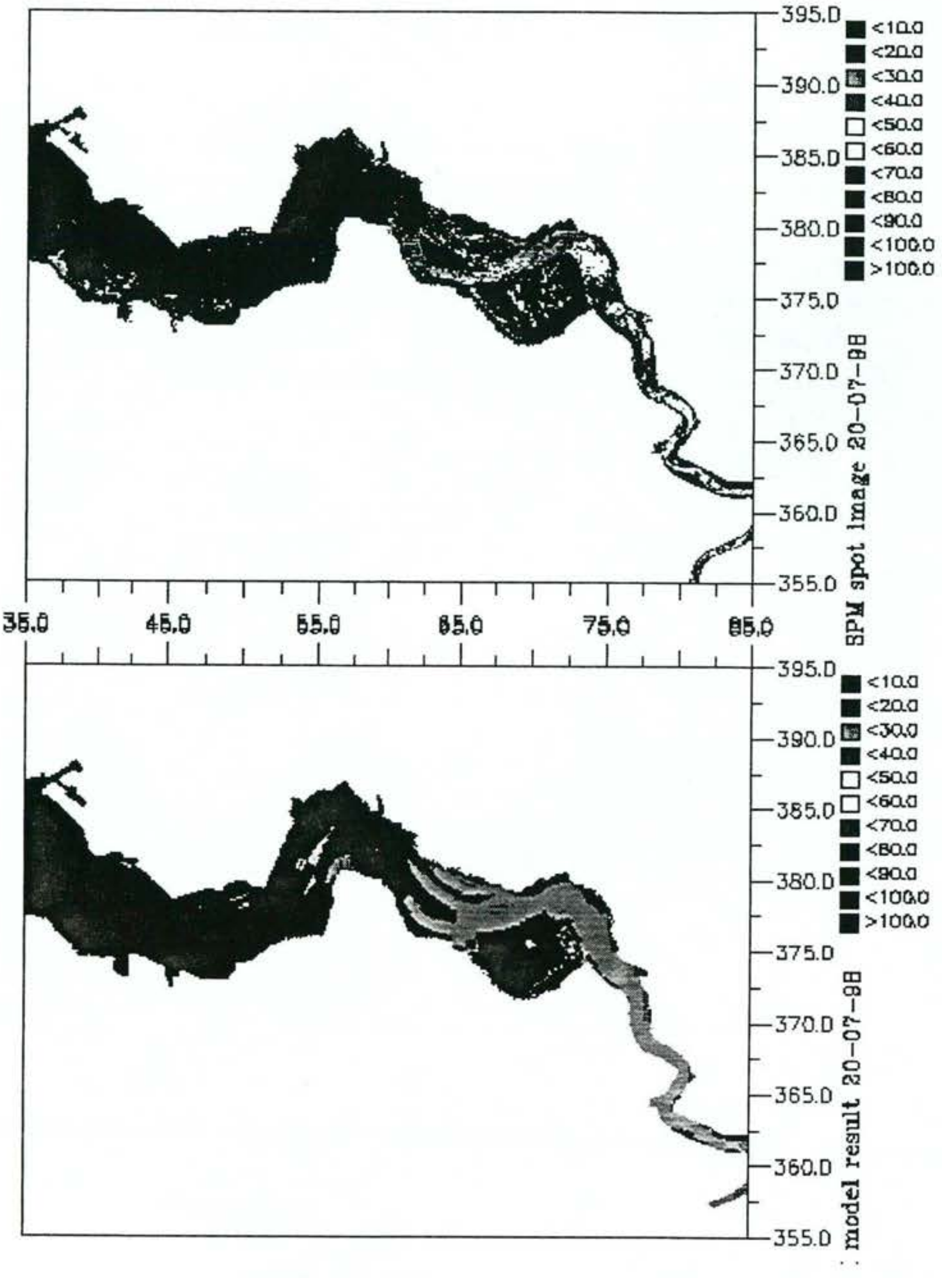


Figure 3.8 Comparison of remote sensing SPM maps with model results for 20 July 1998 (high tide, slack water).

Discussion on integrated model results compared to remote sensing results

For optimum comparison of the Remote Sensing data and the model data, the model has to be run for the dates and times with closest correspondance with the specific acquisition time of the remote sensing images. However, the absolute date of model results could not be used because the model hydrodynamics are slightly out of phase (the modelled spring-neap cycle was 14.5 days, while it should be 14.75 days, see also Section 2.3.2). The application of a 'time shift' in the model results is needed in order to bring the model and remote sensing results to a comparable tidal phase, but the model forcing functions (e.g. wind) are then also shifted, so the comparison is not ideal.

As is illustrated in the examples above, in general, remote sensing images show a lot more detail of SPM patterns and gradients than the model results. Modelled concentrations are based on a limited number of processes, on certain assumptions of boundary conditions and regarding dumping of dredging material, and thus they are simplifications of the real world. Localized and short term temporal variations in processes causing detailed SPM patterns and gradients are not shown in the model results. Remote sensing on the other hand offers a snap shot of the entire area and (within its limitations with respect to spatial and radiometric resolution) reflects the real situation .

- *11 January 1998:* Figure 3.7: This is a (unique) winter remote sensing image Due to the simplified boundary conditions in the model, the complex gradients in the remote sensing image are not shown in the model results. This concerns especially the gradients in Scheur van Wielingen. In addition, the model simulated high SPM values in the inner Scheldt estuary due to erosion by wind. The remote sensing image indicates that this erosion is overestimated by the model.
- *July 1998:* Figure 3.8: For the eastern part of the Western Scheldt the SPM concentrations in the Belgium Scheldt in the Remote Sensing image are much higher than the model results, indicating that for this particular moment in time an SPM influx from Belgium takes place which is not modelled. This might indicate the actual need for proper SPM data from the local Belgium authorities from their continuous monitoring stations at Prosperpolder (examples are given by Fettweiss et al., 1998). However, the remote sensing image shows a very steep concentration gradient moving downstream, and within the estuary the remote sensing concentration is lower than the modelled concentration. This high concentration gradient seen in remote sensing is less pronounced in the model results.

3.6 Conclusions about T0 conditions for SPM in the Western Scheldt, 1998

Conclusions about the T0 conditions for SPM in the Western Scheldt can be drawn from the analysis of the different data sources:
- in-situ data (long term monthly averages and continuous measurements)
- remote sensing
- dynamic water quality model

Each data source provides different information about SPM concentrations. The best description of the T0 conditions is based on a combination of all 3 sources, taking into account the strengths and weaknesses of each.

In-situ data

In-situ data are collected at a number of fixed locations over time. In-situ data are thus ideal for the analysis of variations in SPM concentrations over time at the selected locations, including comparison of the locations

The long-term monthly averaged in-situ data clearly shows the seasonal trend in SPM concentrations over a year and the natural variation in concentrations (based on the standard deviation) in the Western Scheldt. This is the only data source that shows this trend. From this data set it can be seen that all locations in the Scheldt have relatively high concentrations with large natural variation in winter and fall, and low concentrations with low natural variation during the summer months.

Typical winter concentrations are 40-60 ± 40 mg/l. The concentrations are lowest at the sea side, due to influx of North Sea water with relatively low SPM concentrations. Highest concentrations are measured at Saeftinghe, where the average monthly concentrations for January - March are 80-90 ± 40 mg/l.

Typical summer concentrations at all locations in the Western Scheldt are 10-20 ± 10 mg/l. Again, concentrations are lowest at the sea side, and highest near the Belgian border (e.g. Saeftinghe) where summer concentrations are slightly higher than 20 mg/l.

The continuous in-situ data are important in showing short time scale details in concentrations that are not present in the monthly average data. This is the only data set that shows concentrations changes correlated to the daily tidal cycle, the spring-neap tidal cycle as well as the seasonal cycle (from Vlissingen only). This high-temporal data shows that large changes in SPM concentration can occur over very short time periods, perhaps due to wind conditions or localized erosion from bottom sediments.

Continuous data at Terneuzen for October -December 1998 show concentrations between 60-150 mg/l, varying regularly over the spring-neap cycle. Continuous data at Baalhoek over the same period show a much larger concentration range (25-250 mg/l), with much more extreme concentration variations over short time periods. The difference in these signals may be due to very localized effects.

Remote Sensing data

The strength of remote sensing is that it provides details about SPM concentrations and patterns at any moment in time (snapshot), which are not available from any other data source. An example is the elevated SPM concentrations seen at the Vlakte van Raan, or along the Belgian coast at the south side of the mouth of the Western Scheldt. Information about these SPM features is not available from in-situ data or the model. With sufficient remote sensing images, detailed SPM concentrations and patterns can be seen over time. However, due to variations in SPM over tidal and spring-neap cycles (as seen in the continuous in-situ data), the validity of a remote sensing image is restricted to one moment in the tidal cycle and is therefore not representative for longer periods.

Due to large fluctuations in SPM concentration within a tidal cycle and a spring-neap cycle, making composites of remote sensing images is not recommended (either daily, weekly or monthly). This is in contrast to previous RESTWAQ studies, specifically southern North Sea and Dutch coastal zone, where such composites were very valuable remote sensing products. In the North Sea and Dutch coastal zone, SPM variation over time scales of days-week (tidal cycle and spring - neap cycle) were not significant compared to variation over months. Also for purposes of the previous RESTWAQ studies, i.e. large scale SPM transport over a year, the weekly and monthly composites provided sufficient detail.

Dynamic water quality model

The dynamic water quality model combines the high temporal scale of the (continuous) in-situ data with the large spatial scale of remote sensing data. The model is the only information source which can give estimated information on SPM at all times at all locations in the Western Scheldt. The model is controlled by real meteorological data is therefore able to show the effect of storms. Through the process of data model integration as used in the cost function, the available information from both in-situ and remote sensing data are incorporated as best as possible into the model. The model is thus optimized on in-situ and remote sensing data.

The model results clearly show the seasonal pattern as well as the spring-neap variation of SPM concentrations in the Western Scheldt. Also the model shows generally increasing SPM concentrations moving from west to east. The model is limited in its ability to simulate detailed patterns in SPM concentration as seen in the remote sensing, and very short term variations in SPM concentrations as seen in the continuous in-situ data. It can be concluded that these are effects caused by localized conditions and effects which are not included in the general model processes.

4 Modelling of effects of tunnel boring material discharge / T1 scenario.

4.1 Introduction

With the water quality model calibrated for 1998 it is possible to estimate the silt distribution in the Western Scheldt during the building of the 'Westerschelde-tunnel' and the associated dumping of tunnel material. This may be done by simulating tunnel material dumping scenarios for this so-called T1 situation. In this chapter, results are presented for one hypothetical dumping scenario.

The dumping encompasses 'Boomse Klei' to be dumped with a pipeline near Terneuzen Dow Chemicals (Figure 4.1). The Boomse Klei consists primarily of very fine silt (<63 μ) (RWS, 1998). The course and progress of the discharge of tunnel boring material being unknown a simple dumping scenario was chosen. In the modelled 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 1998). 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. As a rough estimate, a conversion factor of 1ton per m^3 is assumed. It is recognized that the amount of the dumped material in this scenario is a (very) rough estimate, but a new scenario can be calculated when more precise information on the dumping amounts and strategies is available. The chosen scenario provides an indication of the expected increase in SPM concentration, as well as the spreading patterns and the transport of the dumped material.

For the T1 prediction, the 1998 model simulation is run again, with the addition of the tunnel material. The tunnel material is modelled as a separate (additional) sediment fraction, having the same characteristics as the river silt. The dumped material is added to one model segment, in the water column. All other model inputs are the same as in the 1998 model simulation (i.e. wind conditions, boundary conditions, initial conditions, and dumping from harbour dredging), and all parameter settings are the same.

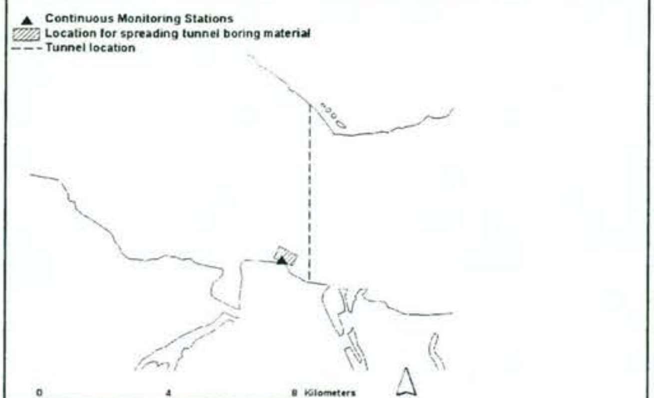


Figure 4.1 Location of dumping site for tunnel boring material

4.2 Predictions for the T1 scenario

4.2.1 Results per location

Predictions of T1 SPM concentrations for locations Vlissingen, Terneuzen and Baalhoek are presented in Figures 4.2 a-c, with the modelled 1998 concentrations without tunnel boring material as a reference (lower line).

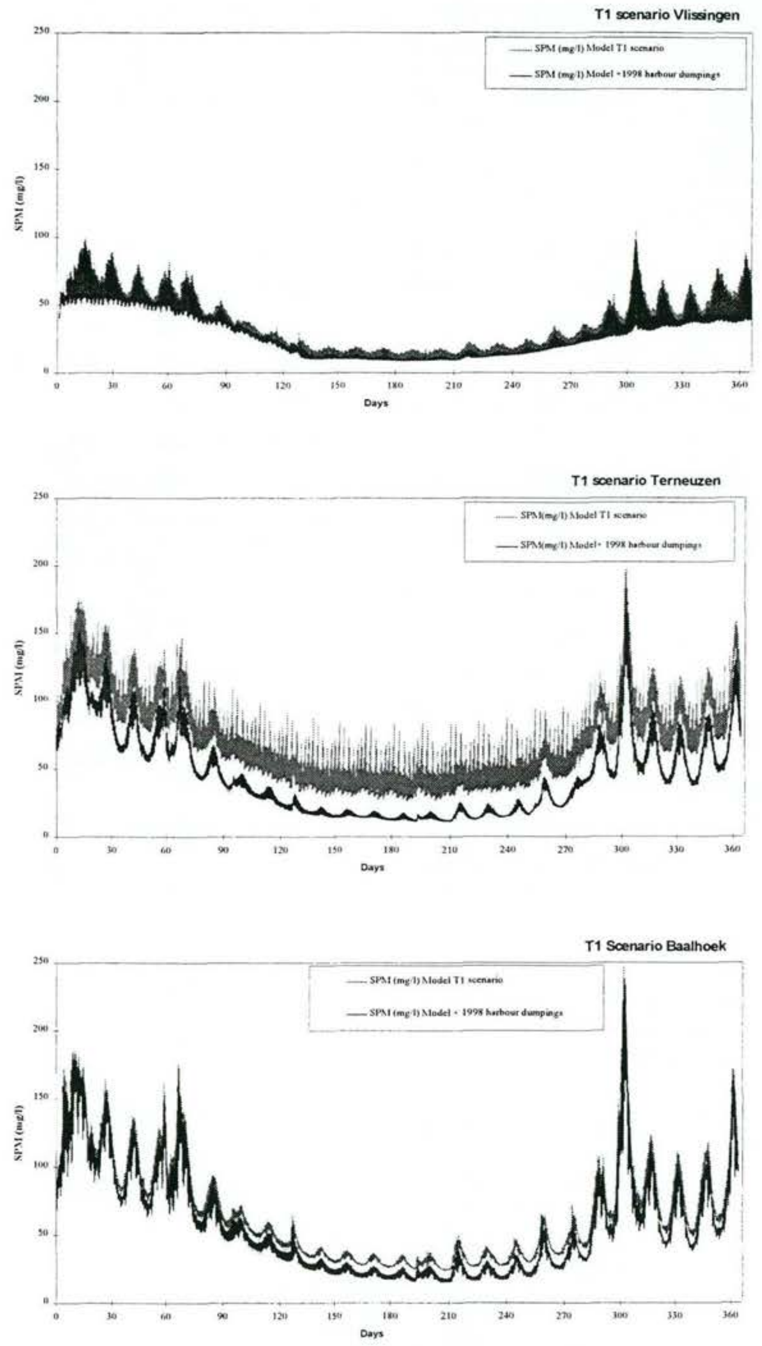


Figure 4.2 Predicted T1 concentration of SPM due to continuous dumping of 1Mton tunnel boring material Vlissingen (a), Terneuzen (b) and Baalhoek (c); 1998 concentrations are shown as reference.

Additionally, T1 predictions can be presented as monthly averaged concentrations. Figure 4.3a-h shows expected increases in monthly averaged SPM concentration at 8 locations. The 1998 model predictions and in-situ data with standard deviation (Van Maldegem, 1992) for the same locations are shown as reference. The in-situ data are important since they indicate the normal background levels, and the natural variability. This gives an indication of whether the increase of SPM is significant in comparison to the natural situation.

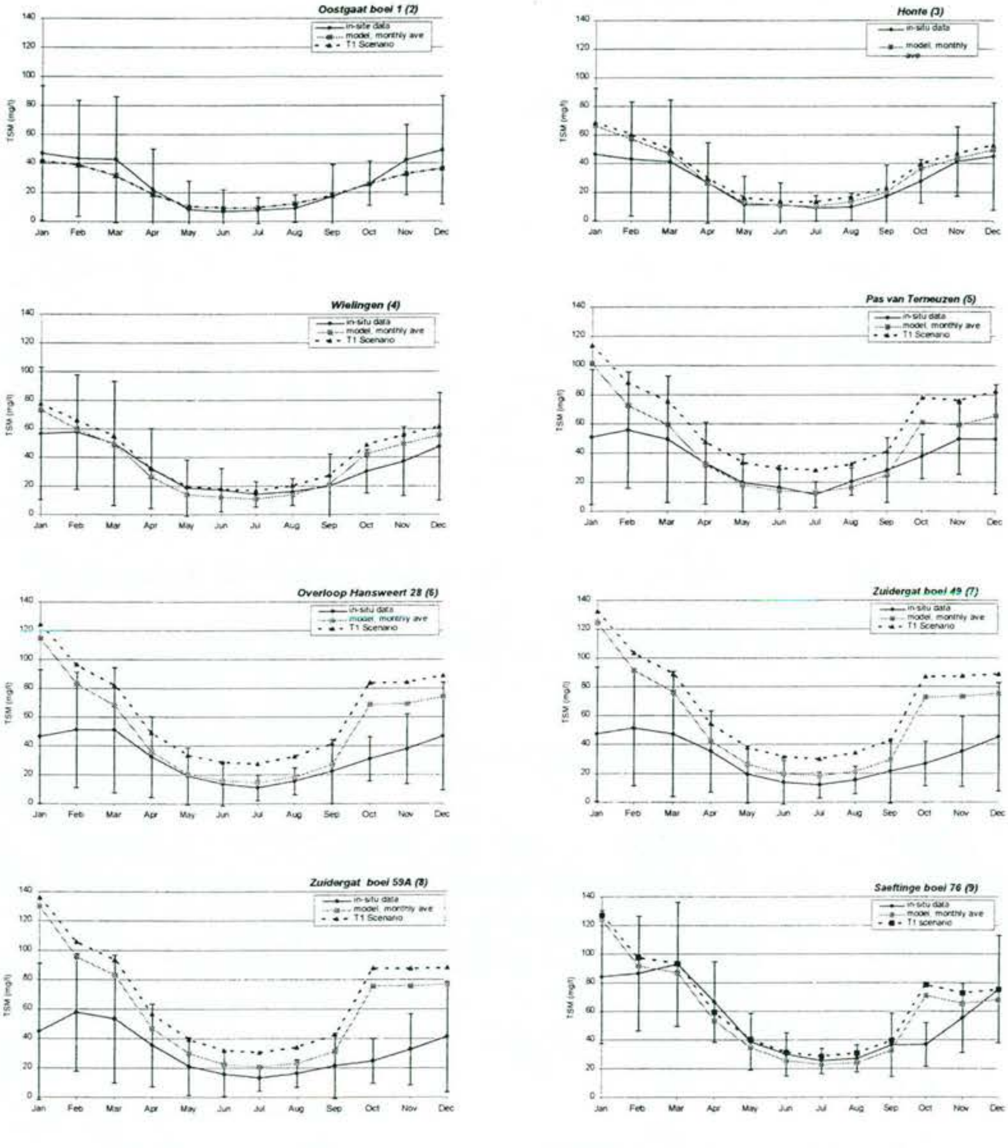


Figure 4.3a-h Predicted T1 monthly average SPM concentrations at Oostgaat, Honte, Wielingen, Terneuzen, Hansweert, Zuidergat and Saeftinghe

The model results of Figures 4.2 and 4.3 show that:

- an increase in SPM concentration of ~30-40 mg/l can be expected close to the dumping location. This can be seen in Figure 4.2b, showing the predicted results at continuous monitoring station Terneuzen.
- an increase in SPM concentration of 5-20 mg/l can be expected further away from the dumping location, depending on the exact location. This can be seen at Vlissingen

(Figures 4.2a) where the increase is <5 mg/l. At Baalhoek (Figure 4.2c) the increase is ~10mg/l.

- the highest increase is noted at Pas van Terneuzen (~20 mg/l), looking at the monthly averaged results (Figure 4.3) for the continuous monitoring stations,
- during the summer, the increase of SPM at Terneuzen due to the dumping of tunnel silt is much larger than the fluctuations due to tide and wind in the background signal for SPM ('natural' SPM) (Figure 4.2 b). Here, the largest impact of the dumping can be seen (which obviously can be expected since the monitoring location is directly next to the dumping location.);
- at Baalhoek and Vlissingen, the increase in SPM during summer is relatively small, but probably can still be observed. At Baalhoek the increase is in the order of the tidal fluctuations for summer. At Vlissingen the increase is somewhat larger than the tidal fluctuations;
- the increase of SPM during winter, due to the dumping of tunnel silt, is much smaller than the fluctuations due to tide and wind in the background signal for SPM ('natural' SPM) for all 3 stations (Figures 4.2 a-c);
- at most stations in the Western Scheldt the predicted concentrations during the summer are higher than the natural range of SPM concentrations, which can be seen in the monthly averaged results of Figure 4.2. In the winter months, the predicted concentrations are usually within the natural range of SPM concentrations and will therefore be difficult to be distinguished.

Thus, the effect of the dumping of tunnel material will be most prominent during the summer months, when the natural background concentrations of SPM are lowest. During the winter months, the increased SPM concentration will likely be within the range of natural fluctuations.

4.2.2 Synoptic Results

Like was done for the T0 phase the model can also show (predicted) concentrations for the T1 phase synoptically for a selected moment in time (snapshot). For this purpose the model was run for 4 moments during the year, corresponding to results previously shown for the T0 situation (see Figures 3.5-3.6): February, May, August and November. Results for February and May are shown in Figure 4.4. The modelled concentrations for the tunnel material are shown in the lower frame, while the total SPM concentrations for the T1 situation are shown in the upper frame.

A computer animation of a time series of synoptic results has also been recorded, which shows how the dumped tunnel material moves through the Western Scheldt with the tidal motion.

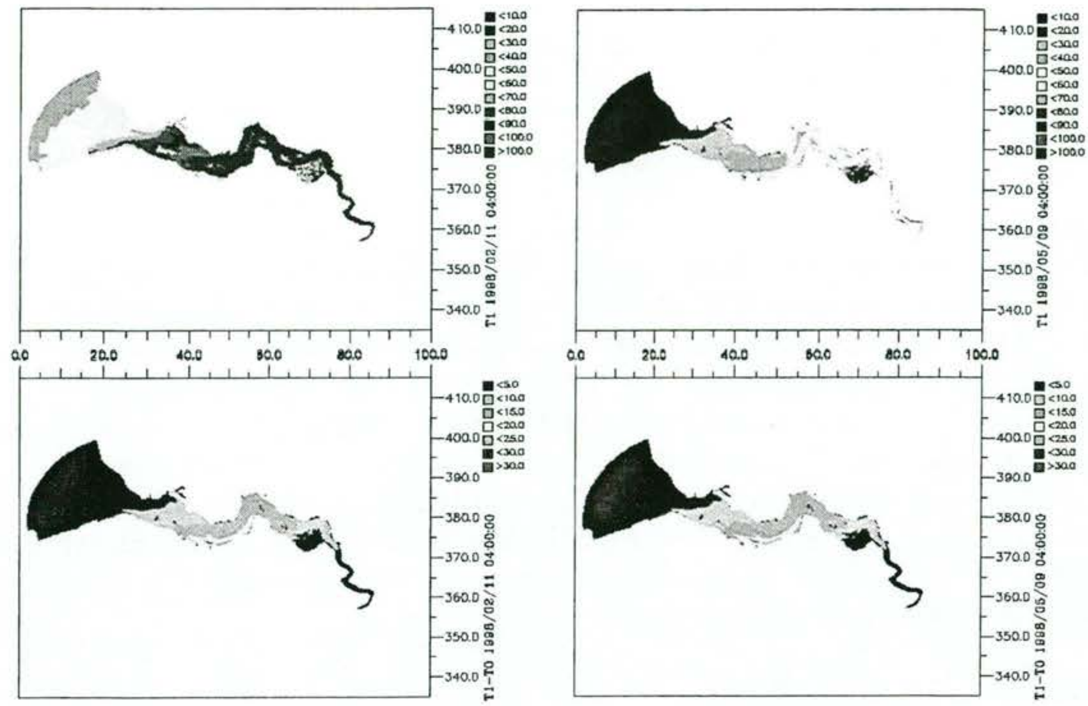


Figure 4.4 Modelled total T1 SPM concentrations, i.e. including tunnel material (top) for 11 February 1998 and 9 May 1998 (all concentrations in mg/l.); differences between modelled T1 and T0 concentrations, i.e. impact of discharge of tunnel boring material. T0 concentrations of the same dates are shown in Figure 3.5.

From Figures 4.3 and 4.4 it follows that:

- the dumping of tunnel sediment creates a 'plume' of increased concentration which fluctuates around the dumping location, moving upstream and downstream with the tide. The predictions show a maximum SPM concentration of about 30 mg/l in the immediate vicinity of the dumping location (see e.g. Figure 4.4).
- a concentration increase of 25 mg/l is seen in a limited area, which extends to a few kilometers from the dumping location. A concentration increase of 10-15 mg/l is seen in a large area, extending upstream to Baalhoek (~17 km). At Vlissingen, on average a concentration increase of 2mg/l is predicted.

Because a constant discharge rate of tunnel sediment has been assumed, the increase in SPM concentration is constant over the year. The 'visibility' of concentration increase will be relatively low in the fall and winter period, when background concentrations and natural variability are high. The SPM concentration increase will most likely be best 'visible' in the summer months, when background concentrations and natural variability are low.

4.2.3 Modelling results for bottom sediment

Modelling of changes in bottom sediment thickness

A mathematical model of silt distribution in the water column can be (partly) calibrated on remote sensing data (giving synoptic spatial information on suspended sediment distribution near/at the water surface). The output of the model is a mass-conservative prediction of the suspended matter concentration and distribution. Additional modelling of sedimentation and erosion fluxes enables the estimation of the net changes in height of the tidal flats. Figure 4.5a presents results of the modelling of the changes in bottom height in the Western Scheldt on the 27th June 1998 relative to the 1st of January 1998, following the hypothetical scenario with respect to the dumping of tunnel boring material, which was already used (1 Mton (dry weight) of material being discharged at a constant rate into the Western Scheldt over a period of 1 year (1 January 1998 - 31 December 1998). Figure 4.5 b. addresses the situation on 31 December 1998.

a. b.

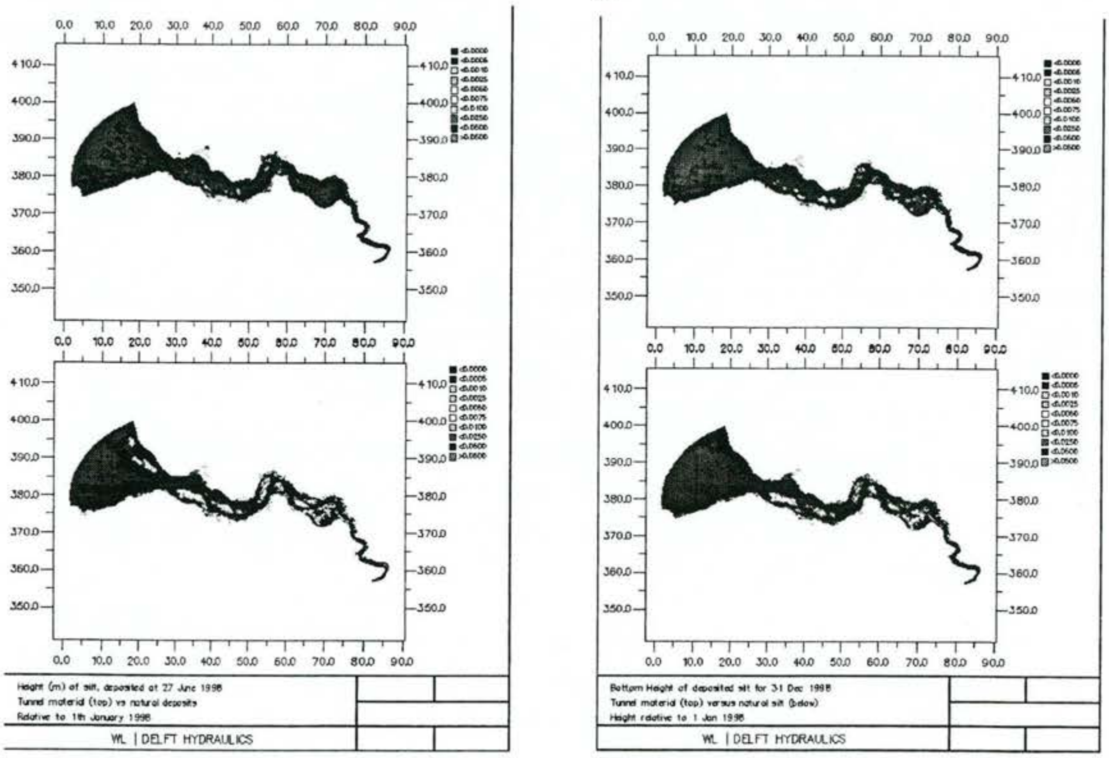


Figure 4.5. Net changes in bottom height for deposited tunnel material (top) and deposited natural material (bottom) on a. 27 June 1998.
b. 31 December 1998.

The thickness of the sedimented material was calculated assuming a sediment density of 2650 kg/m^3. The upper part of the figures presents results for the sedimented thickness of tunnel silt (expressed in meters), while in the lower figure the result of net sedimentation of naturally occurring material (fluvial silt, marine silt and sand) is depicted.

Modelling of sedimentation on tidal flats

The prediction of silt distribution on tidal flats with mathematical models can be improved when information is available on the spatial and temporal variability of suspended particulate material.

Figure 4.6 presents the modelled net change in bottom height in metres over a period of one year (1 January 1998 - 31 December 1998) for a location on the Hooge Platen (Fig. 4.5a) and for two locations (central part and south western edge) on the Molenplaat (Fig. 4.5b). Again the constant rate scenario (1 Mton in 1 year (1998)) with respect to dispersal of tunnel boring material was followed. For all locations initial conditions were assumed. The model estimates the amount of bottom sediment (both natural and tunnel material) as a function of time.

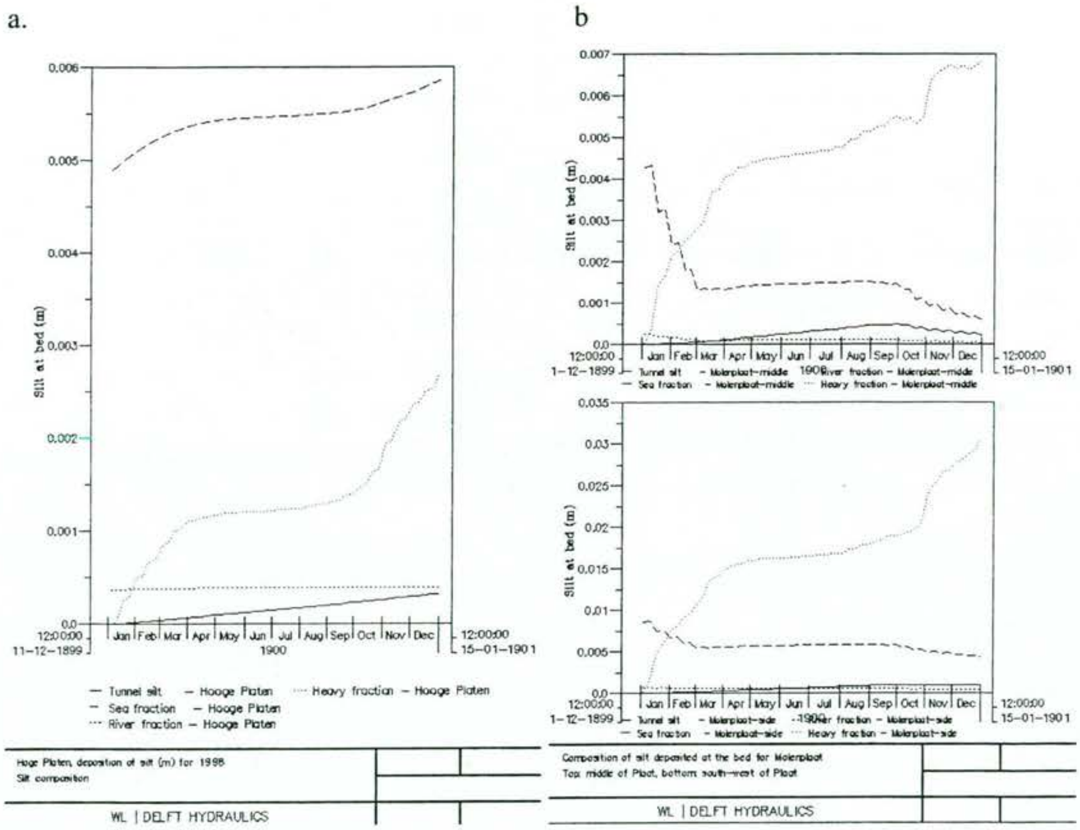


Figure 4.6 Deposition of silt (in metres)

a. for a location on the Hooge Platen.
b. for two location on the Molenplaat (central part (upper figure), south western art (lower figure).

The Hooge Platen (Fig. 4.6a) are initially covered with a layer of the sea fraction of silt (uppermost discontinuous line). The river fraction of silt (the lower discontinuous line) has a steady height of 0.0004m. The tunnel fraction of silt (continuous line) shows a linear increase in time. The heavy sand fraction (dotted line) shows a seasonal behaviour. In summer there is no accumulation, because there is hardly any heavy fraction in the water column. In winter there is an accumulation, because the strong winds resuspend the heavy fraction into the water column and the suspended sediment subsequently settles on the tidal flat. The fraction of sea silt shows a similar seasonal behaviour.

In Figure 4.6b similar trends are shown for two locations on the Molenplaat. The heavy fraction (dotted line) again shows seasonal trends. The sea fraction of silt (upper discontinuous line) shows an immediate decrease in height as a result of the decreasing wind speeds. In summer the sea fraction of silt is stabilised. The tunnel fraction of silt (continuous line) initially shows a linear increase in time, but at the end of the season shows an oscillatory decrease as a result of erosion-cycles on the tidal flat. The river fraction of silt (lower discontinuous line) shows a similar behaviour as the sea fraction but is less significant in absolute numbers.

From Figures 4.5 and 4.6 showing accumulation of bottom sediment, it follows that:

- the amount of silt from the tunnel boring that deposits at the bed is small compared to the natural deposits. An exception is the south coastline close to the dumping location;
- the amount of silt at Molenplaat is dominated by the sedimentation of the heavy fraction in the model; the accumulating amount of tunnel material is small compared to the natural sediment. There is however a strong seasonal variation. The amount of tunnel silt significantly contributes to the total amount of silt in summer on the Molenplaat.

4.2.4 Transport analysis

An assessment was made of the transport fluxes of SPM in the estuary for the above given scenario (and for the natural background). The model grid was first aggregated into the 14 SAWES segments of the Western Scheldt (Van Maldegem, 1992; see Figure 2.1). An additional segment was added (No. 15) for the sea part of the model, not included in the model of Van Maldegem. Fluxes between SAWES segments and sedimentation per segment were determined for the T1 scenario simulations (Table 4.1 and 4.2). Separate analysis was made for the first and second half of the year.

Table 4.1 Transport of dumped tunnel silt between the SAWES model grid segments (Ktons)

Transport from→ to:	January - June	July- December	Total
segment 2→ upstream	7.1	9.6	16.7
segment 3→2	7.1	9.7	16.8
segment 4→3	7.8	10.3	18.1
segment 5→4	8.1	10.6	18.7
segment 6→5	11.2	13.9	25.2
segment 7→6	13.3	15.2	28.5
segment 8→7	17.1	18.6	35.7
segment 9→8	23.2	22.3	45.6
segment 10→9	28.0	25.2	53.2
segment 11→10	36.5	32.5	69.0
segment 12→11	53.4	36.5	89.9
segment 13→12	64.2	42.1	106.3
Segment 13	↑ **503 Kton dumped** ↓	↑ **503 Kton dumped** ↓	↑ **1006 Kton dumped** ↓
segment 13→14	384.8	423.6	808.4
segment 14→15	357.6	405.6	763.2
segment 15→ sea	347.2	401.5	748.7

From the dumping location (in Segment 13), approximately 80% of the dumped tunnel material is transported towards the sea (to segments 14), and 10% is transported upstream (to segment 12). The percentages are slightly different for the first and second half of the year. Eventually, 75% of the dumped material is transported out to the North Sea. Less than 2% of the dumped material is transported upstream beyond the model boundary.

Transport of all silt fractions between the SAWES model segments is shown in Figure 4.7

Table 4.2 Net sedimentation of tunnel silt (Ktons) per SAWES model grid segment

SAWES Segment Number	January - June	July- December	Total year
2 (part)	0.0	0.0	0.0
3	0.6	0.4	1.0
4	0.2	0.2	0.4
5	2.8	3.0	5.8
6	1.6	0.9	2.5
7	3.4	3.1	6.5
8	5.5	3.4	8.9
9	3.6	2.5	6.1
10	6.6	6.8	13.4
11	12.6	3.5	16.1
12	6.1	5.4	11.5
13 *	43.5	37.0	80.5
14	20.3	17.7	38.0
15 (new segment)	5.1	2.8	7.9
Total	111.9	86.8	198.7

* Silt is dumped in segment 13

Of the total amount of silt dumped, approximately 20% is sedimented in the Western Scheldt. Most of the sedimentation occurs near the dump location (segments 13-14). The amount which is not sedimented and not transported out of the system, remains in the Western Scheldt, and results in increased silt concentrations (4% of the total mass dumped). The total mass balance of tunnel silt and other silt fractions over a whole year for the tunnel dumping scenario are given in Table 4.3.

Table 4.3 Total mass balance for different silt fraction over the whole Western Scheldt for the complete year (Ktons).

Total Year	Tunnel silt	River silt	Sea Silt	Heavy silt
Loads (dumping)	1006	414.3	0.0	0.0
Outflow at river boundary	16.7 (1%)	-189.1	33.3	314.3
Outflow to sea	748.7 (75%)	649.0	140.9	2262.0
net sedimentation	198.8 (20%)	-71.7	-200.0	-3601.8
Change of Mass in system	41.3 (4%)	26.1	25.8	1025.5

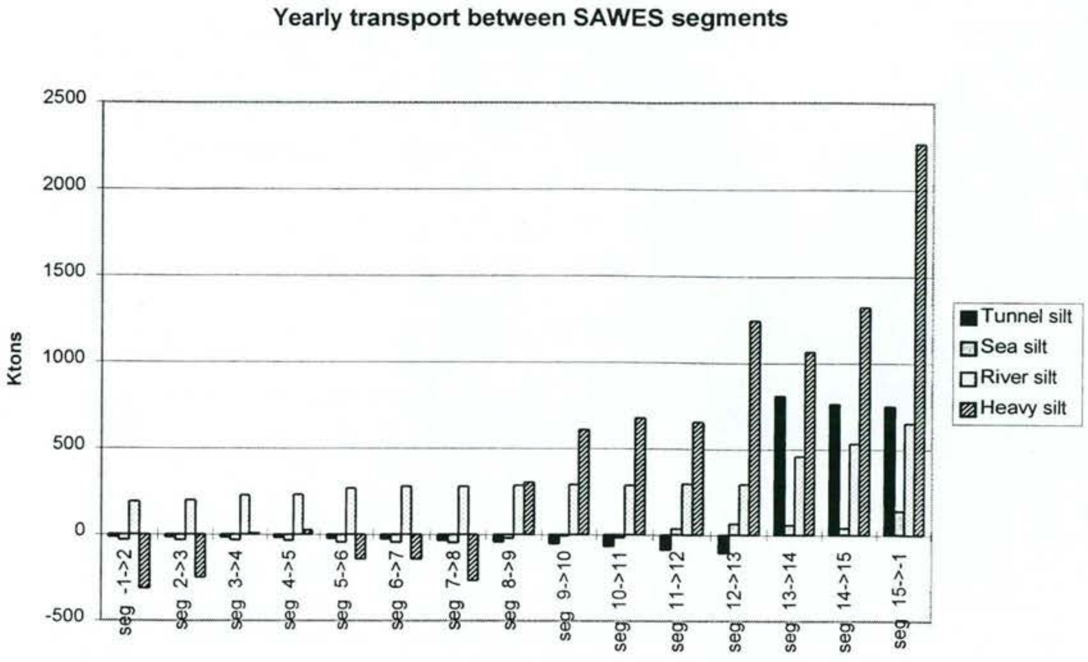


Figure 4.7 Transport of different silt fractions between the SAWES segments of the Western Scheldt

4.3 Conclusions

The amount of tunnel silt dumped may lead to an observable increase of SPM levels around Terneuzen and in an area of roughly 25 km around Terneuzen. This increase in SPM is only significant with respect to SPM background levels for the summer period. For the winter period, this increase is smaller than the natural fluctuations due to tide and wind, and can therefore probably not be discriminated from the natural background of SPM.

Remote Sensing techniques will most likely be able to detect a significant increase in SPM levels during summer. However, support of modelling results will be necessary to identify what SPM concentration increases can be expected in what areas during the tidal phases which correspond to the exact times of the images. Also a plume of SPM starting at the dump location and moving from west to east with tidal motion must be observable with remote sensing techniques. However, for winter periods this is again not possible since:

- natural backgrounds are too high for detection of the SPM plume;
- the cloud cover percentage and low sun angel are unfavourable for the use of remote sensing in these periods;

Unfortunately, the SPM continuous monitoring locations seem not be placed at representative locations:

- The Terneuzen monitoring location is almost at the dumping site, and therefore will measure only local effects and not say anything about the transport of dumped silt;
- The Baalhoek and Vlissingen stations are too far away for detecting a significant increase in SPM during summer;

With this respect, the remote sensing technique is probably (*for the summer period*) the most promising technique available for detecting the SPM increase from tunnel silt.

Any consequences for the environment are not discussed in this report, but are addressed separately in Baptist and Peters (1999). Main issues are probably related to primary production and consequences for fishery due to an increase in turbidity. This increase is not only influenced by the relative increase of SPM concentrations, but also very much affected by the inherent optical properties (especially the scattering efficiency) of the dumped silt, and its contaminants like 'bentonite'. These properties must be identified as soon as possible when the dumping starts, in order to make a correct judgement of the dumping effects for the local environment.
The present dumping can only serve as a test case, for the true T1-scenario. Most important limitations with respect to its validity are:

- the basic simulation was for 1998 (using e.g. 1998 wind conditions) and not for the real T1 period;
- the exact amount of dumped material (and its physical properties) are not known yet;
- the model is a simplification of the natural situation. Predictions still need to be justified/falsified by measurements during the dumping.

5 Monitoring of the ecological effects of the dispersal of tunnel boring material.

5.1 Introduction

The main focus of the RESTWES project was on the water column and the changes in suspended matter concentrations. However, these changes in suspended matter concentration can also affect the silt content of the bottom sediment and may have (negative) ecological implications. The use of remote sensing to classify the sediment composition of intertidal areas and to monitor possible ecological impacts of the dumping of tunnel boring material was the focus of the "RESTWES Ecology" component of the RESTWES project.

The goals of the RESTWES Ecology subproject were to:

1. Assess the potential ecological effects of the dumping of the tunnel material on the ecosystem of the Western Scheldt;
2. Establish a technique for the classification of sand, silt and vegetation on intertidal areas in the Western Scheldt using remote sensing imagery of the SPOT satellite;
3. Discuss the applicability of remote sensing as a monitoring technique to assess the potential ecological effects of the tunnel boring.

A comprehensive report of this study can be found in Baptist and Peters (1999), of which only a selection of the most essential information is presented in this chapter. In the next paragraph a brief description of the ecological functions of silt and the potential ecological effects of the dumping of tunnel boring material on intertidal areas is given. From this it may be concluded that the dumping of tunnel boring material may have a significant effect on the ecosystem, through various interrelated effects on the suspended particular matter concentrations and the sediment composition. Therefore monitoring of sediment in the intertidal areas within the Western Scheldt is required. Remote sensing images of the study area offer a truly synoptical view and may, besides being useful in assessing environmental changes in water quality parameters, be a supporting tool with respect to the assessment of changes in sediment composition of intertidal areas (Kokke, 1996). In section 5.3 the classification of sediment composition on tidal flats in the Western Scheldt, using a single SPOT image, is described. Finally, in section 5.4 the applicability of remote sensing as a monitoring technique for the potential ecological effects of the tunnel boring is evaluated.

This study was carried out in close co-operation between M.J. Baptist (WL | DELFT HYDRAULICS), S.W.M. Peters (Institute for Environmental Studies) and J.M.M. Kokke (National Institute for Coastal and Marine Management).

5.2 Potential Ecological effects of the dispersal of tunnel boring material.

Silt and silt-related processes are very important to the ecological functioning of the Western Scheldt. Any change in silt concentrations and silt characteristics may have an impact on the ecosystem. The most direct, physical effect of the dumping of the tunnel boring material is an increase in the suspended particulate matter (SPM) concentration. The increase in SPM can directly and indirectly affect several ecological processes in the water column and in the sediment. In this paragraph the ecological functions of silt are briefly addressed, and subsequently, potential ecosystem impacts of the dumping of tunnel boring material are discussed. A brief overview of potential effects of the dumping of tunnel boring material in the Western Scheldt. Emphasis is given to potential effects on intertidal areas and on the cockle (*Cerastoderma edule)*.

5.2.1 Silt and ecological functions

Silt* often is mentioned as an important substance in Dutch coastal waters. It is clear that silt plays a significant role in chemical, physical and biological processes. Notable aspects of silt related processes are the formation of salt marshes and sedimentation on tidal flats.

Silt affects ecological functions† by influencing:

1. **Morphology**

   Morphological processes that are affected by silt are:

   - floating, transportation, flocculation, sedimentation, consolidation and erosion;
   - the presence and transport as diluted fluid mud and HCBS;
   - the blowing of silt to coastal dunes;
   - the accumulation of silt on flats;
   - the capture, fixation and release - bio(de)stabilisation - by biota such as filterfeeders (Mussels, Cockles, *Ensis, Spisula*), seagrass beds, salt marsh vegetation, cyanobacterial mats and diatom mats.

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*In this study the following definition holds for *silt*:

<u>Silt</u> is the fraction of the sediment smaller than 63μm, with or without adsorbed organic (C, P, N) or inorganic material and in a floating or (not-consolidated) sedimented condition.

Silt is in a dynamic state: dependent of time, place and physical-chemical-biological surroundings, the quantity of adsorbed organic or inorganic material, shape and size of the resulting complex and the position in the water column, bottom or organism will vary.

† The following definitions with respect to *ecological functions* is used:

<u>ecological functions</u> are processes and interactions within and between abiotic and biotic components of the ecosystem yielding a certain <u>product or service</u>

An <u>ecological product</u> is a measurable quantity such as the biomass of Cockles or the surface area of salt marshes.

An <u>ecological service</u> is a measurable quality such as the buffer against coastal erosion or possibilities for recreation.

2. **Habitats and substrate**

   Processes related to silt that affect the substrate and habitats for biota are:

   - the presence of gradients in sediment composition that is favourable to certain benthic species;
   - the presence of flocs as substrate for bacteria.

3. **Food**

   Processes that are affected in relation to food are:

   - the physical-chemical adsorption of organic material and inorganic nutrients;
   - the exchange of adsorbed organic material with dissolved organic material;
   - the sticking of living cells of algae and bacteria; the consumption by detritus eaters,
   - the filtering by suspension feeders,
   - the bacterial decay and subsequent promotion of mineralisation in sediment and water column and
   - the release of nutrients for primary production.

4. **Water quality**

   Processes related to the quality of the water are:

   - the extinction of light in the water column,
   - the influence on water purification by suspension feeders,
   - the accelerated sedimentation of dying phytoplankton blooms by sticking and flocculation.

5.2.2 Potential ecological effects

Increased suspended sediment

An increased Suspended Particulate Matter (SPM) concentration is especially harmful to ecological processes in the water column, but it may, directly or indirectly, also affect ecological processes that take place in the intertidal areas:

- Phytoplankton is an important food source to the benthic species on intertidal areas. An increased turbidity may lead to a decrease in primary production by phytoplankton.
- A burial by sediment may affect the primary production of phytobenthos.
- An increased SPM may affect the respiration of larvae and the gas-exchange of eggs of fish and shrimp. SPM concentrations over 100 mg/l may lead to an increased mortality (Van Dalfsen, 1994). An increased SPM concentration may also hinder the functioning of the gills of fish.
- Birds and fish that hunt by using their eye-sight can also be sensitive for an increase in turbidity.
- a decrease in the growth rate of filter feeders may result from clogging of the food uptake system combined with a decrease of phytoplankton concentration and food quality (organic to inorganic ratio). As an example: an average Blue Mussel (*Mytilus*

edulis) of 3 centimetres of length will cease filtering at a suspended solids concentration of 250 mg/l.

Burial of Benthic Organisms

An increased sedimentation near the dumping site can lead to burial of benthic species by a layer of (mostly anaerobic) sediment. The sensitivity of benthos for burial is dependent on the ability to grow or move upwards.
The potential effects of burial can be subdivided into effects of an incidental, but large, deposition and effects of a continuous (mostly small) deposition.

1. Incidental deposition

- Non-mobile species, such as the Blue Mussel (*Mytilus edulis*), anemones and oysters are very sensitive to an incidental deposition, resulting in burial of the organism. Other species are more capable of surviving an incidental deposition, either by moving or growing upwards to the sediment surface.
  For benthic organisms a 'fatal depth' can be defined, which denotes at what depth of incidental burial the organism will not survive. This fatal depth is species dependent, but also differs with the type of sediment. The fatal depth for incidental deposition of silt for e.g. the Blue Mussel is 1 cm, the Cockle (*Cerastoderma edulis)* may survive until a depth of 11 cm (Essink ,1993).
- Besides the physical effect of burial, chemical effects of the anaerobic sediment, often together with high sulphide concentrations, play a role. A decreased dissolved oxygen level can amplify the effects of an increased sedimentation. The cleaning of the siphons at an increased sedimentation flux will cost more energy, while at the same time the oxygen levels are lower. The tolerance levels for low oxygen levels and high sulphide levels differ between species. 50% of the Blue Mussels will survive an exposure time to anaerobic conditions (< 0.2 mg O_2/l) of 800 hours and an exposure time to high sulphide concentrations (7 mg/l) of 600 hours. Corresponding numbers for the Cockle 100 hours to anaerobic resp. 100 hours to sulphide rich conditions.

2. Continuous deposition

- A continuous deposition of material to the bottom can have negative effects when the sedimentation rate is higher than the velocity at which the organisms can move or grow upwards. The sensitivity to a long-term continuous deposition again is species dependent and also dependent on the type of sediment. A continuous deposition of silt is in general worse than a deposition of sand.

Siltation on tidal Flats

The substrate composition is important for the benthic communities on intertidal areas. Substrate composition is measured as silt content, median grain size, and organic matter content. The composition is influenced by hydrodynamics and the presence of benthos on the flat which can influence the stabilisation, bioturbation and erodability of the substrate.
A certain amount of the tunnel material may eventually accumulate on the tidal flats of the estuary. This can result in an increased bottom silt content (siltation). In general, highest

densities of benthic species are found in net sedimentation areas, where the deposition of organic material and nutrient concentrations are relatively high.

Bottom siltation could result in:

- a change of habitat distribution.
- a decreased suitability for specific species when the bottom silt contents is very high.

Because the tunnel boring material is mostly inorganic (only 1% organic material) the silt does not have any nutritional value.

Fluid mud

Fluid mud is a suspension of silt with a concentration of more than 10 grams per litre. It has a non-Newtonian behaviour and can be transported under certain circumstances with a current velocity of more than a few metres per minute.

- A direct effect of fluid mud may be that benthic organisms are destroyed when fluid mud separates them from the overlying water upon which they depend for respiration and food (Allen & Hardy, 1980). Information about the recovery time from fluid mud impacts is not well known.
- A long-term potential impact of fluid mud is the later resuspension of sediments into the water column, thus increasing turbidity.

A fluid mud layer may originate nearby the dumping site of the tunnel boring material. It is expected that when this layer reaches the gullies it will resuspend into the water column, due to the dynamic conditions. Therefore monitoring of the presence of fluid mud is recommended.

Drilling mud

A by-product of the tunnel boring is the formation of solid and liquid waste products such as cuttings and drilling muds. Water based drilling muds (WBM's) are aqueous suspensions of clays or polymeric substances which are used to assure the transport of the cuttings to the surface, to clean the drilling hole, to avoid the undesired entry of fluids and to support the bore hole.

The tunnel boring in the Western Scheldt will be carried out with bentonite (as a viscosifier) in the drilling fluid. Bentonite is a mixture of clay-minerals, that contains at least 70% (usually 85% - 90%) minerals. The discharged fraction of the tunnel boring material is expected to contain about 1.5% - 2% bentonite. The bentonite particles are small ($< 1 \mu m$) and are suspended in water or present as a colloid suspension.

Possible effects of bringing the drilling mud in the Western Scheldt are:

- a sealing of the top sediment (one of the applications of bentonite being to seal a sandy layer during drilling by virtue of decreasing of the water permeability of sand). Theoretically this may have detrimental effects on the benthic organisms in the estuary. However, it is to be expected that a concentration of 1.5% to 2% of bentonite will hardly affect the permeability of sand (COB, 1999).
- due to the chemical characteristics of bentonite, it may adsorb heavy metals present in the Boomse klei. It may even result in heavy metal concentrations that exceed the intervention concentrations. This is dependent on the natural concentrations of heavy

metals within the Boomse klei and the number of recirculations of the bentonite in the tunnel boring process (COB, 1999).

- It is not clear whether the drilling fluid in Western Scheldt will contain NaCMC (sodium carboxymethylcellulose) as was the case for the second Heinenoord tunnel (COB, 1999). This cellulose derivative causes a slowing-down of the biodegradation of the material and may have toxic effects. A toxicity test showed no evidence of this having lethal effects to the marine diatom *Phaeodactylum tricornutum* or the brine shrimp *Artemia salina*, which are Mediterranean species (Terzaghi et al., 1998).
- An algal growth inhibition test on water based drilling muds showed some of the products added to that surfactants, lignosulphonates and shale stabilisation agents may inhibit algal growth, dependent on the dilution of the muds (Terzaghi et al., 1998).

Cockles in the Western Scheldt

Cockles are a very important food source to water birds and are also an economic resource in the Western Scheldt. Because of their importance for both ecology and economy, special attention must be paid on the potential effects of the dumping of tunnel boring material on cockles. Cockles prefer the intertidal zone, but they don't live high in the intertidal zone, because there they don't have enough time to feed. Cockles prefer a salinity range of 15‰-20‰ and sediments with a median grain size of about 50μm - 175μm. Their food consists of plankton and detritus which it filters out from the water column. The cockle is often found in dense beds with a density of more than 50 individuals per m^2. The cockle stock shows large year-to-year variations, primarily as a result of winter temperatures. Furthermore, cockle beds are intensively exploited by cockle fishers. Moreover the cockle biomass is not constant over a year (highest biomasses are generally found from August to October) . Starting in 1992 the RIVO yearly monitors the cockle stock in the Western Scheldt. The area of littoral cockle beds between 1992 and 1995 ranged between 1200-1500 ha. Figure 5.1 presents the observed yearly-averaged biomass of Cockles expressed as ash-free dry weight (AFDW) in the Western Scheldt. The Western Scheldt does not have areas that are closed to cockle fishery. There are several cockle beds near the dumping location of the tunnel sediment.

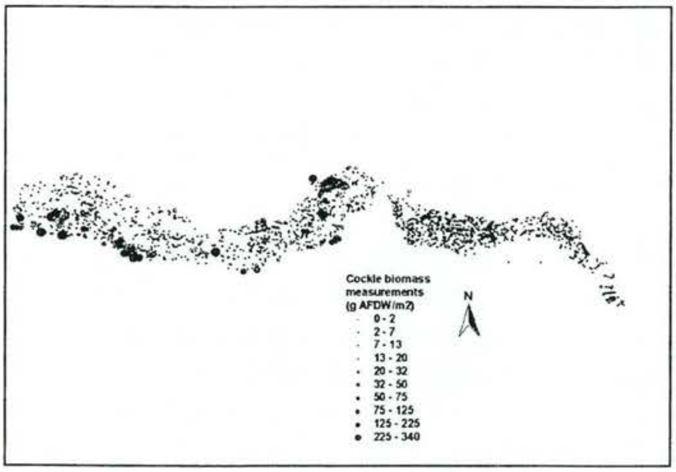


Figure 5.1 Observed biomass (g AFDW/m^2) of Cockles (*Cerastoderma edule*) in the Western Scheldt.

Possible effects of dispersion of tunnel boring material are:

- The cockles which are present near the dumping location may suffer from burial by the sediment by either an increased sedimentation rate of suspended sediments, or worse, by a fluid mud layer. Van Dalfsen (1994) found a high mortality of cockles in a littoral bed after the discharge of dredging material containing 30-50 g silt per litre on the Wadden Sea near Friesland.
- Another potential effect is the decrease in food uptake and growing rate of cockles as a result of the increased suspended particulate matter concentrations. Cockles are probably more sensitive to increased SPM concentrations than mussels. When the SPM concentration reaches more than 50 mg/l the cockles will loose too much energy to grow (Tydeman, 1996). Combined with a decrease in available food (phytoplankton) this can have a synergistic negative effect on the health of the cockles.
- Siltation of the intertidal areas with highly inorganic fine sediments may alter the suitable habitat for settlement of larvae, bury larvae and change habitat conditions of adult cockles.

Effects of the dumping of tunnel boring material can be minimised by dumping in autumn or winter, out of the reproductive season of the cockles, when their demands for food are low (Essink, 1993).

5.2.3 Remote Sensing as a monitoring tool

From the previous section it may be clear that the dumping of tunnel boring material may have a range of effects on the ecosystem of the Western Scheldt, through various interrelated effects on the suspended particular matter concentrations and the sediment composition. Any detrimental effect of the dumping of tunnel boring material to cockle beds, especially those near the dumping location, may lead to claims of fishermen.

Mapping of surface sediments in intertidal areas by conventional methods involves extensive sampling programmes that are often difficult in practice, time consuming and expensive in manpower. No matter how extensive such programmes are, the accuracy of the resultant maps is limited by the need to extrapolate from sample sites to the whole area, usually by linking similar sites in a series of contours.

It was already demonstrated in previous chapters that the use of remote sensing images, providing a synoptic spatial coverage of the study area is very useful in assessing (changes in) water quality parameters. In the remaining part of this chapter possibilities to use remotely sensed optical information of the same type to map and monitor sediment grain size on tidal flats will be addressed. Furthermore 2 examples of the added value of mathematical modelling to study effects of the dumping of tunnel boring material are given.

5.3 Optical Remote Sensing for Sediment Classification

A classification of silt, sand and vegetation on intertidal areas from remote sensing data has been previously carried out by Rijkswaterstaat with the use of a Landsat Thematic Mapper image (Kokke, 1996; Van Essen & Hartholt, 1998). The RESTWES Ecology study continued with the experiences learnt in these previous studies and uses SPOT-HRV images instead of Landsat.

5.3.1 Materials and method for Classification of Sediment Composition

In situ measurements.

The bottom sediment composition of the Western Scheldt has been extensively measured in 1992 -1993 (McLaren, 1993; McLaren, 1994). Samples were taken each 500 metres and in some places with a density of 250 metres. This data set, which is called the McLaren data set, contains the grain size distribution of the samples, expressed in so called *PHI*-units‡.
For this study, the median grain size distribution data, which are also given in the McLaren data set, were imported in a GIS (ArcView). The median grain size distribution for the Western Scheldt is presented in Figure 5.2.

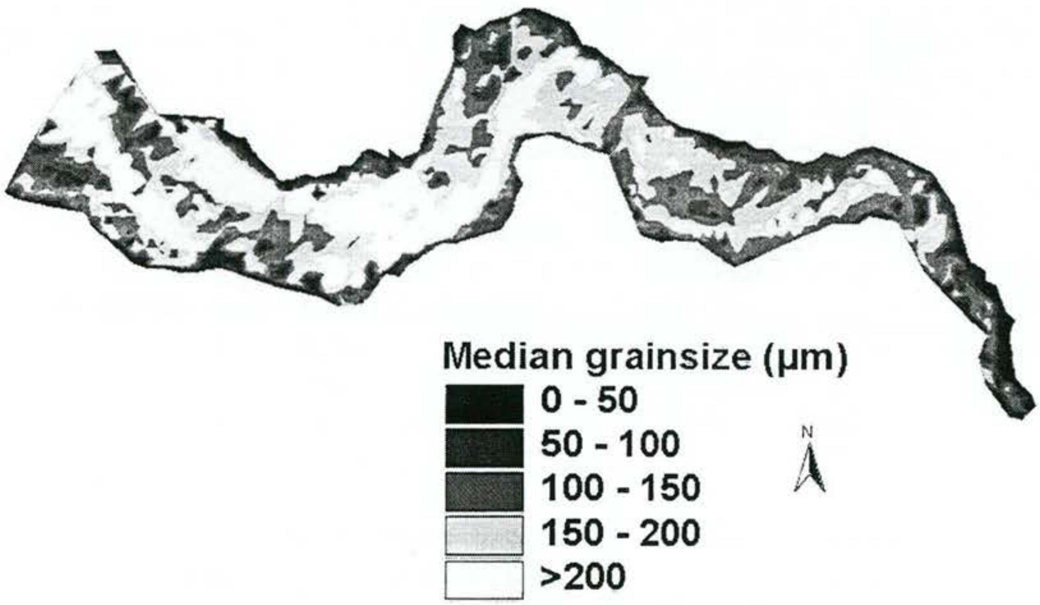


Figure 5.2 Median grain size distribution, based on McLaren data set.

‡ *PHI*-units are defined as follows:

$PHI = -\log_2(D)$ *with: D = grain size diameter in mm.*

Thus, silt-particles with grain sizes between 2µm and 63µm, have PHI-units 9 (2 µm) to 4 (63 µm).

Remote sensing data.

A single SPOT image (7 May 1996) is used in this study to classify the sediment composition of the intertidal areas in the Western Scheldt. Use has been made of a single image of the SPOT-HRV sensor, which records information in three specral bands:

- Band 1: 500 - 590 nm; green
- Band 2: 610 - 680 nm; red
- Band 3: 790 - 890 nm.; near-infrared

A spectral reflectance diagram (reflectance as a function of wavelength) for bare sediment shows an increasing reflectance with wavelength, without dominance of certain wavelengths. The idea behind classification of sediment composition using spectral reflectance is that grain size characteristics and moisture content of a certain sediment type is correlated well enough with (part of) the related spectral reflectance in order to be able to classify sediment composition on the basis of spectral reflectance in a limited number of spectral bands (Kokke, 1996).

Atmospheric correction.

Removal of atmospheric and phase angle effects require information about the gaseous and aerosol composition of the atmosphere and the bi-directional reflectance characteristics of elements within the scene. However, atmospheric and bi-directional reflectance information are rarely available for historical remotely sensed data. Factors such as sun angle, Earth/sun distance, detector calibration differences between the various sensor systems, atmospheric condition, and sun/target/sensor geometry (phase angle) will affect pixel brightness value. Differences in direct beam solar radiation due to variation in sun angle and Earth/sun distance can be calculated accurately, as can variation in pixel brightness values due to detector calibration differences between sensor systems.

A relatively straightforward "empirical scene normalisation" technique can be employed to match the detector calibration, astronomic, atmospheric, and phase angle conditions present in a reference image, for which the atmospheric conditions at the time it was acquired are known, so that atmospheric correction for that particular image is possible. By identification of so called normalization targets in the atmospherically corrected image, i.e. pixels with time invariant spectral reflectances, it is possible to normalize any other image of the same area. After normalization the reflectance of this target will be identical to that in the reference image. Once this is achieved, differences/changes in brightness values between different normalized images may be related to differences/ changes in surface conditions.

Classification methods.

Linear regression:

Linear regression between the means of the median grain size of in situ samples and the associated spectral in band reflectances were used to correlate grain size and spectral reflectance. In this case the linear correlation between in band reflectances and median grain size was optimised for the mean D50-values and the mean LN(D50)-values, which results in the assessment of coefficients α_1 to α_3 in:

$$D(50) = \alpha_0 + \alpha_1 \cdot b1 + \alpha_2 \cdot b2 + \alpha_3 \cdot b3$$

respectively:

$$LN(D50) = \alpha_0 + \alpha_1 \cdot b1 + \alpha_2 \cdot b2 + \alpha_3 \cdot b3$$

(in which: α_i = coefficient, *bj*= reflectance in band i)

Band ratioing:

Another classification technique, which is frequently used when remote sensing data are involved is spectral band ratioing. Use is made of the fact that specific features in multispectral imagery can be enhanced by using ratios of individual spectral bands or ratios of mathematical functions of spectral bands and by displaying the various ratios as colour composites.

A well known example of using ratioing is the NDVI[#] (Normalised Difference Vegetation Index), which is an excellent means of measuring the vegetation cover. The NDVI varies with the absorption of red light by plant chlorophyll and the reflection of infrared radiation by water-filled leaf cells. It is correlated with photosynthesis that occurs in the green parts of a plant and is therefore used to monitor the density and health of green vegetation. A higher NDVI value indicates greater vegetation density/health.

In this study the suitability of a number of band ratios to classify the remote sensing image in terms of sediment composition was considered.

[#] The NDVI is calculated from the red and near infrared portion of the spectrum:

NDVI = (NIR-RED) / (NIR+RED)

For the SPOT satellite Bands 2 and 3 are used: NDVI = (B2-B3)/(B2+B3).

5.3.2 Data processing

Procedure

The goal of the investigations being to establish a multitemporally valid algorithm which describes the relation between spectral reflectance and sediment composition and thus to be able to monitor sediment composition with remotely sensed spatial optical data the following sequence with respect to the data processing was designed:

i. atmospheric correction of the remote sensing image or (in case of monitoring) of a selected reference image (a particular remote sensing image, for which the atmospheric conditions at the time it was acquired are known, so that proper atmospheric correction is possible);
ii. geometric correction of the remote sensing image or (in case of monitoring) of the reference image to enable direct comparison with McLaren sample data;.
iii. (in case of monitoring) identification of normalisation targets in the reference image (areas with time invariant spectral reflectances);
iv. (in case of monitoring) scene normalisation of all other remote sensing images; this results in reflectance images, exhibiting identical reflectances at the position of the normalisation targets; differences/changes in brightness values between different normalized images may be attributed to differences/changes in surface conditions;
v. separation of areas on the river side of the dike from those on the landside;
vi. identification of those areas in the remote sensing image, which are above the actual water level, i.e. separation of land and water, which can be done spectrally by using information from the image itself in the near infrared portion of the spectrum;
vii. separation between vegetated areas and bare soil by application of the NDVI on all samples above the actual water level;
viii. selection of the McLaren samples covering the non vegetated areas above mean water level (alternatively: above the actual water level); identification of the in-band reflectances for those locations in the remote sensing image, which correspond with the McLaren sample locations;
ix. assessment and validation of an optimal algorithm, which relates (a combination of) spectral reflectance values with sediment grain size in terms of D 50 values, by application of either multiple linear regression or band ratioing;
x. application of this algorithm to the rest of the remote sensing image; i.e. to all pixels above the actual water level;
xi. integration and presentation of all information layers, which may be realised in an image processing system or alternatively in a Geographical Information System (GIS).

Result *Multiple linear regression*

Linear regression was applied both to median grain size values and to the natural logarithmic of median grain size. A slightly better correlation was found between the band reflectances and the natural logarithmic of the median grain size values. The coefficients found are shown in Table 5.1. It has to be stated that the coefficient of correlation r^2 (0.5371), which was found in this experiment, is relatively low. Furthermore it is noteworthy that the coefficient α_1 in the linear regression for LN(D50) has a value of zero, in other words, band 1 does not explain any of the variance. Figures 5.3 a. and b. present the correlation between the 'predicted' median grain size values (resulting from application of the coefficients of Table 5.1) and the measured McLaren data.

Table 5.1 Multiple linear regression results.

Coefficient	D50 r^2=0.4938	LN(D50) r^2=0.5371
α_0	56	4
α_1	176	0
α_2	2302	32
α_3	-1508	-21

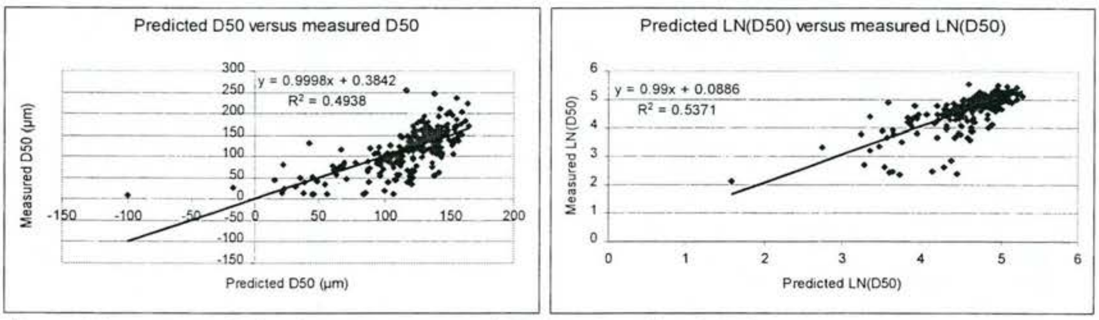


Figure 5.3: a. correlation between measured D50 and predicted D50.
b. correlation between measured LN(D50) and predicted LN(D50).

The correlation between predicted D50-values, resulting from application of the best linear regression result as represented by the equation $D50 = \exp(4 + 32 \cdot b2 - 21 \cdot b3)$, and the measured D50-values is presented in Figure 5.4.

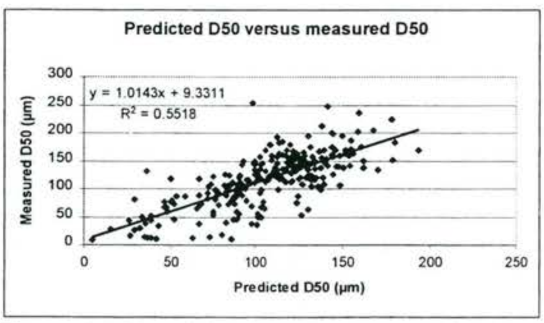


Figure 5.4 Correlation between measured D50 and predicted D50 using D50=exp(4+32*b2-21*b3).

Result *Band ratioing*:

For each of the grain size intervals, the mean of the median grain size values and the mean of the natural logarithmic of the median grain size values were correlated with in band reflectances or ratios of in band reflectances. Table 5.2 presents resulting correlation coefficients for correlation with the mean of D50 or mean of LN(D50).

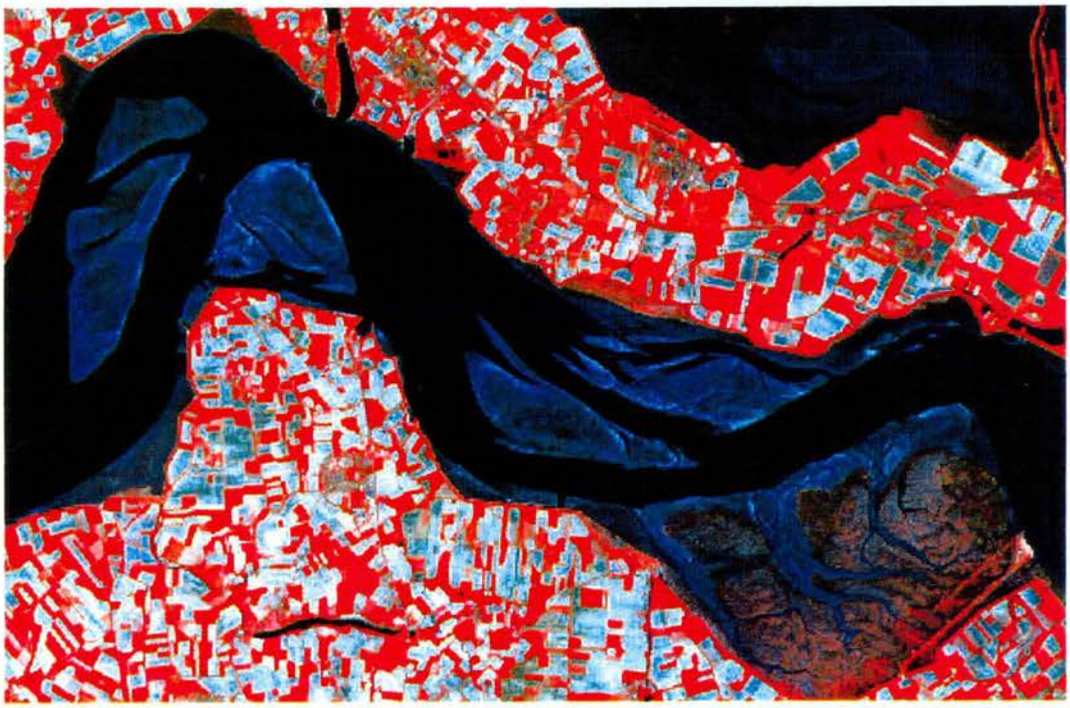
Table 5.2 Correlation coefficients between the (ratios of the) spectral bands and the mean of D50 and LN(D50).

	Mean of D50	*mean of LN(D50)*
D50	1	
LN(D50)	0.952485	1
b1	0.973787	0.943938
b2	0.973298	0.939838
b3	-0.7664	-0.91625
b1/b2	-0.91122	-0.88049
b2/b3	0.968034	0.993656
b1/b3	0.961693	0.995092
(b1+b2)/b3	0.965176	0.994583
(b2-b1)/(b1+b2+b3)	0.893359	0.831872
(b3-b2)/(b3+b2) = NDVI	-0.95566	-0.99653
(b1-b2)/(b3-b2)	-0.6714	-0.53661

The individual bands b1 and b2 have the highest correlation coefficients with the mean of D50. Several band ratios correlate quite well with the mean of the natural logarithm of D50.

Result *Image classification*

The equation for $D50 = \exp(4+32*b2-21*b3)$ was applied to all image pixels above water level to obtain an estimation of median grain size for each pixel in the SPOT image. The image is presented in false colour (band 3 in red, band 2 in green, band 1 in blue) in Figure 5.5 (upper figure). The resulting image for the Western Scheldt is presented in Figure 5.5, lower figure, in which also the observed McLaren samples for median grain size, classified in identical classes, are shown. The procedure described above was followed to do this. The map distinguishes between the landside (no colour) and the river side of the dikes (coloured); the area outside the dike is classified into water (blue) and land/dry fallen areas; the dry part exhibits vegetated parts (darker green indicating denser vegetation cover/healthier vegetation) and bare soil, which is classified in 5 classes w.r.t. median grain size.



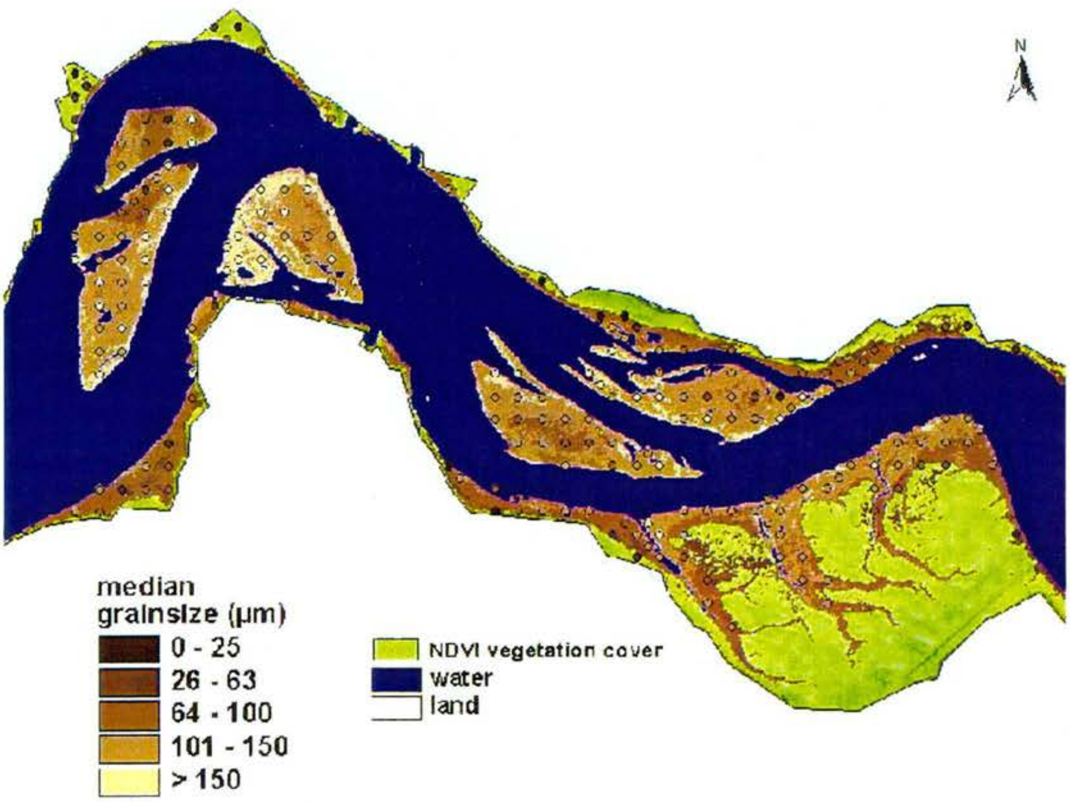


Figure 5.5. upper figure: False colour SPOT-HRV image of the study area; data are optimised as to show remotely sensed reflectance contrast of the intertidal mud flats.

Figure 5.5. lower figure: Interpreted SPOT image, classified for median grain size (5 classes), water and vegetation; McLaren sample locations (open circles) and associated local grain sizes are added, following the same legend.

5.4 Discussion

The correlation between estimated median grain sizes from optical remote sensing imagery of 1996 and from McLaren analysis of in situ measurements of 1993-1994 is not quite strong (the coefficient of correlation r^2 being 0.5371). In fact this already indicates that it is not straightforward to associate optical reflectance data of bare sediment with physical grain size samples in an unambiguous way. In other words, it is difficult to provide a means for very reliable mapping (and monitoring) of grain size distribution with optical remote sensing. Some of the specific properties of remotely sensed data and differences between remote sensing information and information from in situ sampling partly account for this. On the other hand the dynamic character of intertidal areas, both in time and space, also plays a role. Relating the most important aspects to spatial respectively temporal scale effects, the following list may be drawn up:

In situ sampling vs. Remote Sensing:

- Spatial scale aspects:
  - While sediment moisture does not play a role in the determination of an in situ sediment sample, it surely affects the reflectance of sediment in the sense that a pixel with the same sediment composition but a higher moisture content will exhibit a lower reflectance for all optical wavelengths. The actual sediment moisture is correlated to the sediment composition itself, but will on the other hand be influenced by the tidal stage, which is of course not constant over time nor over the entire area covered by the remote sensing image. Therefore moisture contents may have a negative effect on the quality of the sediment grain size estimation from optical information
  - The taking of a McLaren sample is typically a point measurement and offers a direct way of measuring the grain size of the first 5 top centimetres of the sediment present at a particular point in space (at a particular time). A common property of all remote sensors is that a single pixel typically represents averaged information coming from an area of many square meters (a SPOT pixel measures $20x20m^2$). Moreover the spectral reflectance of a pixel only reflects the optical properties of the top millimetres of the sediment surface and only gives indirect information on grain size. This may cause a certain discrepancy between results derived from remotely sensed optical data and McLaren grain size, e.g. at locations where the top layer is not very well mixed, as is the case when a thin layer of silt is deposited on top of a sandy layer.
- Temporal scale aspects:
  - It has to be stated here that it is important to have remote sensing data and in situ data available of approximately the same period (season) in order to minimise this effect (especially if the same algorithm will be used over a longer period).
  - The registration time of information on an area like the Western Scheldt by satellite remote sensing instrument is typically in the order of seconds, while an extensive McLaren sampling of the same area will take many months (and involves a lot more manpower and costs!). In view of seasonal changes it may be concluded that this will hamper direct comparison between remote sensing information and in situ data and will make the establishment of a sediment classification method using remote sensing difficult.
  - The acquisition dates of the data used for the sediment type mapping in this study are:
    in situ data (McLaren sampling) : autumn 1993- spring 1994

remote sensing image (SPOT-HRV) : May 7, 1996.
In view of the dynamic character of the sediment composition in the Western Scheldt area the time lapse between in situ and RS data used in this project does not permit to establish a very reliable sediment classification algorithm.

Dynamic nature of grain size:

- Variations on a spatial scale:
- Tidal stage affects both the area above mean water level present on a remote sensing image and the moisture contents of the sediment. In relation to this mean low tide (MLT) or lower must be regaded the optimal tidal stage for remote sensing classification of sediment grain size in an intertidal area. However, water levels are typically variable within an area like the Western Scheldt, so it is impossible to have an optimal situation for all locations within a synoptic satellite image.
- The covering of a sandy location by a veneer of muddy sediment may result in a different spectral reflectance as compared to a location with essentially the same sediment composition but without a muddy top layer.
- The permeability of sediment is dependent of the silt content. Already a relatively small percentage of silt added to the sediment will decrease the permeability of the sediment with some orders of magnitude. As a rule of thumb: a sandy bottom (<5% silt) will drain water, but a silty bottom (>5% silt) will retain water. All silty sediments will stay wet during the ebb-cycle, and may even be covered by a film of water. This effect seriously hampers grain size classification with remotely sensed imagery.
- Atmospheric circumstances may very well be variable over the area covered by the remote sensing image. This may result in differences in sediment colour (which the algorithm used does not account for) causing erroneous sediment classification
- Variations on a temporal scale:
- In theory a certain location with a time invariant sediment composition may exhibit a varying spectral behaviour over time. This variation may be the result of e.g. the difference in sediment moisture contents of the top layer or the covering with a thin muddy top layer.
- Benthic algae may develop on top of the sediment. These algal mats form a thin, brownish layer on top of the sediment, especially during warm and sunny conditions. The reflectance characteristics from algal mats may alter the total reflectance from the pixel involved a little or even quite drastically (depending on the relative extent of algal mats within the pixel area). Pixels exhibiting algae should in fact be excluded from application of the grain size algorithm. They may be extracted spectrally from the remote sensing image itself with some kind of vegetation index (e.g. NDVI). However, so called mixels (pixels with a mixture of bare soil and algae cover) will always be there and may influence the performance of the algorithm negatively, if included in the analysis.
- On the other hand it is known that algal mats develop in silty areas, so this information may be used for classification in an indirect way. Alternatively, the grain size of areas covered with algae may be estimated by interpolating results of surrounding pixels.
- There are large seasonal changes in bed sediment composition of intertidal areas. In general there will be a build-up of silt in spring (probably related with diatom growth and suspension feeder biodeposits). The situation more or less remains the same during summer and autumn and collapses during winter. The correlation between synoptic

remote sensing data and in situ data, which are collected over a number of months, will of course suffer from this.

- Solar irradiation, wind speed and temperature may be important (medium and long term) meteorological factors with regard to e.g. evaporation and frosting of the top layer. Under dry conditions in summer, a crust may form on top of the sediment. This may significantly change the reflectance characteristics. In winter, an ice-layer may form on top of the sediment, again changing the reflectance characteristics. This kind of effects hamper long term applicability of a classification algorithm.

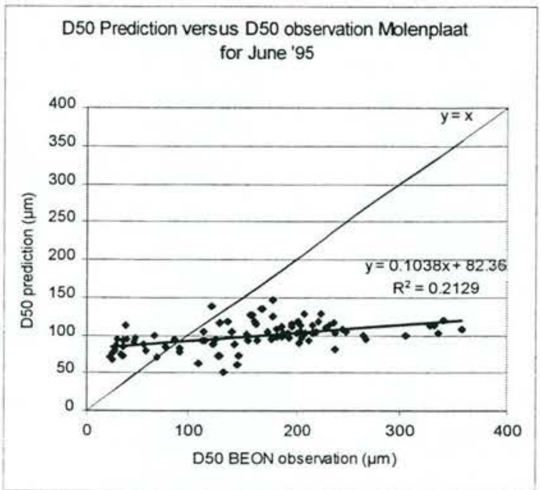
In the framework of a research project to the relation between physical parameters and the distribution of macro-benthos on the Molenplaat, a small intertidal area in the upper middle part of the Western Scheldt estuary (Herman et al, 1996; Thoolen et al., 1997) median grain size values were measured through the year 1995 (in March, June, September and December) on the Molenplaat. Results of a comparison between results of this project, the in situ measurements of 1993-1994 and the classified remote sensing results of Fig. 5.5 may underline some of the aspects treated above. The comparison revealed the following:

- correlation between the sets of 1995 Molenplaat data and McLaren data collected in the winter of 1993-1994 is reasonable, except for the month of June (see Table 5.3). Also in view of the different treatment of samples in case of the Molenplaat-samples as compared to the McLaren samples it is rather speculative to directly relate the results of this comparison to one of the aspects mentioned above. But at least some of the seasonal dynamics of sediment composition seem to be reflected by those results.

Month.	Correlation coefficient r^2
March	0.70
June	0.34
September	0.76
December	0.80

Table 5.3 Correlation between observed McLaren D50 and observed Molenplaat '95 D50 results.

- The correlation between the data of Molenplaat of June 1995 and the associated median grain sizes as derived from the SPOT image appeared to be weak, as is illustrated in Figure 5.6a. The range in the observations on the Molenplaat is much wider than the range in the SPOT-results, which in fact can be visually confirmed by taking (literally) a closer look at the data (see Figure 5.6b, which is a combination of interpreted SPOT data and year averaged Molenplaat data). In other words: use of the algorithm found by combination of SPOT and McLaren data leads to underestimation of grain size values over 100μm, but to overestimation of grain sizes below 100μm. Clearly the algorithm found cannot be applied to reproduce grain sizes on the Molenplaat in June 1995.



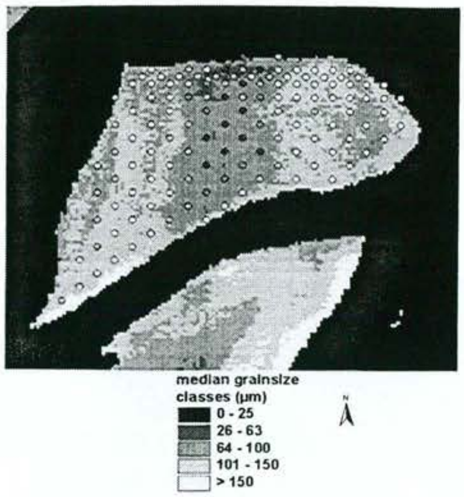


Figure 5.6a. D50 measurement June '95 versus D50 SPOT-results for the Molenplaat.
Figure 5.6b SPOT median grain size results for the Molenplaat combined with year averaged in situ measurements of median grain size for the year 1995 (open circles).

- It is interesting to see (Figure 5.5, lower figure) that the correlation between the subset of McLaren median grain size data of 1993-1994 on the Molenplaat and the classified SPOT image was also very poor. This indicates that
  1) in specific: the sediment composition of the Molenplaat does not fit in very well in the overall picture of the Western Scheldt,
  2) in general: application of an algorithm, which is optimised for the entire area (being based on correlation of remotely sensed data with all available ground samples) may be locally inadequate.

5.5 Conclusions and recommendations

In view of :
a) the highly dynamic character of the area both in spatial and temporal respect
b) the practical imperfection of having to calibrate simultaneously remotely sensed optical spatially dense data with relatively sparse ground sample data, which have been collected over a long period of time, and
c) the possible differences between a (extended) remote sensing pixel and a ground (point) sample in terms of area represented, volume and grain size distribution,

it will be difficult to relate optical satellite imagery to sediment grain size in a reliable quantitative way.

But, still, a satellite image provides a snapshot like overview of a greater part of an area like the Western Scheldt. A sediment grain size map as it is derived from a satellite image offers a truely synoptic overview of the sediment distribution of the area. Application of atmospheric correction to a series of images (which minimizes disturbing atmospheric effects introduced by e.g. differences in solar angle, haze) enables in principle direct comparison and monitoring. By virtue of the spatial resolution of a remote sensor (the SPOT-HRV pixelsize equates to a sediment sample site in every $20x20m^2$ over the entire intertidal area) a coverage is achieved which could only be attained in theory by a highly intensive sampling programme (which of course in practice is impossible, because the number of sampling points would have to be increased by a factor of at least 150). The (pre)processing and sediment grain size interpretation of a remote sensing image typically takes a couple of days (once the remote sensing image is delivered) and is relatively inexpensive in comparison with mapping on the basis of an in situ sampling programme. Offering a relatively dense spatial network of 'measurements' remotely sensed data are very suitable to be combined with other spatial data (e.g. in a Geographical Information System (GIS)) to provide added value to policy making, management and research and/or also to increase the reliability of resulting grain size maps.

In the research described here the median grain size was chosen as the parameter to be mapped, in contrast to earlier work (Kokke (1986), Van Essen & Hartholt (1998), where the amount of silt was mapped. Silt being the interesting factor, this does not seem to be the optimum choice. Median grain size is only representative for silt in an indirect way, because it is also, and even for the larger part, determined by the amount of sand present. The sediment in the Western Scheldt area often exhibits a relatively large sand fraction; therefore the median grain size will only slowly vary when siltation occurs, so te median grain size is not a very good indicator when monitoring of silt is aimed at (de Jong, 2000).

Adopting the approach of Van Essen & Hartholt (1998), the accuracy of the interpretation might be further increased by subdividing the total area and assessing an individual algorithm for each of the subareas (of course at the cost of manpower and time consumption). Information on elevation of the area combined with tidal stage/water levels may be helpful in selecting subareas for this purpose.

6 Blueprint of an operational monitoring framework

6.1 From demonstration to implementation

In general a demonstration project may be succesfully completed more or less irrespective of the operational status of techniques and procedures involved. Timely delivery of information products, which most adequately accommodate the information needs of the end user may not play a crucial part in most demonstration projects. Mostly not an awful lot of attention is paid to a thorough inventory of information needs. A simple precondition for demonstration generally being the availability of prototype versions of techniques and procedures, relatively little attention will be paid e.g. to optimal organisation of the datainfrastructure, communication issues, tasks and roles in that stage of development. Moreover, the required knowledge and associated methods and (software) systems may be scattered over a number of institutes/companies. This may also be true with respect to the required basic data (in situ, remote sensing and modelled data may be expected to reside at different locations). This all implies that the gap between succesfull demonstration and implementation may be quite large and that implementation of a certain technique or procedure may still require major efforts.

The statements above also hold for the RESTWES project, which has typically been a demonstration project in the sense that it shows the added value of innovative techniques without having explicit evidence of the information needs of the end user and without having to bother too much about organizational aspects.

The objective of this chapter is to bring the implementation of RESTWES results into an operational environment closer. After positioning the RESTWES demonstration project with regard to implementation in Section 6.2 some attention will be payed to the method of working and the organisation within the RESTWES project to assess the baseline (T0) conditions in the Western Scheldt estuary. In Section 6.3 an optional outline or blue print for the organisation of operational monitoring of suspended sediment in the Western Scheldt estuary during tunnel construction (T1) will be given together with some additional recommendations for the future.

6.2 Towards implementation of the RESTWES methodology

The focus of RESTWES has been on *demonstration* rather than on *implementation* or *operationalization* of the techniques involved. A number of possibilities to use the (combined) information from in situ data, remote sensing information and modelling to map and monitor suspended matter concentration in the Western Scheldt and silt content of the bottom was treated. Using both in situ and remotely sensed data and incorporating 'real' meteorological data to tune the water quality model the base line conditions with respect to

suspended sediment concentration in the Western Scheldt were established for the year 1998 prior to the construction of the Westerschelde tunnel between Ellewoutsdijk and Terneuzen (T0 situation). Also addressed were perspectives to monitor possible effects of dispersion of tunnel boring material during tunnel construction (mid 1998- early 2003, T1 situation) and thereafter (T2 situation) by the (combined) use of in situ, remote sensing and modelled information.
Of course it will be up to the end user if and how he/she wants to carry on using the kind of information products prepared in the RESTWES project and presented in this report. Actually *project based use of the RESTWES methodology is an option* for the operational monitoring of the effects of the dispersal of tunnel boring material in the Western Scheldt. Some (but not all) aspects of implementation will become important, when this comes into effect. Issues like cost effectiveness, time constraints with respect to delivery of data and information products, adequate measures for data transfer and identification/allocation of tasks and roles may be issues to deal with.
RESTWES techniques may be considered rather generic, so they *might be incorporated in operational monitoring* of suspended sediment concentration in selected parts or the whole of the Western Scheldt estuary at any time or alternatively in another region of the Netherlands (e.g. the Wadden area) or anywhere else where spatial and temporal information on suspended sediment is at stake. Efficient organization of data infrastructure and institutional roles may (in contrast to the situation in the RESTWES project) even become critical, if or when (combined) in situ, remote sensing and modelled information will be embedded in regular monitoring practice.
So it appears worth the trouble of analysing how the RESTWES project was organised, to identify both positive and negative aspects thereof, to learn from the experiences in RESTWES and to try to improve things in case RESTWES results are to be implemented in monitoring practice (be it in a project framework or in a regular monitoring practice). In this section we will start by making an analysis of how RESTWES was organised with respect to e.g. participating insitutes and their tasks, to data-flow/data-management, what went good, what went wrong, etc. On the basis of this analysis a blue print for operational monitoring of suspended particulate matter in the Western Scheldt is drawn up in section 6.3.

An important source of information to arrive at this blue print is a report which was prepared in the framework of the RESTWES project (R.L. Catalan, 1999). In this report the following aspects of the RESTWES project, relevant for implementation of the approach, were analysed:

i) activities/tasks which were performed to assess the T0 situation with respect to suspended sediment in the Western Scheldt were identified and evaluated;
ii) technical procedures/techniques/methods for the monitoring of suspended sediment in the Western Scheldt used in RESTWES and probably required during and/or after tunnel construction (T1 / T2 situation) were identified;

an inventory was made with respect to possible roles and tasks of institutes and/or companies in the processing chain.

6.2.1 RESTWES Analysis: Institutes and Roles, Materials and Methods

A schematic overview of the data flow as it has been in the RESTWES framework is presented in Figure 6.1, together with tasks to be performed and information on the institutes which were primarily responsible for those tasks.

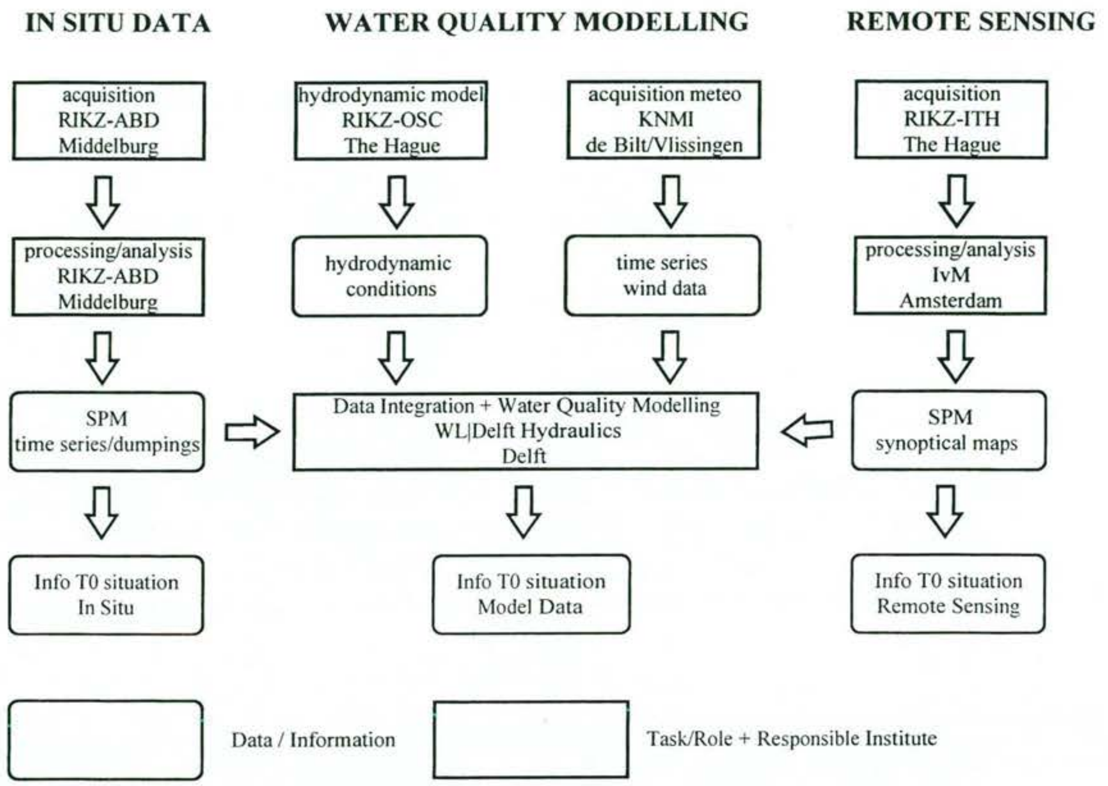


Figure 6.1 Schematic overview of data flow within the RESTWES project; indicated are the institutes/departments, which took primary responsibility for the task involved.

RIKZ took primary responsibility for the overall coordination of data acquisition and selection. The actual acquisition, selection and (pre)processing of in situ data on one hand and remote sensing data on the other requires specific knowledge and expertise and involves the application of dedicated software tools, and was therefore carried out by different institutes, each qualified to do the particular job.

In situ measurements have been acquired by Rijkswaterstaat (Meetdienst Zeeland, RIKZ). RIKZ in Middelburg has taken responsibility for collection of both historical and actual in situ data as well as for transfer to and communication with the other RESTWES partners.

The initial selection of SPOT remote sensing images over the year 1998 was done by RIKZ; subsequent processing of the data was carried out by IvM.

Pre- and postprocessing for the production of relevant information on suspended particulate matter on the basis of remote sensing imagery (right column of Figure 6.1) includes dedicated measurements and processing, which (still) require a lot of expert knowledge, such as:

- atmospheric and air-water interface correction of remote sensing images to assess subsurface reflectance;
- spectroradiometric in situ measurements to assess the inherent optical properties in the area of interest (in our case the Western Scheldt);
- bio optical modelling to relate subsurface reflectances to suspended matter concentrations;

inversion of 'remotely sensed' subsurface reflectance values to suspended particulate matter concentrations.

Both in situ and remote sensing data were processed to the level of suspended particulate matter concentrations (SPM). This level of data may be either

(i) used to produce information products independent of the other sources of data, making full use of the temporal resolution in case of in situ data or the spatial resolution in case of remote sensing data, or

(ii) geared to be integrated into the water quality model enabling both prediction and reconstruction of SPM on relatively high temporal and spatial scale.

WL|Delft Hydraulics took responsibility for the water quality modelling (including collection of information on initial conditions, boundary conditions and additional input parameters and integration thereof in the water quality model). The water quality model used in the RESTWES project, DELWAQ (2-dimensional version of Delft3D-WAQ with only 1 layer in the verical) was run for the full year 1998 to assess the base line (T0) conditions for suspended paticulate matter before the building of the Westerscheldetunnel. Data used to feed the model have been:

- input from a hydrodynamic model for the water flows (advective transport of sediment); the 2D curvilinear SCALWEST fine model was used to generate this input; information source: RIKZ (The Hague)
- input data for wind (stirring up of sediment by water waves); information source: KNMI.
- boundary conditions of SPM concentrations (sediment enters the modelled area at the river boundary and at the open sea boundary), which were taken from longterm monthly averaged concentrations; source: RIKZ (Middelburg).
- the amount of silt in the modelled area at the beginning of the simulation period, i.e. the initial conditions for both the water column and (in particular) the bottom; information source: model runs WL.
- spatial information on SPM derived from remote sensing images is used to calibrate the model (and possibly to adjust it from time to time); information source: IvM.
- the amounts of silt involved with (incidental) dumpings of dredged material, especially from harbour dredgings, may have a significant impact on silt distribution and can be brought into the model as point source inputs; information source: diverse, gathered by RIKZ (Middelburg).

6.2.2 Characteristic aspects of RESTWES

Although very schematic, the overview of Figure 6.1. in fact reflects rather adequately the character of the RESTWES project, which has been a true demonstration project with the associated typical elements thereof. Some characteristics of the project are listed below:

- The overview clearly shows the *scattering of tasks and roles within RESTWES over a number of institutes at different locations*. This does not have to be a real problem but requires special attention with respect e.g. to communications and data exchange. Modern communication techniques like *email and internet* already offer possibilities *for quick communication and transmission of large amounts of data* and will continue to evolve rapidly. In fact within RESTWES the geographical distance between institutes has only been a minor problem in terms of communication.
- A similar statement can be made with respect to data: there has not been a central point for data collection and data storage during the RESTWES project. Indeed both *measured and processed data* were scattered over a number of institutes and locations *during RESTWES*. As the overview also illustrates WL|Delft Hydraulics has been a focal point for a lot of data, but there has not been any formal arrangement for data storage (central or decentral) in a transparent and accessible way. In other words: *data management* has *not been a major issue* during RESTWES.
- With respect to both expert knowledge and supporting (software) systems for (dedicated) processing of data it, which have been applied in the course of the RESTWES project, it can be stated that use was made of *expert knowledge*, which, at the moment, is still quite *uniquely available at individual institutes involved in RESTWES*. A more or less logical consequence of this is that in the majority of cases also *software tools reside at the institutes of the experts who developed or used them*. Although there is nothing wrong with this, there may be some risks involved when it comes to operational monitoring, which should be dealt with.

6.2.3 Points of interest with respect to RESTWES

Without pretending to give it an exhaustive treatment the following list of additional points of interest with regard to RESTWES might be important in relation to implementation:

* Although the identification of the the information need of the Zeeland Directorate with respect to possible effects of spreading of tunnel boring material in the Western Scheldt has been an issue within the RESTWES project, it appeared to be very difficult to make them explicit at the time the project was running. But (possible increase in) turbidity was identified being an important parameter. In fact the RESTWES project took advantage of this circumstance and tried to demonstrate awide range of possible information products derived from (combination of) in situ, remote sensing and modelling;
* in this demonstration project, for which an initial condition has been to have prototypes of methods and tools available, there was no attention for issues like e.g. user-friendliness and documentation of software or for standardisation of methods and approaches;
* Although prototype software was available for all of the processing steps to be expected, some (minor) new developments took place;
* The added value of combined use of in situ, remote sensing and modelled data may be nicely demonstrated, there has not been a lot of attention for accuracy aspects of intermediate and end results;
* Delivery time of (information) products has not been a major issue ;

* Little or no attention has been paid to the interfacing of the various components of the project stages, nor to compatibility of data formats;
* The acquisition of data on dumpings associated with harbour dredging activities, a very important input data source for the water quality model, appeared to be extremely hard. Various local authorities are involved, there is no central information point for this, information had to be acquired via personal contacts; after thorough examination and verification the aggregated set of data had to be digitized;
* The agreement between the average model concentrations and results of analysis of the remote sensing images is good (the model was calibrated in this sense). But in some cases it became evident that the modelled local sediment distribution near the sea entrance was not correct (January image). This may be a consequence of intensive dumpings of silt dredged at the harbour of Zeebrugge. Also a local circulation in the hydrodynamics (that is not observed in the model) may contribute to these high SPM results. Although this needs further investigation it will hardly affect model predictions within the estuary.
* Comparison of remote sensing images and model results indicates that the model underestimates SPM in the curves and near tidal flats and overestimates SPM somewhat in the gullies. Although model results show less detail than SPOT images they correctly represent average seasonal concentrations and tidal variability.
* Accuracy on a detailed spatial scale can probably only be achieved with the full model grid and by application of associated small scale boundary conditions, but very time consuming computations are required in that case;
* Another model improvement may be achieved 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.

6.3 Blue print for operational monitoring of suspended sediment in the Western Scheldt using the RESTWES methodology

6.3.1 Proposal for the organization of operational monitoring T1 phase

The RESTWES project has shown both the relatively strong point of either of these information sources and also pointed out a number of possible applications of the combination of data sources. The methodology certainly offers possibilities to partly fulfil the information need during tunnel construction.
Of course it will be up to the end user to evaluate the RESTWES results, to weigh possibilities of application of this methodology against alternative ways of monitoring total suspended matter in the Western Scheldt during tunnel boring and to decide whether or not this innovative combination of in situ, remote sensing and model information will be applied and integrated into the official monitoring programme.

Based on the experience in the RESTWES project and in view of the analysis of Section 6.2 the following pragmatic approach to the organization of operational monitoring is proposed, if RESTWES results are to be applied in a (semi)operational framework during the tunnel boring project:

I. Apply the Information Cycle to address the information needs, to define a well founded monitoring strategy and to give the RESTWES approach a firmly-embedded position within the monitoring framework.

In case the RESTWES methodology will be integrated into *operational monitoring* of suspended sediment in the Western Scheldt in relation to tunnel boring it will, in the opinion of the RESTWES project team, be an absolute prerequisite to clearly define and specify the information needs and monitoring objectives. Moreover, based on these information needs, an information strategy and design is required to ensure that the monitoring programme operates to produce the desired information in a cost effective way. This will enable the realization of information products which are adequately tailored to the information need of the end user. The so-called Information Cycle, which will be treated briefly at the end of this paragraph, is a generic means to address all issues relevant for a monitoring programme. It also takes into account that information needs are not stationary, but can and will evolve over time due to changing targets or policies. Important issues like data management, integrated data analysis, combination with other sources of information, and reporting will also come up in a natural way in this process.

II. Preserve the organizational framework as it has been during the RESTWES project to start with, i.e. adopt, as much as possible, roles and tasks as they have been during RESTWES, as it is presented in the scheme of Figure 6.1. and only deviate from this if there is an absolute need.

Although there are some alternative options to fill in a number of tasks (see par. 6.2.4), the proposed approach actually seems to be the most pragmatic and effective approach, because:

- spreading of tunnelboring material is already going on and, consequently, there is an actual need to monitor the spatial distribution of suspended sediment; information will have to be available in near real-time (i.e. within a few weeks observation/data acquisition).
- processing of remote sensing data requires a lot of expert knowledge and involves the application of a suite of dedicated processing tools; actually this combination is only available at the Institute for Environmental Studies of the Free University of Amsterdam;
- modelling of water quality requires both expert knowledge and a suite of dedicated software tools, the combination of which were only avilable at WL|Delft Hydraulics during the RESTWES project;
- although all institutes involved in RESTWES are, in principle, willing to transfer knowledge (and software), it is recognized that this would involve too many preparations and would involve too many risks regarding timely delivery of information products.

III) Learn from the experiences during RESTWES and consider implementation of improvements with regard to data infrastructure, data management and procedures.

Amongst others (see also 6.2.3 Points of interest with respect to RESTWES) the following is recommended:

- data management:
  collected in situ data should be validated and archived in a way that they are readily accessible for both current and future use (in particular the collection and interpretation of data on incidental dumpings with regard to harbour dredgings has posed the RESTWES team for major problems). Setting up a focal point for data collection is recommended;
- attention should be paid to compatibility of data formats to enhance smooth data exchange and to accelerate the production of (intermediate) information products.
- in view of possible future application of the RESTWES methodology a start should be made with respect to the transfer of knowledge and software tools; in fact a lot of (expert) knowledge, which was used in the RESTWES project, has only been available within one institute (or even bound to only one person);
- the application of e.g. Geographic Information Systems (GIS) should be considered to produce and present the desired information in an efficient way;
- the use of modern communications means like the Internet should be considered for communication in general and for data communication in particular;
- a 29.5 day spring neap period with (nearly) exactly 28 'lunar days' to run the hydrodynamic model has to be used to prevent the model simulation to get out of phase with the continuous SPM-measurements;
- during the monitoring project information products/ intermediate reports (not necessarily on paper) should be prepared and distributed on a regular basis, with a level of detail tailored to the requirements of the user.

6.3.2 Alternatives

Without going into as much detail as is done in the report of Catalan (1999) some possible alternative options for the filling in of some of the roles within the proposal above (and the scheme of Figure 6.1) should be mentioned:

- *The Survey Department of Rijkswaterstaat (Delft):* being the primary knowledge kernel both on remote sensing and GIS the Survey Department could in principle offer i) Remote Sensing data processing and GIS facilities, ii) Overall quality control iii) General management. However, the Survey Department would only be involved in the implementation phase of new techniques and approaches and would not be inclined to do production work, which would have to be put out to contract or tender in the operational situation. In view of the stage of development of the RESTWES approach the Survey Department could play a role in the process of monitoring suspended sediment during tunnel construction, especially with respect to (the development of) value adding activities like processing and interpretation of remote sensing data and GIS.

- *ARGOSS (Advisory and Research Group on Geo Observation Systems and Services, Vollenhove – The Netherlands)* has shown interest in participation in a possible follow up on RESTWES. They have ambitions in setting up a state of the art data-infrastructure for water quality of remote sensing. The scope of their activities encompasses, among others:
  * Extraction and interpretation of various marine parameters from satellite-acquired data.
  * Development and support of software systems for information management and assessment
  * Research & development, often in cooperation with academic institutes and other agencies
  * Consultancy support on technical, commercial and strategic issues.

  ARGOSS is specialized in radar techniques (a.o. bathymetry) and has experience in the assessment of Total Dissolved Matter using NOAA-AVHRR, LANDSAT, MOS and CASI. ARGOSS has a partnership with the IvM.

- *The Information Service of the Zeeland Directorate Rijkswaterstaat (Middelburg):* the former Meetdienst (*Measurement Service*) of the Zeeland Directorate of Rijkswaterstaat is in the process of developing into an *Information Service* and will include value adding in its package of activities; amongst others a GIS-group is developing. Physical location in Zeeland of a coordinating role within monitoring of suspended sediment in addition to value adding and production facilities would facilitate participation and integration of the different institutions and specialists of the region, particularly the Directie Zeeland, into the operational aspects of monitoring.

- *The Institute for Environmental Studies (IvM),* already participating in RESTWES with regard to the processing and interpretation of remote sensing imagery, intends to extend its activities and to include modelling. IvM aspires to participate in a follow up of RESTWES with respect to both remote sensing and water quality modelling.

By using the stronger points of each of the participating institutes and filling in the weaker point by involvement of another an organizational structure should be established for semi-operational monitoring during tunnel construction.

The Information Cycle

In Figure 6.2 the Information Cycle is presented, which offers a nice generic tool to analyse the successive steps of monitoring and their interrelations. (The Information Cycle is closely related to the Monitoring Cycle (UN/ECE, 1996)). The cycle starts with the identification of priorities in environmental management and the definition of information needs, and ends with a relevant information product which can be used for environmental management and policy making.

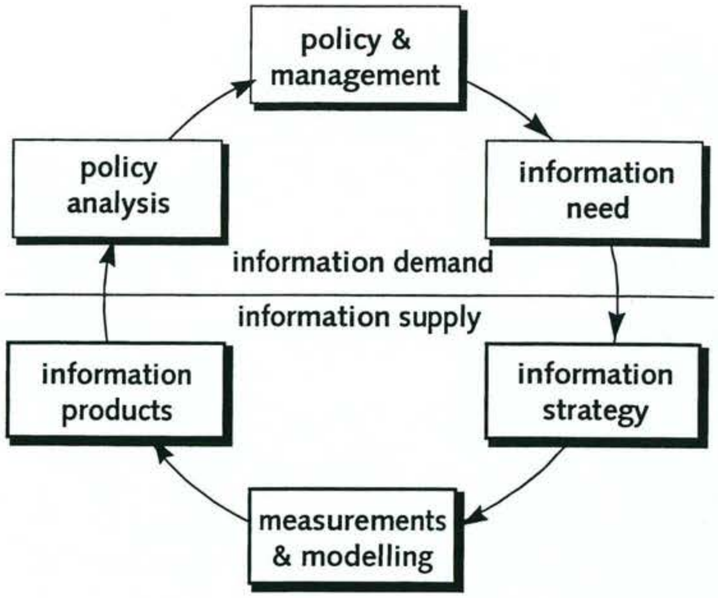


Figure 6.2: The Information cycle

1. **Policy and Management**: the need for information should be based on the core elements in environmental management, including identified priority issues.
2. **Information need**: the most critical and difficult step in developing a successful monitoring programme is the clear definition and specification of information needs and monitoring objectives (this was also recognized during the RESTWES project). Information needs are often based on priority issues, environmental pressures, and consideration of possible management measures. Information needs are not stationary, but can and will evolve over time due to developments in environmental management, attaining of targets or changing policies.
3. **Information strategy**: after the specification of information needs, an information strategy and design is required to ensure that the monitoring programme operates to produce the desired information. The strategy and design must translate the information needs into an operational monitoring programme. Design includes the details regarding the selection of variables, selection of sites, sampling frequency, methods, etc. etc.
4. **Measurements and Modelling**: data is collected based on the monitoring strategy and the details specified in the monitoring design. The data collected should be validated and archived in a way that they are accessible for current and future use.
5. **Information products**: it is the actual goal of the monitoring programme to convert the collected data into information that will meet the specified information needs. This conversion involves integrated data analysis and interpretation.The reporting of information links the gathering of information with the information users. To distribute information, reports (not necessarily on paper) should be prepared and distributed on a regular basis, with a level of detail tailored to the requirements of the user.
6. **Policy analysis**: the evaluation of the obtained information (or other developments or circumstances) may lead to new or redefined information needs, thus starting a new sequence (cycle) of activities. In this way the monitoring process will be improved, activities will be substantiated and the involvement and commitment of end users will be enhanced.

Actual introduction of the information cycle within Rijkswaterstaat and the identification and realisation of necessary supporting tools to apply the information cycle have become spearheads of the Meetstrategie 2000+ programme (Programmabureau Meetstrategie 2000+, 1999). Although the application of the information cycle to adress all relevant issues for actual implementation of methods and techniques is strongly recommended in the case that RESTWES results will be implemented in a regular monitoring scheme, it was a bit beyond the scope of the activities planned within the RESTWES project. Within RESTWES one mainly concentrated on the issues below the horizontal line of Figure 6.2 by addressing the datainfrastructural and institutional framework to be established.

7 Conclusions and Recommendations

7.1 Conclusions

SPM concentrations and distribution:

The RESTWES study has focused on characterising the SPM conditions in the Western Scheldt, specifically the 1998 baseline conditions (T0) prior to dumping of tunnel boring material 'Boomse Klei' from the Western Scheldt tunnel construction. This study has shown that the T0 situation can be optimally characterized based on three sources of information, namely:

- in-situ data
- remote sensing
- water quality model

Based on these three sources of information, a number of important characteristics of the suspended particulate matter have been described, including the dynamic behaviour as well as the spatial variability. Also important processes affecting the SPM concentrations are identified, such as the spring-neap tidal cycle. This work also indicates the strengths and weaknesses of the individual information sources for describing SPM in the Western Scheldt. Specific conclusions drawn from each data source are presented.

In-situ Data

The long-term monthly averaged data indicate seasonal trends in SPM concentration which occur over the whole estuary: high winter concentrations and low summer concentrations. There is a gradient in concentrations over the length of the Western Scheldt, with lowest concentrations in the east at the mouth of the estuary, and highest concentrations near the Belgian border.

Typical winter concentrations are 40-60 ± 40 mg/l. The concentrations are lowest at the sea side, due to influx of North Sea water with relatively low SPM concentrations. Highest concentrations are measured at Saeftinghe, where the average monthly concentrations for January - March are 80-90 ± 40 mg/l.

Typical summer concentrations at all locations in the Western Scheldt are 10-20 ± 10 mg/l. Again, concentrations are lowest at the sea side, and highest near the Belgian border (e.g. Saaftinghe) where summer concentrations are slightly higher than 20 mg/l.

Continuous data from locations Vlissingen, Terneuzen and Baalhoek indicate a consistent 14 day spring-neap cycle, with an additional 12 hour cycle caused by the tidal period. Some additional patterns in the data occur due to storm events (high wind), and possibly other localized conditions (e.g. dumping of dredged sediment or localized bottom sediment erosion). Continuous data at Terneuzen for October - December 1998 show concentrations between 60-150 mg/l, varying regularly over the spring-neap cycle.

Continuous data at Baalhoek over the same period show a much larger concentration range (25-250 mg/l), with much more extreme concentration variations over short time periods. The difference in these signals may be due to very localized effects.

Remote Sensing Data
Remote sensing maps of SPM can be prepared from SPOT satellite reflectance data, using an optical model. The optical model was developed based on inherent optical properties of Western Scheldt sediment as measured during a field campaign in March 1999 (see Pasterkamp et al., 1999). Retrieved SPM concentrations could be mapped in steps of 3 mg/l at the lowest concentration range with errors (roughly estimated) from approximately 5 up to 33%.

The remote sensing images are 'instantaneous pictures' of the suspended matter concentration in the estuary, and the 9 processed images show a high level of spatial detail which is not available in either the in-situ data or the model results. One example is the elevated SPM concentrations seen at the Vlakte van Raan, or along the Belgian coast at the south side of the mouth of the Western Scheldt. With sufficient remote sensing images, detailed SPM concentrations and patterns can be seen over time. However, due to variations in SPM over tidal and spring-neap cycles (as seen in the continuous in-situ data), the exact moment of a remote sensing images (e.g. period in the tidal cycle) must be known in order to make proper analysis.

NOAA satellite images
The possibility of using NOAA satellite images for model boundary conditions has been investigated. Because NOAA has 2 daytime images per day, the images are in principle available at a high enough frequency to be used as boundary conditions for the water quality model. However, the resolution of the data (approximately 1 x 1 km) and problems of signal saturation at high concentrations, and calibrating the images, results in insufficient detail and accuracy for use as model boundary conditions. NOAA however, does give information on the main patterns in SPM that can be seen (at low spatial resolution).

Water Quality Model
The dynamic water quality model combines the high temporal scale of the (continuous) in-situ data with the large spatial scale of remote sensing data. The model is the only information source which can give information on SPM at all times at all locations in the Western Scheldt. The water quality model integrates the main trends, patterns and causal effects that are analyzed in the in-situ and RS data.

An integration of in-situ and remote sensing data with the water quality model has been made with data model integration using the method of a cost function. With the cost function, the available information from both in-situ and remote sensing data are incorporated as best as possible into the model. Seasonal patterns, spring-neap cycle, dumping of sediment from harbour dredging activities and wind effects are all incorporated. The model gives a mass conservative spatial representation of SPM, can calculate transport of material and can predict concentrations from dumping.

Due to restrictions in data of inputs, boundaries and forcings, the present model application is limited in its ability to simulate detailed patterns in SPM concentration as seen in the remote sensing, and very short term variations in SPM concentrations as seen in the continuous in-situ data. It can be concluded that these are effects caused by localized conditions and effects which are not included in the general model processes.

Sediment classification:

In the research described here the median grain size was chosen as the parameter to be mapped. It appeared not to be possible to map this parameter in a reliable quantitative way. Nevertheless, a satellite image provides a snapshot like overview of a greater part of an area like the Western Scheldt. A sediment grain size map as it is derived from a satellite image offers a truely synoptic overview of the sediment distribution of the area. Application of atmospheric correction to a series of images (which minimizes disturbing atmospheric effects introduced by e.g. differences in solar angle, haze) enables in principle direct comparison and monitoring. By virtue of the spatial resolution of a remote sensor (the SPOT-HRV pixelsize equates to a sediment sample site in every $20x20m^2$ over the entire intertidal area) a coverage is achieved which could only be attained in theory by a highly intensive sampling programme (which of course in practice is impossible, because the number of sampling points would have to be increased by a factor of at least 150). The (pre)processing and sediment grain size interpretation of a remote sensing image typically takes a couple of days (once the remote sensing image is delivered) and is relative inexpensive in comparison with mapping on the basis of an in situ sampling programme. Offering a relatively dense spatial network of 'measurements' remotely sensed data are very suitable to be combined with other spatial data (e.g. in a Geographical Information System (GIS)) to provide added value to policy making, management and research and/or also to increase the reliability of resulting grain size maps.

Predictions of the T1 situation

Predictions for the T1 situation were made assuming a discharge of 1 million tons of fine silt over a year at one location (near Terneuzen).

Concentration increases

The dumping of tunnel sediment creates a 'plume' of increased concentration which fluctuates around the dumping location, moving upstream and downstream with the tide. The predictions show a maximum SPM concentration of 30-40 mg/l in the immediate vicinity of the dumping location.

A concentration increase of 25 mg/l is seen in a limited area, which can extend a few kilometers from the dumping location. A concentration increase of ~10 mg/l is seen in a large area, extending upstream to Baalhoek (~17 km). At Vlissingen, a concentration increase of, on average, 2mg/l is predicted.

Because a constant discharge of tunnel sediment has been assumed, the predicted *increase* in SPM concentration is constant over the year. Due to the natural seasonal variation in SPM, the concentration increase may not be 'visible' in the fall and winter months (when background concentrations and natural variability are high). The SPM concentration increase will most likely be 'visible' in the summer months, when background concentrations and natural variability are low.

Transport of the tunnel sediment
The concern about the effects of dumped sediment on specific regions of ecological or economical concern (nature areas, sand mining regions, fishing/shellfish areas) requires an analysis of *transport* and fluxes of material, i.e. 'Where does the dumped material end up?'

The water quality model can provide this information on the transport of the dumped tunnel sediment. For the transport analysis, the model results were aggregated to the 14 segments of the SAWES Western Scheldt model (also a 15th segment was added at the mouth of the estuary). Transport between segments, and sedimentation per segment were calculated.

Analysis of the sediment transport shows that of the total amount of silt dumped (1 Mton), approximately 75% is transport out to the North Sea, and 20% is sedimented in the Western Scheldt. Most of the sedimentation occurs near the dump location (SAWES segments 13-14). About 10% of the dumped sediment is transported upstream from the dump site towards Belgium. Most of this eventually sediments within the Western Scheldt.

7.2 Recommendations for T1 monitoring

SPM concentrations and distributions

General recommendation:
Data from all three information sources (in-situ, remote sensing and model) have proven to be valuable in characterizing the state of the total suspended matter in the Western Scheldt. Each of the sources has its own value and provides unique information which cannot be substituted by one of the other sources. As a general recommendation, it is urged that all three sources be used in characterizing the T1 phases, i.e. operational monitoring.

The expected increase in SPM concentrations due to the dumping will be 25 mg/l or less, except for the region immediately near the dumping location. During much of the year, this concentration increase will be difficult to observe, as it falls within the natural variation in SPM concentrations. However, in the summer months, an increase of 25 mg/l SPM is significant compared to both the average concentrations and the expected variability. Therefore, more detailed monitoring of the T1 situation should take place during the summer months. For example, more remote sensing images could be procured during the summer months.

Recommendations for Remote Sensing

Although the current study has proven that remote sensing can provide high resolution spatial SPM data with sufficient accuracy for integrated methods of sediment monitoring in the Western Scheldt, the method can be improved:

- In such a tidal estuary where fresh water interacts with salt waters, the spatial variation of SIOPs (specific inherent optical properties) was probably under sampled (5 locations were sampled on one day: 10 March 1999). This should be addressed in further sampling campaign(s), which would also provide insight as to the temporal and spatial variation in SIOPs for such dynamic systems.
- During the present study, variations in chlorophyll (TCHL) and coloured dissolved organic matter (CDOM) were neglected in the calculation of SPM concentrations. In view of the possible effects of variations in TCHL and CDOM concentrations on SPM retrieval (especially during the summer months), it is advised to study the optical properties and concentrations at some times during the year.
- The approach to atmospherically correct the remote sensing data proved to be feasible. In future, a downwelling irradiance spectroradiometrical measurement at e.g. a fixed point would increase the accuracy.
- For the monitoring of effects of tunnel material dumping on the sediment budget it would be advisable to study the IOPs (inherent optical properties) of Western Scheldt water containing various concentrations of the dumped material ("Boomse Klei"). It is possible that the Boomse Klei has a unique optical signal which will allow it to be distinguished from other sediment in the Western Scheldt.

Alternative satellite systems, such as Landsat-5 and 7 can provide additional temporal coverage at almost the same resolution. For providing boundary conditions (SPM concentrations e.g. in the North Sea outside the Estuary) to the water quality model, the suitability of low resolution remote sensing (e.g. SeaWiFS and IRS/P3 MOS products) should be investigated.

During the T1 phase, the remote sensing images may be able to show the direction of transport of dumped sediment, and qualitatively how much material moves in which direction. However, the remote sensing data cannot give quantitative results on sediment fluxes.

Recommendations for in-situ data: data from continuous monitoring stations:

For monitoring in the T1 situation, both the availability and the format of the continuous monitoring data are important. Data should be available in near real-time (i.e. within a few weeks of the observation). It is recommended that the data be made available in plain ascii format, as continuous records of time and observation. In the data files currently available, the data records are interrupted by blank lines and headers, thus the files require processing before they can be used for analysis.

Recommendations for data on dredging from harbours:

An analysis of data concerning sediment dumping from harbours for 1997 and 1998 indicates that the total amount of dumped material (fine sediment) from harbour dredging activities may be significant, possibly on the order of 1-1.5 million tons. This is of the same order of magnitude as the total amount of dumping expected from the tunnel material. However, this material is dumped over short time spans, so that localized impacts may be very high.

Available data from 1997 and 1998 showed approximately a factor 6 difference in total amounts of dumped material, and this raises some questions as to the accuracy of the data. It is recommended that the existing procedures for data management and data processing of harbour dredging data needs significant improvement. For operational monitoring of the T1 situation, it is necessary that data are available in near real-time. These data need to be processed and should provide a summary of: location, amount (tons) dumped, and time period dumped (dates); (see Table 4.2 as example).

Recommendations for data on spreading of tunnel boring material.
For operational monitoring of the T1 situation, it is necessary that data on spreading of tunnel material are available in near real-time. These data need to be processed and should provide a summary of: amount (tons), location, and time period dumped (weeks).

Recommendations for modelling
The hydrodynamic model which forms the input to the water quality model must be re-run so that the period of the spring-neap cycle is exactly 14.756 days. In this case, the calculated results will be in phase with measured concentrations and can be directly compared..

For monitoring of the T1 situation, the model can either be run in forecast mode, or hindcast mode.

In *forecast* mode, the model can be used to make predictions about the transport and fate of the dumped tunnel sediment (i.e. what will happen to the sediment that is dumped in the next month?). To make a prediction, assumptions about the model inputs need to be made, specifically:

- Hydrodynamics
- Wind
- Boundary Conditions
- Dumping of harbour dredging sediment and tunnel sediment

A recent remote sensing SPM map can be used to provide the starting conditions for the model calculation.

In the *hindcast* mode, the model can be used to assess the transport and fate of tunnel sediment that has *already* been dumped (i.e. Where has the sediment gone that was dumped in the last 2 months?). To make this assessment of past dumping, real data can be used to supply the necessary model inputs: hydrodynamics, wind, boundary conditions, and dumping of harbour dredging sediment and tunnel sediment.

Remote sensing SPM maps can be used to provide the model boundary conditions, and can also be used to validate the model results.

Sediment classification:

It is advised to choose the amount of silt present as the parameter to be mapped rather than the median grain size, because median grain size is also determined by the amount of sand present and thus is only representative for silt in an indirect way. The sediment in the Western Scheldt area often exhibits a relatively large sand fraction; therefore the median grain size will only slowly vary when siltation occurs, so the median grain size is not a very good indicator when monitoring of silt is aimed at (de Jong, 2000).

Subdivision of the total area to be classified and assessing an individual algorithm for each of the subareas might further increase the accuracy of the interpretation. Information on elevation of the area combined with tidal stage/water levels may be helpful in selecting subareas for this purpose.

Blue print:

Based on the experience in the RESTWES project and in view of the topicality of monitoring of suspended sediment in the Western Scheldt estuary the following is recommended:

- Apply the Information Cycle to address the information needs, to define a well founded monitoring stragey and to give the RESTWES approach a firmly-embedded position within the monitoring framework.
- Preserve the organizational framework as it has been during the RESTWES project to start with, i.e. adopt, as much as possible, roles and tasks as they have been during RESTWES, as it is presented in the scheme of Figure 6.1. and only deviate from this if there is an absolute need.
- Learn from the experiences during RESTWES and consider implementation of improvements with regard to data infrastructure, data management and procedures:
    - data management: issues like validation, archiving, accessibility of data, compatibility of data formats should be settled; setting up a focal point for data collection is recommended;
    - a start should be made with respect to the transfer of knowledge and (software) tools;
    - the application of e.g. Geographic Information Systems (GIS) should be considered to produce and present the desired information in an efficient way;
    - the use of modern communication means like the Internet should be considered, in particular for data communication.

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