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RESTWES Ecology

Use of remote sensing for classification of intertidal areas and preliminary ecological assessment of the disposal of tunnel boring material in the Western Scheldt

Report

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Contents

Summary

The purpose of the RESTWES Ecology subproject of the RESTWES project (Villars & Vos, 1999) is to investigate the applicability of remote sensing as a classification technique of the sediment composition of intertidal areas and as a monitoring tool to assess possible ecological impacts of the dumping of tunnel boring material.

Silt plays a significant role in chemical, physical and biological processes in Dutch coastal waters. In the Western Scheldt, the continuous dredging of the shipping channel and harbours brings extra silt into the water system and soon a large amount of dredged tunnel material with a high silt percentage will be dumped. Any change in silt concentrations and silt characteristics may have a potential impact on the ecosystem.

The most direct, physical effect of the dumping of the tunnel boring material is an increase in the 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. A preliminary description of potential effects on the ecosystem is given in this study, with emphasis on burial of benthic species, change of sediment composition, fluid mud, pollutants in the drilling mud and effects on the economically important Cockle.

Image information from the SPOT satellite with regard to the reflectance intensities (called '*reflectances*') of multiple spectral bands were analysed to obtain a classification of the sediment composition of intertidal areas. Hereto, a remote sensing image from 7 May 1996 was used for classification with the aid of an extended data set of observed median grainsize values, the McLaren data set. By means of a multiple linear regression of band reflectances with median grainsize observations a spatial coverage of predicted median grainsize values was produced. A verification of the resulting image with a separate data set of median grainsize values for a single tidal flat, the Molenplaat, was carried out. The results of this verification show that the prediction of the median grainsize distribution from the remote sensing information is not in accordance with observed median grainsize values for the Molenplaat, therefore, the applicability of this classification for the Western Scheldt is not reliable.

The combination of remote sensing images with mathematical models and measurements improves the possibilities for assessing the effects of the tunnel material dumping on tidal flats. Based on sedimentation and erosion fluxes, the net changes in height of the tidal flats can also be modelled. This is demonstrated by the RESTWES main project (Villars & Vos, 1999) and shows that the amount of tunnel silt has a significant contribution to the total amount of silt in summer on the Molenplaat.

Finally, this study provides an evaluation on the applicability of remote sensing to monitor the ecological effects of the dumping of tunnel boring material. Each of the potential effects and the applicability of remote sensing is discussed, as well as the influence of seasonal changes on the predictability, effects of tidal stage, reflectance of the top layer of the sediment and various techniques to detect changes in sediment composition of intertidal areas.

1 Introduction

The RESTWES project aims to provide a technique to monitor the effects of the dumping of tunnel material in the Western Scheldt on water quality. The main focus of the project is on the water column and the changes in suspended matter concentrations. Results of the main project are reported in Villars & Vos (1999). The changes in suspended matter concentration can however 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 is the focus of the "RESTWES Ecology" component of the RESTWES project.

The goals of the RESTWES Ecology subproject are 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 by analysing remote sensing images 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.

Outline

This report first describes in Chapter 2 what the ecological functions of silt are and what the potential ecological effects on intertidal areas of the dumping of tunnel boring material may be. From this analysis it follows that monitoring the potential changes in the ecosystem of the Western Scheldt is required. A possible and rather new technique for monitoring is the use of remote sensing images. Chapter 3 describes the classification of intertidal areas from a remote sensing image. Finally, chapter 4 evaluates the applicability of remote sensing as a monitoring technique for the potential ecological effects of the tunnel boring.

Project team

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

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2 Potential Ecosystem Impacts

2.1 Introduction

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 a potential impact on the ecosystem. In this chapter the ecological functions of silt are briefly addressed, and subsequently, potential ecosystem impacts of the dumping of tunnel boring material are discussed. This study does not aim to provide a complete environmental impact assessment of the dumping of tunnel boring material, but it will give a brief overview of potential effects that may occur in the Western Scheldt. Emphasis is given to potential effects on intertidal areas and on the cockle *Cerastoderma edule*.

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. A brief overview of potential effects is given in the paragraph on 'Increased SPM Concentration'. The suspended material may also settle to the bottom. A direct effect may be the burial of benthic species. This is described in the paragraph on 'Burial of Benthic Species'. An indirect effect of the sedimentation of the fine tunnel boring material may be a change of the sediment composition. This is described in the paragraph on 'Siltation on tidal flats'. A special type of settled material is fluid mud, which is briefly discussed in the paragraph on 'Fluid mud'. Subsequently, the drilling mud that is discharged into the estuary may have ecological effects, which are described in the paragraph on 'Drilling Mud'. Finally, special attention is paid on the cockle *Cerastoderma edule* because of its ecological and economical importance in the Western Scheldt. Effects of sediment dumping with respect to nutrients, toxic compounds, oxygen levels, etc. are not discussed here, but may be found in Goossens (1990).

2.2 Ecological Functions of Silt

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.

In the Netherlands a number of developments may affect the distribution of silt on various spatial scales. Examples are the coastal development plans, such as the extension of the Maasvlakte or an island off the coast. National and international policy on river management may affect the discharge and silt concentration of rivers. Climate change can also affect the river flow. In the Western Scheldt, the continuous dredging of the shipping channel and harbours brings extra silt into the water system and soon a large amount of dredged tunnel material with a high silt percentage will be dumped.

To understand the potential ecological effects of the dumping of tunnel boring material, this paragraph will provide a synopsis of the ecological functions of silt.

2.2.1 Definitions

In this study *silt* is defined as follows:

- Silt: *that fraction of the sediment that is smaller than 63μm, with or without adsorbed organic (C, P, N) or inorganic material and that is 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.

Partly overlapping definitions that are often used besides or instead of silt are:

- Particular detritus: All not-living particular organic material, such as pseudofaeces, feacal products, excretion products, dead algae, dead bacteria and other dead organisms.
- Seston: the particulate material that consists of inorganic sediment smaller than 63μm, particulate detritus and living cells of algae and bacteria
- Macroflocs or marine snow: fragile flocs of sediment, organic material, algae and bacteria sizing in between several hundreds μm's to more than a mm.
- Fluid mud: 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.
- Highly Concentrated Benthic Suspension (HCBS): a suspension of silt with a concentration of several to 10 grams per litre and with a Newtonian behaviour that can be transported with a velocity that is similar to that of non-disturbed water.

2.2.2 Ecological Functions

Silt affects ecological functions, i.e. processes and interactions within and between abiotic and biotic components of the ecosystem that yield a certain product or service. An ecological product is a measurable quantity such as the biomass of Cockles or the surface area of salt marshes. An ecological service is a measurable quality such as the buffer against coastal erosion or possibilities for recreation.

Silt affects ecological functions by influencing:

1. Morphology
2. Habitats and substrate
3. Food
4. Water quality

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.

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.

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.

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.

2.3 Impact of Increased SPM Concentration

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.

The growth of phytoplankton in the Western Scheldt is limited by light. An increased turbidity may therefore lead to a decrease in primary production (PP) by phytoplankton. Phytoplankton is an important food source to the benthic species on intertidal areas.

The primary production by phytobenthos is less sensitive to turbidity, because these species live on intertidal flats. A burial by sediment however may affect the PP of phytobenthos.

Larvae and eggs of fish and shrimp, that are most abundant in shallow areas, are sensitive to increased suspended particulate matter concentrations, more sensitive than adults. An increased SPM may affect the respiration of larvae and the gas-exchange of eggs. 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. In general pelagic species are more sensitive than bottom fish (Baveco, 1988).

Birds and fish that hunt by using their eye-sight can also be sensitive for an increase in turbidity.

As a result of the increased suspended solids concentrations, the food uptake by filter feeders can be negatively affected in two ways. First, the high concentrations of particles can clog the food uptake system and secondly the food quality (organic to inorganic ratio) may decrease. The extra energy it takes to filter the SPM out of the water can result in a decrease in the growth rate. The increased turbidity may also lead to a decreased concentration of phytoplankton, what in combination with a hindered food uptake can increase the effect on filter feeders.

The decreased food uptake may lead to a reduced growth of filter feeders. The filtering speed of filter feeders shows an optimum curve with SPM concentrations. Research to the filtering capacity of the Blue Mussel (*Mytilus edulis*) has shown that an average Mussel of 3 centimetres of length will cease filtering at a suspended solids concentration of 250 mg/l. When the SPM concentration is 225 mg/l, the filtering capacity has decreased to about 30% of the maximum filtering speed which is reached at a concentration of 125 mg/l (Widdows et al., 1979).

2.4 Impact on 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, but small, deposition.

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. Essink (1993) provides a literature overview of fatal depths for different organisms and two sediment types, silt and fine sand. In general benthic species are more sensitive to burial by silt than by sand. Furthermore, species of a sandy bottom are more sensitive to burial by silt than species of a silty bottom. Larger species are generally more capable of moving upwards than smaller species. However, the adult *Mya arenaria* is exceptionally large and is not able to move at all.

The fatal depth for incidental deposition of silt for a number of benthic species, selected from Essink (1993), is presented in Table 2.1.

Table 2.1. Fatal depth (cm) for incidental deposition with silt (Essink, 1993 after: Bijkerk, 1988).

Scientific name	Name	Fatal depth (cm)
Mytilus edulis	Blue Mussel	1
Petricola pholadiformis		3
Mya arenaria	Sandgaper	7
Cerastoderma edulis	Cockle	11
Hydrobia ulvae	Mudsnail	18
Macoma balthica	Balthic Tellin	38
Ensis ensis		43
Nephtys hombergii		60

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. A species such as the Brown Shrimp is a lot more sensitive to anaerobic conditions than species that are used to similar situations.

The exposure time to anaerobic conditions (< 0.2 mg O_2/l) and for high sulphide concentrations (7 mg/l) at a 50% mortality level is presented in Table 2.2.

Table 2.2. Exposure time to anaerobic and sulphide rich conditions at 50% mortality (Essink, 1993 after: Theede, 1973).

Scientific name	Name	Exposure time oxygen (hours)	Exposure time sulphide (hours)
Mytilus edulis	Blue Mussel	800	600
Scrobicularia plana		600	500
Mya arenaria	Sandgaper	500	400
Nereis diversicolor	Ragworm	150	100
Cerastoderma edule	Cockle	100	100
Asterias rubens	Common Starfish	90	70
Carcinus maenas	Beach Crab	40	30
Amphiura filiformis	a Brittle Star	25	30
Crangon crangon	Brown Shrimp	2	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. Table 2.3 presents the maximum tolerance for different benthic species for a continuous deposition of silt and fine sand in cm/month.

Table 2.3. Maximum tolerance for continuous deposition of silt and fine sand in cm/month (Essink, 1993 after: Bijkerk, 1988)

Scientific name	Name	Deposition of silt (cm/month)	Deposition of fine sand (cm/month)
Mya arenaria	Sandgaper	2	5
Cerastoderma edule	Cockle		17
Macoma balthica	Baltic Tellin	15	>17
Arenicola marina	Lugworm	11	>17
Nephtys hombergii		>35	>17
Carcinus maenas	Crab	31	

2.5 Impact of Siltation on Tidal Flats

The substrate composition is important for the benthic communities on intertidal areas. Substrate composition is measured as silt content, median grainsize, 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.

As a result of the dumping 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. An increase in bottom silt content does not directly have to result in higher densities of benthic species. This is dependent on the suitability of high silt contents for different species. Furthermore, because the tunnel boring material is mostly inorganic (see Table 2.4), the silt does not have any nutritional value. The siltation could result in a change of habitat distribution. Very high bottom silt contents can lead to a decreased suitability for specific species.

An analysis of a Boomse klei sediment, used for experiments at Delft Hydraulics, revealed the following composition (Lubking, 1982):

Table 2.4. Composition of a Boomse klei sediment.

Substance	Percentage
kaolinite	30
illite	30
montmorillonite	5
chlorite	10
smectite	10
quartz	10
feldspar	<1
calcite	2
organic material	1

2.6 Occurrence of Fluid Mud

Another concern is that of 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.

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. Recovery in the tidal area of James River, Virginia, was nearly complete in 3 weeks but some adjustments were still occurring after 3 months. Other less resistant or resilient communities would probably require a much longer recovery period (Diaz & Boesch, 1977). 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. Monitoring of the presence of fluid mud is recommended.

2.7 Impacts of 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. Products that may be added to the water for obtaining these physical-chemical properties are (Terzaghi et al., 1998):

- viscosifiers (clays as bentonite or biopolymers);
- weighting agents (barite);
- dispersants (lignosulphonates);
- surfactants (used as defoamers, detergents, lubricants and emulsifiers);
- shale stabilisation agents (bituminous materials such as asphalt);
- fluid loss reducers (modified starch such as sodium carboxymethylcellulose and polyanionic cellulosic polymer).

The tunnel boring in the Western Scheldt will be carried out with bentonite in the drilling fluid. Bentonite is a mixture of clay-minerals, that contains at least 70% (usually 85% - 90%) montmorillonite minerals. The mineral plates of bentonite are positively charged at the ends and attracted to the negatively charged sides. This will result in a structure that resembles a construction with play-cards. Water molecules are attracted to the charged particles and a gel will originate. An important characteristic is that the structure will break up when the bentonite moves, but that it will recover when the bentonite is resting. Usually a sodium bentonite is used, a calcium bentonite may be used as well. Sodium bentonite will make a more stable suspension in water and can be more easily suspended than calcium bentonite. When sodium bentonite is discharged in sea water the rather weak Na^{+}-linkage will be replaced by a stronger Ca^{2+}-linkage, resulting in aggregation and subsequent sedimentation of the suspension (Huisman, 1999).

The concentration of bentonite in the discharged drilling mud is dependent on the effectiveness of the separation installation (sieves and cyclones), and the number of recirculations of the bentonite (bentonite is re-used three to five times). The discharged fraction of the sediment is expected to contain about 1.5% - 2% bentonite. The bentonite particles are small (< 1μm) and are suspended in water or present as a colloid suspension.

When bentonite is mixed with sand, the water permeability will decrease. One of the applications of bentonite is to seal a sandy layer during drilling. Theoretically a sealing of the top sediment may have detrimental effects to 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).

The drilling fluid that is used in the second Heinenoord tunnel not only contains bentonite, but sodium carboxymethylcellulose (NaCMC) is also added (COB, 1999). This is added to prevent the disintegration of large clay lumps into smaller pieces. It is not clear whether NaCMC will be used in Western Scheldt. NaCMC is a cellulose derivative in which a sodium-carboxymethyl group has been attached to a carbon atom via an ether linkage. This semi-synthetic polymer is more stable than a natural starch. This is also demonstrated by its biodegradation percentage. After 28 days, only half of the material is biologically degraded. A toxicity test did not show any lethal effects of NaCMC 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 that surfactants, lignosulphonates and shale stabilisation agents may inhibit algal growth, dependent on the dilution of the muds (Terzaghi et al., 1998).

In summary, the bentonite is not expected to significantly decrease the water permeability of the sediment, it may adsorb heavy metals and the additives to the drilling mud may have toxic effects.

2.8 Potential Effects on Cockles in the Western Scheldt

2.8.1 Introduction

The Edible Cockle (*Cerastoderma edule*) is a common bivalve of the Western Scheldt. This mollusc lives buried in the sediment and is most abundant on low intertidal flats. Its 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.

2.8.3 Potential Effects on cockles

There are several cockle beds near the dumping location of the tunnel sediment. It is noteworthy to monitor the distribution of suspended sediment and the possible effects on the cockle beds. These areas are important for cockle fishers and any detrimental effects of the dumping may lead to claims of fishermen.

The cockles that are present near the dumping location may suffer from burial by the sediment. This can be caused by 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. More important than the burial (max. 8 cm) this author thinks that the changed sediment structure and low oxygen levels were responsible for the massive mortality. The sediment structure was changed to a depth of 30 centimetres. Due to erosion and the natural dynamics of the system, the sediment structure was recovered after one winter season. Van Dalfsen (1994) further found that the density of cockles decreased strongly with an increase in sediment structure changes. One year after the last discharge, the density and biomass of the benthos was recovered.

Another potential effect is the decrease in food uptake and growing rate by 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).

2.9 Conclusion

The distribution and concentration of fine particulate material and related processes play an important role in the functioning of the ecosystem of the Western Scheldt. 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. Monitoring the potential changes in the ecosystem of the Western Scheldt is required. A possible, and rather new, technique for monitoring is the use of remote sensing images. Remote sensing images provide a spatial coverage of the study area and it is already demonstrated that image information is very useful in assessing environmental changes in water quality parameters. This study will evaluate the applicability of the use of remote sensing for assessing changes in sediment composition.

3 Classification of Intertidal Areas with a Remote Sensing Image

3.1 Introduction

Every object on earth reflects and emits characteristic amounts of electromagnetic energy from the sun. The reflected radiation is known as the *spectral reflectance* of the object. It can be unique to the object and is often called an object's spectral signature. For example plants have a specific spectral signature, caused by the green pigments in their leaves. By analysing the spectral reflectance of the intertidal parts of the Western Scheldt estuary a classification of silt, sand and vegetation can be made.

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 continues with the experiences learnt in these previous studies and uses SPOT-images instead of Landsat. One SPOT image is used in this study to classify the sediment composition of intertidal areas, the image from 7 May 1996. Part of the original false colour image is presented in Figure 3.1.

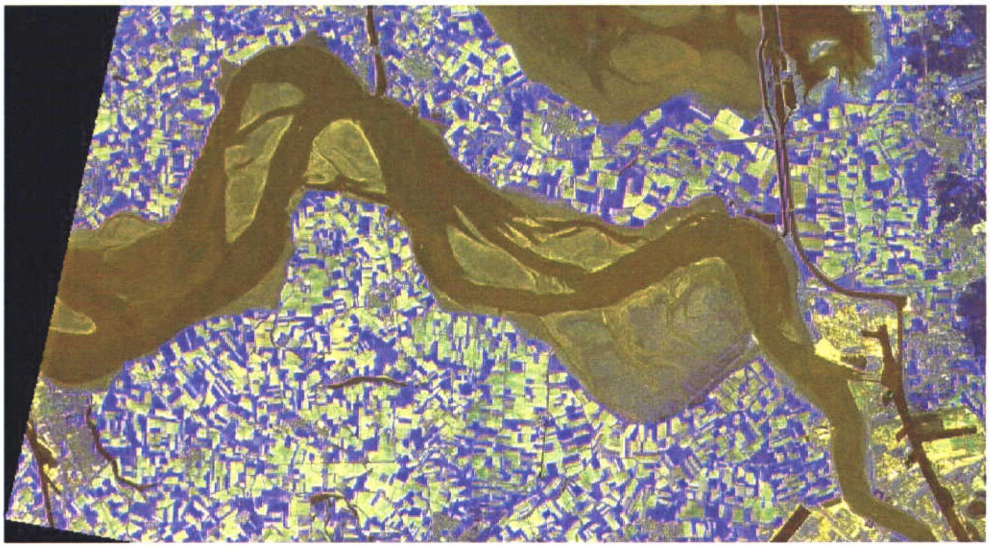

Figure 3.1. False colour SPOT-HRV image of the study area; data are optimized as to show remotely sensed reflectance contrast of the intertidal mud flats.

3.2 Aspects of Remote Sensing

3.2.1 SPOT satellite

Different remote sensing recording instruments record different regions (bandwidths) of the spectrum of electromagnetic energy. The regions or bands which can be recorded by an instrument are known as the instrument's spectral resolution. The SPOT-HRV sensor records information in three specral bands:

- Band 1: 500 - 590 nm;
- Band 2: 610 - 680 nm;
- Band 3: 790 - 890 nm.

Bands one and two lie within the visible spectrum of light (Band 1 = green, band 2 = red) and band three lies within the 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 grainsize 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).

3.2.2 Image Analysis

Image information with regard to the reflectance intensities (called *'reflectances'*) of multiple spectral bands can be analysed to obtain a classification of intertidal areas. There are a number of techniques which can be used to enhance such multispectral imagery. One technique which is frequently used is using spectral band ratios. By using ratios of individual spectral bands and displaying the various ratios as colour composites the multispectral imagery can be enhanced. One of these ratios is the NDVI, which is explained in the next paragraph. Before defining ratios of bands it is crucial to correct the data for atmospheric effects.

3.2.3 NDVI

NDVI stands for Normalised Difference Vegetation Index and is a means of measuring the vegetation cover. Specifically, it is a measure of the spectral signature of chlorophyll in both the visible and near infrared part of the spectrum. The NDVI varies with the absorption of red light by plant chlorophyll and the reflection of infrared radiation by water-filled leaf cells. Because it is correlated with photosynthesis that occurs in the green parts of a plant, it is used to monitor the density and health of green vegetation. A high NDVI value indicates greater vegetation density. 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: $NDVI = (B2-B3)/(B2+B3)$.

3.2.4 Atmospheric Conditions

Ideally, there should be no clouds, haze, or extreme humidity on the days remote sensing data are collected. Even a thin layer of haze can alter spectral signatures in satellite images enough to create the false impression of spectral change between two dates. Obviously, 0% cloud cover is preferred for satellite imagery. At the upper limit, cloud cover >20% is usually unacceptable. It should also be remembered that clouds not only obscure terrain but the cloud shadow also causes major image classification problems. Any area obscured by clouds or affected by cloud shadow will filter through the entire classification process, severely limiting the utility of the final product.

Assuming no cloud cover, the use of anniversary dates (comparing for example 1 October 1998 with 1 October 1999) helps to ensure general, seasonal agreement between the atmospheric conditions on two dates. However, if differences exist in the atmospheric conditions present on the dates of imagery it may be necessary to remove the atmospheric attenuation in the imagery. Sophisticated atmospheric transmission models can be used to correct the remote sensor data if substantial in situ data are available on the day of the overflights. Or an alternative empirical method, normalisation, may be used to remove atmospheric effects. The normalisation method is used for this study.

The use of remotely sensed data to classify tidal flats on individual dates is contingent upon there being a robust relationship between remotely sensing brightness values and actual surface conditions. However, 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 also 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. 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. Hence, a relatively straightforward "empirical scene normalisation" is employed to match the detector calibration, astronomic, atmospheric, and phase angle conditions present in a reference scene.

Image normalisation reduces pixel brightness values variation caused by non-surface factors so variations in pixel brightness values between dates can be related to actual changes in surface conditions. Normalisation enables the use of image analysis developed for a base scene to be applied to the other scenes. Image normalisation is achieved by developing simple regression equations between the brightness values of "normalisation targets" present in a reference scene and the scene to be normalised. Normalisation targets are assumed to be constant reflectors, therefore any changes in their brightness values are attributed to detector calibration, astronomic, atmospheric, and phase angle differences. Once these variations are removed, changes in brightness values may be related to changes in surface conditions.

3.3 Sediment Composition of the Western Scheldt

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 *PHI*-units. *PHI*-units are defined as follows:

$$PHI = -\log_2(D)$$

In which:

D = grain diameter in mm.

Silt-particles for example, which are defined as a grain size between 2μm and 63μm, have PHI-units 4 (63 μm) to 9 (2 μm). The median grainsize is given as well.

For this study, the grain size distribution data were imported in a GIS (ArcView). The median grainsize data were interpolated using a Triangular Irregular Network (TIN). The spatial distribution of the median grainsize data for the Western Scheldt is presented in Figure 3.2.

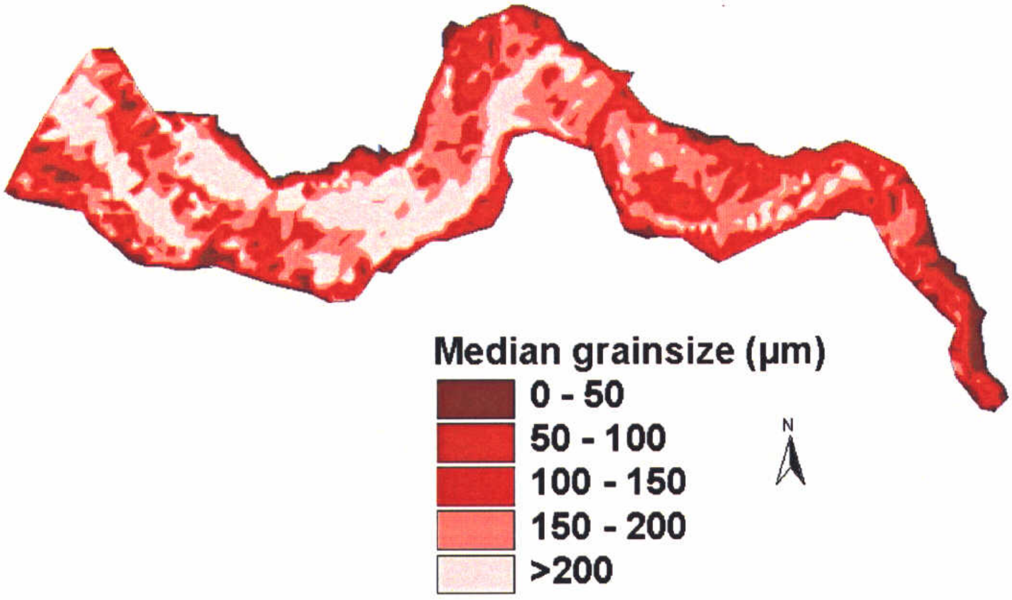

Figure 3.2. Median grainsize distribution, based on McLaren data set.

3.4 Classification of RS images

3.4.1 Data processing

The data analysis should enable the use of both in situ (McLaren) data and remote sensing data for monitoring of the sediment composition in intertidal areas. Therefore the following sequence with respect to data processing was followed:

i. normalisation of the remote sensing image, resulting in in-band reflectances, which are essentially independent of atmospheric circumstances.

ii. geometric correction of the remote sensing image for direct and unambivalent comparison with McLaren sample data;.
iii. identification of the areas in the Western Scheldt above mean water level (MWL) in the remote sensing image, using information on the MWL-line as a filter;
iv. subsequent selection of the McLaren samples covering the areas above mean water level;
v. subdivision of the grainsize of the selected McLaren samples (230 of a total of 1004) into 5 D50-intervals, according to Table 3.1; computation of some additional attributes for each interval (the mean of the D50 values as well as the mean of the natural logarithm of the D50 values);
vi. identification of the corresponding locations in the remote sensing image and calculation of in-band reflectances for all three SPOT-bands for those locations (also Table 3.1).

Table 3.1 Intervals of median grainsize (D50) data and corresponding mean band reflectances.

Intervals for D50 (μm)	Mean value for interval D50 (μm)	Mean value for interval LN(D50)	Mean for Band 1 (b1)	Mean for Band 2 (b2)	Mean for Band 3 (b3)
0 - 50	30.03	3.25	0.09513	0.092264	0.148399
50 - 100	77.91	4.34	0.098865	0.096441	0.129977
100 - 150	126.61	4.83	0.107336	0.10541	0.127516
150 - 200	167.99	5.12	0.113232	0.112901	0.130471
> 200	225.49	5.42	0.114076	0.113446	0.126222

Figures 3.3 and 3.4 show that the median grainsize values increase with an increasing reflectance for bands 1 and 2 and a decreasing reflectance for band 3. Furthermore, bands 1 and 2 are highly dependent of each other.

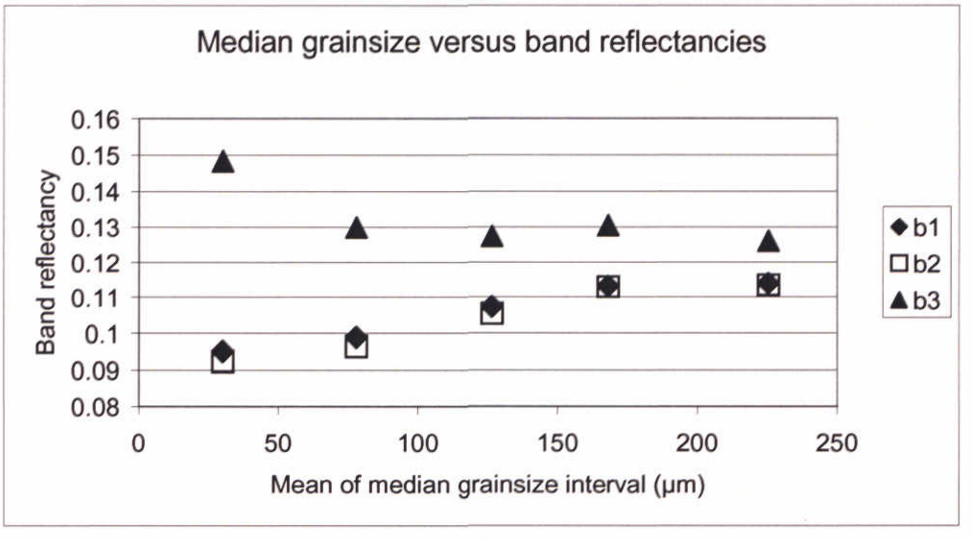

Figure 3.3. Mean of median grainsize interval versus band reflectances.

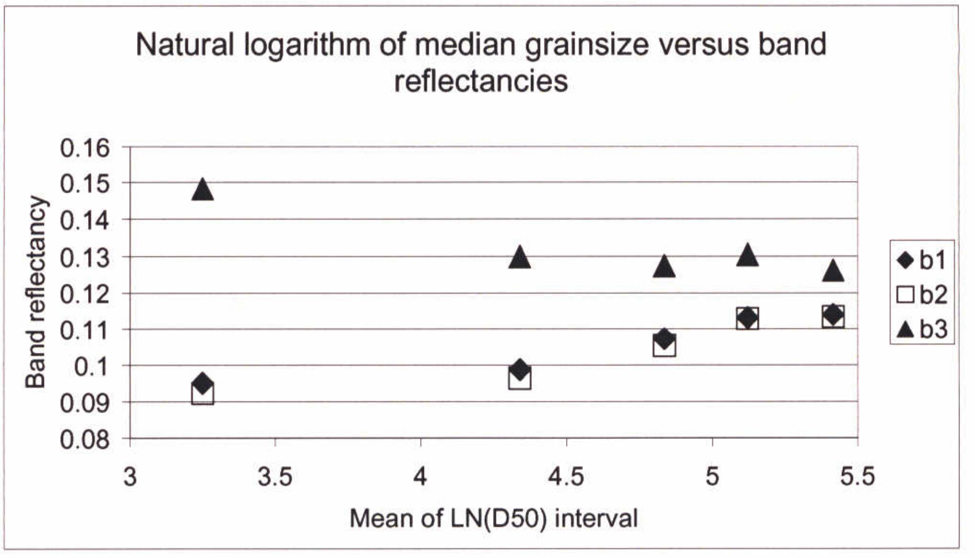

Figure 3.4. Mean of natural logarithm of median grainsize interval versus band reflectances.

For each of the grainsize intervals, the mean of the median grainsize values and the mean of the natural logarithmic of the median grainsize values were correlated to the reflectances of the spectral bands or ratios of the spectral bands. Table 3.2 presents the correlation coefficients between the (ratios of) the spectral bands and the mean of D50 or mean of LN(D50).

Table 3.2 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
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. The mean of the natural logarithm of D50 correlates very well with several band ratios.

3.4.2 Multiple linear regression on classified data

The means of the median grainsize values of the classified data were correlated using a multiple linear regression model, according to:

$$\alpha_0 + \alpha_1 \cdot b1 + \alpha_2 \cdot b2 + \alpha_3 \cdot b3$$

In which:

α = coefficient

b = band intensity

The linear correlation between band reflectances and median grainsize was optimised for the mean D50-values and the mean LN(D50)-values. The best fit was obtained with the coefficients presented in Table 3.3. For the optimisation of coefficients, both integers and non-integers were looked for. The best correlation between the mean of the D50 and LN(D50) and the prediction of mean of D50 and mean of LN(D50) using the linear combination of band reflectances is presented in Figures 3.5 and 3.6.

Table 3.3. Coefficients for the linear combination of band reflectances.

Coeff.	Mean of D50 r^2=09383	Mean of LN(D50) r^2=0.9982	Mean of D50 r^2=0.9383	Mean of LN(D50) r^2=0.9980
α_0	-505.7299	6.6910	-489	6
α_1	4261.5657	-75.0680	3310	-38
α_2	3136.7128	117.0396	3968	85
α_3	-1099.8498	-47.8818	-1120	-47

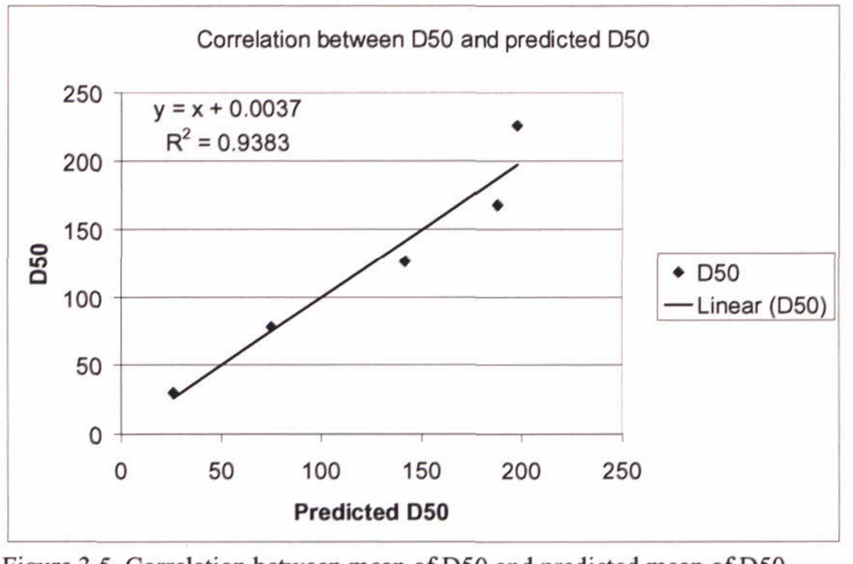

Figure 3.5. Correlation between mean of D50 and predicted mean of D50.

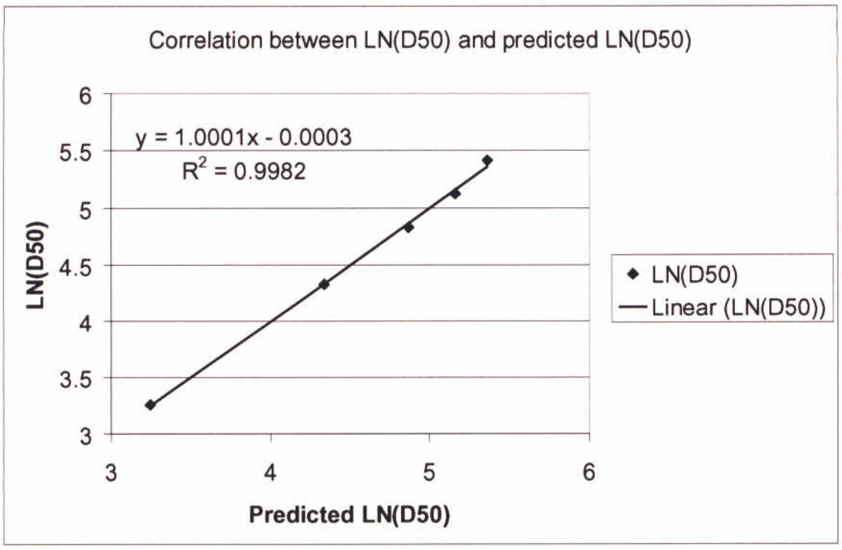

Figure 3.6. Correlation between mean LN(D50) and predicted mean of LN(D50).

The best correlation was found between the linear combination of band reflectances and the mean of the natural logarithm of median grainsize values.

3.4.3 Multiple linear regression on raw data

A multiple linear regression model was also applied on the McLaren D50-values without prior transformation into intervals. The coefficients after optimisation are shown in Table 3.4.

Table 3.4. Coefficients for the linear combination of band reflectances.

Coeff.	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

Again, the highest correlation was found between the band reflectances and the natural logarithmic of the median grainsize values. Noteworthy is 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 3.7 and 3.8 present the correlation between the predicted and measured median grainsize values.

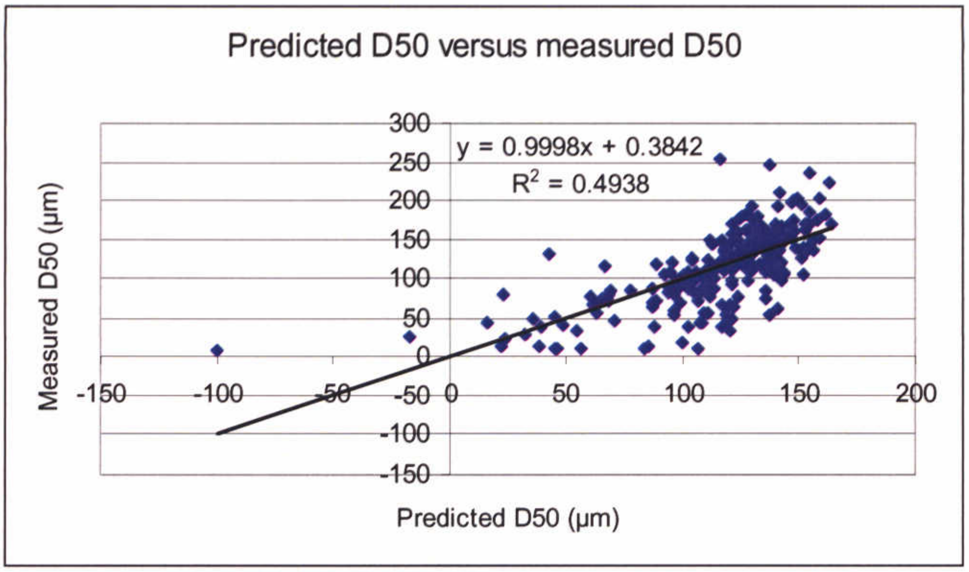

Figure 3.7. Correlation between observed D50 and predicted D50.

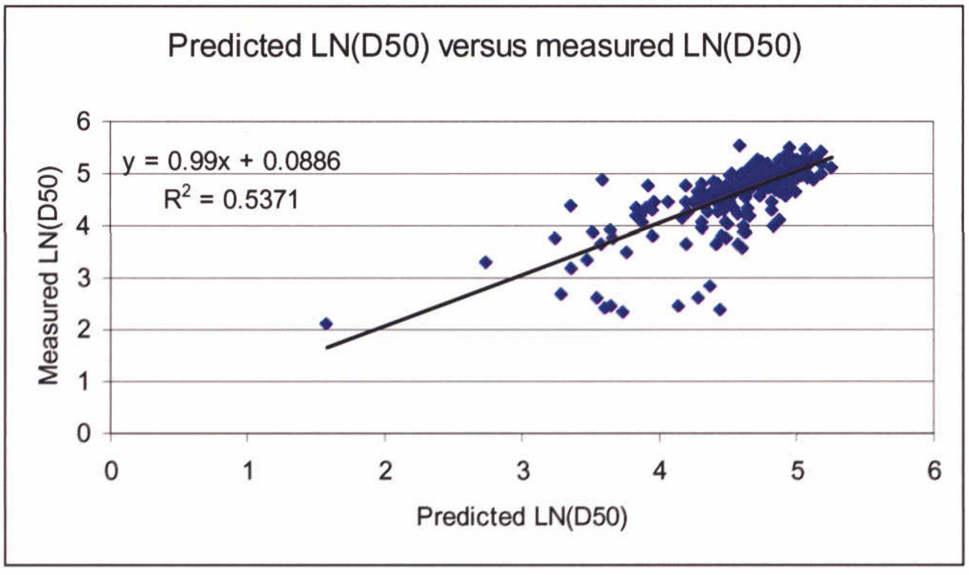

Figure 3.8. Correlation between observed LN(D50) and predicted LN(D50).

The best correlation between band reflectances and median grainsize values, with integers for coefficients, is:

$$D50 = \exp(4 + 32 \cdot b2 - 21 \cdot b3)$$

In which:
D50 = median grainsize.
b1, b2, b3 = band reflectances.

Figure 3.9 presents the correlation between predicted D50-values and observed D50-values, when the above mentioned equation is used to compute the predicted D50-values.

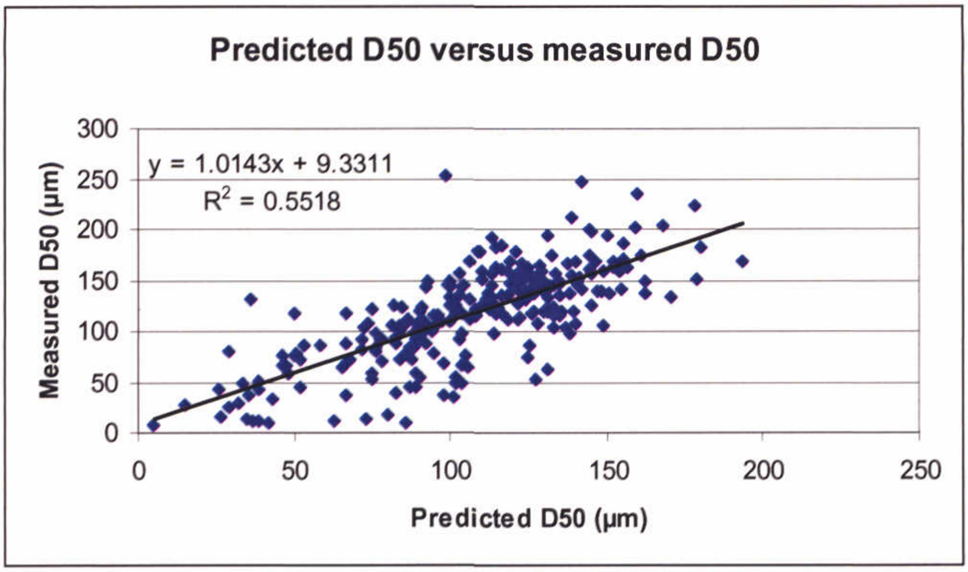

Figure 3.9. Correlation between D50 and predicted D50 using D50=exp(4+32*b2-21*b3).

3.4.4 Image classification

The equation for D50 = exp(4+32*b2-21*b3) is applied on the total image to obtain predictions of the median grainsize for each pixel in the image.

Image classification was also carried out using the NDVI to distinguish between parts that have vegetation and parts that are barren. Image information of band 3 was used to distinguish between parts that were submerged and parts that were emersed.

The resulting image for the Western Scheldt is presented in Figure 3.10.

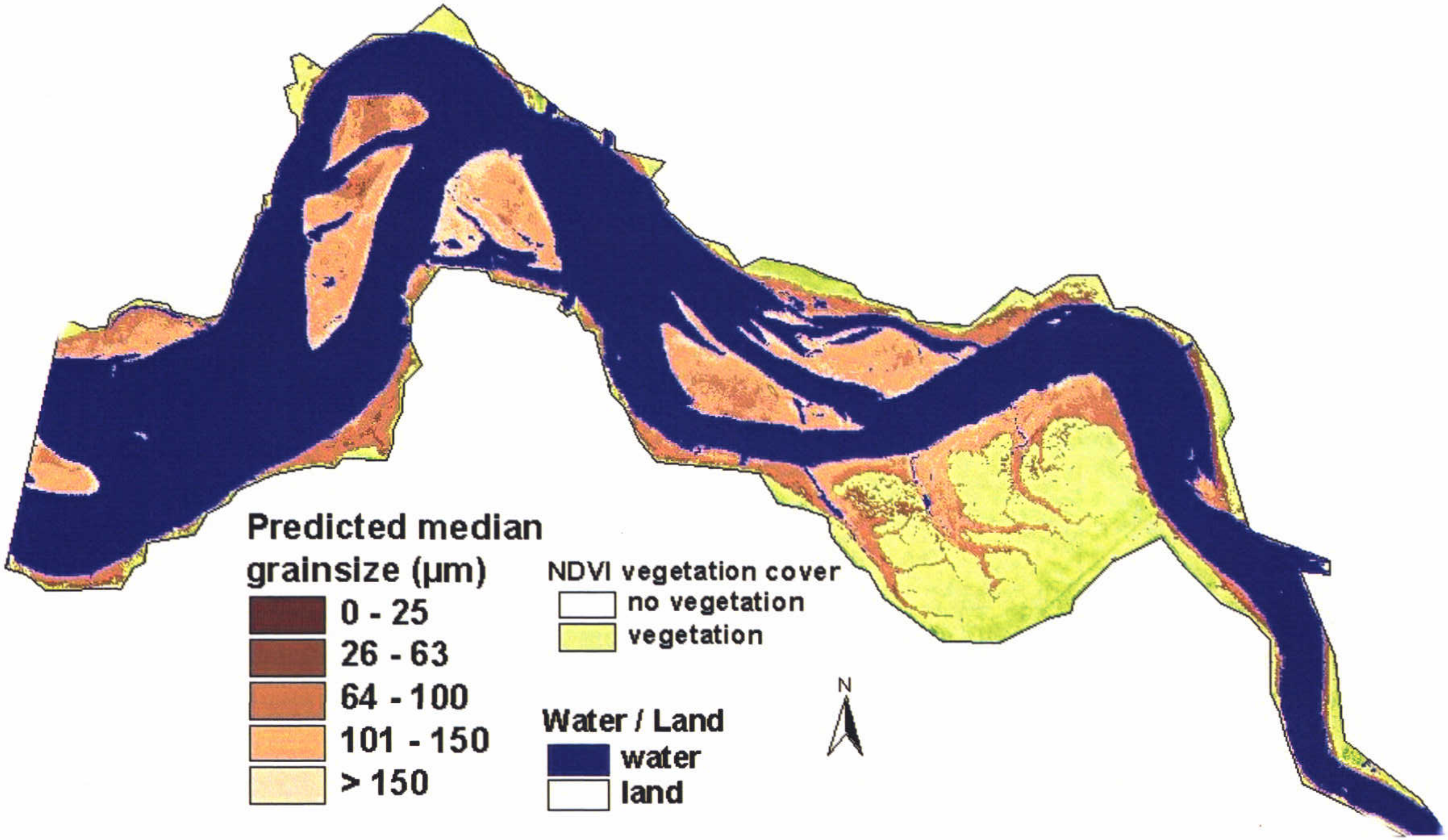

Figure 3.10. Classified remote sensing image for median grainsize, water and vegetation.

Figure 3.11 presents a part of Figure 3.10 in which the observed McLaren samples for median grainsize are shown. The median grainsize values of both prediction and measurement were classified in identical classes.

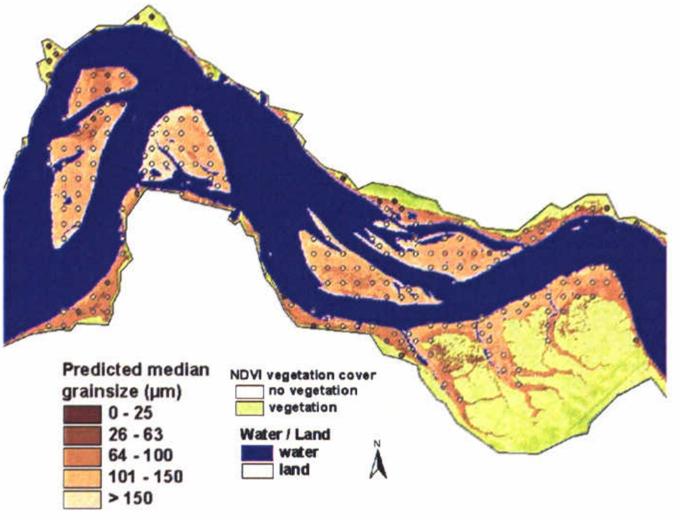

Figure 3.11. Part of the remote sensing image together with observed McLaren data for median grainsize.

3.5 Verification

In 1995, data of grain size distribution were collected on a small intertidal area in the upper middle part of the estuary, called the Molenplaat, for the BEON project (Herman et al., 1996; Thoolen et al., 1997). The median grainsize values were measured in March, June, September and December. The tidal flat classification of the remote sensing image is compared with this separate BEON data set, to test the applicability of the classification.

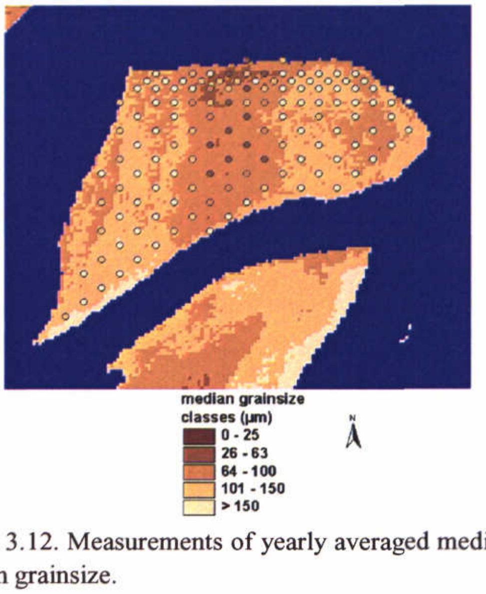

Figure 3.12. Measurements of yearly averaged median grainsize of the Molenplaat and prediction of median grainsize.

Figure 3.12 presents the Molenplaat area and the prediction of median grainsize together with the yearly-averaged median grainsize values that were measured in 1995. The median grainsize values of both prediction and measurement were classified in identical classes in this figure.

The correlation between the measurements and the prediction was tested for each season, correlation coefficients are presented in Table 3.5.

Table 3.5. Correlation between measured D50 and predicted D50 for the Molenplaat

Month.	Corr. coeff. r^2
March	0.40
June	0.21
September	0.23
December	0.24

The correlation between the measurements and the predictions for the Molenplaat is very low, except for the month of March. In March there is less variation in median grainsize values, because the siltation in spring has not taken place yet. The minimum median grainsize in March is 108 µm, while in June for example the minimum is 23 µm, and the maximums for both months are comparable. The lower variance in grainsize values in March explains the improved fit for the predictions.

Figure 3.13 presents the fit between the measured and predicted values for June '95. This season is selected, because the remote sensing image was taken in May (of 1996). A good correlation should follow the relationship $y = x$ and has a high correlation coefficient, this is clearly not a very good relationship. One aspect that is noteworthy is that the range of the BEON observations on the Molenplaat is much wider than the range of the predictions. The maximum predicted median grainsize is about 150µm, while the maximum observed median grainsize is about 350µm.

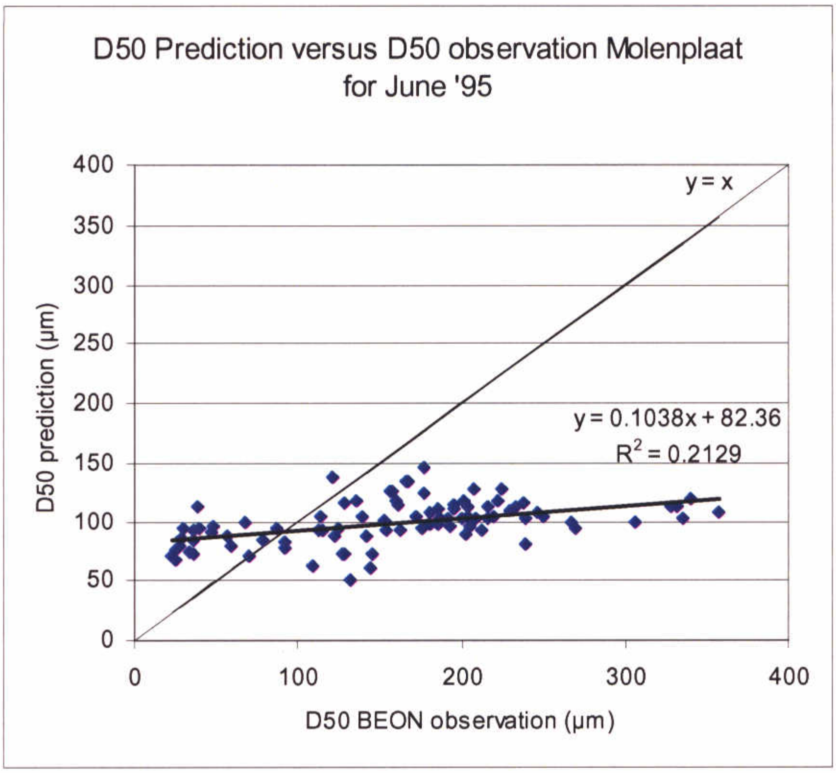

Figure 3.13 D50 measurement versus D50 prediction for the Molenplaat, June '95.

The results of this verification would indicate that the prediction of the median grainsize distribution from the remote sensing information is not in accordance with observed median grainsize values for the Molenplaat, and therefore the applicability for the Western Scheldt is questionable.

Before this conclusion is drawn, the correlation between both data sets of observations (McLaren data and BEON data) is investigated. The McLaren samples in the Molenplaat area (10 samples) were correlated to the most nearby BEON sample, or in some cases, the mean of the two most nearby samples. The correlation between both data sets is presented in Table 3.6.

Table 3.6. Correlation between observed McLaren D50 and observed BEON D50.

Month.	Corr. coeff. r^2
March	0.70
June	0.34
September	0.76
December	0.80

The correlation coefficients between both measurements are much higher than the correlation coefficients that were found between the BEON measurements and the prediction, except for the month of June. Figure 3.14 presents the fit between the most nearby BEON observations for each season in 1995 and the McLaren observations.

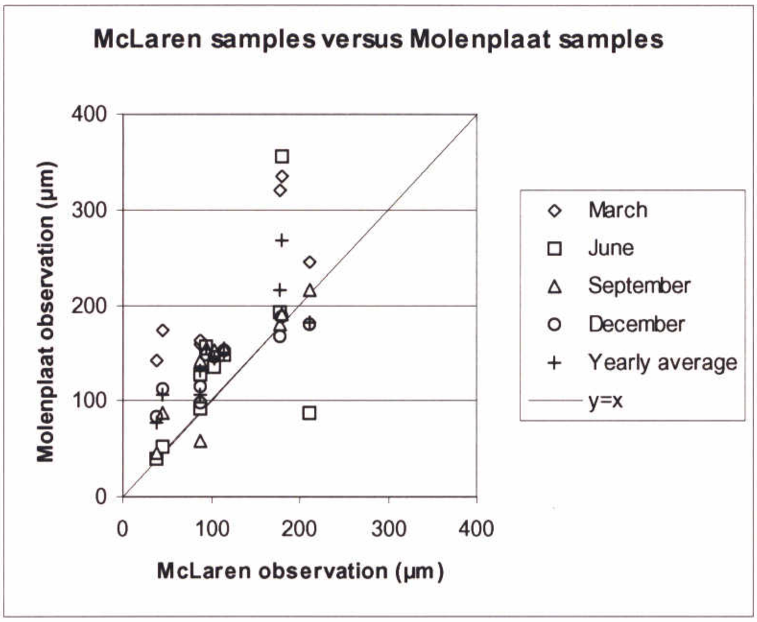

Figure 3.14. BEON observations versus McLaren observations for the Molenplaat, June '95.

Remarkable is that the BEON observations in general have higher values than the McLaren observations. The observed McLaren grainsize values underestimate the observed BEON grainsize values on the Molenplaat.

Although the prediction of D50 from the remote sensing image is based on the (lower) range of McLaren samples, there is no indication of an overall underestimation of the predicted median grainsize on the Molenplaat. Median grainsize values over 100µm are underestimated, but values under 100µm suffer from overestimation (see Figure 3.13).

It can be concluded that the correlation between the BEON observations and the predicted median grainsize on the Molenplaat is very low compared to the correlation between the BEON observations and the McLaren observations on the Molenplaat. Therefore, this verification shows that the classification of median grainsize values in the Western Scheldt, derived from a multiple linear regression of remote sensing band reflectances and corresponding McLaren samples, is not reliable.

3.6 Combination of Remote Sensing with Modelling and Measurements

The combination of RS images with mathematical models and measurements improves the possibilities for assessing the effects of the tunnel material dumping on tidal flats. The prediction of silt distribution on tidal flats with mathematical models can be improved when information from RS images is available on the spatial and temporal variability of suspended particulate material. A mathematical model of silt distribution in the water column that is (partly) calibrated on remote sensing data gives a mass-conservative prediction of the suspended matter concentrations and distribution. Based on sedimentation and erosion fluxes, the net changes in height of the tidal flats can also be modelled. This is demonstrated by the RESTWES project.

Results of the modelling of the changes in bottom height are shown in Figures 3.15 and 3.16. Both figures show the net changes in bottom height relative to 1st of January 1998 expressed in meters. The upper part of the figures presents the net changes in height as a result of the net sedimentation of the tunnel boring material and the lower part presents the net changes in height as a result of the net sedimentation of naturally occurring material (fluvial silt, marine silt and sand). Figure 3.15 shows the situation in the middle of the year on 27 June 1998, Figure 3.16 shows the situation at the end of the year, on 31 December 1998. Figures 3.17 and 3.18 present the net change in bottom height in metres over a period of one year starting in January 1998 for two locations. Figure 3.17 presents a location on the Hooge Platen and Figure 3.18 presents two locations on the Molenplaat.

In Figure 3.17, the Hooge Platen 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 settle on the tidal flat. The fraction of sea silt shows a similar seasonal behaviour.

In Figure 3.18 similar trends are shown for two locations on the Molenplaat. The heavy fraction (dotted line) shows similar 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 in absolute numbers less significant.

From these figures 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 sea fraction in the model; The amount of the tunnel material which accumulates is small compared to the natural sediment. There is however a strong seasonal variation. The amount of tunnel silt has a significant contribution to the total amount of silt in summer on the Molenplaat.

For a more elaborate discussion on the model assumptions and results, this study refers to the report of the main RESTWES project (Villars & Vos, 1999).

Without any additional modelling effort, the images themselves do provide useful information on potential effects. The classification of the sediment composition on intertidal areas may show additional accumulation of silt on some places. Special attention can be paid to those areas where littoral cockle beds are present. The decision to carry out local measurements to the condition of the cockle beds can be taken depending on whether or not the RS images show evidence of additional silt in these areas. Related to the locations of sensitive or economically important species or communities in a GIS the sediment composition can also be used together with habitat suitability models to assess the potential effects.

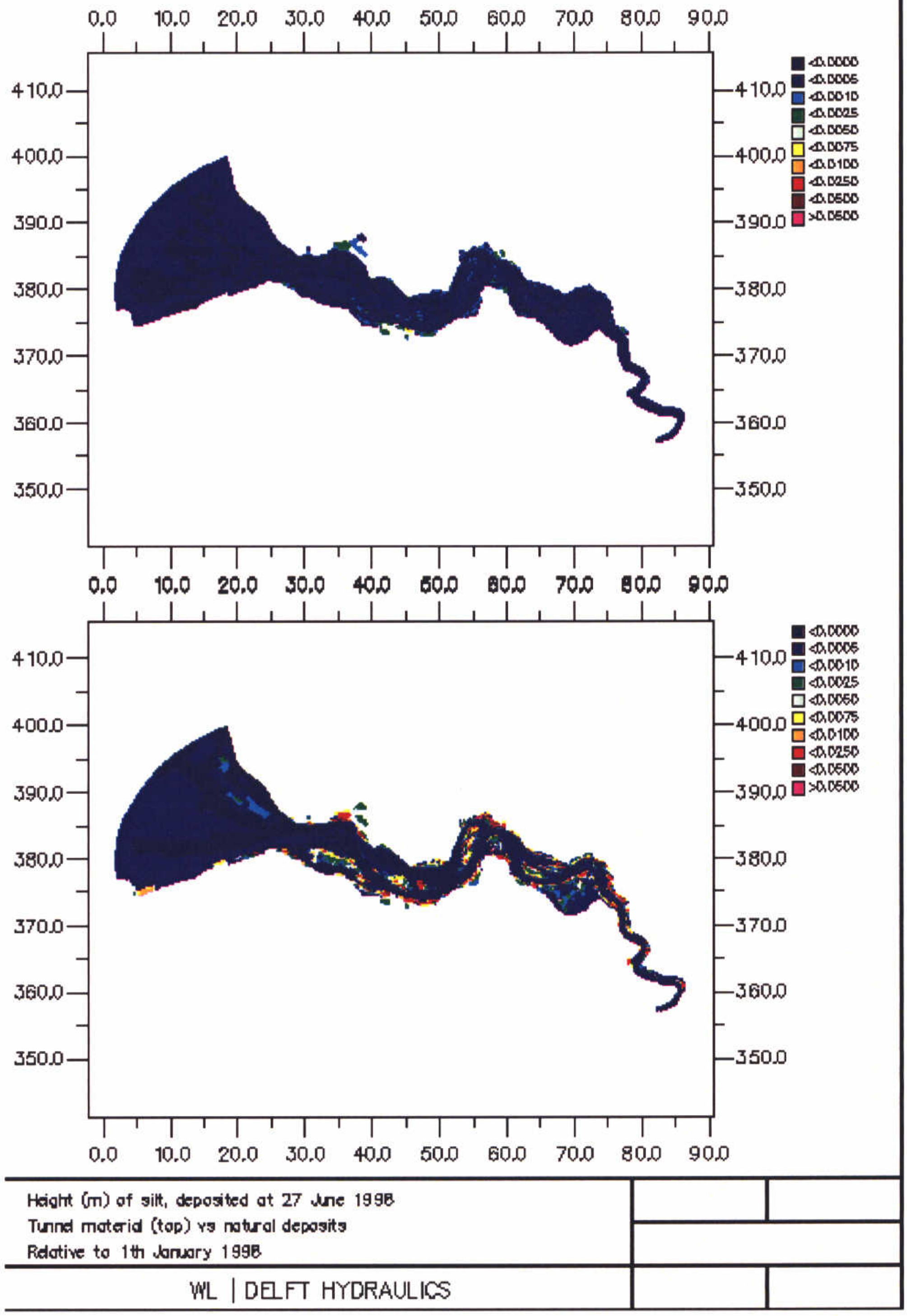

Figure 3.15. Net changes in bottom height for deposited tunnel material (top) and deposited natural material on 27 June 1998.

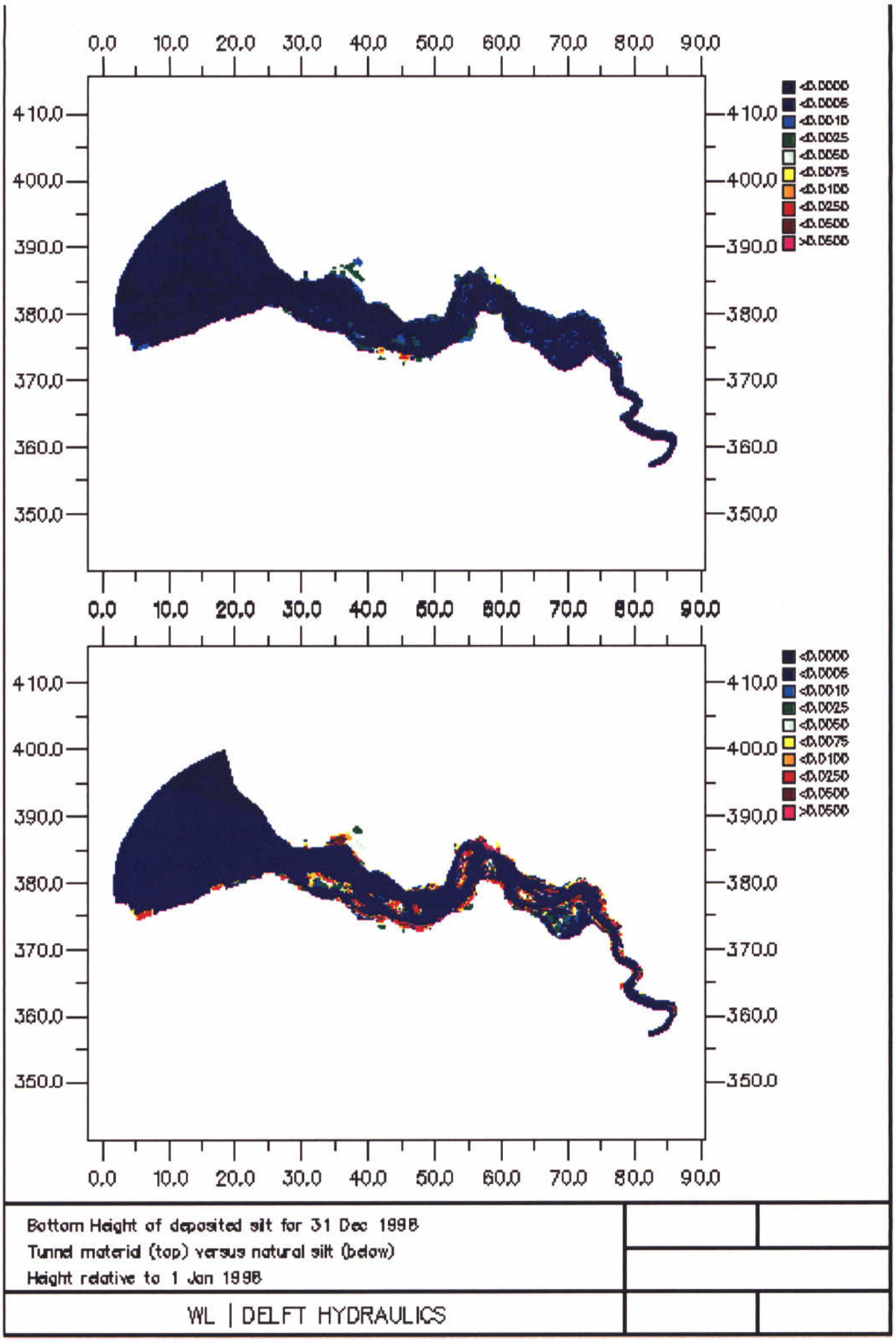

Figure 3.16. Net changes in bottom height for deposited tunnel material (top) and deposited natural material on 31 December 1998.

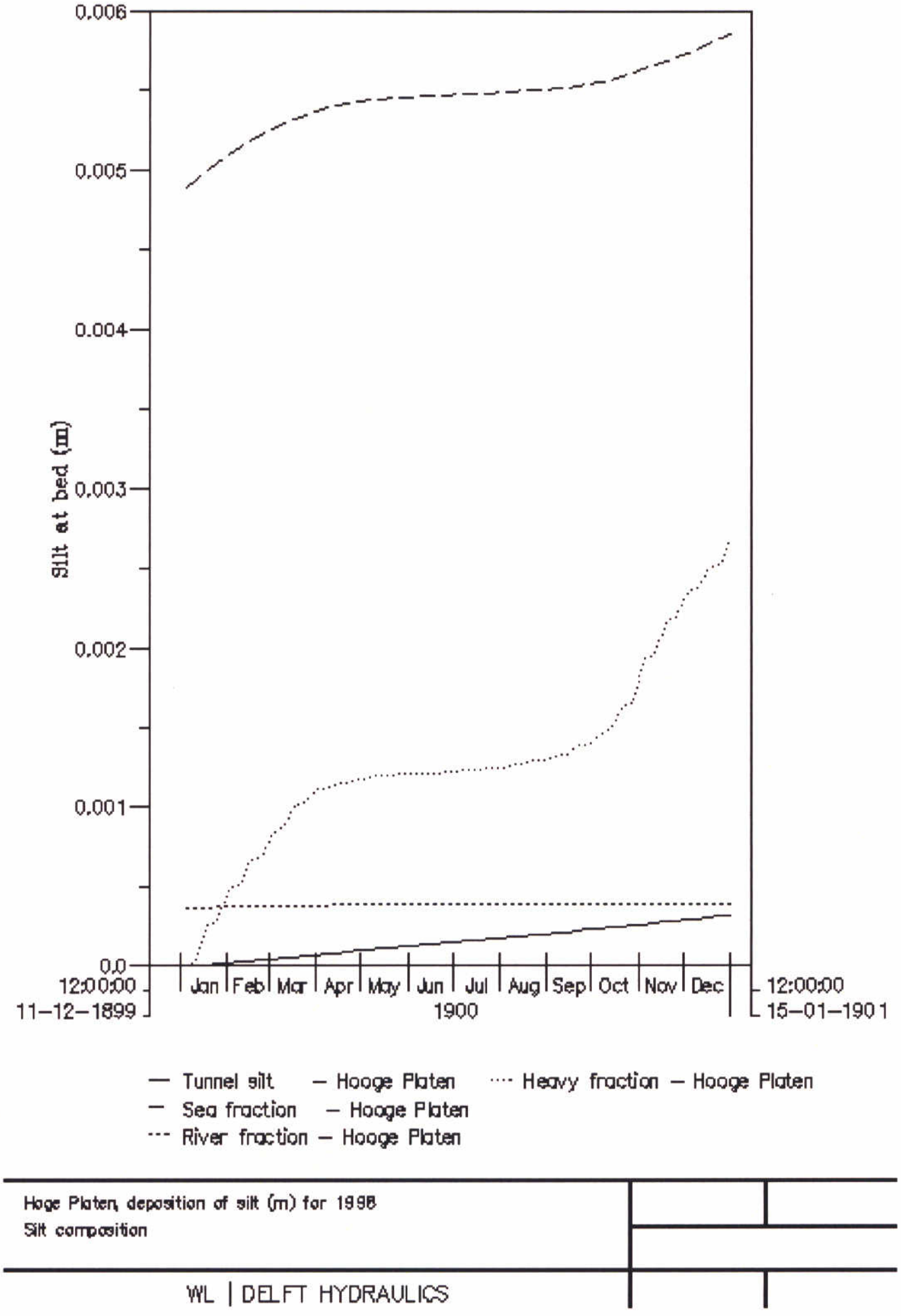

Figure 3.17. Deposition of silt in metres for a location on the Hooge Platen.

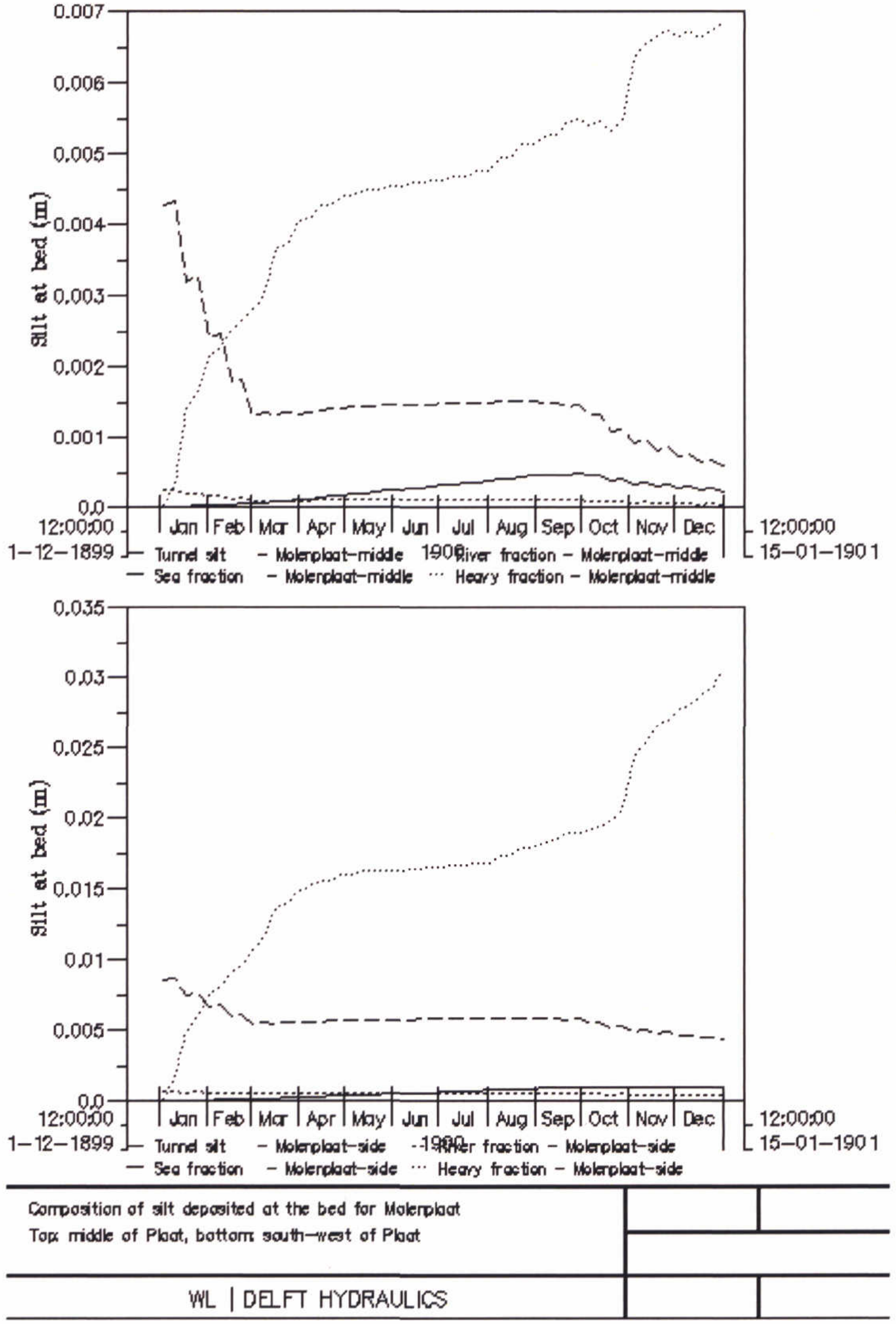

Figure 3.18. Deposition of silt in metres for a location on the Molenplaat.

4 The Applicability of Remote Sensing for Monitoring Effects on Intertidal Areas

This report gives a brief overview of the potential ecological effects of the dumping of tunnel boring material and a method to describe the sediment composition on the intertidal areas of the Western Scheldt. This chapter will evaluate the applicability of remote sensing to monitor the ecological effects of the dumping of tunnel boring material.

In Chapter 3, a number of potential ecological effects are mentioned. Some of these effects are more applicable for monitoring with remote sensing than others. Each of the potential effects and the applicability of remote sensing will be discussed here.

Increased SPM Concentration

The RESTWES project, as well as the previous RESTWAQ project have shown that remote sensing images can be used to quantify suspended matter concentrations in the water column. Together with in situ measurements and mathematical modelling, a reliable prediction of SPM concentrations is possible. A subsequent water quality and ecological modelling (primary production and consumption by phytoplankton, zooplankton and filter feeders) may be used for an assessment and quantification of potential effects.

Burial of benthic species

The burial of benthic species by an increased sedimentation rate is hard to monitor with remote sensing images. The SPOT images do not contain any information on surface heights. Without information on the height changes through time the burial rates cannot be quantified. Furthermore, remote sensing images do not provide any information on oxygen or sulphide concentrations in the overlying sediment.

Remote sensing images from the SPOT satellite may play a role in the calibration of water quality models that can compute the expected sedimentation rates and water quality parameters. The remote sensing images may also be used for a rapid identification of locations that are potentially affected by the increased suspended matter concentrations, to assure a more effective in situ monitoring.

Other satellites may be used to analyse changes in elevation of tidal flats. A German research project focuses on elevation models of tidal flats using the Synthetic Aperture Radar on the ERS-2 satellite, see:
http://www.dfd.dlr.de/projects/db/TIDE.html and:
http://www.dfd.dlr.de/app/iom/1998_05/index.html

Siltation

The RESTWES Ecology project is focused on the classification of intertidal areas with respect to the sediment composition. With a proper classification it should be possible to detect changes in bottom composition by comparing remote sensing images of different dates. The resulting bottom composition maps may be used for habitat classification and impact assessment of the dumping of tunnel boring material.

Fluid Mud

The possible occurrence of fluid mud cannot be monitored with remote sensing techniques. The fluid mud will typically be present (if present at all) at the bottom nearby the dumping location in (relatively) deep water.

Drilling Mud

The transport and distribution of the discharged drilling mud may be monitored with remote sensing images. A quantification of the different substances in the discharged material (Boomse klei, bentonite, heavy metals, chemical additives) cannot be made. Potential effects of these compounds must be measured in situ or can be modelled.

Summary

Table 4.1 presents a summary on the applicability of remote sensing to monitor the ecological effects of the dumping of tunnel boring material.

Table 4.1. Summary on the applicability of remote sensing to monitor the ecological effects of the dumping of tunnel boring material.

Potential effect	Applicability
Increased SPM	++
Burial of benthos	0
Siltation	+
Fluid mud	-
Drilling mud	+

5 Conclusion, Discussion and Recommendations

5.1 Conclusion

This study has resulted in the classification of one single image in median grainsize values. By means of a multiple linear regression of band reflectances with median grainsize observations a spatial coverage of predicted median grainsize values was produced. The correlation coefficient R^2 between the McLaren observations and the predicted values was 0.55. A verification of the resulting image with a separate data set of median grainsize values for a single tidal flat, the Molenplaat, was carried out. The results of this verification show that the prediction of the median grainsize distribution from the remote sensing information is not in accordance with observed median grainsize values for the Molenplaat, therefore, the applicability of this classification for the Western Scheldt is not reliable.

The combination of remote sensing images with mathematical models and measurements improves the possibilities for assessing the effects of the tunnel material dumping on tidal flats. Based on sedimentation and erosion fluxes, the net changes in height of the tidal flats can also be modelled. This is demonstrated by the RESTWES main project (Villars & Vos, 1999) and shows that the amount of tunnel silt has a significant contribution to the total amount of silt in summer on the Molenplaat.

It is concluded that the classification of sediment composition from remote sensing images is in this stage not an operational method for monitoring. To further develop this method as an operational tool, first a more reliable classification has to be made. This involves dealing with spatial and temporal variations and whether or not the information from the sediment surface is representative for the bed sediment composition. These aspects are discussed below.

To monitor potential effects of the dumping of tunnel boring material it is necessary to compare images that are taken prior, during and after the dumping of the tunnel boring material. Different techniques for detecting changes from RS-images are available. A discussion on these techniques is given in Appendix I of this report.

5.2 Discussion

Seasonal Changes

There are large seasonal changes in bed sediment composition of intertidal areas. Sediment data from the Molenplaat for example show that the silt content in March (of 1995) did not reach values larger than 30%. In spring there is a build-up of silt up to 80%, which remains there until December and collapses during winter. The building up of silt probably has a relationship with diatom growth and suspension feeder biodeposits (Herman et al, 1996; Thoolen et al., 1997).

Any analysis of remote sensing images with regard to the sediment composition on tidal flats as a result of the dumping of tunnel material should therefore be preceded by an analysis of the natural variations on the intertidal areas. Remote sensing images from the SPOT satellite theoretically provide a daily coverage of the Western Scheldt. Cloud cover is the most frequent problem in the Netherlands to obtain images of good quality. In a tidal system, such as the Western Scheldt, the moment with respect to the tide is another concern. To analyse the intertidal areas, images taken at low water are necessary. All in all it may be possible, but hard, to obtain images on a monthly basis of the Western Scheldt at low tide to analyse seasonal trends in sediment composition. A minimum number of images that is required to analyse seasonal changes is one image per season, i.e. in March, June, September and December.

Effects of Tidal Stage on Image Classification

Tide stage is a crucial factor in satellite image scene selection for classification of intertidal areas. Ideally, tides should be constant between alternative images. Alternatively, the tide stages occurring throughout the images can be taken into account when analysing images.

For classifying intertidal areas in the Western Scheldt, mean low tide (MLT) or lower will be preferred, up to 50 centimetres above MLT will be acceptable, but more than 50 centimetres above MLT will be unacceptable. But even when the water height between images is constant, the exact moment within the tide also may play a role. Suppose that two similar locations within alternative images have a similar water level relative to MLT, then it can be a crucial difference if the one image was taken prior to low water and the other was taken after low water. This difference may be the result of the sediment moisture of the top layer or the growth of benthic algae on top of the sediment. It can be the case that the same location has a different reflectance characteristic say, one hour before low water compared to one hour after low water. To make things worse, tide stages are not synchronised within the Western Scheldt region, so they're also not synchronised within a single image. Low water at Bath near the Belgium border will be reached about one and a half hour later than low water at Vlissingen.

Top Layer of the Sediment

The spectral reflectance of the intertidal areas is limited to the top millimetres of the sediment surface. Usually, the measurements for grainsize distribution are taken from the top centimetres. These different techniques may theoretically lead to a complete misclassification. On the other hand, it can be observed in the field that the activity of benthic organisms results in a relatively fast mixing of the top centimetres of the sediment. This implies that the sediment surface is representative for the top centimetres.

Sediment moisture

The sediment moisture is probably very important in determining the sediment composition. The pixel information in the remote sensing image will also contain information on the sediment moisture. The sediment moisture itself is correlated to the sediment composition.

The permeability of sediment is dependable on the silt content. When a relative small percentage of silt is present in the sediment, the permeability of the sediment will decrease with some orders of magnitude. In other words, 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. For these sediments the solar irradiation and wind speeds may be more important with regard to the evaporation of the sediment. Under dry conditions in summer, a crust may form on top of the sediment. This can significantly change the reflectance characteristics. In winter, an ice-layer may form on top of the sediment, and therefore also change the reflectance characteristics.

Algal mats

In spring and summer algal mats of microphytobenthos may develop in some places on intertidal mudflats. 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 reflectances from the intertidal areas, and thus making it difficult to classify the sediment with regard to sediment composition. On the other hand it is known that algal mats develop in silty areas, this information may be used to make a classification. It is expected that the NDVI will give a high score in areas with algal mats.

5.3 Recommendations

In order to further develop the sediment composition classification from remote sensing images it is recommended to carry out in-situ measurements of the reflectance characteristics of different types of sediment together with sediment samples. It may then be possible to develop a more reliable algorithm for sediment classification similar to the method that is used for the water parameters in the main RESTWES-project (Figure 5.1). A 'bio-optical' model for sediment composition from measured sediment parameters, such as median grainsize, sediment moisture and algal density may be developed. The bio-optical model may then be coupled to the band reflectances R(0) of the SPOT satellite and by an improved sediment composition algorithm a more reliable classification may be carried out.

It is recommended to carry out in situ measurements of spectral reflectance characteristics and sediment conditions:

- On a spatial scale: select locations with a variety of median grainsizes, algal densities and sediment moisture;
- On a time scale: select time steps within a tidal cycle for samples with similar conditions.

It is further recommended to carry out measurements of vertical profiles of sediment composition on various locations in the Western Scheldt or collect existing measurements.

It is recommended to collect at least one remote sensing image per season to analyse seasonal changes, i.e. in March, June, September and December.

Remote sensing images taken during the dumping of tunnel material may serve to assess the additional net effect on sediment composition. Additional information on the characteristics of the dumped fine sediment will help to distinguish between the dumped material and the natural silt. The dumped fine sediment consists of 'Boomse klei' and may have different spectral characteristics than the naturally occurring marine and fluvial silt.

It is recommended to measure the spectral characteristics of Boomse klei in situ, so it will be easier to establish the distribution of Boomse klei over the Western Scheldt from RS images.

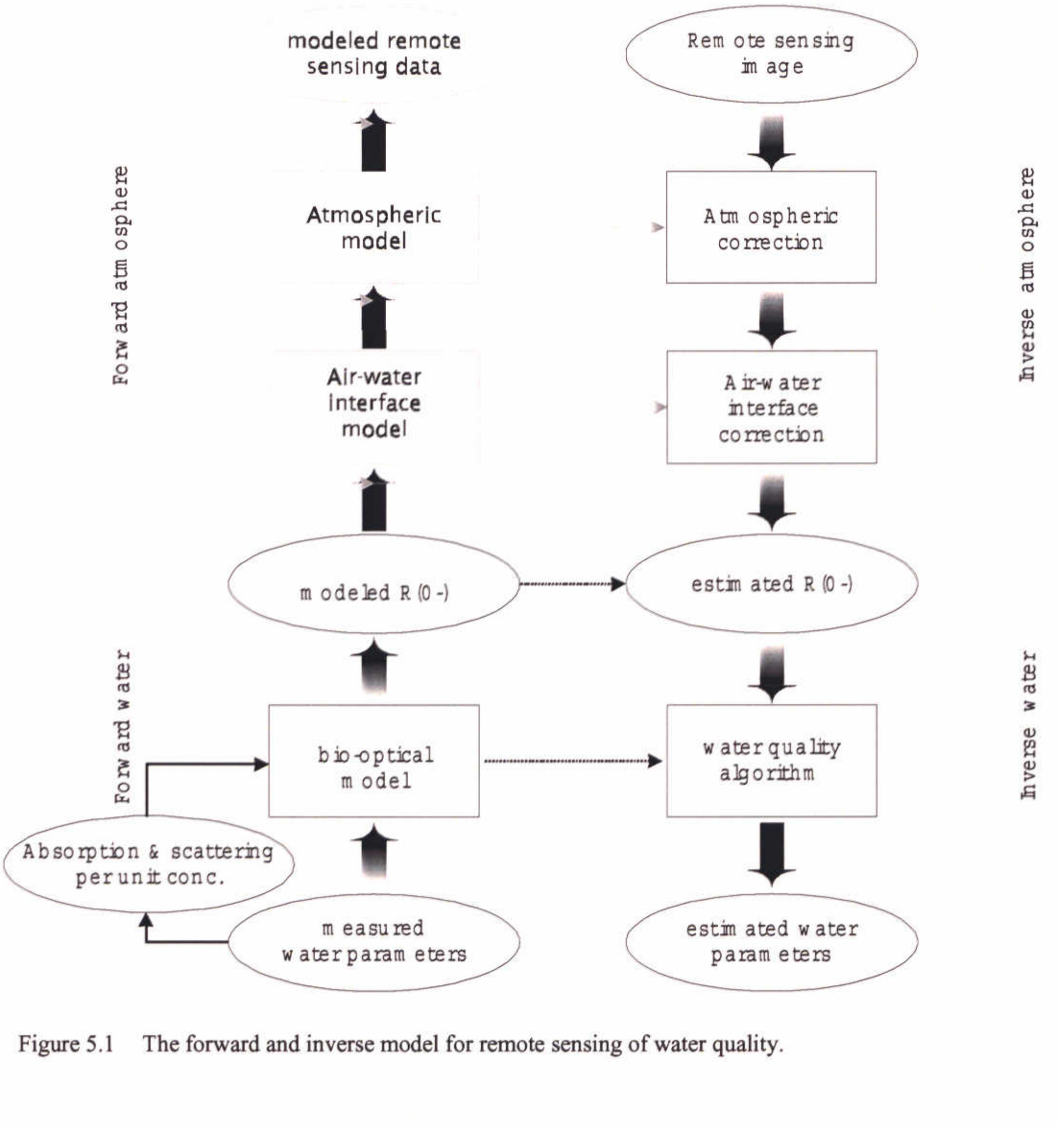

Figure 5.1 The forward and inverse model for remote sensing of water quality.

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Appendix I

Detecting Changes in Intertidal Areas

Introduction

When a reliable and robust classification method is available for mapping intertidal areas, it is possible to process the data to extract information on changes of sediment composition in intertidal areas over a certain time period.

For this purpose atmospherically corrected images have to be georeferenced first. This involves a spatial registration of a remotely sensed image to a standard map projection. Georeferencing uses Ground Control Points (GCP's) to compute rectification transformation coefficients. These GCP's should be relatively static features in the landscape (e.g. road intersections) or based on new Global Positioning System (GPS) measurements taken in the field. When GCPs are digitized from maps, analysts should use the marginal information and updates available to improve location of the control points. Traditional paper maps expand and contract with changes in relative humidity and should not be used for digitising GCP's (NOAA, 1995).

All images which have been used in the RESTWES project have been atmospherically corrected and georeferenced.

Techniques

When atmospherically corrected, georeferenced images are available, a selection of an appropriate change detection algorithm must be made. At least seven change detection algorithms are commonly used by the remote sensing community, including (NOAA, 1995):
1. Change Detection Using Write Function Memory Insertion;
2. Multi-date Composite Image Change Detection;
3. Image Algebra Change Detection;
4. Post-classification Comparison Change Detection;
5. Multi-date Change Detection Using A Binary Mask;
6. Multi-date Change Detection Using Ancillary Data Source;
7. Manual, On-screen Digitisation of Change.

1. Change Detection Using Write Function Memory Insertion

This technique is based on the possibility to insert individual bands of remotely sensed data into specific write function memory banks (red, green, and/or blue) in the digital image processing system. For example, one can place Band 1 of a 1998 image in the green image plane and Band 1 of a 1999 image in the red image plane (and no image in the blue image plane). All areas which did not change between the two dates are then depicted in shades of yellow (i.e. in additive colour theory, equal intensities of green and red make yellow). This will visually identify change in the imagery.

Advantages of this technique include the possibility of looking at two and even three dates of remotely sensed imagery at one time. Unfortunately, the technique does not produce a classified land cover database for either date and, thus, does not provide quantitative information on the amount of area changing from one land cover category to another. Nevertheless, it is an excellent method for quickly and qualitatively assessing the amount of change in a region which might help with the selection of one of the more rigorous change detection techniques to be discussed.

2. Multi-date Composite Image Change Detection

Numerous researchers have rectified multiple dates of remotely sensed imagery (e.g. selected bands of two scenes of the same region) and placed them in a single data set. This composite data set can then be analysed in a number of ways to extract change information. First, a traditional classification using all bands may be performed. Unsupervised classification techniques will result in the creation of 'change' and 'no-change' clusters. The analyst must then label the clusters accordingly.

Other researchers have used principle component analysis (PCA) to detect change. Again, the method involves registering two (or more) dates of remotely sensed data to the same planimetric basemap as described earlier and then placing them in the same data set. A PCA based on variance-covariance matrices or a standardised PCA based on analysis of correlation matrices is then performed. This results in the computation of eigenvalues and factor loadings used to produce a new, uncorrelated PCA image data set. Usually, several of the new bands of information are directly related to change. The difficulty arises when trying to interpret and label each component image. Nevertheless, the method is of value and is used frequently.

The advantage of this techniques is that only a single classification is required. Unfortunately, it is often difficult to label the "change" classes and no "from-to" change class information (in what direction have the changes taken place?) is available.

3. Image Algebra Change Detection

It is possible to identify the amount of change between two images by image differencing the same band in two images which have previously been rectified to a common basemap. Image differencing involves subtracting the imagery of one date from that of another. The subtraction results in positive and negative values in areas of radiance change and zero values in areas of no-change in a new "change image". In an 8-bit (28) analysis with pixel values ranging from 0 to 255, the potential range of difference values is -255 to 255. The results are normally transformed into positive values by adding a constant, (usually 255).

The "change image" produced using image differencing usually yields a brightness values distribution approximately Gaussian in nature, where pixels of no brightness value change are distributed around the mean and pixels of large change are found in the tails of the distribution.

Another approach is band ratioing. Band ratioing involves exactly the same logic except a ratio is computed between similar bands of two images and the pixels which did not change have a value of "1" in the change image.

A critical element of both image differencing and band ratioing change detection is deciding where to place the threshold boundaries between "change" and "no-change" pixels displayed in the histogram of the change image. Often, a standard deviation from the mean is selected and tested empirically. Conversely, most analysts prefer to experiment empirically, placing the threshold at various locations in the tails of the distribution until a realistic amount of change is encountered. Thus, the amount of change selected and eventually "recoded" for display is often subjective and must be based on familiarity with the study area. There are also analytical methods which can be used to select the most appropriate thresholds. Unfortunately, image differencing simply identifies those areas which may have changed and provides no information on the nature of the change, i.e. no "from-to" information. Nevertheless, the technique is valuable when used in conjunction with other techniques such as the multiple-date change detection using a binary change mask.

4. Post-classification Comparison Change Detection

This is the most commonly used quantitative method of change detection. It requires rectification and classification of each of the remotely sensed images. These two maps are then compared on a pixel by pixel basis using a "change detection matrix". Unfortunately, every error in the individual date classification map will also be present in the final change detection map. Therefore, it is imperative that the individual classification maps used in the post-classification change detection method be extremely accurate.

Suppose that nine classes for intertidal areas are inventoried for two images on different dates. These classification maps can then be compared on a pixel by pixel basis using an *n* by *n* matrix algorithm. This will result in the creation of a "change image map" consisting of brightness values from 1 to 81 (9x9). The analyst may now select specific "from - to" class changes for emphasis and produce specific change detection maps (for example *from* sandy *to* muddy).

Post-classification comparison change detection is widely used and easy to understand. It represents a viable technique for the creation of change detection products. An advantage is the detailed 'from-to' information. Unfortunately, the accuracy of the change detection is heavily dependent on the accuracy of the two separate classifications.

5. Multi-date Change Detection Using A Binary Mask

In this technique one of the bands from both dates of imagery are placed in a new data set. The two date data set is then analysed using various image algebra functions (e.g. band ratio, image differencing, principal components) which produces a new image file. The analyst usually selects a "threshold" value to identify spectral "change" and "no-change" pixels in the new image. The spectral change image is then recoded into a binary mask file, consisting of pixels with spectral change between the two dates, and these are viewed as candidate pixels for categorical change. Great care must be exercised when creating the "change/no-change" binary mask. The change mask is then overlaid onto one of the used images and only those pixels which were detected as having changed are classified. A traditional post-classification comparison (previous section) can then be applied to yield "from-to" change information. Hence, many pixels with sufficient change to be included in the mask of candidate pixels may not qualify as categorical land cover change.

This method may reduce change detection errors and provides detailed "from-to" change class information. The technique reduces effort by allowing analysts to focus on the small amount of area that has changed between dates. The method is complex, requiring a number of steps and the final outcome is dependent on the quality of the "change/no-change" binary mask used in the analysis.

6. Multi-date Change Detection Using Ancillary Data Source

Sometimes there exists a land cover data source which may be used in place of a traditional remote sensing image in the change detection process. Instead of using a remotely sensed image as in the analysis, it is possible to substitute a digital map of the region. The Multi-data change analysis is similar to the one described in the previous section.

Advantages of the method include the use of a well-known, trusted data source and the possible reduction of errors of omission. Detailed "from-to" information may be obtained using this method. Also, only a single classification of the remote sensing image is required. The disadvantage is that the land cover data source must be digitised, generalised to be compatible with the classification used in the RS images and then converted from vector to raster format to be compatible with the raster remote sensor data. Any manual digitisation and subsequent conversion introduces error into the database which may not be acceptable and is time-consuming.

7. Manual, On-screen Digitisation of Change

Considerable amounts of high resolution remote sensor data are available from aerial photographs. These data can be rectified and used as planimetric base maps or orthophotomaps. Often aerial photographs are scanned (digitised) at high resolutions into digital image files. These photographic data sets can then be registered to a common base map and compared to identify change. Digitised high resolution aerial photographs displayed on a screen can be interpreted easily using standard photo interpretation techniques based on size, shape, shadow, texture, etc. Therefore, it is becoming increasingly common for analysts to visually interpret both dates of aerial photographs (or other type of remote sensor data) on the screen, annotate the important features using heads-up "on-screen" digitising, and compare the various images to detect change. The process is especially easy when:

a) both digitised photographs (or images) are displayed on the screen at the same time, side by side, and;

b) they are topologically "linked" through object-oriented programming so that a polygon drawn around a feature on one photograph will have the same polygon drawn around the same object on the other photograph.

Scanning aerial photographs unavoidably will reduce the spatial and spectral resolution of the source data. This loss may be significant in photographs of submerged features, which are subject to interferences from aquatic as well as atmospheric sources. The manual on-screen approach is recommended as a useful adjunct to other change detection methods. Its principle drawback is the time required to cover large regions in such a labour-intensive fashion.

Conclusion and Recommendations on Change Detection

For change detection it is important to have information on the nature and direction of the changes ("from-to" information). The previous sections indicated that three of the seven most commonly used change detection algorithms have this kind of information:

- Post-Classification Comparison;
- Change Detection Using A Binary Change Mask;
- Change Detection Using Ancillary Data Source.

Each of these requires a complete pixel by pixel classification of one date of imagery and, at least, a partial classification of an additional date. The latter two techniques are more complex than the first, and each technique has its advantages and disadvantages.

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