PROGRAMMATORISCHE FEDERALE OVERHEIDSDIENST

WETENSCHAPSBELEID

RESEARCH PROGRAMME FOR EARTH OBSERVATION "STEREO"

Partnerships between Industry and Research

ONDERZOEKSCONTRACT

CONTRAT DE RECHERCHE

SR/67/36

PROJECT

Operational Remote sensing Mapping of Estuarine suspended Sediment concentrations (ORMES)

Operationele kartering van suspensiesedimentconcentraties in estuaria door middel van aardobservatie (ORMES)

THE PARTNERSHIP

SCIENTIFIC PARTNER

Vlaamse Instelling voor Technologisch Onderzoek (VITO)

PRIVATE PARTNER

International and Marine Dredging Consultants (IMDC)

FINAL REPORT

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

ACRONYMS AND ABBREVIATIONS

AGI	De Adviesdienst Geo-informatie en ICT
AISA	Airborne Imager Spectrometer for Applications
AWZ	Administratie Waterwegen en Zeewezen
CASI	Compact Airborne Spectrographic Imager
CDOM	Colored, Dissolved Organic Matter
CHL	Chlorophyll
ENVI	Environment for Visualizing Images
IDL	Interactive Data Language
IDL VM	Interactive Data Language Virtual Machine
IMDC	International and Marine Dredging Consultants
ORMES	Operational Remote sensing Mapping of Estuarine suspended Sediment concentrations
SPOT	Satellite Probatoire d'Observation de la Terre
SPM	Suspended Particulate matter
TSM	Total suspended matter
VITO	Vlaamse Instelling voor Technologisch Onderzoek
WLH	Waterbouwkundig Laboratorium

1. EXECUTIVE SUMMARY

To support IMDC in their activities, a service is developed in the ORMES project which provides suspended sediment maps from remote sensing images in an efficient way.
Our main test site is a part of the Belgian Scheldt Estuary near Antwerp. It was chosen because of the wide ranges of sediment content and IMDC's thorough knowledge of the river system.
Airborne hyperspectral data were acquired at different stages during the tidal cycle. Simultaneously with the airborne campaign a field survey took place. The goal was to collect ground truth data while the hyperspectral sensor was imaging the study area. This ground truth is essential for calibration and validation of the airborne remote sensing data. Three survey vessels were used at different stretches of the Lower Sea Scheldt to include some spatial variability. Several measurements were done on board of each vessel on predetermined locations at the time of airplane crossing over the study area. Surface water samples were collected for analyzing total suspended matter concentration, optical reflectance measurements were carried out and a turbidity sensor continuously measured turbidity in the surface water layer.
Using these field data and the high resolution airborne data, a reliable semi-empirical algorithm has been developed to derive near-surface suspended matter maps in an operational way. The produced TSM maps showed good agreement with known variations of the suspended sediment content over the tidal cycle: maximum turbidity around high water and gradual settling of the sediment in the succeeding slack water. A resuspension of sediment takes place at the onset of the ebb flow stage, especially at the bend-related shoals.
The suspended sediment maps were validated against sediment transport model simulations and cross-section turbidity measurements.
To export the methodology to other data sources and other areas SPOT and/or Formosat data were requested from the Scheldt area and also from some foreign sites. Unfortunately these requests were unsuccessful. To overcome this problem it was decided to spatially and spectrally resample the airborne hyperspectral data to the

characteristics of Landsat and SPOT sensors. On the basis of these simulated data empirical algorithms for SPOT and LANDSAT sensors were determined.

Finally a user friendly software has been written which gives IMDC the opportunity to generate suspended sediment maps from airborne and satellite images, provided that some calibration points with known TSM are available for the image used.

2. ADMINISTRATIVE INFORMATION

- The list of personnel and organisations involved is given in table 1

***Table 1:** List of personnel and organisations involved*

Name	Organisation	e-mail
Els Knaeps	VITO	Els.knaeps@vito.be
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Koen Trouw	IMDC	Koen.trouw@imdc.be
Mark Bollen	IMDC	Mark.bollen@imdc.be
Marc Sas	IMDC	Marc.sas@imdc.be
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- The steering committee members are :

Dr. Hans Hakvoort, De Adviesdienst Geo-informatie en ICT (AGI), Rijkswaterstaat (RWS), the Netherlands. E-mail : J.H.M.Hakvoort@agi.rws.minvenw.nl

Ir. Joris Vanlede, Ministerie van de Vlaamse Gemeenschap; Administratie Waterwegen en Zeewezen; Afdeling Waterbouwkundig Laboratorium (WLH) en Hydrologisch

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Ir. Eric Taverniers, Ministerie van de Vlaamse Gemeenschap; Administratie Waterwegen en Zeewezen (AWZ), Afdeling Waterbouwkundig Laboratorium (WLH) en Hydrologisch Onderzoek, Cel Hydrometrie Schelde. E-mail : eric.taverniers@lin.vlaanderen.be

- Execution period : December 2004 – December 2006

- Steering committee meetings have been organised on February 24th 2006 and on December 5th 2006.

- No specific website has been set-up. However a very short description of the project is given on the general website of our research group (http://publications.vgt.vito.be/). Here you can also find and download the published papers.

3. RATIONALE, OBJECTIVES AND APPROACH

Each year, dredging companies remove more than two million m3 of estuarine sediment from the Scheldt River (Belgium). This is necessary to assure access to the harbour of Antwerp. International Marine and Dredging Consultants (IMDC) advises government agencies and dredging companies to help them carry out their activities. Information on the sediment concentration is essential if accurate advice is to be given. IMDC uses this information to select new dumping sites, to estimate possible movements of sediment clouds and to calibrate sediment transport models. At the moment turbidity meters and water samples can provide measurements of suspended sediment concentration. However, these types of analysis are time consuming and expensive. Furthermore traditional in-situ measurements performed at single points or along transects are insufficient to provide a complete view of the spatial variability of suspended sediments. A cost-effective way of providing this information is to use remote sensing data. These data can cover relatively large areas instantaneously at relatively low cost and are therefore ideal for this type of assessment. For these reasons, IMDC relies on the ORMES project in order to develop a simple and robust procedure for near surface sediment concentration mapping from remote sensing images.

This project objectives as stated in the original proposal are :

(1) to develop a simple and robust procedure for near surface sediment concentration mapping from remote sensing data. This procedure has to be applicable to tidal rivers (in Belgium and abroad) with only a limited number of in-situ / calibration measurements required as input.

(2) to operationalise and automate the procedure.

(3) to implement the procedure/software at the private partner. With this software the private partner will be able to generate sediment concentration maps.

In the ORMES project the Scheldt Estuary has been chosen as main study site mainly because of its dynamic complexity. A large dataset consisting of a series of airborne hyperspectral images was obtained at different stages of the tidal cycle. Simultaneously with the airborne campaign a field survey took place. Using these field data and the high resolution airborne data, a reliable semi-empirical algorithm has been developed to derive near-surface suspended matter maps in an operational way. The algorithm showed to be insensitive for external effects such as varying cirrus cloud cover during the flights and adjacency influences. The produced TSM maps were in very good agreement with known variations of the suspended sediment content over the tidal cycle.

The ORMES project focused mainly on the full capability of state-of-the-art airborne hyperspectral sensors, with some minor tasks devoted to satellite based TSM derivations. The final product of the ORMES project is a user-friendly software for the production of suspended matter maps.
This software will be implemented at IMDC and TSM concentration maps can be generated from remote sensing data with a limited number of water samples for calibration

4. SUMMARY OF RELEVANT LITERATURE

A short literature review has already been made for the first progress report and is repeated in Annex 1 of this final report. Table 2 summarizes the (dis)advantages of the different approaches to generate suspended sediment maps.

***Table 2**: Comparison of analytical and (semi-)empirical models*

	SEMI-EMPIRICAL	ANALYTICAL MODELS
Approach	Statistical using some physical knowledge	Physical model
Advantages	+ fast + easy to apply	+ model applicable to other regions + simultaneous determination of different water parameters (CHL, CDOM, SPM)
Disadvantages	- several in-situ measurements of SPM simultaneously with image acquisition required - difficult to apply to other regions without in-situ measurements	- absorption and scattering properties of the area of interest should be known - very sensitive to errors in input parameters - complex

With respect to the (semi-)empirical approaches we found the papers of Doxoran et al., 2005, Matthews et al., 2001, Kallio et al., 2001 most relevant for the ORMES project. They tried to find empirical algorithms that are not specific to a certain environment or time period. They showed that the best algorithms for each region mostly employ the same wavelength channels but the empirical parameters of the algorithms differ. This means that a number of in situ water samples are always needed to calibrate the algorithm for a specific environment. For example, Doxoran et al. (2005) established an empirical relationship in the Tamar estuary (south-west UK) using a ratio of a NIR band at 850 nm and a band at 550 nm. For the Gironde estuary a similar linear relationship was established which uses the same bands but different regression coefficients. Still, these results are based on large in situ hyperspectral datasets and can not always be applied to airborne data without further research. In-situ reflectance spectra are almost unaffected by atmospheric variability, adjacency effects and radiometric calibration issues which is often the case with airborne or satellite data.

Kallio et al. (2001) on the other hand used airborne AISA data for the retrieval of water quality parameters of lakes with relatively low TSM concentrations making the algorithms not directly suitable for the more turbid estuarine or coastal environments.

Matthews et al. (2001) determined an empirically derived general algorithm using airborne CASI data which worked well for two different sites in the UK: the Bristol Channel and the north Norfolk coast. These sites have (1) differing morphologies and (2) The Bristol Channel is dominated by inorganic red sediment and the Norfolk coast site has a higher organic content

Doxoran, D., R.C.N. Cherukuru, S.J. Lavender, 2005, *Use of reflectance band ratios to estimate suspended and dissolved matter concentrations in estuarine waters*, international Journal of Remote Sensing, 26(8), 1763-1769

Kallio, K., T. Kutser, T. Hannonen, S. Koponen, J. Pulliainen, J. Vepsäläinen, T. Pyhälahti, 2001, *Retrieval of water quality from airborne imaging spectrometry of various lake types in different seasons*, The Science of the Total Environment, 268, 59-77

Matthews, A.M., A.G. Duncan, R.G. Davison, 2001, *Error assessment of validation techniques for estimating suspended particulate matter concentration from airborne multispectral imagery*, international Journal of Remote Sensing, 22(2,3), 449-469

5. ACHIEVEMENTS AND PROBLEMS ENCOUNTERED

The following results have been obtained :

- We have had a very successful field and airborne campaign. On the basis of this campaign a large database has been generated which contains:

- hyperspectral data cubes at different processing levels (radiometrically, atmospherically and geometrically calibrated) covering several stages in the tidal cycle.
- turbidity data measured almost continuously during the campaign
- in-situ spectral reflectance measurements
- specific inherent optical properties (backscattering and absorption spectra)
- suspended sediment concentration of a large number of water samples
- chlorophyll content of several water samples

- A reliable semi-empirical algorithm, based on a band difference term log-linear regressed against suspended sediment concentration, has been developed to generate suspended sediment maps from airborne hyperspectral data. This algorithm was shown to compensate for some disturbing factors, such as varying cirrus cloud cover and adjacency effects. The use of this difference term has to our knowledge not been reported before. This may be due to the often limited wavelength range of the used multi- and hyperspectral sensors. For algorithm development image spectra were used instead of in-situ measured reflectance spectra. This approach has the advantage that perfect optical closure between in-situ reflectance spectra and image spectra is not required. This perfect closure was very difficult to achieve under the highly variable atmospheric conditions occurring during the data acquisition.
- The suspended sediment maps produced describe well the known variation of sediment behaviour in the Lower Sea Scheldt area and contribute to the improvement of our knowledge of spatial and temporal sediment distribution in this complex river system. The suspended sediment maps also agreed well with sediment transport model simulations (see ANNEX 2) and cross-section turbidity measurements.
- A user friendly software has been developed (see next point description of the end product)

The following problems were encountered

- No satellite data could be acquired simultaneously with the airborne data acquisition due to poor SPOT constellation at that day. To overcome this problem SPOT and Landsat data were simulated by resampling spatially and spectrally the AHS data. The results have already been given in the ORMES progress report #3 and will not be repeated here..

- Our request for new satellite data (SPOT/FORMOSAT) from a foreign site was unsuccessful. We therefore thought of an alternative: we searched in the SPOT archive for data of the harbour of Doha in Quatar. Several images exist for which we also have ground truth data available. Unfortunately no STEREO image budget was left to purchase the images.

Some smaller problems were encountered such as deteriorating weather conditions during the airborne data acquisition and some radiometric calibration problems with AHS sensor data.

6. DESCRIPTION OF THE END PRODUCT

A user friendly software has been developed to generate suspended sediment maps from airborne and satellite remote sensing data (Figure 1). The software can be run without the need of having to buy expensive software packages. The software has been written in IDL without using ENVI functionalities. The application can be run using the IDL Virtual Machine (VM). IDL VM is a freely distributed, cross-platform utility for running compiled IDL code.

The software consists of the following modules :

(1) a module to read in hyperspectral airborne data and multi-spectral satellite data (a number of sensors have been selected). At any time new sensors can be added.

(2) a module to display the image and to zoom in to areas of interest

(3) a module to read in and to display the coordinates of in-situ measurements and the corresponding suspended sediment concentrations

(4) a module to select the appropriate semi-empirical algorithm

(5) a module to plot the regression result of the selected algorithm

(6) a module to interactively mask out non-water pixels

(7) a module to apply the algorithm to the image and to store the resulting suspended sediments maps as GeoTIF and/or ASCII files

In the future, new modules can easily be added or existing modules can be changed

Figure 1: User-interface of the ORMES software

7. RELEVANCE OF THE RESULTS FOR IMDC

The end product of the developed tool provides suspended sediment maps of the surface layer of an estuarine of coastal environment at one single moment. This cannot be achieved using conventional measurement techniques. Worldwide satellite cover expands the applicability of this tool, if a good calibration can be established.

It is eligible for project concerning background measurements of a larger region using minimal ground measurements, which could be very valuable on remote "unknown" project locations.

Historical satellite data could be used for qualitative analysis of the sediment distribution pattern for a remote or new project site over a longer term. In this way the tool provides a source of 'historical data', being satellite imagery.

Also it could be used to calibrate or validate sediment transport models.

8. VISIBILITY OF THE PROJECT

The ORMES project has been presented at different conferences and workshops. Not only remote sensing conferences were attended but also some more user oriented conferences to attract possible end-users. In table 3 a list is given of the attended conferences.

Table 3: *Overview of attended conferences*

conference name	Location	Date	Type of presentation
Hydro06	Antwerp, Belgium	7/11/2006	Oral
International Dredging Days	Tangiers, Morocco	2/11/2006	Oral
Bruhyp 2006	Bruges, Belgium	10/10/2006	Poster
The Future of Remote Sensing	Antwerp, Belgium	18/10/2006	Oral
International seminar on hyperspectral technology	Jakarta, Indonesia	20/11/2006	Oral
5th EARSeL SIG IS workshop	Bruges, Belgium	April 2007	Abstract submitted for oral presentation

The following peer reviewed paper has been submitted. This paper has been accepted and will normally be published beginning of 2007.

- Sterckx, S. , Knaeps, E., Bollen, M., Trouw, K., Houthuys, R. *Retrieval of Suspended Sediment from Advanced Hyperspectral Sensor Data in the Scheldt Estuary at Different Stages in the Tidal Cycle.* Marine Geodesy: 5th special issue on Marine and Coastal Geographic Information Systems (M&CGIS). Accepted.

Several conference papers and abstracts have been published about the ORMES project. Below, a list of these papers are given. The full papers are given in ANNEX 3.

- Knaeps, E., S. Sterckx, M. Bollen, K. Trouw, R. Houthuys, *Operational Remote sensing Mapping of Estuarine Suspended sediment concentrations (ORMES).* In: proceedings of the International Dredging Days, 01-03 November 2006, Tangiers, Morocco.

- S. Sterckx, Knaeps, E., M. Bollen, K. Trouw, R. Houthuys, *Operational Remote sensing Mapping of Estuarine Suspended sediment concentrations (ORMES).* In: proceedings of Hydro06,6-9 November 2006, Antwerp, Belgium.

- B. Deronde, S. Sterckx, L. Bertels, E. Knaeps and P. Kempeneers, 2006, Imaging spectroscopy and Integrated Coastal Zone Management, a promising marriage. In proceedings of Sixth International Conference on Environmental Problems in Coastal Regions including Oil and Chemical Spill Studies, 5 - 7 June 2006, Rhodes, Greece.

Furthermore a short description of the ORMES project entitled "Slibconcentraties bepaald vanuit de lucht" has been published in the Annual Report 2004 of VITO .

Good contacts with Peter van den Bergh (Dredging International Benelux) en Alain Bernard (Dredging International Director). Both were interested in the project and were pleased with the good results.

9. NATIONAL AND INTERNATIONAL COLLABORATION

The ORMES project resulted in a number of national and international collaborations. On a national level, there was the collaboration between IMDC as partner and WLH as steering committee member. The collaboration with IMDC will be continued in the RESORT project.

On an international level, we collaborated with Hans Hakvoort. He provided us with useful comments during the Steering Committee meetings of this project.

10. OPERATIONAL MEASURES

The tool has been presented in IMDC, and will be marketed by including it in relevant offers to our clients. IMDC has already included the ORMES tool in 3 offers to its clients.

11. LESSONS LEARNED

N/A

12. RECOMMENDATIONS

N/A

13. CONCLUSIONS

We consider the ORMES project as successful from both a scientific and a users point of view. A large dataset has been built up for the Scheldt. We were able to generate accurate sediments maps for the Scheldt estuary which is a very complex region. The developed software is very user-friendly and can directly be implemented by IMDC. A peer reviewed paper has been accepted for publication in Marine Geodesy and results have been presented in several conferences. However, the work is not finished.. Therefore we are glad to be able to continue the work in the framework of the RESORT project where we will focus on the validation step.

We would like to thank the steering committee members Hans Hakvoort, Joris Vanlede and Eric Taverniers for their recommendations and the Federal Science Policy Office for their support.

14. PROJECT FORM

The ORMES project form is given on the next page.

Operationele kartering van gesuspendeerde slibconcentraties in estuaria door middel van aardobservatie - ORMES - SR/67/36

(Geographic) study area : Scheldt river near Antwerp

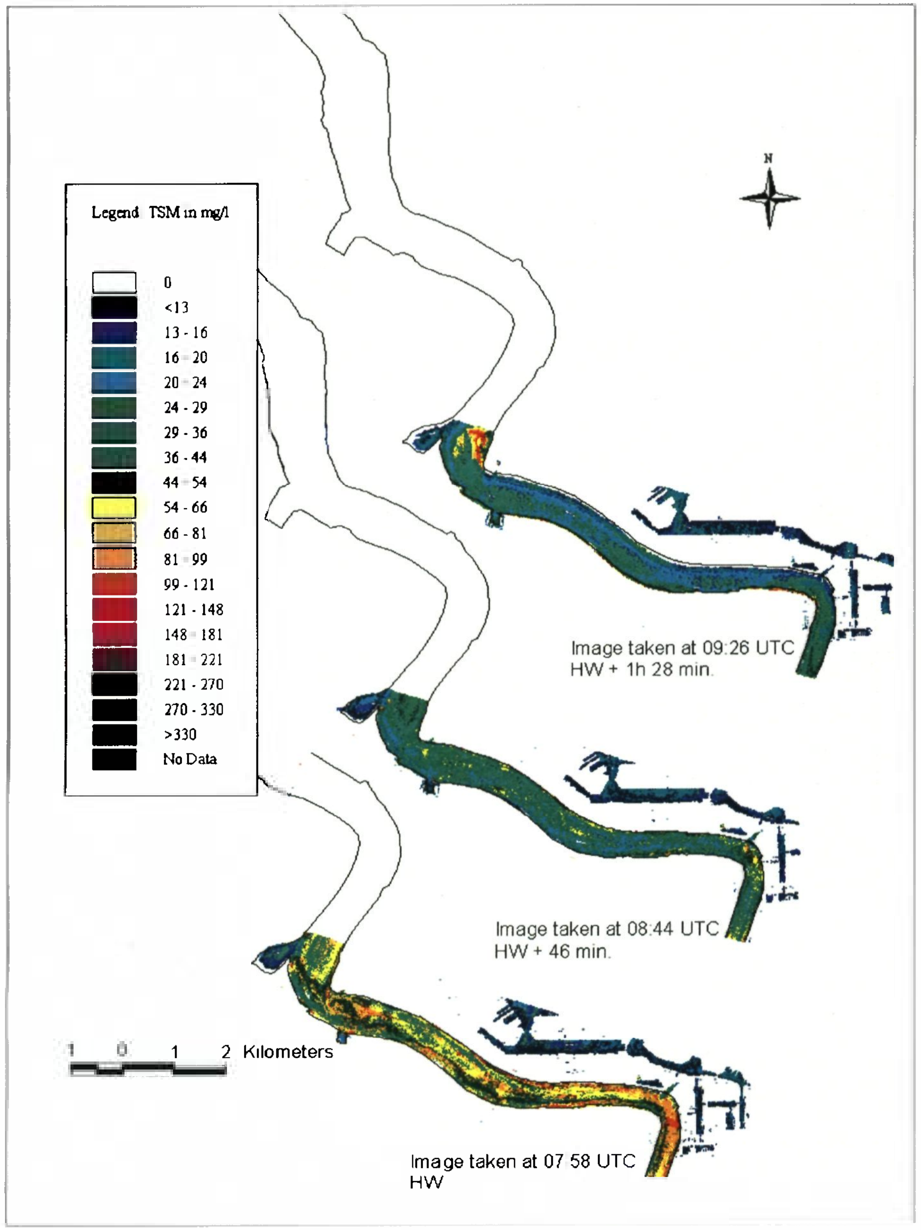
Science policy testsite (if applicable) : /

Satellite imagery used (type and co-ordinates of images purchased by Science Policy): requested but not obtained

Other data :AHS airborne images of 2005

Website (with project results): no website has been set-up

Pictures illustrating the project:



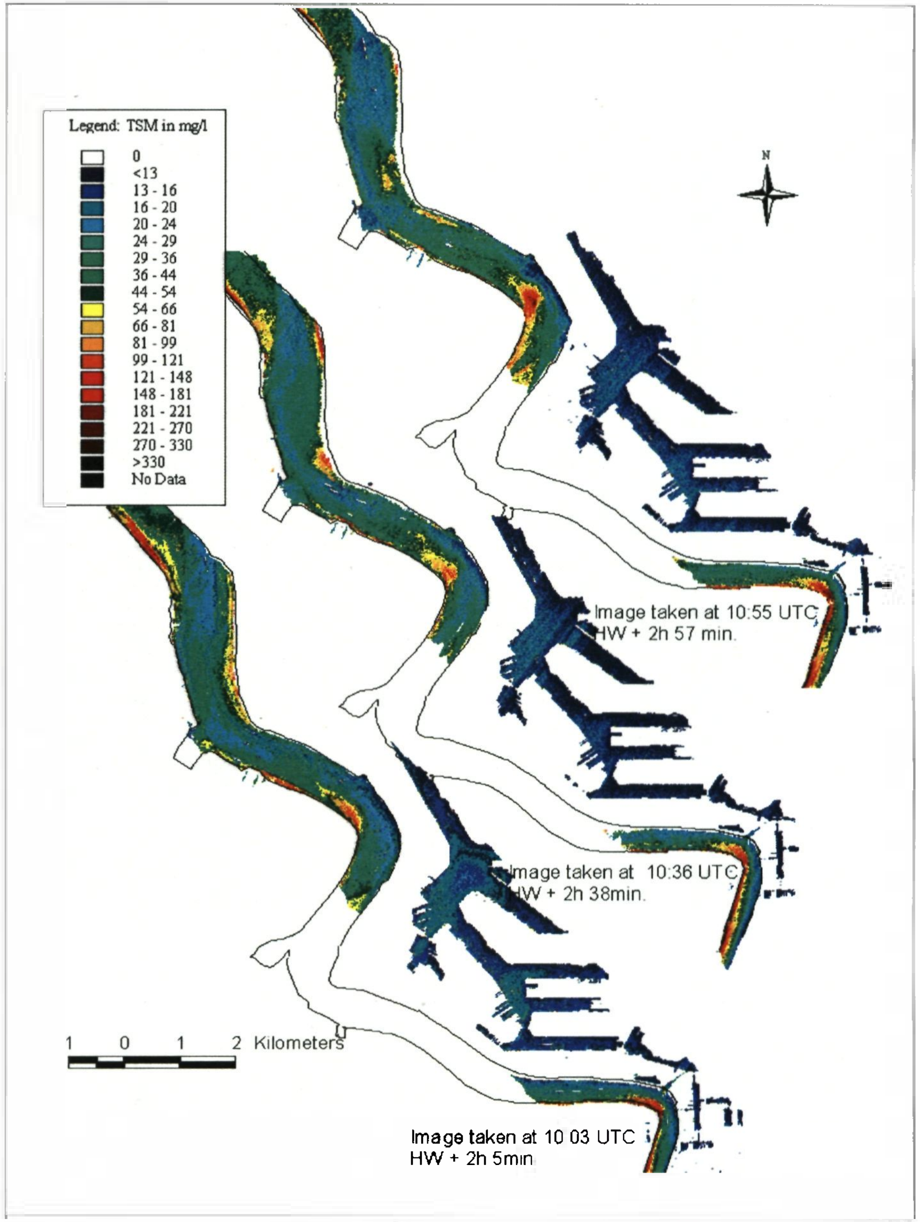


Fig.1: TSM maps for the Scheldt at 07:58, 08:44 and 09:26 UTC and 10:55 TC.

Fig 2. TSM maps for the Scheldt at 10:03, 10:36

Context and objectives

To assure the accessibility of ports, shipping channels must be dredged regularly to maintain an adequate water depth. Dredging operations are subjected to strong environmental regulations which require that the sediment dynamics are monitored, temporally as well as spatially, in an ever increasing manner. IMDC, the private partner in this project, prepares specifications and recommendations of techniques, equipment and methods for any dredging project. IMDC requires information on the spatial variation of turbidity for e.g. the optimization of the dredging locations to minimize the recirculation of sediments towards harbors after dumping.

To support IMDC in their activities, a service is developed in the ORMES project which provides suspended sediment maps from remote sensing images in an efficient way.

This project aims: (1) to develop a simple and robust procedure for near surface (or 2 D) sediment concentration mapping from remote sensing data (2) to operationalise and automate the procedure and (3) to implement the procedure/software at the private partner.

Methodology

In the ORMES project the Scheldt Estuary has been chosen as main study site mainly because of its dynamic complexity. A large dataset consisting of a series of airborne hyperspectral images was obtained at different stages of the tidal cycle. Simultaneously with the airborne campaign a field survey took place. Using these field data and the high resolution airborne data, a reliable semi-empirical algorithm has been developed to derive near-surface suspended matter maps in an operational way. The produced TSM maps were in very good agreement with known variations of the suspended sediment content over the tidal cycle. The ORMES project focused mainly on the full capability of state-of-the-art airborne hyperspectral sensors, with some minor tasks devoted to satellite based TSM derivations. The final product of the ORMES project is a user-friendly software for the production of suspended matter maps.

This software will be implemented at IMDC and TSM concentration maps can be generated from remote sensing data with a limited number of water samples for calibration.

Results

The following results have been obtained :

- We have had a very successful field and airborne campaign. On the basis of this campaign a large database has been generated which contains:
  - hyperspectral data cubes at different processing levels (radiometrically, atmospherically and geometrically calibrated) covering several stages in tidal cycle.
  - turbidity data measured almost continuously during the campaign

    - in-situ spectral reflectance measurements
    - specific inherent optical properties (backscattering and absorption spectra)
    - suspended sediment concentration of a large number of water samples
    - chlorophyll content of several water samples
- A reliable semi-empirical algorithm, based on a band difference term log-linear regressed against suspended sediment concentration, has been developed to generate suspended sediment maps from airborne hyperspectral data.
- The suspended sediment maps produced describe well the known variation of sediment behaviour in the Lower Sea Scheldt area and contribute to the improvement of our knowledge of spatial and temporal sediment distribution in this complex river system. The suspended sediment maps also agreed well with sediment transport model simulations and cross-section turbidity measurements.
- A user friendly software has been developed (see next point description of the end product)

Products and services

User-friendly software for the production of suspended matter maps has been written. The user can interact with the software by a self-evident graphical user interface. A manual describing input, output and operation is also delivered. The software will be implemented at the private partner's and personnel will be trained.

Execution

Period: December 2004 – December 2006

Laboratory: /

Discipline

Hydrology & freshwater resources

General earth observation

ANNEX 1 – LITERATURE REVIEW

1. Introduction

The color of water is determined by:

- water molecules themselves
- phytoplankton and its pigment chlorophyll a which scatter and absorb light
- suspended sediments which predominantly scatter light
- colored dissolved organic matter (CDOM) from biodegradation of plants which absorb light at ultraviolet and blue wavelengths, often referred to as yellow substance or gelbstoff

Since these constituents affect the color of the water it is possible to detect their presence in water and quantify their respective concentrations. Substances (i.e. nutrients, metals) that do not change the optical characteristics of waters can only be inferred by measuring surrogate properties which may have responded to an input of chemicals (Ritchie and Cooper, 2001).

Suspended sediments increase the radiance emergent from surface waters in the visible and near infrared proportion of the electromagnetic spectrum (Ritchie and Scheibe, 2000). According to the same authors reflectance from almost any wavelength can be related to suspended sediment concentrations, if the range of suspended sediments is between 0 and 50 mg/l. If the range of suspended sediments increases to 200 mg/l or higher, curvilinear relationships have to be developed (Figure 2) .

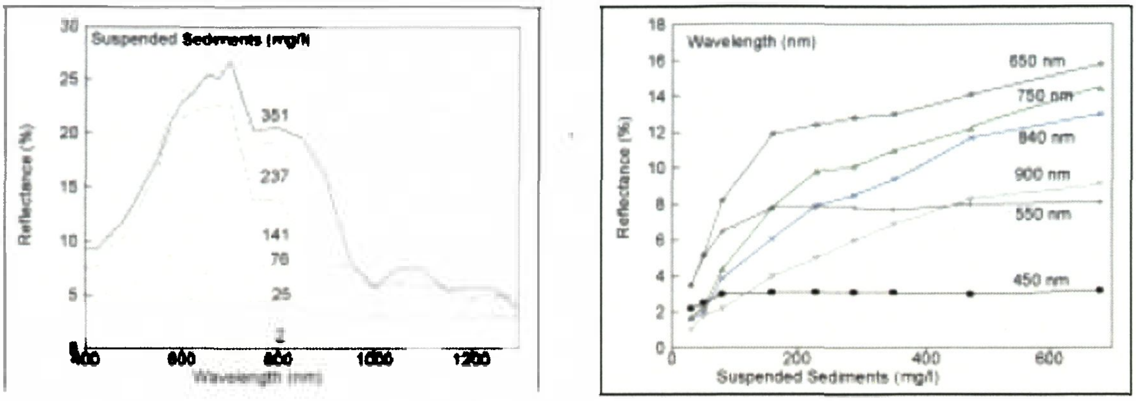


***Figure 2** The relationship between reflectance and wavelength as affected by the concentration of suspended sediments (taken from Ritchie, 2005)*

It is important to note that the water-leaving electromagnetic radiation which can be detected by remote optical sensors originates within a surface layer, the "penetration depth" after Gordon and McCluney (1975). When light penetrates water its intensity decreases exponentially with increasing depth. The penetration depth depends on wavelength and water composition. In the red and near-infrared region of the spectrum the water penetration depth is small (~ 1 meter or less in turbid water), and as such the turbidity signal will originate from a level similar to the in situ samples. Shorter wavelength channels integrate over larger columns and may even pick up bottom reflectance in shallow waters. The strong variation of the penetration depth water with wavelength may provide information on sediment stratification, since radiation penetrates deeper at shorter wavelengths and thus records the optical signature of deeper water (Tassan, 1997).

2. Glossary of terms / definitions

a. Classification of water types

Case 1 waters contain phytoplankton particles (phytoplankton and bacterial plankton) and associated detrital material and coloured dissolved organic matter (CDOM) which are well correlated with concentrations of chlorophyll. Open oceans are typical examples of case 1 waters.

Case 2 waters the optical properties are influenced not only by phytoplankton and related particles, but also by other substances such as CDOM or suspended sediments, that can vary independently from phytoplankton. Typically, Case 2 waters are coastal zones and inland seas.

b. Apparent and inherent optical properties (AOP and IOP)

Apparent Optical Properties (AOP): Properties that depend both on inherent optical properties (IOPs) and on the light field in which they are measured. Reflectance, radiance and irradiance belong to this group. AOPs are measured in situ, or in the field. These properties will vary slightly with the time of day the measurements are taken, because they are dependent on the intensity and angle of the sun.

Inherent Optical Properties (IOP): Properties that depend only on the water and other substances that are dissolved or suspended in it. IOPs are often measured in the laboratory do not depend on the presence of sunlight under water. The two fundamental IOPs are absorption (a) and the Volume Scattering Function (ß). Others commonly derived from these include the total scattering coefficient (b), backscattering coefficient (b_b), and beam attenuation coefficient ($c = a + b$).

3. Overview of algorithms

Many researchers have tried to derive total suspended matter from remotely sensed data. Algorithms are empirically, semi-empirically derived or based on an analytical method.

a. Empirical relations

The empirical approach is based on a statistical calibration relationship between spectral data, expressed as reflectance, radiance or digital numbers (DNs) and SPM. Literature review on empirical algorithms revealed a large variety of algorithms used. A number of these empirical relations are listed in table 1.

***Table 1** : Empirical relationships between SPM and reflectance derived for various remote sensing platforms and environments*

Author(s)	Relation	Sensor	Concentrations	Area
Ahn et al., 2005	SPM(g/m³) = 401.5[Rrs(555)]^0.92	Field spectroradiometer	0.2 - 120 g/m³	Korean waters
Forget and Ouillon, 1999	R(0-)= aLog10 SPM + b*	Field spectroradiomer resampled to Landsat		Rhone river
Herut et al., 1999	SPM ~ R(624)/R(534)	Field spectroradiometer	< 50 mg/l	Haifa bay
Kallio et al., 2001	SPM ~ Rapp[705-714]	airborne AISA	< 30 mg/l	Finnish lakes
Matthews et al., 2001	SPM = exp(-0.739+0.929[R(618)/(R754)]	airborne CASI	< 24 mg/	Norfolk coast, UK
Matthews et al., 2001	SPM = exp(-5.920+3.607[R(618)/(R754)]	airborne CASI	< 90 mg/l	Bristol Channel, UK

*for Landsat TM band 1 : a = 8.059, b = 0.947
*for Landsat TM band 2 : a = 11.514, b = 0.249
*for Landsat TM band 3 : a = 13.977, b =-5.509

As illustrated in table 1 the empirical relationship has been developed for one specific region. Matthews et al. (2001) tested the seasonal and geographical portability of empirical algorithms developed for the Bristol channel. The authors concluded that accurate estimations of SPM are achievable when applying an algorithm to data collected from the same site later in the year, however the development of a global algorithm was unsuccessful. Scatter plots of reflectance ratios against SPM showed that the 2 optical datasets were clearly different (figure 2).

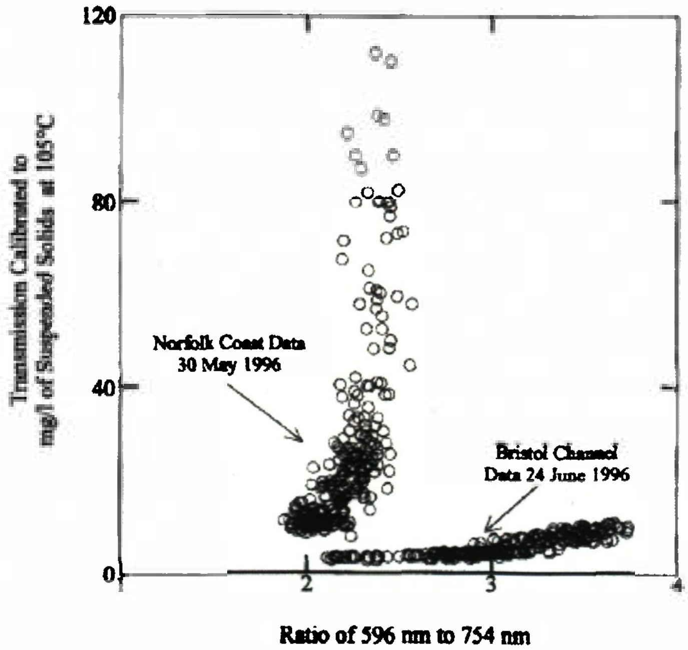


Figure 2 Scatter plot of transmission data converted to total SPM concentration against a CASI band ratio for data from Bristol Channel and Norfolk coast. The plot shows the diffculty in establishing a global algorithm for these two datasets (taken from Matthews et al., 2001).

The problem is that variations in particle size and type strongly influence scattering behaviour and thus reflectance and consequently introduce errors in simple empirical algorithms. This is clearly a problem for estuaries where the characteristics of the suspended particles vary depending on the upland basins, river discharge, tidal cycles and floculation processes.

b. Semi-empirical relationships

In semi-empirical methods the spectral characteristics of the parameters of interest are known. This knowledge can be included in the statistical analysis by focusing on well chosen spectral bands or combination of bands (de Haan et al., 1998).

Such a semi-empirical approach has been followed by Doxaran et al. (2002) to show that changes in sediment composition and grain size can be reduced when considering reflectance ratios. They established invariant exponential calibration curves between remote sensing reflectance (Rrs) ratios in SPOT bands (XS3/XS1) or Landsat bands (L4/L2) and SPM in the range 15 – 2000 mg/l.

On the other hand, the effectiveness of reflectance ratios incorporating NIR wavebands may be limited to extreme turbidity levels (Binding et al., 2005).

Binding et al. (2005) suggested to use prior knowledge of the scattering efficiency of the particles (b^*_{MMS}) to obtain improved accuracy in estimations of mineral suspended sediments (MSS) concentrations from subsurface irradiance reflectance at 665 nm. The variation in the relationship between MSS and R(0-, 665) is illustrated with figure 3. At low scattering efficiencies, the relationship between R_{665} and MSS was linear whilst at higher b_{MSS}*, the relationship appeared to saturate at higher concentrations of MSS.

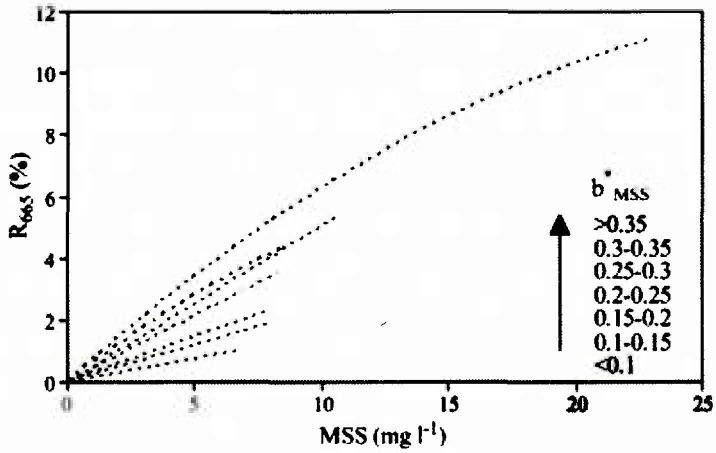


Figure 3 *The varying best-fit relationships between MSS (mg/l) and* R_{665} *for different categories of* b_{MSS}*

To derive the backscattering efficiencies from the reflectance at 715nm for each image pixel Gould et al. (2004) used a near-infrared (NIR) slope algorithm. This NIR algorithm is based on the observation that the total absorption in the 715 – 735 nm wavelength range is controlled by pure water absorption. Furthermore it is assumed that the spectral shape of the (back-)scattering is linear and relatively flat in this narrow NIR wavelength range.

c. Analytical methods

In the analytical approach the water constituent concentrations are physically related to the measured reflectance spectra using sophisticated radiative transfer models (e.g. Hydrolight) or (semi-)analytical bio-optical models. To determine the water quality parameters (e.g. SPM) these models are inverted through neural networks, matrix inversion (Hakvoort et al., 2001) or curve fitting (Keller, 2001). This approach requires detailed information about the inherent optical properties (IOP) like the absorption and the backscattering coefficients. This is the major drawback of analytical approaches since the various input parameters are often not available.

Several analytical models for water quality retrieval which relate the subsurface irradiance reflectance R(0-) to the water constituent concentrations via their IOPs are given in Dekker et al. (2001). All these models are very similar to an analytical solution given by Aas (1997):

$$R(0-,\lambda) = f \cdot \frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)} \quad \text{with } f = \frac{1}{1 + \overline{\mu_d}(\lambda) / \overline{\mu_u}(\lambda)}$$

(1)

with $a(\lambda)$ the spectral total absorption coefficient (m^{-1}), $b_b(\lambda)$ the spectral total backscattering coefficient (m^{-1}) and $\overline{\mu_d}$, $\overline{\mu_u}$ are the average cosines of the downwelling and upwelling light field respectively. In general, the higher the backscattering, the higher the reflectance and the higher the absorption, the lower the reflectance. This model implicitly assumes a homogenous water column (i.e. the IOP are constant over the water depth). The absorption and backscattering coefficients are linear functions of the constituents' concentrations and pure water:

$$a = a_w + a^*_{SPM} * SPM + a^*_{CDOM} * CDOM + a^*_{CHL} * CHL$$

(2)

$$b_b = b_{b,w} + b^*_{b,SPM} * SPM + b^*_{b,CHL} * CHL$$

(3)

Equation 1 can therefore be written as (omitting the wavelengths):

$$R(0-) = f \cdot \frac{b_{b,w} + b^*_{b,SPM} * SPM + b^*_{b,CHL} * CHL}{a_w + a^*_{SPM} * SPM + a^*_{CDOM} * CDOM + a^*_{CHL} * CHL + b_{b,w} + b^*_{b,SPM} * SPM + b^*_{b,CHL} * CHL}$$

and solved for SPM (assuming no backscattering from CHL):

$$SPM = \frac{f * b_{b,w} - R(0-) * \left[a_w + a^*_{CDOM} * CDOM + a^*_{CHL} * CHL + b_{b,w}\right]}{R(0-) * \left[a^*_{SPM} + b^*_{b,SPM}\right] - f * b^*_{b,SPM}} \quad \textbf{(5)}$$

When neglecting the contribution of yellow substance (CDOM) and phytoplankton pigments Binding et al. (2005) derived the following semi-analytical equation from (4) for the retrieval of Mineral Suspended Sediments (MSS) at 665 nm :

$$MSS = \frac{f * b_{b,w}(665) - R(0-,665) * b_{b,w} - R(0-,665) * a_w}{R(0-,665) * a^*_{SPM}(665) + R(0-,665) * b^*_{b,MSS}(665) - f * b^*_{b,MSS}(665)}$$

(6)

This reflectance model presented by Binding et al. (2005) highlights the dependence of reflectance on $b^*_{b,MSS}$. The authors suggest that the errors in predicted MSS concentrations can be reduced from 56% to as little as 12% with prior knowledge of the scattering properties of the sediments under study.

Using a representative set of inherent optical properties and fixed values for CDOM and CHL van der Woerd and Pasterkamp (2004) derived from equation (5) a single band algorithm (referred to as POWERS algorithm) for suspended matter retrieval in the North Sea :

$$SPM = \frac{0.001 - 0.53 * R(0-,555)}{0.03 * R(0-,555) - 0.0059}$$

(7)

The accuracy of the algorithm was estimated to be between 9% and 27% in areas that can be described by the SIOP dataset. It is clear that error in SPM concentration increases when the difference with the fixed CDOM, CHL values increases. Woerd and Pasterkamp (2004) have chosen the 0.555 □m band based on several considerations: maximal sensitivity for TSM, minimal sensitivity to other constituents like CHL and CDOM, and minimal sensitivity to inaccuracies in atmospheric correction.

An important problem when using model (1) in Case 2 waters is the fact that the f-factor is not constant and can very in time and location. A new parameterization of the irradiance reflectance has therefore been developed by Albert and Mobley (2003). Their analytical model not only uses the IOP of the water as input, but also the solar zenith angle, the viewing angle are the surface wind speed considered.

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ANNEX 2 - VALIDATION USING A TRANSPORT MODEL

A second validation was performed using the 'Delft 3D-slibmodel'. The model returns SPM concentrations every 30 minutes, time is given relative to High Water (HW).

Simulations were made for 3 locations:

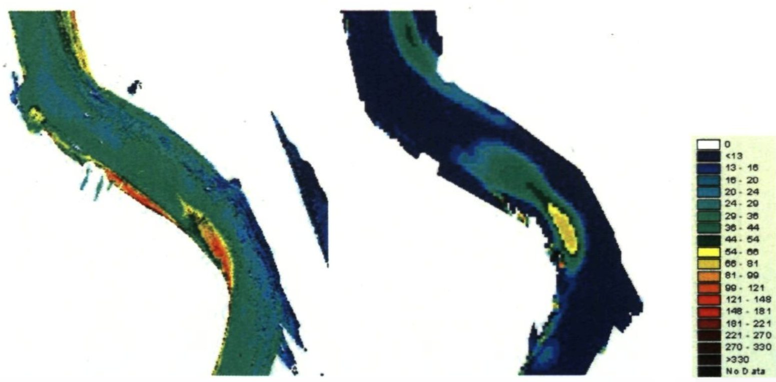
- BW-VC sluis – Doel
- Plaat van de Parel
- Antwerp

In the following examples one can clearly observe the same patterns in the remote sensing derived map and the map from the transport model.

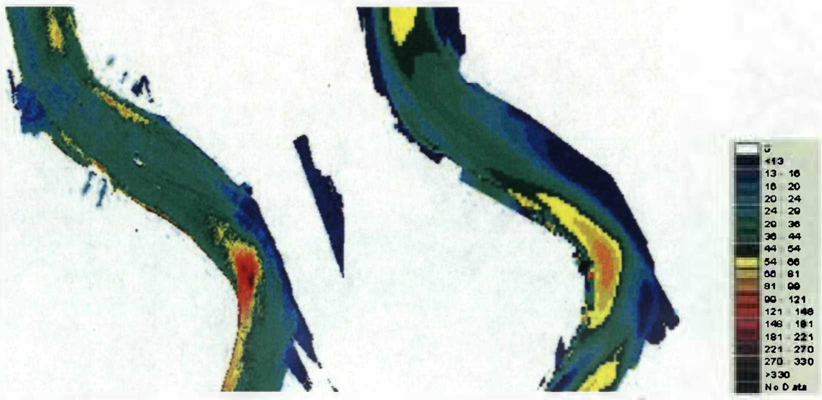
<u>Location 1: BW-VC sluis – Doel</u>

HW+0:31

HW+2:03

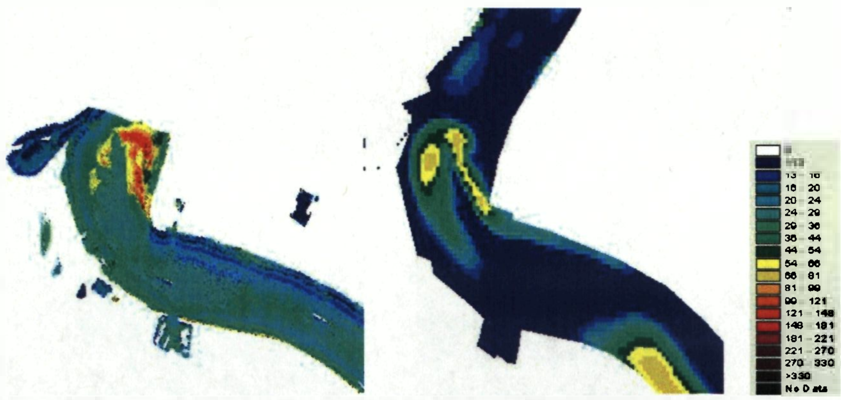


HW+2:55

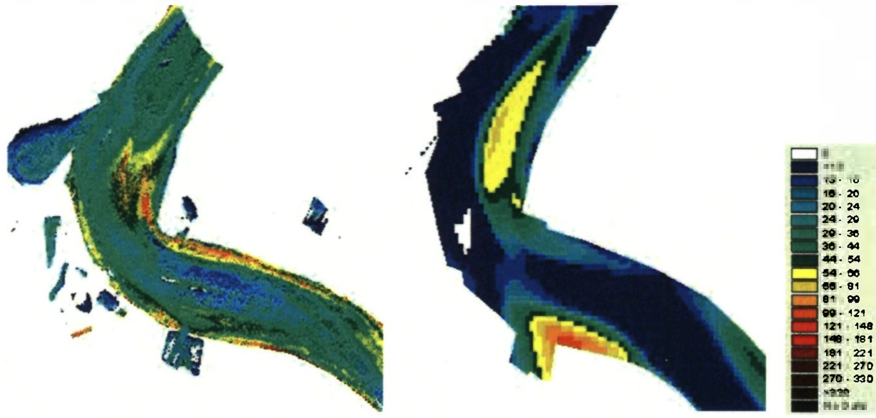


Location2: Plaat van de Parel

HW+1:26

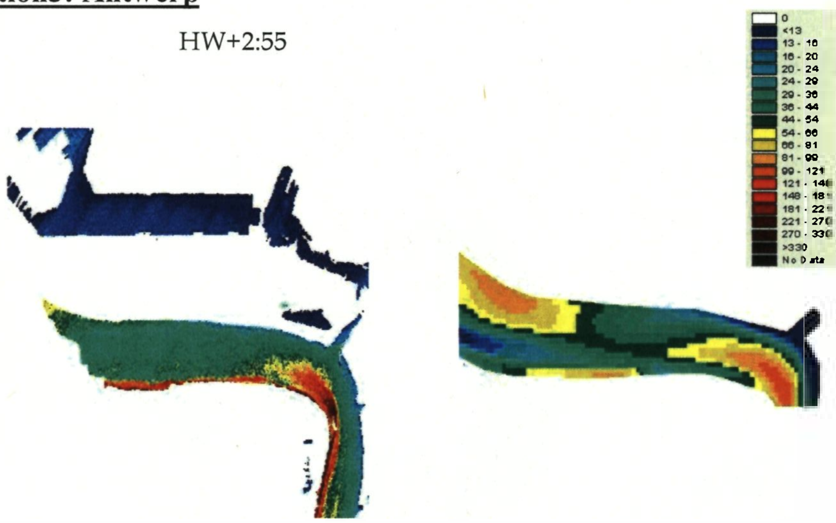


HW+2:55



Location3: Antwerp

HW+2:55



ANNEX 3 – PUBLICATIONS

1. Sterckx, S. , Knaeps, E., Bollen, M., Trouw, K., Houthuys, R. *Retrieval of Suspended Sediment from Advanced Hyperspectral Sensor Data in the Scheldt Estuary at Different Stages in the Tidal Cycle*. Marine Geodesy: 5th special issue on Marine and Coastal Geographic Information Systems (M&CGIS). Accepted.

2. Knaeps, E., S. Sterckx, M. Bollen, K. Trouw, R. Houthuys, *Operational Remote sensing Mapping of Estuarine Suspended sediment concentrations (ORMES)*. In: proceedings of the International Dredging Days, 01-03 November 2006, Tangiers, Morocco.

3. S. Sterckx, Knaeps, E., M. Bollen, K. Trouw, R. Houthuys, *Operational Remote sensing Mapping of Estuarine Suspended sediment concentrations (ORMES)*. In: proceedings of Hydro06, 6-9 November 2006, Antwerp, Belgium.

4. B. Deronde, S. Sterckx, L. Bertels, E. Knaeps and P. Kempeneers, 2006, Imaging spectroscopy and Integrated Coastal Zone Management, a promising marriage. In proceedings of Sixth International Conference on Environmental Problems in Coastal Regions including Oil and Chemical Spill Studies, 5 - 7 June 2006, Rhodes, Greece

Retrieval of Suspended Sediment from Advanced Hyperspectral Sensor Data in the Scheldt Estuary at Different Stages in the Tidal Cycle

Short title : TSM retrieval in the Scheldt over the tidal cycle

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Abstract

Hyperspectral airborne remote sensing images and in-situ data are combined to assess the spatial and temporal sediment dynamics in the tidal Scheldt river. A log-linear empirical relationship has been developed between a near-infrared reflectance difference and total suspended matter. The relationship was shown to be relatively insensitive to the varying cirrus cloud cover occurring during data acquisition. The produced sediment maps show good agreement with known variations of turbidity over the tidal cycle: maximum turbidity around high water, gradual settling of the sediment in the succeeding slack water and resuspension at the onset of the ebb flow stage.

Introduction

Each year several millions m^3 of estuarine sediment have to be dredged in the Scheldt River (Belgium) and are dumped in the system (IMDC, 2004). This is necessary to assure access to the

Sterckx, S , Knaeps, E , Bollen, M , Trouw, K , Houthuys, R *Retrieval of Suspended Sediment from Advanced Hyperspectral Sensor Data in the Scheldt Estuary at Different Stages in the Tidal Cycle* Marine Geodesy 5th special issue on Marine and Coastal Geographic Information Systems (M&CGIS) Accepted

harbour of Antwerp. Similar figures apply to the Westerscheldt (The Netherlands) and the harbours of Ostend and Zeebrugge (Belgium). Reliable information on the spatial variation of turbidity is necessary to monitor the ecological impact of dredging and sediment related operations, and to study regional sediment dynamics such as needed to better plan the location of new harbour infrastructure. High-quality spatial information on suspended sediment concentration is also needed for the calibration and validation of numerical sediment transport models (Jørgensen and Edelvang, 2000). Tidal coasts and rivers present especially variable suspended sediment concentration patterns both in time and in space. Traditional in-situ measurements performed at single points or along transects are insufficient to provide a complete view of the spatial variability of suspended sediments. Furthermore, the high degree of time and labour intensity prevents these field campaigns to be carried out repeatedly. This explains the high interest in the use of remote sensing data. Since the late 1970's numerous spaceborne sensors have been utilized to map the surface turbidity or total suspended matter (TSM). Due to the better spatial resolution, airborne remote sensing is very well suited for the study of sediment fluxes in coastal bays (Herut *et al.*,1999), estuaries (Robinson *et al.*, 1998), rivers (Wass *et al.*, 1998) and lakes (Hakvoort *et al.*, 2002; Hoogenboom *et al.* 1998). Furthermore the temporal resolution of airborne platforms is easier to control allowing data acquisition at the most critical moments in the tidal cycle and under a wider range of weather conditions.

This paper presents quantified near-surface TSM maps of the Lower Sea Scheldt near Antwerp (Belgium). The data used were acquired in a study project intended to operationalize remotely sensed water surface images from different sources for consultant work related to ecological monitoring, sediment transport studies and maintenance dredging operations.

In order to obtain a sufficient range of near-surface TSM values, the study area was overflown at different stages in the tidal cycle, while non-tidal harbour docks characterized by low TSM values were also included in the study area. In order to allow sufficient image-calibration strategies to be tested, a hyperspectral sensor was used to acquire the aerial image data. Hyperspectral sensors offer the advantage of a wide range of spectral information to be acquired for each ground pixel.

Study Site

The Scheldt river finds it origin in northern France and flows through Belgium via Antwerp towards the North Sea. Our study site is restricted to a part of the Lower Sea Scheldt as illustrated in Figure 1. Although the open North Sea is about 60 km away from Antwerp, the Scheldt is an important shipping channel giving access to the vast port area of the city.

The Scheldt is a rain and tide river discharging, on average, 100 m^3 of water per second to the sea and forms a complex river system where concentrations of suspended sediment are highly variable in place and time. Our study area is situated in an area with maximal turbidity of the Scheldt estuary (Fettweis *et al.*, 1998). At this location, the tidal range is more than 4 m. The suspended sediment concentrations are in the range of a few hundred mg/l (IMDC, 2004).

Airborne and field data

Remote sensing data

Hyperspectral data were collected with the AHS Advanced Hyperspectral Sensor (SenSytech Inc). The AHS was installed on board a CASA 212-200 aircraft and flown over the study area on 15 June 2005. The data were collected in 80 spectral channels, covering the 0.430 µm to 12.70 µm electromagnetic wavelength range. The properties of the first 20 spectral bands, which were used to develop the TSM algorithm, are given in Table 1. To minimize the effects of sunglint all flight tracks were flown in line with or opposite to the sun. Because of this, the orientation of the flight lines varied with time and slightly different areas of the Scheldt were covered. Although weather forecasts were optimistic and the sky was clear at the beginning of the campaign, thin cirrus clouds covered the study area gradually. The cloud base was estimated at 3000m. The nominal flight height was 1373 m, resulting in a spatial resolution of 4m. In total 15 images were acquired between 07:58 and 11:14 UTC. In Figure 2 the image acquisition times are given in relation to the tidal cycle.

Field data

Simultaneously with the aircraft overpasses, an extensive field survey took place. Two survey vessels were used at different stretches of the Lower Sea Scheldt to include some spatial variability. An extra vessel was deployed at the docks in the harbour of Antwerp. Several measurements were done on board of each vessel at predesignated locations at the time of the airplane crossing over the study area. Figure 3 shows the locations of the vessels at the moments of data capture. Measurements were done at these locations and also between locations before and after data capture. Four jetties served as additional fixed sampling locations.

150 surface water samples were collected from the near surface water layer (sampling depth less than 0.5 m) for the entire time series and stored in 1 litre bottles to determine total suspended matter concentration. The sampling depth corresponds to the expected penetration depth of near infrared (NIR) wavelengths in our study area. At selected locations extra water samples were taken and subsequently stored in dark bottles for optical measurements and chlorophyll analysis. From the vessels on the Scheldt river in-situ spectroradiometric measurements were carried out using a GER-1500 or ASD FieldSpecPro FR spectoradiometer. Both spectrometers are radiometrically calibrated and cross calibration was checked in the laboratory. First, the downwelling irradiance (E_d) was measured using a Spectralon reference panel and then the upwelling radiance (L_u) was measured by pointing the sensor at the water surface at 40° from nadir, maintaining an azimuth of 135° from the solar plane to minimize sun glint. Downward skylight radiance (L_s) was measured at a zenith angle of 40° to account for the skylight reflection. The remote-sensing reflectance (R_{rs}) was calculated using the following equation:

$$R_{rs} = (L_u - fL_s)/E_d \quad (1)$$

where f is the effective Fresnel reflection coefficient.

At one vessel in the Scheldt a turbidity sensor (Aanderaa RCM-9) continuously logged turbidity in the surface water layer. The location of the boats was continuously logged with a Trimble GeoXT GPS. Differential correction of the GPS data was performed in post-processing using data from the FLEPOS (FLemish POsitioning Service) GPS network, which contains 42 receivers distributed over the Flemish region in Belgium (FLEPOS, 2006). Sun-photometric data were measured with a

Microtops sunphotometer to estimate the aerosol content and water vapour in the atmosphere to calibrate the radiative transfer model used in the atmospheric correction. General atmospheric conditions were registered by taking photos of the sky at all the sampling locations of the boats.

Data processing

Field data processing

The TSM concentration was determined by filtering 250 ml of the water samples on pre-weighed 0.45-µm membrane filters. Filters were then dried and re-weighed. The measured TSM concentration in the Scheldt river ranged from 13 to 336 mg/l. The average concentration was 65 mg/l with a high standard deviation of 65.6 mg/l. In the docks the concentration was much lower, ranging from 7 to 12 mg/l with an average of 10 mg/l and a standard deviation of only 1.5 mg/l.

To convert the continuous turbidity measurements from the Aanderaa RCM-9 in nephelometric turbidity units (NTUs) to TSM (measured in mg/l), the relationship between turbidity and TSM from water samples was statistically modelled for coincident points. A linear relationship was found with an R^2 of 0.83 and an RMSE of 35.2 mg/l (Figure 4). This best-fit regression equation was then applied to all turbidity measurements.

Chlorophyll-a concentration was determined for six water samples following the ASTM D 3731-87 Standards (ASTM, 1993). The average CHL-a concentration was 4.4 (+/-1.4) µg/l in the Scheldt river and 19,1 µg/l at the docks. The variation of CHL-a in the Scheldt was rather small, the highest concentration measured was 6.8 µg/l..

Samples were not analysed for colored dissolves organic carbon (CDOC) concentration. The organic carbon load of the Scheldt basin is known to be very high with a mean dissolved matter concentration (DOC) of 7 mg-C/l (Baeyens *et al.*, 1998).

Image data pre-processing

The atmospheric and geometric correction of the AHS data was performed by VITO's Processing and Archiving Facility for Airborne data. The airborne radiance spectra (L_{rs}) were converted to subsurface irradiance reflectance spectra R(0-) by correcting for atmospheric and air-interface effects following the algorithms given by de Haan and Kokke (1998). The radiative transfer model Modtran4 (Berk *et al.*, 2003) was used to calculate the correction parameters. As input to Modtran4 a maritime aerosol model and mid-latitude summer atmospheric profile was chosen. Visibility and water vapor were derived from the Microtops sunphotometer measurements. Where no aerosol optical depth data were available, the visibility was iteratively adjusted by comparison of the AHS-derived reflectance spectra with *in situ*-measured reflectance spectra of several reference targets (asphalt parking lots). Because of a low wind speed on the day of the flight campaign and appropriate flight line specifications sun glint effects were not observed and there was no need for an extra correction. Both the airborne and shipborne reflectance spectra showed high reflectance values at near infrared wavelengths which can not be explained by high TSM concentration only. It can probably be attributed to an insufficient correction for skylight reflection. For the airborne spectra also sensor radiometric calibration inaccuracies and adjacency influences may play a part. As stated by Doxaran *et al.* (2004) the correction of surface reflection effects is still problematic and further measurements and computations are needed to improve the understanding.

The AHS dataset was geo-referenced using roll, pitch, yaw, D-GPS and geometric sensor information.

TSM Algorithm

Sub-surface irradiance reflectance R(0-) spectra were extracted from the hyperspectral images at the sampling locations. An average spectrum calculated from a 5-by-5 box of pixels (corresponding to an area of 20 m-by-20 m) was preferred to remove random noise. In the study area, the suspended matter concentrations and patterns change very rapidly as the tide fluctuates. Hence, to calibrate as accurately as possible, only the samples taken within a few minutes of the airborne data recording were included. In total 41 samples were available to find a band combination which best predicts the TSM concentrations. For each of the 15 image acquisition periods at least 2 samples were included. Single bands, band ratios, differences of 2 bands were linearly or logarithmically regressed against

TSM. Bands or band combinations with the highest correlation and minimal root-mean-square-error (RMSE) were judged on their physical relevance. The best fit with an R^2 of 0.83 and an RMSE of 15.53 mg/l was found to be a log-linear line fit to a band difference (Figure 5):

$$Ln(TSM) = 34.18*(R(0-,833)-R(0-,1004)) + 3.16 \qquad (2)$$

where R(0-,833) and R(0-,1004) are respectively the subsurface irradiance reflectance at 833 nm and 1004 nm. No samples were included from the docks because of lower accuracies. This might be attributed to a different composition of the water and the absence of a tidal regime.

The use of a near infrared (NIR) band for TSM retrieval in surface waters was previously suggested by several authors (Richie *et al.*, 1976). NIR bands have the least impacts from chlorophyll and coloured dissolved organic carbon. Furthermore shorter wavelengths integrate over a larger water column while penetration depth at 833 nm is small (much less than 1 m in turbid waters). The latter corresponds to the depth of the *in situ* water sampling. Although single-bands reflectance in the near-IR (746, 774, 803, 833 or 862 nm) performed well for the shipborne reflectance spectra with a R^2 above 0.8, they failed for the airborne reflectance spectra ($R^2 < 0.6$). Subtracting the reflectance at 1004 nm from the reflectance at 833 nm proves to provide a simple and robust correction for external effects such as varying cirrus cloud cover during the flights, sky light reflection (Doxaran *et al.*, 2002) and adjacency influences near the quay. Indeed, the reflectance at 1004 nm is uncorrelated to TSM concentration since at 1004 nm, the penetration depth of sunlight into the water is virtually zero and therefore the possibility of reflection by suspended sediments at this wavelength is eliminated. This is also demonstrated by the fact that absolutely no correlation was found between TSM and reflectance at 1004 nm ($R^2 = 0.03$). Furthermore, the variation of optical properties of cirrus clouds is negligible in the 0.4 – 1 μm spectral range (Gao *et al.*, 2002). This is also supported by Figure 2 given in Heidinger and Stephens (2000) which shows that the cirrus cloud optical properties (the single-scatter albedo of particles, asymmetry parameter of scattering and the extinction coefficient) computed from Lorentz–Mie theory using model cirrus size distributions can be taken constant from visible wavelengths up till 1.2 μm. To support the adjacency effect assumption reflectance spectra, corresponding to a large range of TSM (between 0 and 300 mg/l) and CHL concentrations (between 0 and 8 μg/l), were generated based on the analytical model of Albert and Mobley (2003). With the radiative transfer code Modtran-4 atmospheric scattering and absorption was simulated in order to convert the reflectance spectra to at-sensor radiance spectra. No atmospheric variability between the spectra was modeled i.e. atmospheric parameters remained constant. Two test sets were generated, one without adjacency effects (test set 1) and one with adjacency effects (test set 2). This latter dataset was created by randomly varying the background spectra (water, vegetation and asphalt) used in the Modtran-4 simulations. Next single bands or band combinations were linearly or logarithmically regressed against TSM. For test set 1 a single band algorithm performed best, while for test set 2 the difference of band 833 nm and band 1004 nm outperformed the others. Clearly this simulation confirms our assumption that the subtraction of the 1004 nm band can correct for unwanted adjacency affects.

Leave-one-out cross-validation (LOOCV)

The algorithm providing the best fit (2) was then applied to all the AHS images data to map TSM concentration at different tidal stages. To predict how well the algorithm will perform for the entire dataset a cross-validation is applied. Cross-validation is often carried out by splitting the dataset into two parts - one part for training and one part for testing. However, it was preferred here to apply a leave-one-out cross-validation because of the limited number of ground sample calibration points available. Applying the leave-one-out cross-validation, all samples except 1 are used for establishing the calibration relation. The suspended sediment concentration and RMSE is estimated for this one point. Hence a single observation is used as validation data and the remaining data as training set. This is repeated such that each observation in the original dataset is used once for validation. At the end all estimates are combined and an average RMSE is computed. By applying a LOOCV, the possible bias by relying on a single split into training and test samples is avoided. The RMSE of the LOOCV for our log-linear line model was 17.06 mg/l.

Validation with turbidity data

TSM data are also available from indirect measurements i.e. converted from turbidity measurements. As the turbidity meter logged every 14 seconds a large dataset is available for validation purposes. The accuracy of this dataset depends, amongst others, on the calibration relation between turbidity and TSM (Figure 4). Although this dependence increases the uncertainty, the dataset can still give an idea of the accuracy.

In total 88 data points were used for validation which were collected within 10 minutes of the data acquisition. At the location of these turbidity measurements , the average TSM concentrations were extracted from the AHS derived TSM maps from a 5-by-5 box of pixels. These were compared to the TSM concentration derived from the turbidity data. This resulted in a RMSE of 19.6 mg/l, which is only slightly higher than the error found using LOOCV on the basis of the water samples.

TSM maps

The 15 produced TSM maps are in good agreement with the known distribution of the suspended sediment content over different tidal phases. In Figure 6 a selection of TSM maps is given which best illustrates the variation of near-surface TSM concentration over the tidal phases. Figure 6a, taken at high tide, shows –compared to the other figures – high surface silt concentration. These general high near-surface TSM concentrations are mainly explained by high current velocities at high tide. The high concentrations are spread out over the whole cross-section, similar to the velocity distribution pattern observed by Fettweis *et al.* (1998). In the entrance channel of Kallo where velocities are much lower, lower silt concentrations at the surface can be observed.

In the succeeding slack tide high water (Figure 6b) the observed TSM concentrations are much lower. At this stage velocities are very low, which results in much lower surface concentrations, due to the sinking of the sediment particles (IMDC, 1999, 2004).

During ebb (Figure 6c) downstream velocities are observed, i.e. the sediment concentration is higher downstream of the inside of curbs which are shallower areas. Eroded sediment at the shallow area is dragged in the downstream direction. The horizontal cross-section variation in TSM matches the variation measured at previous field campaigns. Surface silt concentrations are higher at the right bank than at the left bank (IMDC, 2005). The submerged flow guidance dike near Doel clearly separates high silt concentrations west of the dike from low silt concentrations east of the dike. This dike is the border between a shallow area (resulting in high sediment concentrations at the surface) west and the navigation channel eastward.

Another known feature, well present in all the produced maps, is the low-TSM concentration in the harbour docks. Some sediment enters the docks near the access locks during sluicing operations. This sediment settles in the adjacent harbour dock.

Conclusion

A series of hyperspectral images was retrieved, together with a fair amount of ground data, intended to produce quantified near-surface total suspended matter maps of the Lower Sea Scheldt near Antwerp at different stages in the tidal cycle. The high spectral resolution allowed different image calibration strategies to be tested and evaluated. A log-linear model of TSM against a reflectance difference term appeared to produce the best fit. The difference term sets off two reflectance values in the near infrared range, of which one is and the other is not sediment-dependent. This strategy was shown to compensate for some disturbing factors, such as varying cirrus cloud cover and adjacency effects. The use of this difference term has to our knowledge not been reported before. This may be due to the often limited wavelength range of the used multi- and hyperspectral sensors. For algorithm development image spectra were used instead of in-situ measured reflectance spectra. This approach has the advantage that perfect optical closure between in-situ reflectance spectra and image spectra is not required. This perfect closure was very difficult to achieve under the highly variable atmospheric conditions occurring during the data acquisition. The suspended sediment maps produced describe well the known variation of sediment behaviour in the Lower Sea Scheldt area and contribute to the improvement of our knowledge of spatial and temporal sediment distribution in this complex river system. The magnitude of error in the retrieved TSM maps (17 mg/l) is in the same order as reported by Doxaran *et al.* (2002) for comparable concentration ranges.

In this paper only near-surface suspended sediment concentrations were mapped. Still, these surface concentrations are deemed sufficient in many dredging related projects. They indicate regions of high and low turbidity, the area of the turbidity maximum, movements of sediments and they show dredging plumes. Moreover in situ concentration profiles of the area can establish a relationship between the surface concentrations and deeper concentrations during every tidal phase. Therefore surface concentrations are a useful indicator for total suspended sediment concentrations.

Acknowledgments

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TABLE 1 The first 20 spectral channels of the AHS sensor (FWHM: Full Width Half Maximum)

Channel	Wavelength (nm)	FWHM (nm)
1	455	27
2	484	28
3	513	29
4	542	28
5	571	28
6	601	28
7	630	28
8	659	28
9	689	28
10	718	28
11	746	27
12	774	27
13	804	28
14	833	28
15	862	28
16	891	27
17	918	28
18	948	28
19	975	28
20	1004	30

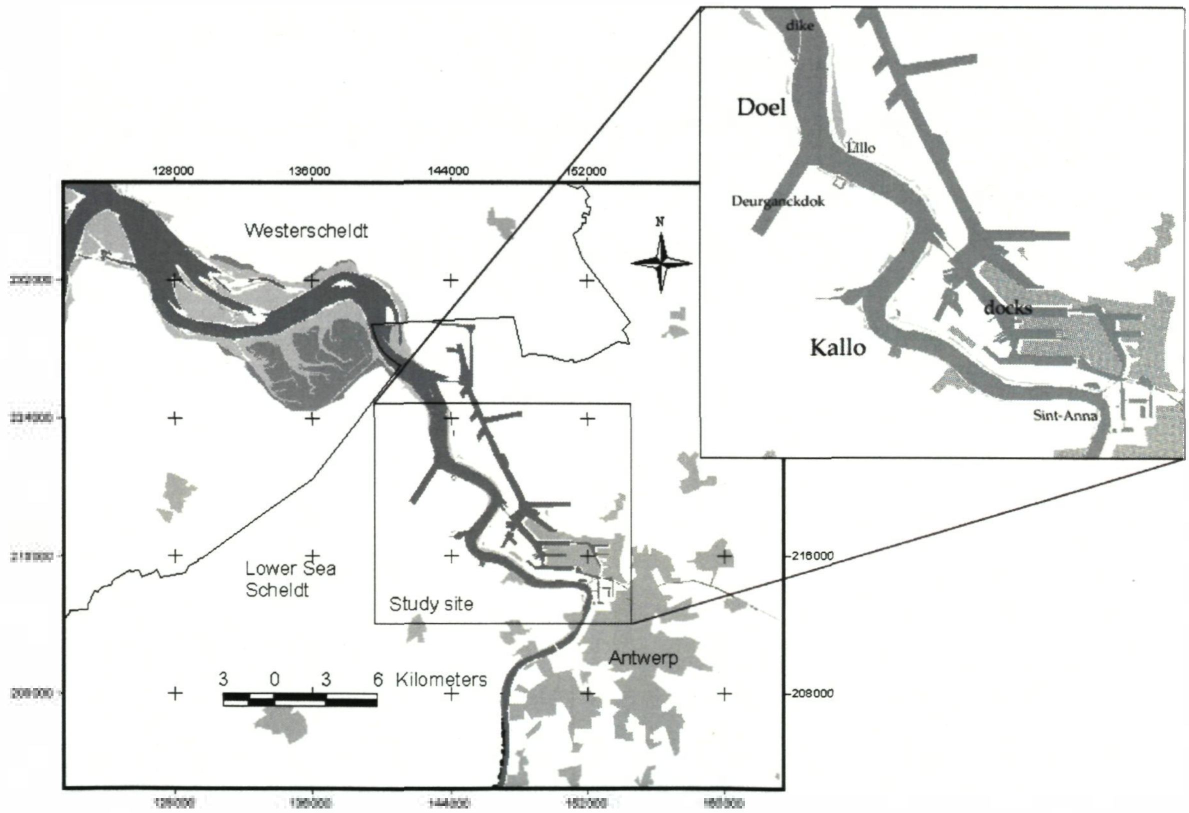

FIGURE 1 The Scheldt Estuary with the study site indicated (Source: IMDC, 2004)

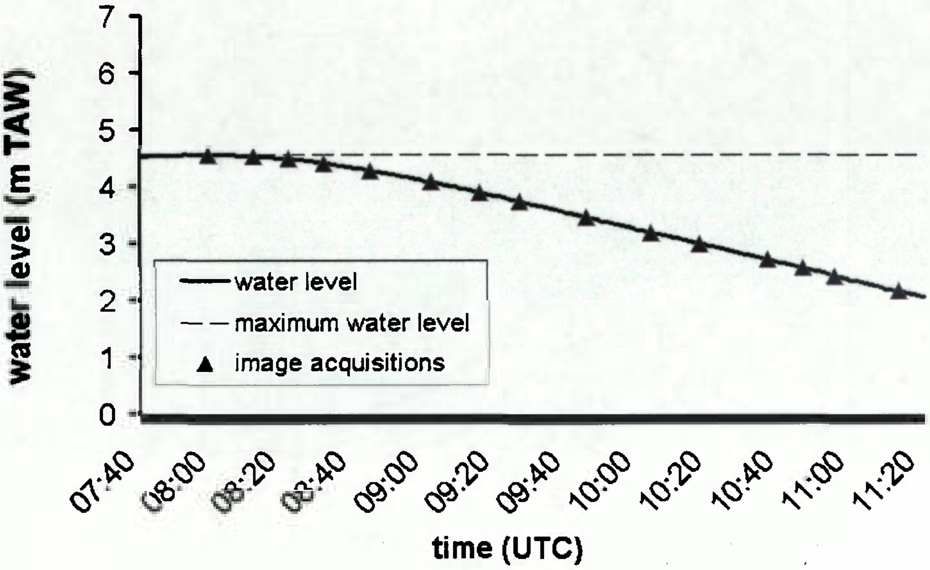

FIGURE 2 Image acquisition times in relation to the tidal cycle. The data are referred to TAW (Tweede Algemeene Waterpassing), the Belgian National Reference Level.

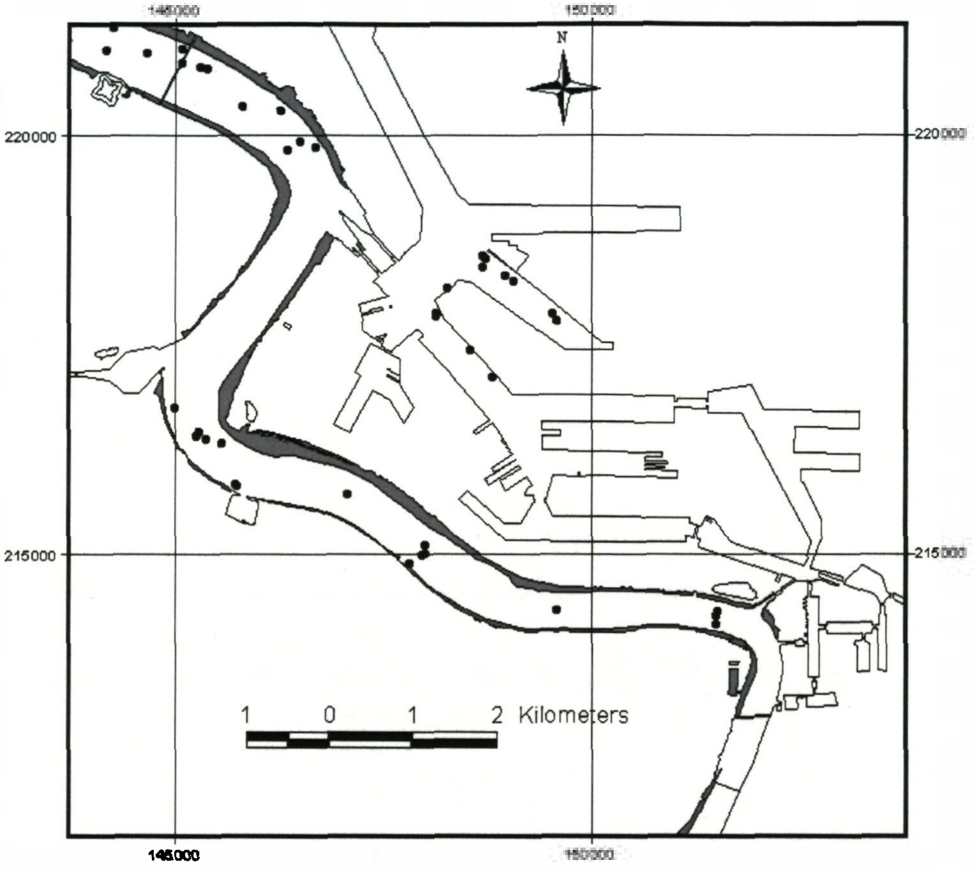

FIGURE 3 Locations vessels at moment of data capture (Source: IMDC, 2004)

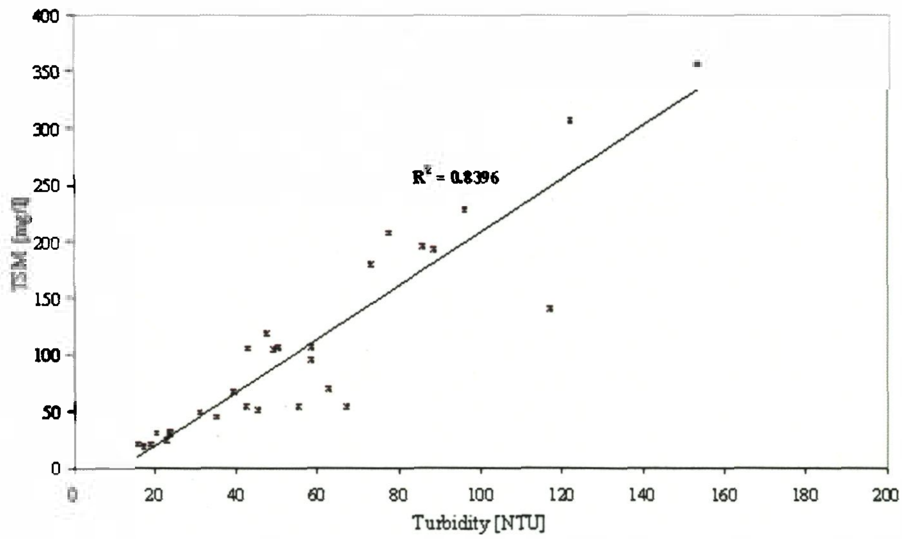

FIGURE 4 Scatterplot of turbidity versus TSM

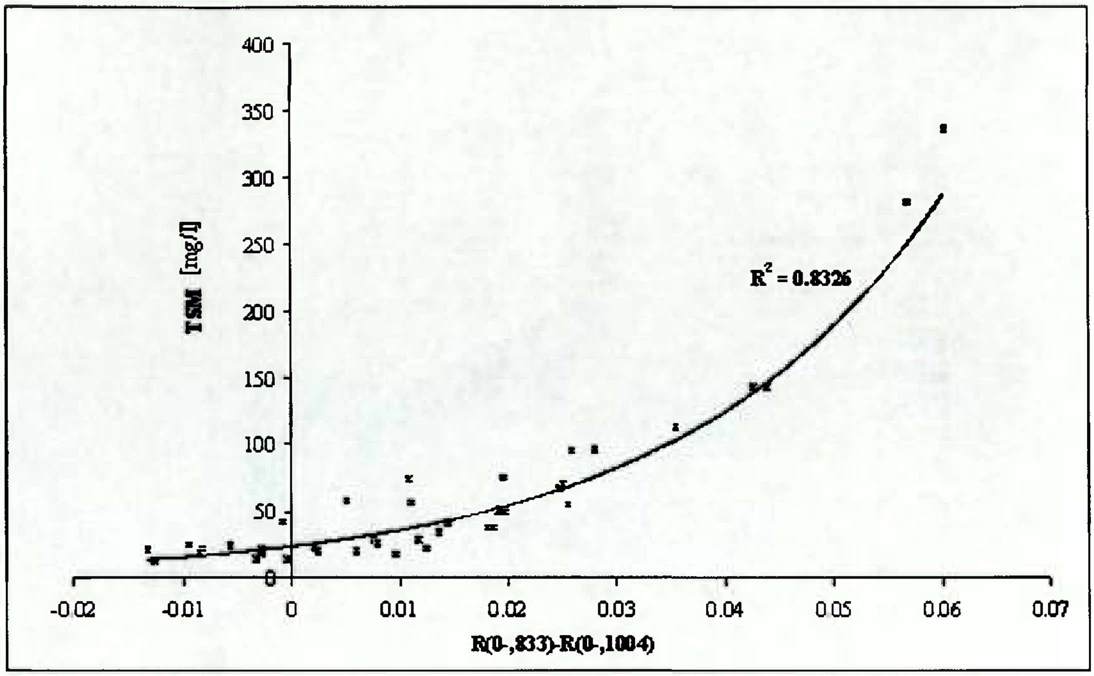

FIGURE 5 Scatterplot of R(0-,833)-R(0-,1004) versus TSM

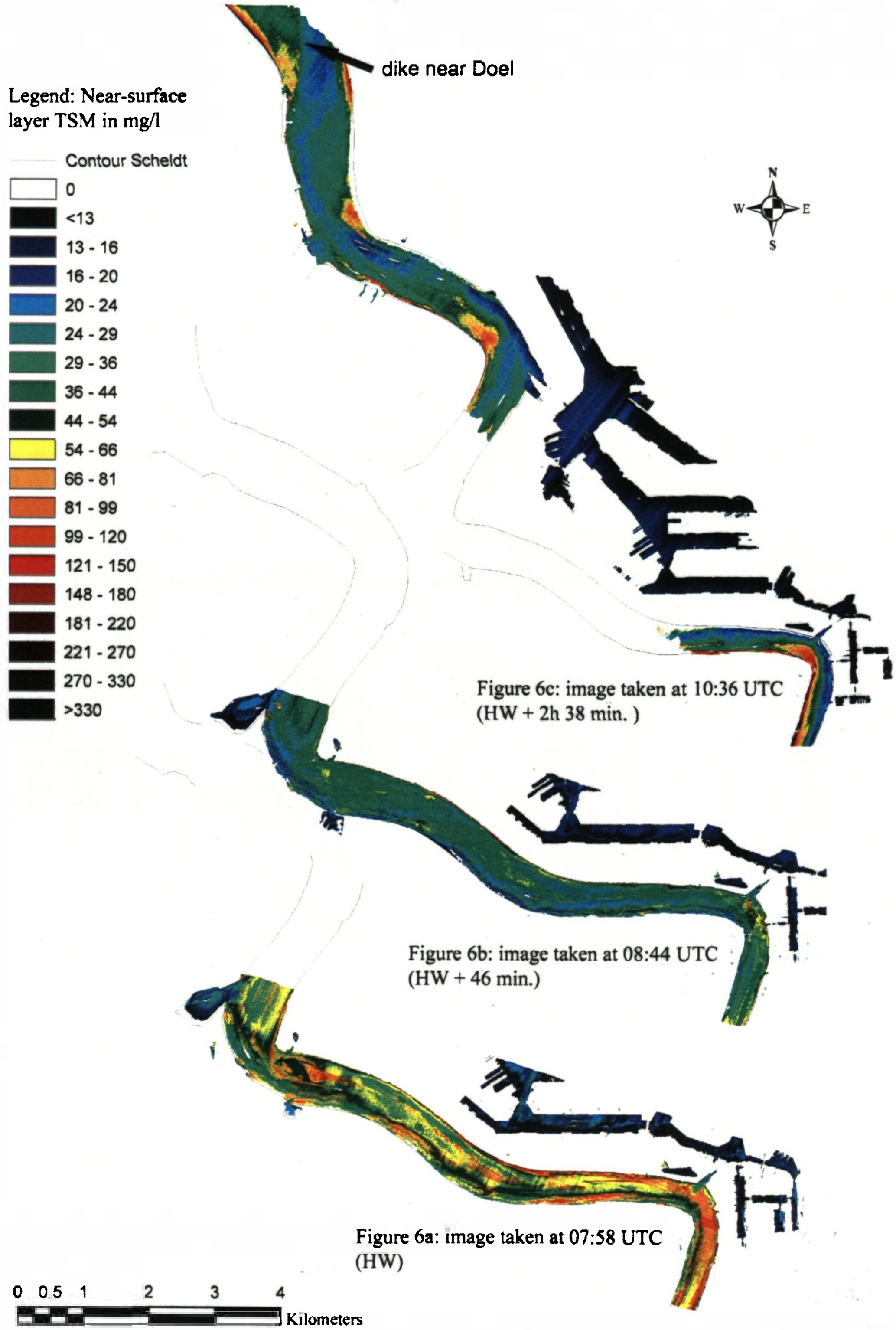

FIGURE 6 Near-surface layer TSM in mg/l at three different stages in the tidal cycle (HW: high water)

Operational Remote sensing Mapping of Estuarine suspended Sediment concentrations (ORMES)

E. Knaeps[1], S. Sterckx[1], M. Bollen[2], K. Trouw[2], and R. Houthuys[3]

Abstract: Each year, dredging companies remove more than two million m3 of estuarine sediment from the Scheldt River (Belgium). This is necessary to assure access to the harbour of Antwerp. International Marine and Dredging Consultants (IMDC) advises government agencies and dredging companies to help them carry out their activities. Images of the sediment concentration are essential if accurate advice is to be given. IMDC uses this information to select new salvage locations, to estimate possible movements of sediment clouds and to calibrate sediment transport models. To support IMDC in their activities, a service is developed in the ORMES project which provides suspended sediment maps from remote sensing images in an efficient way. Our main test site is a part of the Belgian Scheldt Estuary near Antwerp. It is chosen because of the wide ranges of sediment content and IMDC's thorough knowledge of the river system. Here, we will present the results obtained within the ORMES project for this test site.
The dataset consisted of a series of airborne hyperspectral images obtained at different stages of the tidal cycle. Airborne hyperspectral data have a high potential for mapping the sediment concentrations in rivers or coastal waters because of its high spectral and spatial resolution. Simultaneously with the airborne campaign a field survey took place. Using these field data and the high resolution airborne data, a reliable semi-empirical algorithm has been developed to derive near-surface suspended matter maps in an operational way. The produced TSM maps showed good agreement with known variations of the suspended sediment content over the tidal cycle : maximum turbidity around high water and gradual settling of the sediment in the succeeding slack water. A resuspension of sediment takes place at the onset of the ebb flow stage, especially at the bend-related shoals. The cross-river differences in TSM matched well the variation measured at previous field campaigns.

Keywords: remote sensing, Scheldt, suspended sediments

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1 INTRODUCTION

International organizations like the International Maritime Organization have predicted a high increase in the transport of cargo and goods by sea over the coming decades. Due to this increase in sea transport existing harbours need to be improved and new ports need to be developed. For the improvement of existing as well as the development of new ports feasibility studies are carried out for the design of the harbours and its infrastructure. Governments are implementing strict rules and regulations which will affect the construction activities to protect the environment. Amongst others, construction and dredging companies will have to assess the impact of these activities on the environment by carrying out environmental impact assessment studies. Governmental agencies will have to determine baseline conditions and will have to monitor long term effects of works.
In the feasibility phase as well as in environmental assessment studies an important aspect is the assessment of the effect of the port development on the sediment transport patterns in the surrounding area. Whether more or less sediment is being transported in and out of the harbour or whether sites of erosion or deposition have changed due to the creation of dredging dumping sites is of particular interest. All these effects can have an impact on the surrounding environment such as the gradual or rapid destruction of the natural coastal defense.
At the moment turbidity meters and water samples can provide measurements of suspended sediment concentration. However, these types of analysis are time consuming and expensive. Furthermore traditional in-situ measurements performed at single points or along transects are insufficient to provide a complete view of the spatial variability of suspended sediments. A cost-effective way of providing this information is to use remote sensing data. Furthermore remote sensing data can cover relatively large areas instantaneously at relatively low cost and are therefore ideal for this type of assessment. Remotely sensed data therefore lends itself for detecting changes to sediment transport regimes.
The aim of the ORMES project is to develop a simple and robust procedure for near surface sediment concentration mapping from remote sensing data, both airborne and satellite borne. The ORMES project focuses on the full capability of state-of-the-art airborne hyperspectral sensors but also looks into possibilities to monitor the turbidity and deduce sediment concentration on a more routinely basis by converting the operational methodology to UAV (http://www.pegasus4europe.com), micro-satellite platforms equipped with programmable narrow spectral band sensors and to broadband multi-spectral satellite sensors (eg. SPOT HRV, FORMOSAT).
IMDC, the private partner in the ORMES project, prepares specifications and recommendations of techniques, equipment and methods for any dredging project. IMDC requires information on the spatial variation of turbidity for among others the optimization of the dredging locations and dumping sites, the better planning of new harbor locations at places with low turbidity to minimize dredging maintenance and validation of the sediment transport models. For these reasons, they rely on the ORMES project in order to develop an operational methodology for suspended sediment mapping from remote sensing images in a cost effective and efficient way.
Within the ORMES project the Scheldt Estuary has been chosen as main study site mainly because of its dynamic complexity. If the developed sediment mapping procedure works fine here, it is expected that the algorithm can relatively easily be applied to other tidal regions abroad. In this paper we will present the results obtained within the ORMES project for the Scheldt test site using hyperspectral airborne data.

2 BACKGROUND ON REMOTE SENSING OF SUSPENDED SEDIMENTS

The colour of water is affected by certain constituents including suspended sediments and therefore it is possible in suitable circumstances to detect their presence in water and quantify their respective concentrations using remote sensing. Passive remote sensing uses the light coming from the sun which is transmitted, scattered or absorbed by particles or molecules in the water body. The scattered light may subsequently leave the water body. This water-leaving radiance can reach the field-of-view of a remote sensor. The sensor measures the scattered light in several wavelength bands, often, even beyond the range of human vision (ultra-violet, infrared, microwave). For example, Landsat ETM+ acquires data in 7 bands ranging from blue to thermal infrared wavelengths. Suspended sediments increase the radiance emergent from surface waters in the visible and near infrared proportion of the electromagnetic spectrum (Ritchie and Schiebe 2000). Hence, satellite or aircraft remote sensing data can be used to study near-surface suspended sediment patterns. Still, to derive concentrations of suspended sediment, some additional surface water samples are usually needed to set-up a calibration relationship between remote sensing data and suspended sediment. The calibration relationship is influenced by the composition and grain size of the suspended sediments and the spectral characteristics of the remote sensor (i.e. number, width and location of the wavelength bands).
The remote sensors can be categorized in function of the platform (aircraft versus satellite), the spectral, spatial or temporal resolution. Land multi-spectral sensors as Landsat and SPOT HRV, record data in a few broad spectral bands with a moderate spatial resolution (20 – 30 m). They pass over the same area at the same angle only a few

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times a month. However, by making use of the off-nadir viewing capability of SPOT HRV the revisit frequency can strongly be increased. Furthermore, this temporal resolution limitation has now been overcome by FORMOSAT-2, the first High Resolution satellite offering daily revisit acquisition services. The ocean water colour satellites as MERIS, MODIS have more and smaller spectral bands and can acquire images from the same area several times a week. Their major drawback is the low spatial resolution with pixel size of +/- 1 x 1km.

Due to the better spatial resolution (pixel size in the range of 1 to several meters), airborne remote sensing is very well suited for the study of sediment fluxes in coastal bays, rivers and lakes. Hyperspectral airborne data are most suited for this purpose because they provide both a high spatial and spectral resolution. An hyperspectral sensor can acquire images in hundreds of registered, contiguous spectral bands (Figure 1). Hence, for each pixel of an image it is possible to derive a complete reflectance spectrum (Goetz, 1992) which enables us to derive suspended sediment more accurately. Still hyperspectral airborne data are quite expensive and the use of airborne remote sensing for routinely monitoring might be critical with respect to the costs. In the near future this problem can probably be overcome with the unmanned airborne vehicle (UAV) and micro-satellite platforms under development. These systems will combine the advantages of both satellite and airborne systems i.e. the ability to revisit the sites at regular time intervals at a high spatial resolution.

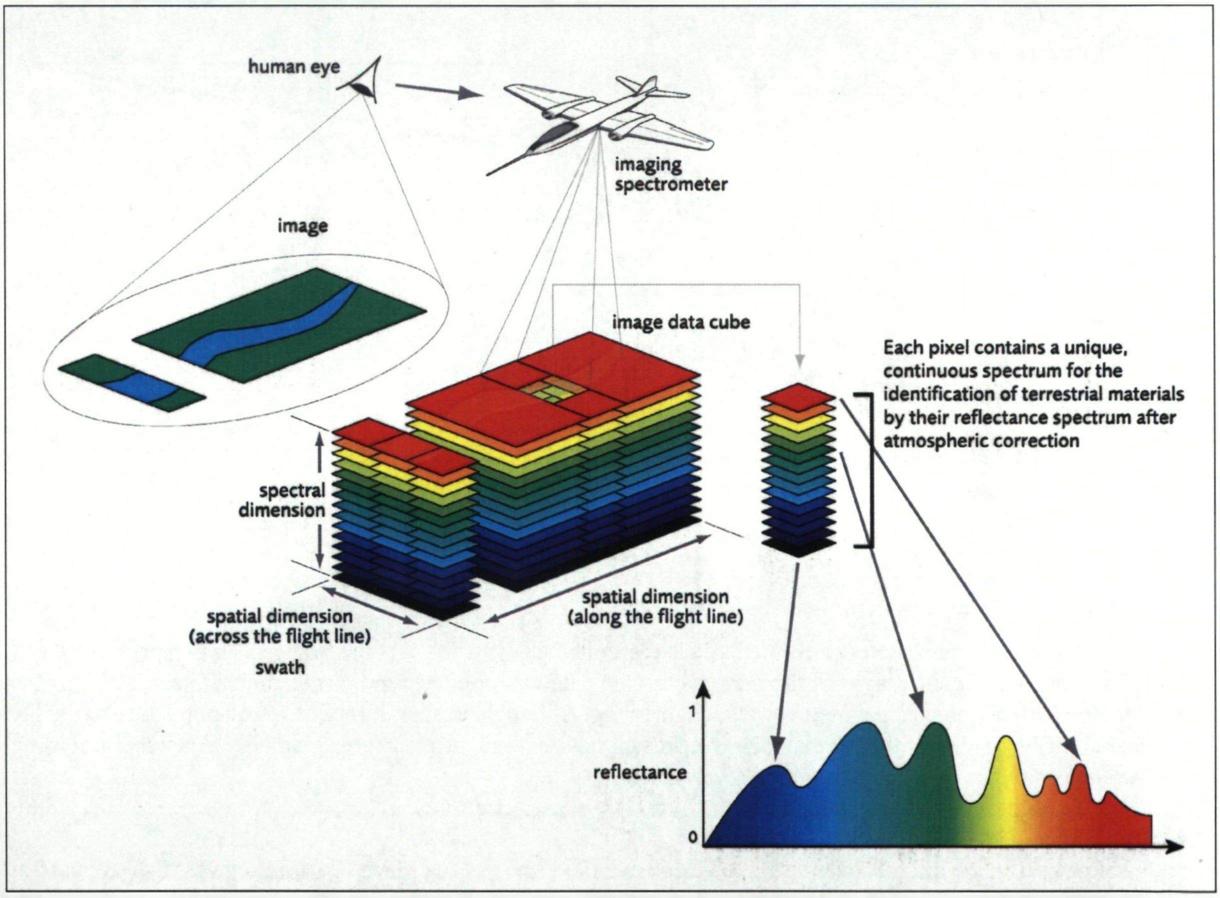

Fig. 1: Principle of hyperspectral airborne remote sensing

3 TEST CASE : AIRBORNE HYPERSPECTRAL DATA OVER THE SCHELDT

3.1 Study Site

The Scheldt river finds it origin in northern France and flows through Belgium via Antwerp towards the North Sea. Our study site is restricted to a part of the Lower Sea Scheldt as illustrated in Fig. 2. Although the open North Sea is about 60 km away from Antwerp, the Scheldt is an important shipping channel giving access to the vast port area of the city.

The Scheldt is a complex river system where concentrations of suspended sediment are highly variable in place and time. The concentrations are in the range of a few hundreds mg/l (IMDC, 2004). At this location, the tidal range is more than 4 m.

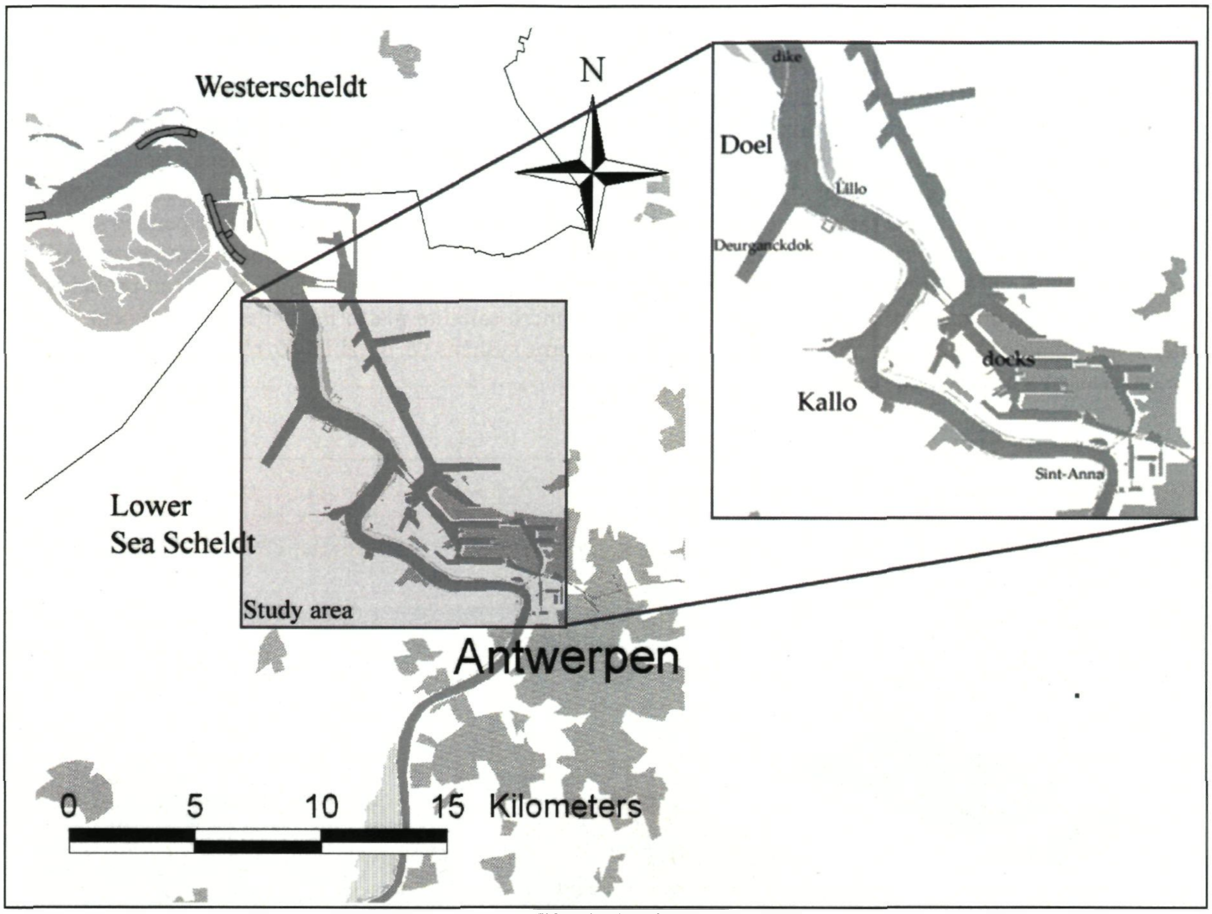

Fig. 2: Study area

3.2 Airborne and field data

Remote sensing data

On June 15th 2005 hyperspectral airborne data were collected with the AHS Advanced Hyperspectral Sensor (SenSytech Inc) at different stages of the tidal cycle. The data was collected in 80 spectral channels, covering the 0.430 µm to 12.70 µm electromagnetical wavelength range. Although weather forecasts were optimistic and the sky was clear at the beginning of the campaign, thin cirrus clouds covered the study area gradually. The remote sensing data were atmospherically and geometrically corrected.

Field data

Simultaneously with the aircraft overpasses, an extensive field survey took place. Two survey vessels were used at different stretches of the Lower Sea Scheldt to include some spatial variability. An extra vessel was deployed at the docks in the harbour of Antwerp. Several measurements were done on board of each vessel on predesignated locations at the time of airplane crossing over the study area. Four jetties served as additional fixed sampling locations. 150 surface water samples were collected and stored in 1 liter bottles to determine total suspended matter concentration. At one vessel in the Scheldt a turbidity sensor (Aanderaa RCM-9) continuously logged turbidity in the surface water layer. The location of the boats was continuously logged with a Trimble GeoXT GPS. Sun-photometric measurements were performed to estimate the aerosol content and water vapour in the atmosphere to calibrate the radiative transfer model used in the atmospheric correction. General atmospheric conditions were registered by taking photos of the sky at all the sampling locations of the boats.

3.3 Data processing

Field data processing

The TSM concentration was determined by filtering 250 ml of the water samples on pre-weighed 0.45 µm membrane filters. Filters were then dried and re-weighed. The measured TSM concentration in the Scheldt river and the docks ranged from 13 to 336 mg/l and 7 to 12 mg/l respectively.
To convert the continuous turbidity measurements in nephelometric turbidity units (NTUs) to TSM (measured in mg/l), the relationship between turbidity and TSM from water samples was statistically modeled for coincident points. A linear relationship was found with an R^2 of 0.83 and an RMSE of 35.2 mg/l. This best-fit regression equation was then applied to all turbidity measurements.
Chlorophyll-a concentration was determined for six water samples following the ASTM D 3731-87 Standards (ASTM, 1993). The average CHL-a concentration was 4.4 µg/l in the Scheldt river and 19,1 µg/l in the docks.

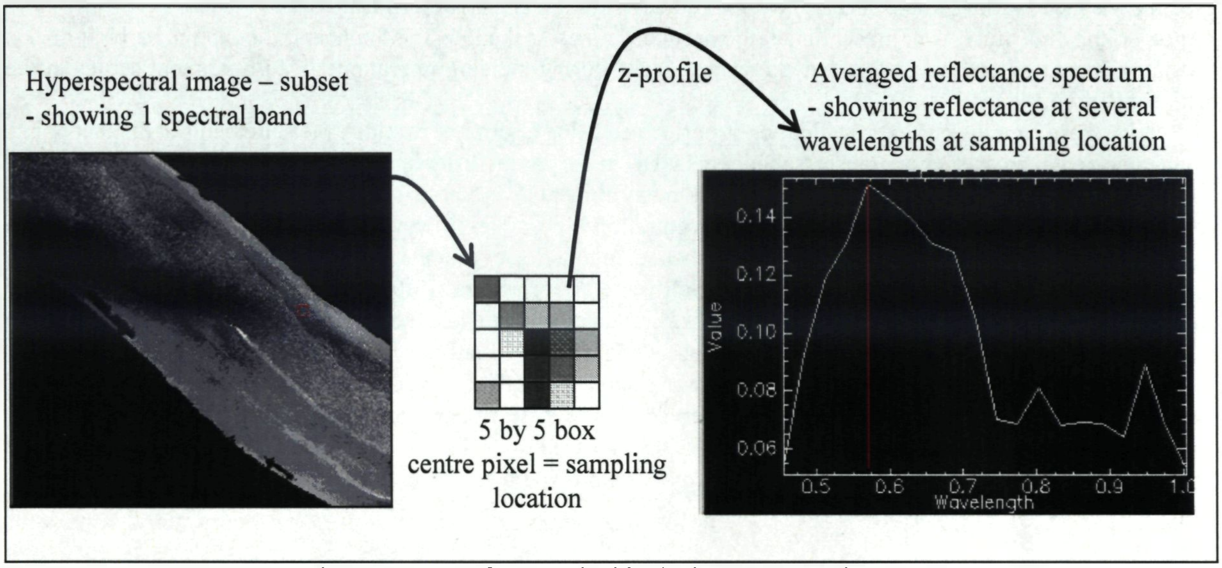

Fig.3: Spectrum for one pixel in the hyperspectral image.

TSM Algorithm

Reflectance spectra R(0-) were extracted from the hyperspectral images at the sampling locations as shown in Fig. 3. An average spectrum calculated from a 5 by 5 box of pixels (corresponding to an area of 20 m by 20m) was preferred to remove random noise. In the study area, the suspended matter concentrations and patterns change very rapidly as the tide fluctuates. The timing between airborne and in-situ sampling is therefore a critical issue. Hence, to calibrate as accurately as possible, only the samples taken within a few minutes of the airborne data recording were included. In total 41 samples were available to find a band combination which best predicts the TSM concentrations. The best fit with an R^2 of 0.83 and an RMSE of 15.53 mg/l was found to be a log-linear line fit to a band difference :

$$Ln(SPM) = 34.18*(R(0-,833)-R(0-,1004)) + 3.16 \quad (1)$$

where R(0-,833) and R(0-,1004) are respectively the reflectance at 833 nm and 1004 nm.

The algorithm (1) providing the best fit was then applied to all the AHS data to map TSM concentration at different tidal stages. To predict how well the algorithm will perform for the entire dataset a leave-one-out cross-validation (LOOCV) is applied. The RMSE of the LOOCV for our log-linear line model was 17.06 mg/l.
For more detailed information on the data processing the reader is referred to Sterckx et al. (2007).

3.4 TSM maps

The produced TSM maps (Fig. 4 and Fig.5) are in good agreement with the known distribution of the suspended sediment content over different tidal phases. Figure 4a, taken at high tide, shows –compared to the other figures – high surface silt concentration. These general high near-surface TSM concentrations are mainly explained by high current velocities at high tide. The high concentrations are spread out over the whole cross-section, similar to the velocity distribution pattern observed by Fettweis et al. (1998). In the entrance channel of Kallo where velocities are much lower, lower silt concentrations at the surface can be observed.
In the succeeding slack tide high water (Figure 4b) the observed TSM concentrations are much lower. At this stage

velocities are very low, which results in much lower surface concentrations of TSM, due to the sinking of the sediment particles (IMDC, 1999, 2004).
A resuspension of sediment takes place at the onset of the ebb flow stage, especially at the bend-related shoals (Figure 4c). During ebb (Figure 5a-c) downstream velocities are observed, i.e. the sediment concentration is higher downstream of the inside of curbs which are shallower areas. Eroded sediment at the shallow area is dragged in the downstream direction. The distribution and concentration of the sediments remain relatively constant during these 3 successive tidal stages (Figure 5a-c). The horizontal cross-section variation in TSM matches the variation measured at previous field campaigns. Surface silt concentrations are higher at the right bank than at the left bank (IMDC, 2005). A striking feature of sediment plume at this stage of the tide is observed at the Doel flow guidance dam, which emerges at low water. The submerged flow guidance dike clearly separates high silt concentrations west of the dike from low silt concentrations east of the dike. This dike is the border between a shallow area (resulting in high sediment concentrations at the surface) west and the navigation channel eastward.
Another known feature, well present in all the produced maps, is the low-TSM concentration in the harbour docks. Some sediment enters the docks near the access locks during sluicing operations. This sediment settles in the adjacent harbour dock.
To verify these conclusions extra validation is performed using a series of turbidity measurements at distinct points along horizontal cross-section transects made by IMDC in the past at different stages of the tidal cycle. The location of these transects is given in figure 6. As these measurements were not done coincident with the airborne data acquisition no absolute comparison of TSM concentration is possible. However these measurements can be used to verify observed patterns of TSM concentration change in function of the tide. In figures 7 – 11 TSM concentration in function of the tide derived from both the turbidity and airborne data (15/06/2006) are given for the Oosterweel and 'Ka-d' transects. In general the TSM patterns observed during the field measurements and derived from airborne data agree quite good. The 'Oosterweel left' transect (fig. 9) show relatively high TSM concentrations around high water, a strong decrease in the succeeding slack water and a gradual increase during ebb. For 'Oosterweel right' (fig. 10) and 'Ka' (fig. 7) similar patterns are observed. For 'Oosterweel middle' (fig. 11) these patterns are less consistent: (1) concentrations are relatively high at high water and low at slack water, (2) during ebb both the transects indicate first an increase in TSM immediately followed by a decrease.

4 CONCLUSION

A calibrated regression model, that relates remote sensing reflectance data with field measurements of suspended sediment concentration, was applied to airborne remote sensing data. This procedure provided a detailed and synoptic overview of the suspended sediment fluxes and concentrations at the Lower Sea Scheldt near Antwerp at different stages of the tidal cycle. Even without calibration on the basis of in-situ data, remote sensing data complements traditional data collection techniques as satellite and airborne data can easily indicate the spatial pattern of suspended sediments which is not possible trough traditional measurement campaign. Furthermore remote sensing can provide high temporal coverage which is almost impossible by other existing techniques. However remote sensing will not fully replace the traditional field surveys as the measuring range is limited to the top few feet of the water column, especially in turbid waters (Wren et al, 2000) and cloud cover may obscure remote sensing data. Ideally, different techniques, i.e. limited field survey combined with remote sensing data and sediment transport models, should be deployed simultaneously as they complement each other.

5 ACKNOWLEDGMENTS

The authors wish to thank Ir. Taverniers and Ir. Vanlede of The Ministry of the Flemish community, Hydraulic Research Laboratory and Hydrological Research division for their fruitful comments and support during the field campaign. BELSPO, the Belgian Federal Science Policy Office, supported the "ORMES" (Operational Remote sensing Mapping of Estuarine suspended Sediment concentrations) project (STEREO research project n° NR. SR/67/36).
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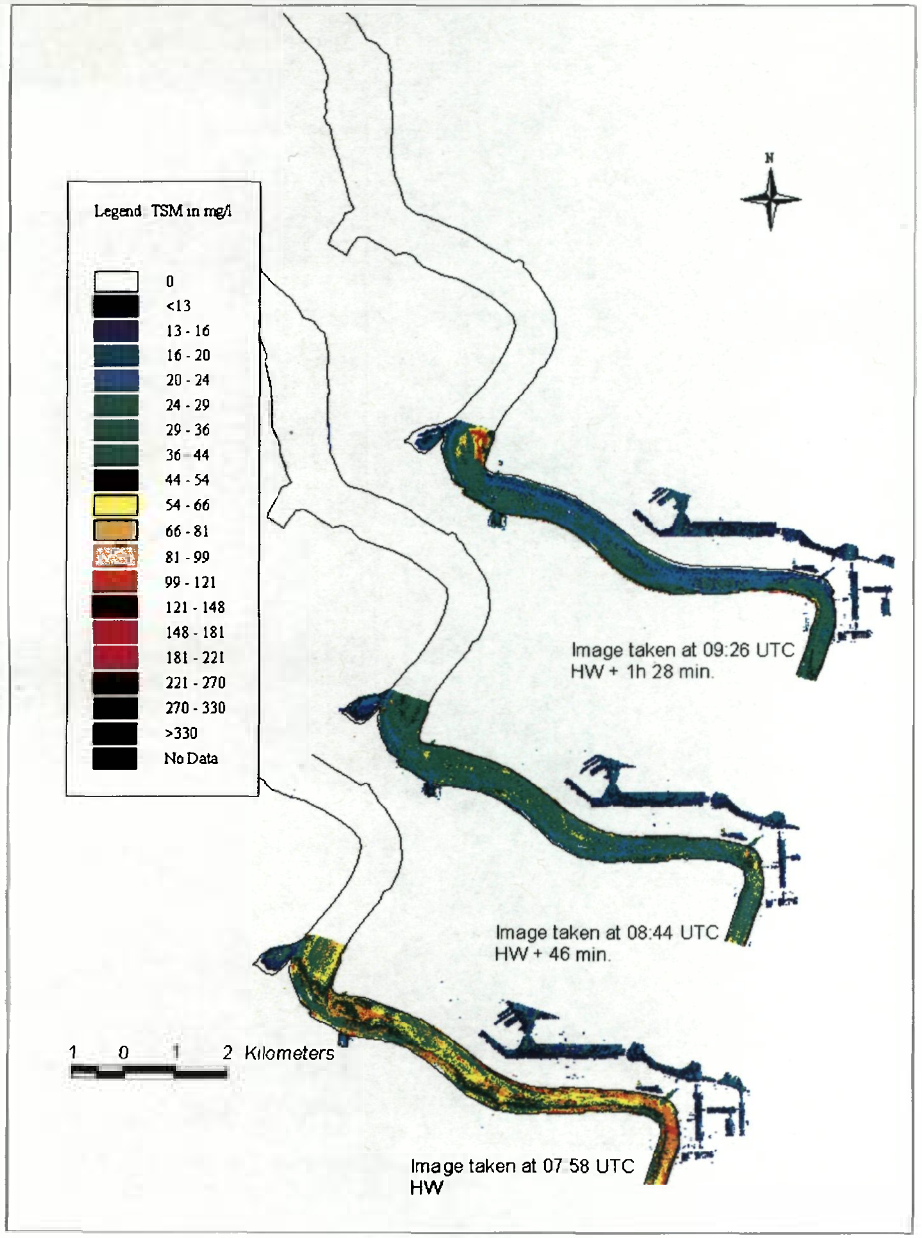

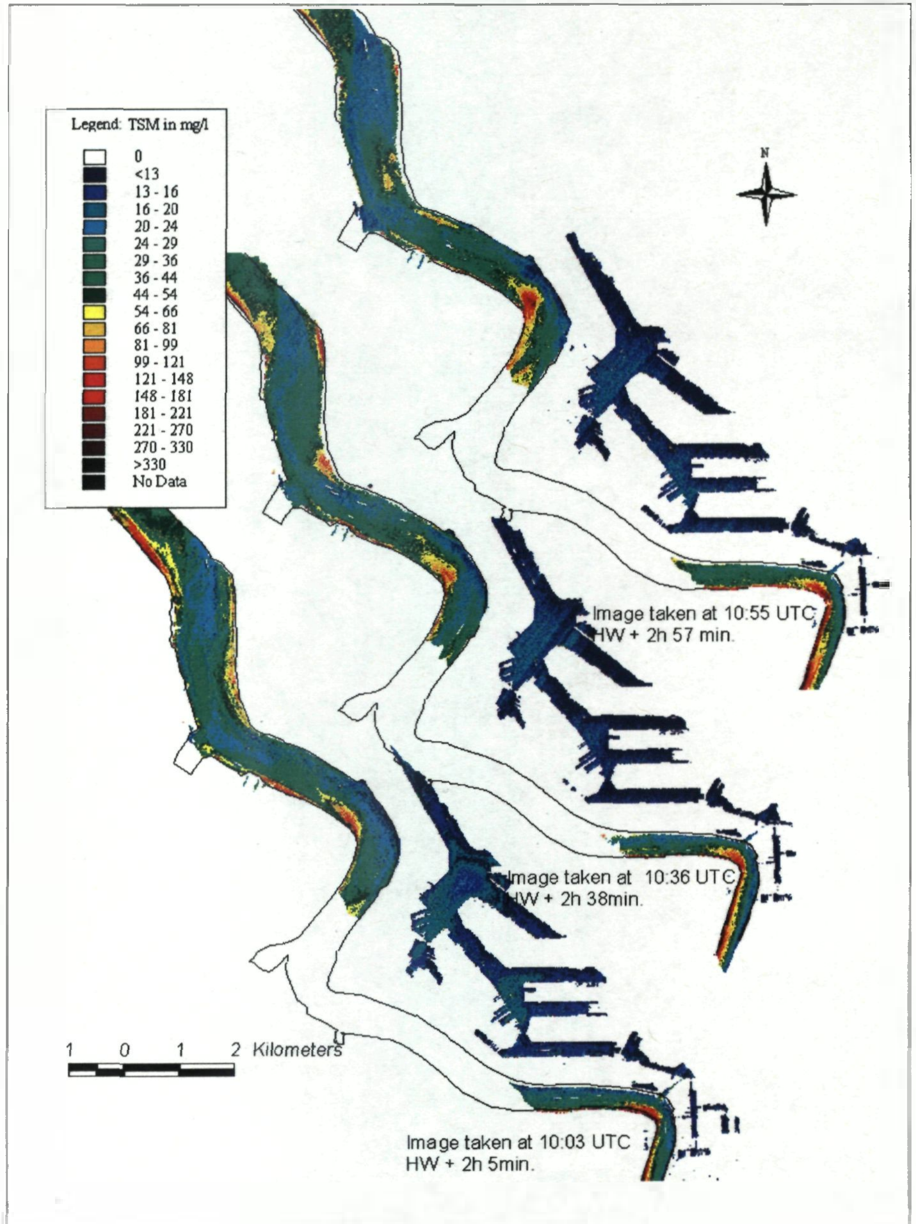

Knaeps, E., S. Sterckx, M. Bollen, K. Trouw, R. Houthuys, *Operational Remote sensing Mapping of Estuarine Suspended sediment concentrations (ORMES)*. In: proceedings of the International Dredging Days, 01-03 November 2006, Tangiers, Morocco.

Fig.4: TSM maps for the Scheldt at 07:58, 08:44 and 09:26 UTC

Fig.5: TSM maps for the Scheldt at 10:03, 10:36 and 10:55 UTC.

Entrance channel of Kallo

Knaeps, E., S. Sterckx, M. Bollen, K. Trouw, R. Houthuys, *Operational Remote sensing Mapping of Estuarine Suspended sediment concentrations (ORMES).* In: proceedings of the International Dredging Days, 01-03 November 2006, Tangiers, Morocco.

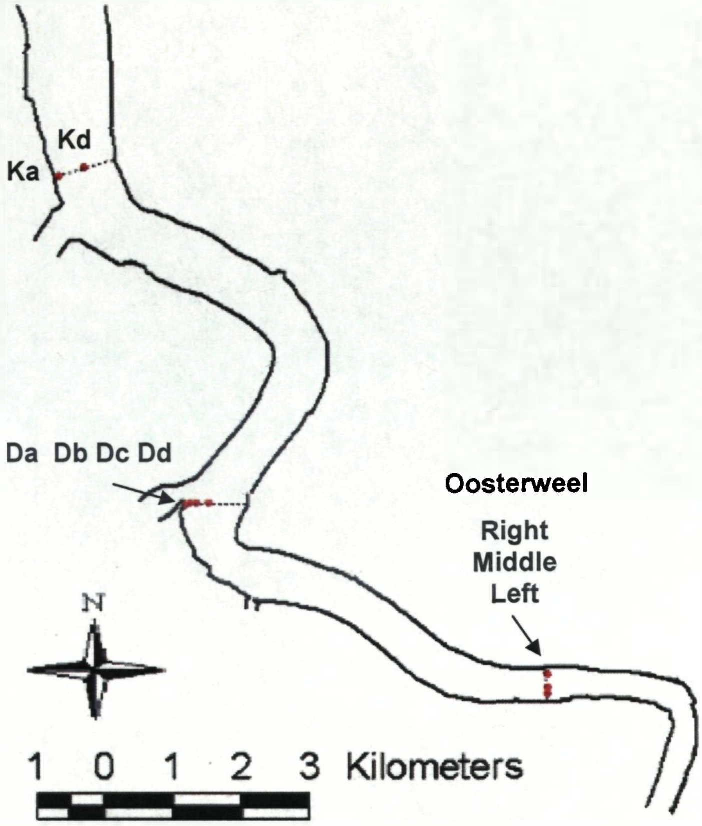

Fig. 6: Location of transects where turbidity measurements were performed in the past (transect 'Ka-d' 17 Feb. 2005; transect 'Da-b-c-d' 18 Feb. 2005 ; 'Oosterweel Right-Middle-Left' 3 June 2004 and 10 June 2004)

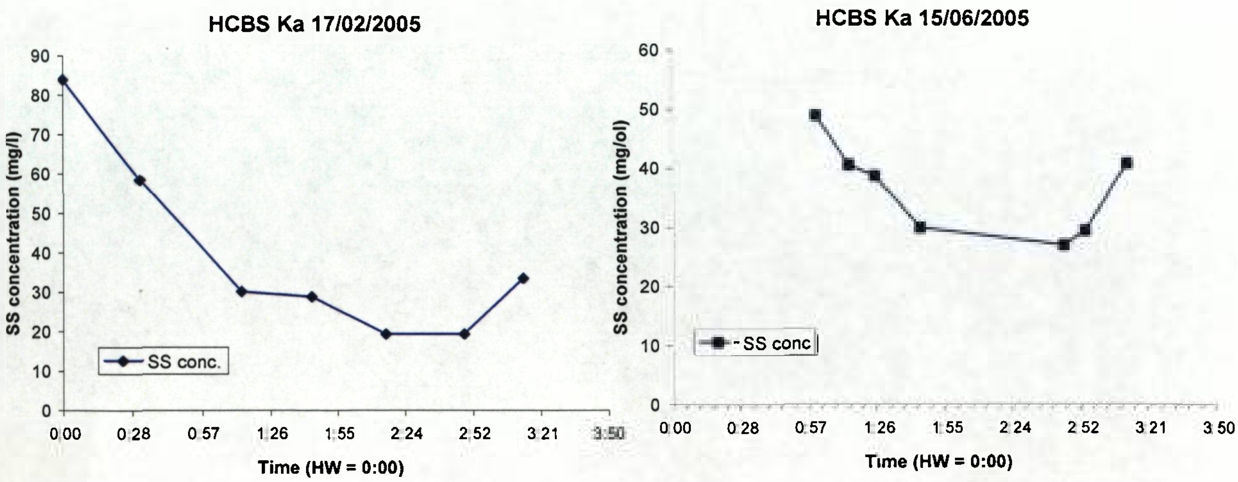

Fig. 7: Transect Ka , on 17 Feb. 2005 (field data) and 15 June 2005 (airborne derived data)

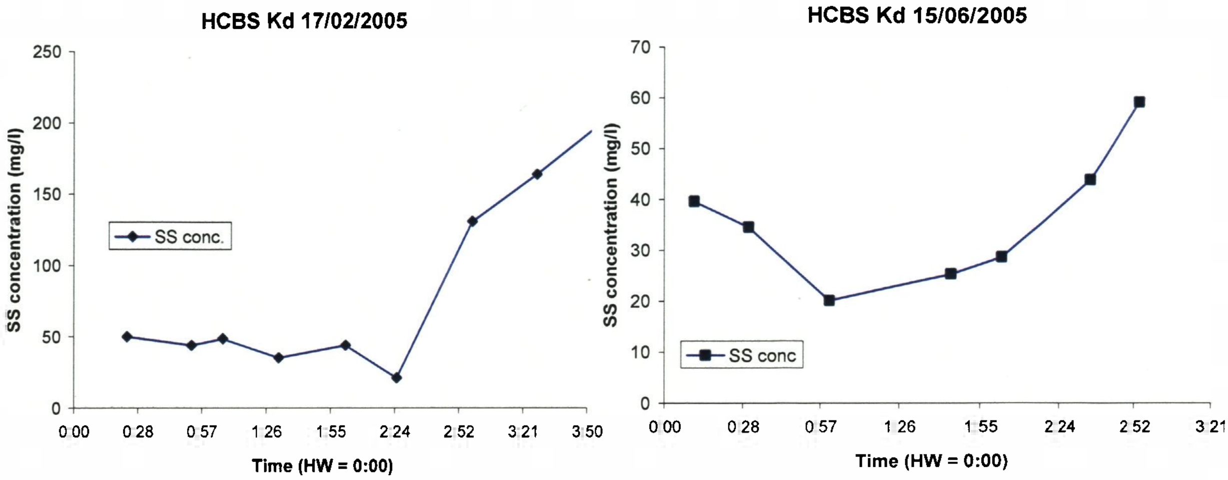

Fig. 8: Transect Kd , on 17 Feb. 2005 (field data) and 15 June 2005 (airborne derived data)

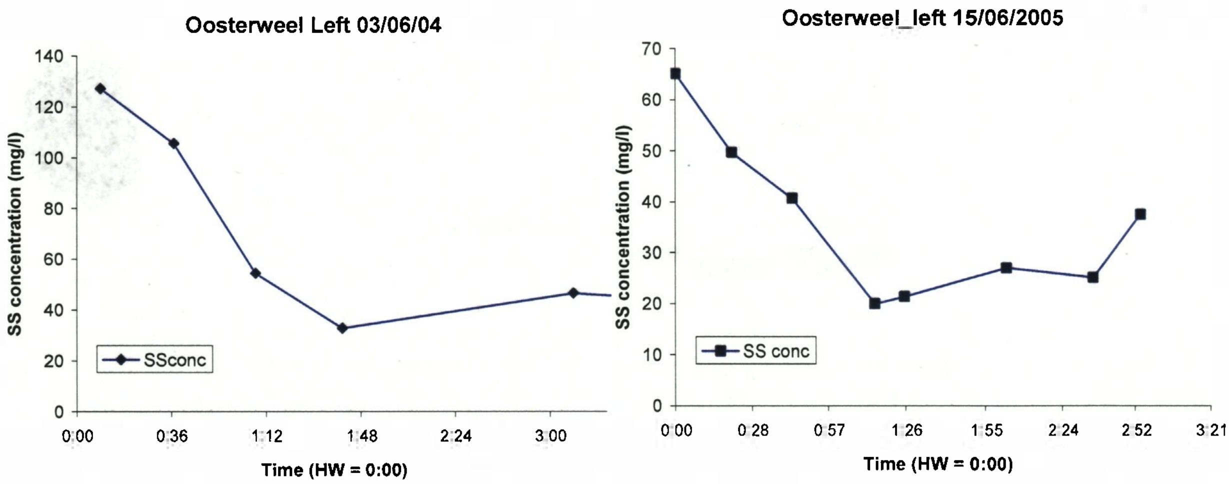

Fig. 9: Transect Oosterweel_Left , on 3 June 2004 (field data) and 15 June 2005 (airborne derived data)

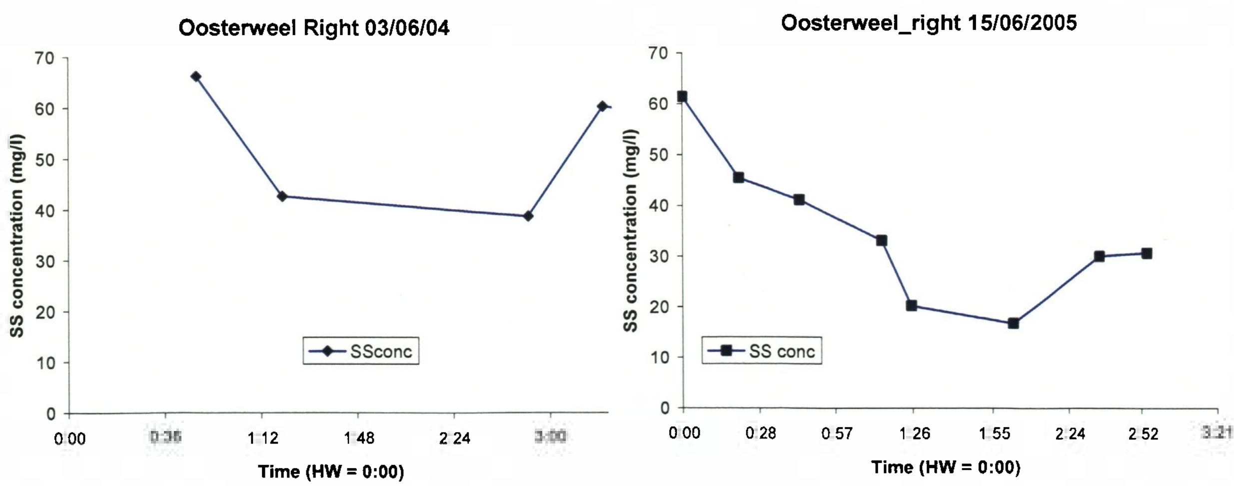

Fig. 10: Transect Oosterweel_Right , on 3 June 2004 (field data) and 15 June 2005 (airborne derived data)

Knaeps, E., S. Sterckx, M. Bollen, K. Trouw, R. Houthuys, *Operational Remote sensing Mapping of Estuarine Suspended sediment concentrations (ORMES).* In: proceedings of the International Dredging Days, 01-03 November 2006, Tangiers, Morocco.

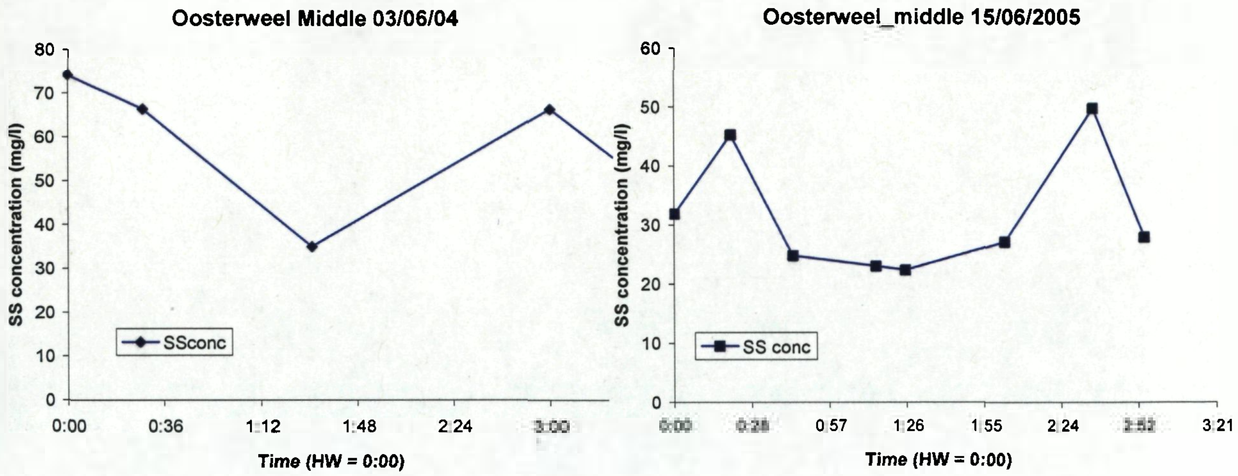

Fig. 11: Transect Oosterweel_Middle , on 3 June 2004 (field data) and 15 June 2005 (airborne derived data)

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Operational Remote Sensing Mapping Of Estuarine Suspended Sediment Concentrations (ORMES)

Sindy Sterckx, Els Knaeps, Mark Bollen, Koen Trouw and Rik Houthuys

Within the ORMES project a service is developed which provides suspended sediment maps from remote sensing images in an efficient way. Our main test site is a part of the Belgian Scheldt Estuary near Antwerp. A reliable semi-empirical algorithm has been developed to derive near-surface suspended matter maps in an operational way. This algorithm is applied to a series of hyperspectral airborne data obtained at different stages of the tidal cycle. The produced TSM maps showed good agreement with known variations of the suspended sediment content over the tidal cycle: maximum turbidity around high water and gradual settling of the sediment in the succeeding slack water. The cross-river differences in TSM matched well the variation measured at previous field campaigns.

Introduction

Each year, dredging companies remove more than two million m³ of estuarine sediment from the Scheldt River (Belgium). This is necessary to assure access to the harbour of Antwerp. International Marine and Dredging Consultants (IMDC) advises government agencies and dredging companies to help them carry out their activities. Information on the sediment concentration is essential if accurate advice is to be given. IMDC uses this information to select new salvage locations, to estimate possible movements of sediment clouds and to calibrate sediment transport models. At the moment turbidity meters and water samples can provide measurements of suspended sediment concentration. However, these types of analysis are time consuming and expensive. Furthermore traditional in-situ measurements performed at single points or along transects are insufficient to provide a complete view of the spatial variability of suspended sediments. A cost-effective way of providing this information is to use remote sensing data. These data can cover relatively large areas instantaneously at relatively low cost and are therefore ideal for this type of assessment.

For these reasons, IMDC relies on the ORMES project in order to develop a simple and robust procedure for near surface sediment concentration mapping from remote sensing images. The ORMES project focuses on the full capability of state-of-the-art airborne hyperspectral sensors but also looks into possibilities to monitor the turbidity and deduce sediment concentration on a more routinely basis by converting the operational methodology to UAV (http://www.pegasus4europe.com), micro-satellite platforms and to broadband multi-spectral satellite sensors (eg. SPOT HRV, FORMOSAT).

Within the ORMES project the Scheldt Estuary has been chosen as main study site mainly because of its dynamic complexity. If the developed sediment mapping procedure works fine here, it is expected that the algorithm can relatively easily be applied to other tidal regions abroad. In this paper we will present the results obtained within the ORMES project for the Scheldt test site using hyperspectral airborne data.

Background on remote sensing of suspended sediments

The colour of water is affected by certain constituents including suspended sediments and therefore it is possible in suitable circumstances to detect their presence in water and quantify their respective concentrations using remote sensing. Passive remote sensing uses the light coming from the sun which is transmitted, scattered or absorbed by particles or molecules in the water body. The scattered light may subsequently leave the water body. This water-leaving radiance can reach the field-of-view of a remote sensor. The sensor measures the scattered light in several wavelength bands, often, even beyond the range of human vision (ultra-violet, infrared, microwave). Suspended sediments increase the radiance emergent from surface waters in the visible and near infrared proportion of the electromagnetic spectrum [1]. Hence, satellite or aircraft remote sensing data can be used to study near-surface suspended sediment patterns. Still, to derive concentrations of suspended sediment, some additional surface water samples are usually needed to set-up a calibration relationship between remote sensing data and suspended sediment. The calibration relationship is influenced by the composition and grain size of the suspended sediments and the spectral characteristics of the remote sensor (i.e. number, width and location of the wavelength bands).

Test case : airborne hyperspectral data over the scheldt

Study Site

The Scheldt river finds it origin in northern France and flows through Belgium via Antwerp towards the North Sea. Our study site is restricted to a part of the Lower Sea Scheldt as illustrated in Figure 1. Although the open North Sea is about 60 km away from Antwerp, the Scheldt is an important shipping channel giving access to the vast port area of the city.

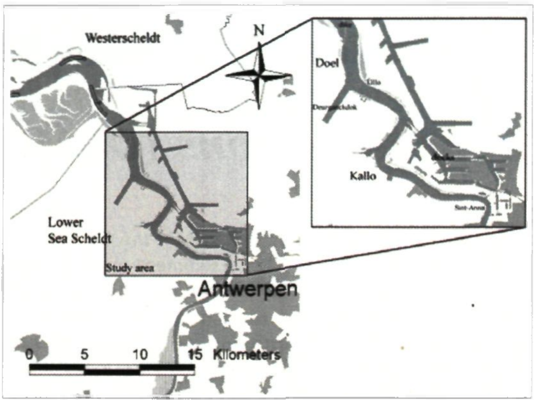

Figure 1: Study area.

The Scheldt is a complex river system where concentrations of suspended sediment are highly variable in place and time. The concentrations are in the range of a few hundreds mg/l [2]. At this location, the tidal range is more than 4 m.

Airborne and field data

On June 15th 2005 hyperspectral airborne data were collected with the AHS Advanced Hyperspectral Sensor (SenSytech Inc) at different stages of the tidal cycle. The data was collected in 80 spectral channels, covering the 0.430 µm to 12.70 µm electromagnetical wavelength range. Although weather forecasts were optimistic and the sky was clear at the beginning of the campaign, thin cirrus clouds covered the study area gradually. The remote sensing data were atmospherically and geometrically corrected.

Simultaneously with the aircraft overpasses, an extensive field survey took place. Two survey vessels were used at different stretches of the Lower Sea Scheldt to include some spatial variability. An extra vessel was deployed at the docks in the harbour of Antwerp. Several measurements were done on board of each vessel on predesignated locations at the time of airplane crossing over the study area. Four jetties served as additional fixed sampling locations. 150 surface water samples were collected and stored in 1 liter bottles to determine total suspended matter concentration. At one vessel in the Scheldt a turbidity sensor (Aanderaa RCM-9) continuously logged turbidity in the surface water layer. The location of the boats was continuously logged with a Trimble GeoXT GPS. Sun-photometric measurements were performed to estimate the aerosol content and water vapour in the atmosphere to calibrate the radiative transfer model used in the atmospheric correction. General atmospheric conditions were registered by taking photos of the sky at all the sampling locations of the boats.

Data processing

Field data processing

The TSM concentration was determined by filtering 250 ml of the water samples on pre-weighed 0.45 µm membrane filters. Filters were then dried and re-weighed. The measured TSM concentration in the Scheldt river and the docks ranged from 13 to 336mg/l and 7 to 12mg/l respectively.

To convert the continuous turbidity measurements in nephelometric turbidity units (NTUs) to TSM (measured in mg/l), the relationship between turbidity and TSM from water samples was statistically modeled for coincident points. A linear relationship was found with an R^2 of 0.83 and an RMSE of 35.2mg/l. This best-fit regression equation was then applied to all turbidity measurements.

Chlorophyll-a concentration was determined for six water samples following the ASTM D 3731-87 Standards [3]. The average CHL-a concentration was 4.4µg/l in the Scheldt river and 19.1µg/l in the docks.

TSM Algorithm

Reflectance spectra R(0-) were extracted from the hyperspectral images at the sampling locations. An average spectrum calculated from a 5 by 5 box of pixels (corresponding to an area of 20 m by 20m) was preferred to remove random noise. In the study area, the suspended matter concentrations and patterns change very rapidly as the tide fluctuates. The timing between airborne and in-situ sampling is therefore a critical issue. Hence, to calibrate as accurately as possible, only the samples taken within a few minutes of the airborne data recording were included. In total 41 samples were available to find a band combination which best predicts the TSM concentrations. The best fit with an R^2 of 0.83 and an RMSE of 15.53mg/l was found to be a log-linear line fit to a band difference:

$$\mathrm{Ln(SPM)} = 34.18*(R(0-,833)-R(0-,1004)) + 3.16 \quad (1)$$

where R(0-,833) and R(0-,1004) are respectively the reflectance at 833nm and 1004nm.
The algorithm (1) providing the best fit was then applied to all the AHS data to map TSM concentration at different tidal stages. To predict how well the algorithm will perform for the entire dataset a leave-one-out cross-validation (LOOCV) is applied.

The RMSE of the LOOCV for our log-linear line model was 17.06mg/l.

For more detailed information on the data processing the reader is referred to [4].

TSM maps

The produced TSM maps (Figure 2 and Figure 3) are in good agreement with the known distribution of the suspended sediment content over different tidal phases. Figure 2a, taken at high tide, shows – compared to the other figures – high surface silt concentration. These general high near-surface TSM concentrations are mainly explained by high current velocities at high tide. The high concentrations are spread out over the whole cross-section, similar to the velocity distribution pattern observed by [5]. In the entrance channel of Kallo where velocities are much lower, lower silt concentrations at the surface can be observed.

In the succeeding slack tide high water (Figure 2b) the observed TSM concentrations are much lower. At this stage velocities are very low, which results in much lower surface concentrations of TSM, due to the sinking of the sediment particles [2,6].

A resuspension of sediment takes place at the onset of the ebb flow stage, especially at the bend-related shoals (Figure 2c). During ebb (Figure 3a-c) downstream velocities are observed, i.e. the sediment concentration is higher downstream of the inside of curbs which are shallower areas. Eroded sediment at the shallow area is dragged in the downstream direction. The distribution and concentration of the sediments remain relatively constant during these 3 successive tidal stages (Fig. 3a-c). The horizontal cross-section variation in TSM matches the variation measured at previous field campaigns. Surface silt concentrations are higher at the right bank than at the left bank [7]. A striking feature of sediment plume at this stage of the tide is observed at the Doel flow guidance dam, which emerges at low water. The submerged flow guidance dike clearly separates high silt concentrations west of the dike from low silt concentrations east of the dike. This dike is the border between a shallow area (resulting in high sediment concentrations at the surface) west and the navigation channel eastward.

Another known feature, well present in all the produced maps, is the low-TSM concentration in the harbour docks. Some sediment enters the docks near the access locks during sluicing operations. This sediment settles in the adjacent harbour dock. To verify these conclusions extra validation will be performed using a series of turbidity measurements along horizontal cross-section transects made by IMDC in the past at different stages of the tidal cycle.

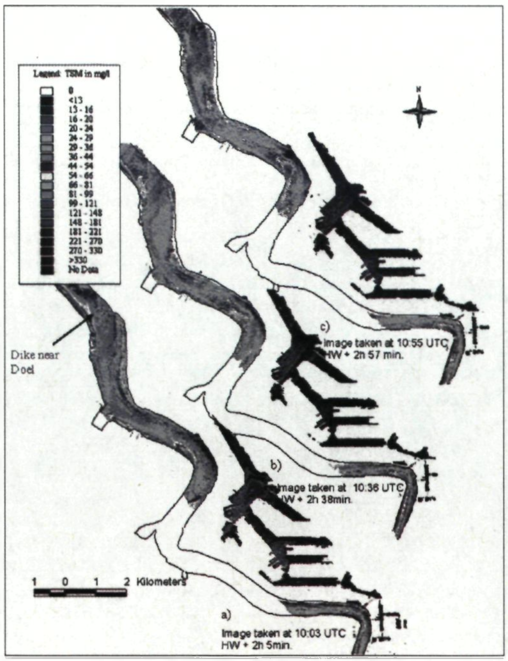

Figure 3: TSM maps for the Scheldt at 10:03, 10:36 and 10:55 UTC.

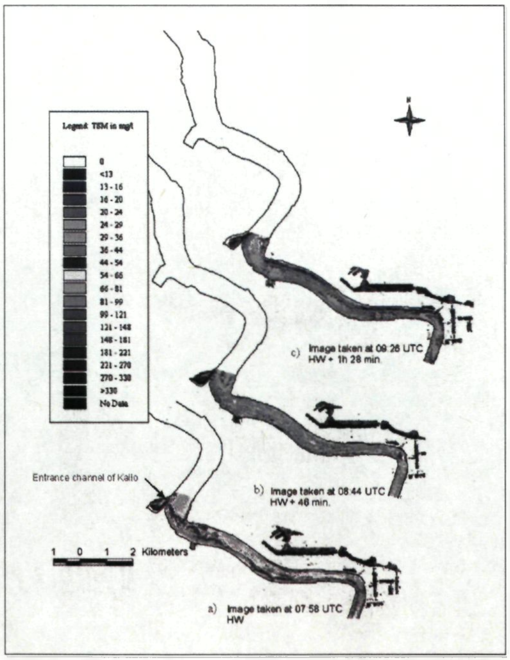

Figure 2: TSM maps for the Scheldt at 07:58, 08:44 and 09:26 UTC.

Conclusion

A calibrated regression model, that relates remote sensing reflectance data with field measurements of suspended sediment concentration, was applied to airborne remote sensing data. This procedure provided a detailed and synoptic overview of the suspended sediment fluxes and concentrations in the Lower Sea Scheldt near Antwerp at different stages of the tidal cycle. Even without calibration on the basis of in-situ data, remote sensing data complements traditional data collection techniques as satellite and airborne data can easily indicate the spatial pattern of suspended sediments which is not possible trough traditional measurement campaign. Remote sensing can provide high temporal coverage which is almost impossible by other existing techniques. However remote sensing will not fully replace the traditional field surveys as the measuring range is limited to the top few feet of the water column, especially in turbid waters [8] and cloud cover may obscure remote sensing data. Ideally, different techniques, i.e. limited field survey combined with remote sensing data and sediment transport models, should be deployed simultaneously as they complement each other.

Acknowledgments

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Imaging spectroscopy and Integrated Coastal Zone Management, a promising marriage

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Abstract

This paper provides an overview of the coastal and marine applications which make use of Imaging Spectroscopy (IS), recently under development in Vito. It should be considered as a concise overview rather than an in depth presentation of one application or development. The first two applications focus on sediment mapping; firstly, a classification of sediment habitat types of the Molenplaat, a tidal sand bank in the Westerschelde, is presented. By means of feature selection and a supervised binary classification approach the sediment is classified according to its grain size, moisture content, organic matter content and chlorophyll a concentration. The second application uses airborne IS to classify the different sand types present along the Belgian coast, in combination with airborne laserscanning to derive accurate erosion maps. The combination of both data products results in a method which proves to be very suited to monitor the sand transport processes along the Belgian coast. Afterwards two aquatic applications are presented; in the first, coral reef communities in Indonesia are classified. Extensive field work served to collect a spectral library which is used to classify the coral reef communities as detailed and accurately as possible. The second aquatic application addresses the difficult challenge of quantifying the amount of suspended sediment and chlorophyll-a in water and rivers; this is performed by inversion of a bio-optical model using a set of Specific Inherent Optical Properties (SIOP's) measured in-situ. Many marine applications ask for some specific processing steps which are inherent to the aquatic environment. Therefore the last study in this overview focuses on the atmospheric correction above water bodies. Due to the high absorption and transmission of water bodies

the reflected radiation level is low compared to land. To extract this small signal from a much greater base of other radiance a very accurate atmospheric correction algorithm is required. Therefore a specific atmospheric correction algorithm, WATCOR, has been developed to account for the marine atmospheric conditions as well as for the air-water interface.

1 Introduction

Imaging spectroscopy is an innovative remote sensing technique which can be defined as the acquisition of images in hundreds of registered, contiguous spectral bands such that for each picture element of an image it is possible to derive a complete reflectance spectrum (GOETZ, 1992). The high spatial and spectral resolution of imaging spectrometers offer the opportunity to study the Earth's surface in more detail than conventional multispectral remote sensing techniques offer. This paper focuses on the applications of imaging spectroscopy in coastal areas. The economic and social importance of the coastal zone as well as the challenges for the application of remote sensing in these areas are described by CRACKNELL (1999). The paper should not be considered as an in-depth presentation of one particular study but rather as an overview of a few applications of imaging spectroscopy in coastal zone studies. The first two applications focus on the mapping of sediments: in the first one sandy beaches are classified according to different sand types and the sand transport is quantified, while in the second application a tidal sand bank is classified according to its grain size, moisture content, organic matter content and chlorophyll a concentration. Afterwards two aquatic applications are presented: in the first, coral reef communities in Indonesia are classified while the second deals with the quantification of the amount of suspended sediment and chlorophyll-a in water and rivers. The last chapter is reserved for the atmospheric correction over water bodies; this is a methodological application which is needed in the processing of hyperspectral data for aquatic applications.

2 Applications

2.1 Mapping of sediment habitat types on the Molenplaat (Westerschelde)

2.1.1 Introduction

The Westerschelde estuary is home for one of the largest wading bird populations in western Europe. Several rare habitat types such as freshwater tidal marshes make the Schelde estuary a site of international recognition and importance for nature. But the estuary is also a site of heavy industry, and it is an important commercial shipping transport route. Coastal zone managers must constantly balance the demands of many conflicting interest groups when making planning decisions which affect this complex system. Decision making can be improved if better knowledge of ecological processes is available. Many of the most important bio-geochemical processes occur on the large areas of soft sediments which are exposed at low tide. This study focuses on the use of imaging spectroscopy for the mapping of sediment habitat types in these areas. A supervised binary classification approach based on feature selection and linear discriminant analysis is adopted to classify the median grain size, the moisture content, the total organic matter content and the chlorophyll-a concentration.

The detailed description of this research can be found in DERONDE *et al.*, submitted.

2.1.2 Results

In this paper the results of the classification of the median grain size are presented. Table 1 lists the overall accuracies, after classification of the training samples, for each optimal band set. It can be seen that the accuracy rises in an pseudo-asymptotic way when selecting more bands, i.e. when only one band can be used, the highest possible accuracy is 63% (when using the most suited band), in case of two bands 79 % etc. Using more than 4 bands does not result in higher accuracies.

Table 1: Classification accuracies of the median grain size for different band sets.

# of bands	Overall accuracy
1	63%
2	79%
3	84%
4	86%
5	86%
6	86%

A feature selection algorithm served to define the bands which are most suited to classify the sandy sediments according to its median grain size. It was found that the bands in the VNIR range led to the highest classification accuracies. Especially wavelengths 466, 497, 558, 619, 665, 846, and 862 were often selected for classification. The classification of the image was performed with four bands. The classified map is shown in Figure 1. The yellow zones indicate areas with (mostly fine) sand (125 – 250 μm). This fraction is found in a large area in the middle of the plate and on the south-western part of the plate which is quite elevated (indicated as regions I and II). In the eastern part it is found in combination with the loamy sand class. Note the mega-ripples in this part of the scene (III); the top of the ripples is characterized by sand while loamy sand occurs in the valleys. The yellow class is also found in the bed of small run-off channels in the north of the scene (IV), while finer classes occur around the channels. This can easily be explained by the higher current velocities and shear stress within the run-off channels. The finest class, clayey loam, is found in the large central part of the scene and in an area in the west (V en VI). Another remarkable feature on the classified image is the difference between the eastern and western part of the Molenplaat. The black dashed line indicates the border between both entities. The sedimentological differences make it likely that the actual Molenplaat originated from two separate banks. This assumption is strengthened by the fact that recent shipping maps refer to the Brouwersplaat for the western part and to the Molenplaat for the eastern part of the actual Molenplaat. The historical maps of the hydrographical unit of the harbour of Antwerp show clearly that between 1930 and 1935 the old Molenplaat and the Brouwersplaat merged into the actual Molenplaat, although at that time there was still a tidal gully between both plates. In the forties the gully disappeared and both plates were joined. It is an interesting conclusion that remote sensing images show signs of this history.

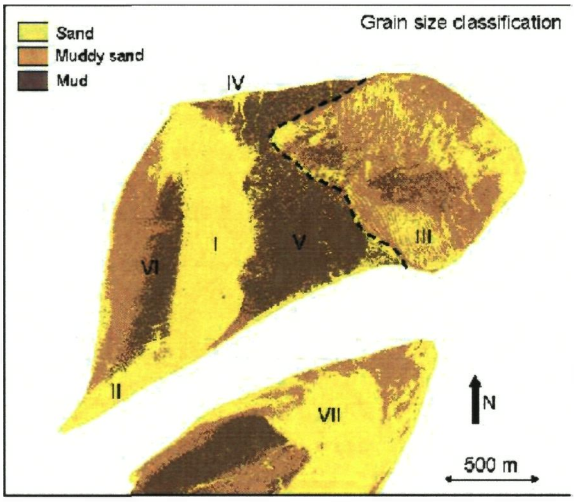

Figure 1: Classified image of the Molenplaat indicating three grain size classes: sand, loamy sand and clayey loam.

Similar analyses were performed for the three other parameters studied. As little as 3 to 5 bands were required to classify each of these parameters with the highest possible accuracy. The bands were most often selected in the VNIR part of the spectrum. The SWIR bands were barely used in the classifications what implies that for this application it is probably sufficient to use a more common VNIR sensor. The overall accuracy is highest for the total organic matter content (87%) and the median grain size (86%). The moisture content and the Chlorophyll-a content score somewhat lower with 81% and 80% respectively.

2.2 Monitoring of sand transport processes along the Belgian coast

2.2.1 Introduction

The Belgian Coast stretches for about 65 km between De Panne in the Southwest and Knokke-Heist in the Northeast. From a geological point of view, this coastline is part of the 'Flemish coastal plain', a depositional system at the southern edge of the North Sea Basin which is commonly known as the Southern Bight. Since the beach is of major economic importance to Belgium and since it is part of the natural defense protecting the polders against flooding, it is very important to obtain a better understanding of the processes that control the beach. In the study presented airborne hyperspectral data and airborne LIDAR data have been used to study the sand transport processes controlling the morphology of the beach. The detailed description of this study can be found in DERONDE et al. (in press). In August 2000, August 2001 and October 2002 airborne hyperspectral data were acquired over the Belgian coast. All data were recorded with a CASI-2 sensor measuring the reflected sunlight in a 545 nm spectral range (410-955nm). A supervised SAM (Spectral Angle Mapper) algorithm was applied to classify the images.

Almost simultaneously to the hyperspectral campaigns, an airborne laserscanner was deployed. The distance to the Earth's surface is determined by measuring the laser pulse return time. The position and attitude of the sensor is calculated from d-GPS and INS (Inertial Navigation System) data. In combination with the scan angle, the 3D position of each laser beam spot on the surface can be determined, resulting in DTMs with a vertical accuracy of 5cm. By subtracting the DTMs from consecutive years maps indicating the erosion/accretion zones could be extracted.

The combination of the erosion/accretion maps and the classifications derived from the hyperspectral data, generated a product which is well suited to follow up the sand transport processes which are responsible for the beach morphology.

2.2.2 Results

Figure 2 illustrates a classification of the beach near Zeebrugge; in the west the image is bounded by the pier of Blankenberge, in the east by the harbour of Zeebrugge. Eastward of the Pier of Blankenberge, a beach nourishment zone stands out. Between October 1998 and April 1999, nearly 500,000 m^3 of sea sand were put on the backshore. The sea sand is coarser grained than the original sand, contains a large amount of shells and even some gravel. Because of its different composition, it can spectrally be distinguished from other types of sand what implies that, in this case, IS is very suited to follow up the soft defense structures along the Belgian coast. In total 8 sand classes were distinguished.

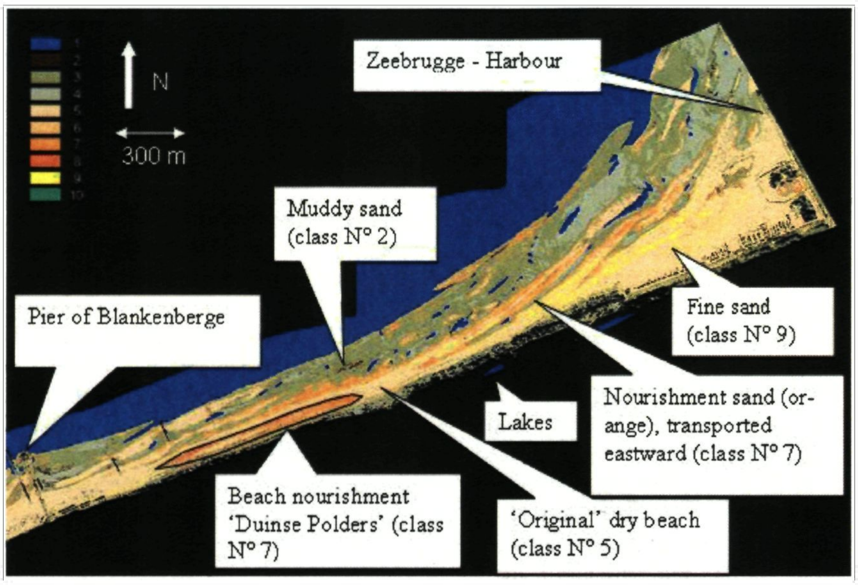

Figure 2: Classified image (2000 survey) of the beach between Blankenberge and Zeebrugge. Eight different sand types could be distinguished (labelled 2 – 9 in the legend; class 1 is water and class 10 is vegetation).

The classified sand maps were combined with the erosion/accretion maps. This resulted in a product that indicates the amount of erosion or accretion between two surveys, as well as a possible change in type of sand at the surface during that period. The classified sand map helps explaining the erosion/accretion maps, i.e. the classes serve as tracer. Figure 3 illustrates the sand dynamics map for the Knokke-Zoute area. Between March and May 1999 a beach nourishment with sea sand was performed from section 233 till section 243. On the seaward side of the nourishment area there is an important erosion zone of 31,800 m³ (area 17); the mean height difference here is -49 cm. However, the type of sand remains the same which means that the erosion is still limited to the nourished volume. In area 16 class 7 is replaced by class 5 indicating that the erosion reached the underlying sand type. In area 18 a small erosion strip replaced class 7 by class 3 and 4; these are typical sand types of the wet beach which means that there is probably a landward regression of the nourishment area.

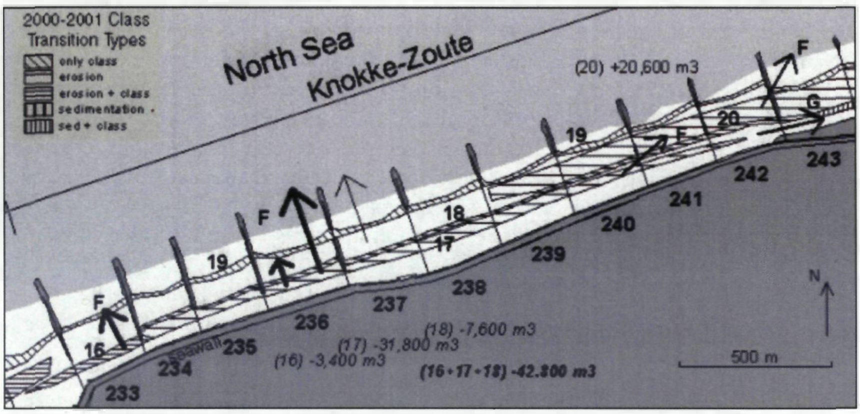

Figure 3: Schematical representation of the sand transport directions and volumes between 2000 and 2001 in Knokke-Zoute. The thickness of the arrows is an indication of the amount of sand transported: thick arrows indicate more sand transport than fine arrows. ('erosion' = erosion without class change, 'sedimentation' = sedimentation without class change, 'erosion + class' = erosion and change in class, 'sedimentation + class' = sedimentation and change in class, 'only class' = change in class but no erosion or sedimentation)

Similar analyses and maps have been made for the entire Belgian coast. They lead to more insight in the sand transport processes controlling the beach.

2.3 Coral reef monitoring in Fordate, Tanimbar (Indonesia)

2.3.1 Introduction

Coral reefs are considered to be one of the most spectacular marine ecosystems on earth displaying an extremely rich biodiversity. They also represent valuable socio-economic resources. Despite this natural wealth and socio-economic significance, many threats are posing stress on coral reefs. According to BRYANT et al. (1988) 58% of the coral reefs in the world are potentially endangered by devastating human activities. The most important worldwide threats generated by human activities are pollution, sedimentation and unsustainable fishing activities (BRYANT et al., 1988, SPALDING et al., 2001). Current coral reef monitoring techniques range from underwater transect monitoring to remote sensing data analysis (BRYANT et al., 1988). Remote sensing data offer the opportunity to gather information over vaster areas compared to traditional 'on-the-spot' survey methods where only limited spatially distributed information can be collected. Remote sensing makes it also possible to follow up the situation in a multi-temporal manner. In this way remotely sensed observations can help to monitor changes in coral reefs and to differentiate between anthropogenic and natural effects on coral reef health

(KUTSER et al., 2003). Most satellite data are well suited for coarse-level mapping of the geomorphology and bottom-type composition of the reefs. However, today, they are often lacking the spatial and/or the spectral resolution which is required to create detailed bottom-type maps and to detect and monitor the health status and vitality of coral reefs. Hyperspectral airborne sensors, on the other hand, have a high potential for not only mapping small coral reef ecosystems but also for identifying areas with bleached or stressed corals. KUTSER et al. (2003) recognise three main advantages of hyperspectral sensors: they possess a large number of narrowband channels capable of discriminating bottom-types in more detail (MUMBY and EDWARDS, 2002), their large number of bands increase the capacity to unmix spectral signatures (HEDLEY and MUMBY, 2003), and they can also distinguish bottom-types in deeper waters.

A feasibility study on Fordate, a small island to the Northeast of Tanimbar archipelago (South-East Moluccas, Eastern Indonesia), was undertaken to assess and verify the technical feasibility of a future-generation, spaceborne hyperspectral sensor. This preliminary study was based on the analysis and interpretation of experimental CHRIS/PROBA satellite imagery. A short overview of the results of this preliminary study is discussed below, more details can be found in BERTELS et al., 2006.

2.3.2 Results

A CHRIS/PROBA dataset was acquired over Fordate on 27 January 2004. The CHRIS instrument was programmed in its mode 2 (optimized for water applications), which contains 18 spectral bands and a full spatial resolution of 20 m at nadir. The atmospheric correction was performed with the in-house software WATCOR (See Chapter 2.5). Since no actual field survey has been undertaken, the classification was based on image inherent information. Both spectral and spatial image information was used to select the endmembers automatically. After the endmember selection, all image pixels were compared to the endmembers using a Spectral Angle Mapper (SAM) procedure. SAM computes a spectral angle between each pixel spectrum and each endmember spectrum. The smaller the spectral angle, the more similarity between the pixel and target spectra is assumed. In this way a map of the bottom-types was created using the CHRIS/PROBA data. The result of the classification is shown in Figure 4. An attempt was made to assign names to the endmember classes. As no ground-truth information was available, this was based on the visual examination of the endmember reflectance spectra and a priori knowledge of the reef geomorphology. More detailed, supervised classifications, achieved after a water-column correction, will be produced in an ongoing research project (BERTELS et al., 2006).

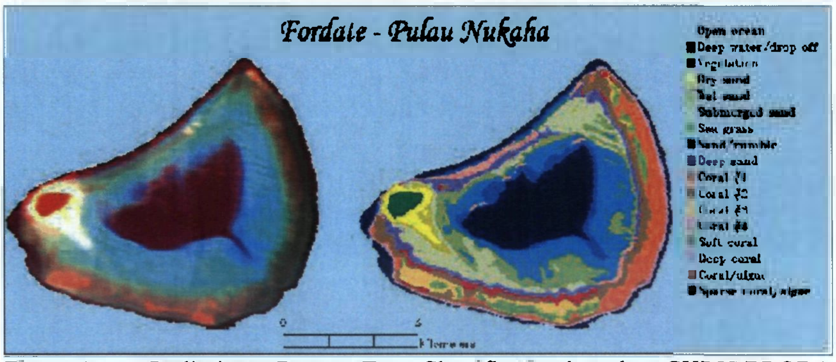

Figure 4: Preliminary Bottom-Type Classification based on CHRIS/PROBA Data over Pulau Nukaha, Fordate.

2.4 Water quality monitoring

2.4.1 Introduction

There exists a high interest in chlorophyll (CHL) and suspended particulate matter (SPM) maps of the Belgian coastal and estuarine waters. In the framework of the Oslo and Paris Commissions for the prevention of marine pollution (OSPARCOM) Belgium has to classify their coastal waters according to their eutrophication status. The eutrophication problems of the coastal waters results from an augmentation of anthropogenic nutrient inputs via the main rivers, the Atlantic waters and regional atmospheric deposition. Furthermore sustainable dredging is required to keep the ports of Zeebrugge and Antwerp accessible for large ships. The large quantities of dredged material is often dumped back into the sea. Besides the economic costs, dredging and dumping of dredged material can cause serious environmental problems. To optimize the dredging operations knowledge of the suspended sediment concentration is required.

Water quality monitoring using hyperspectral airborne data is carried out by VITO in the framework of two projects: ORMES and BELCOLOUR. In ORMES a methodology is being developed to derive suspended sediment concentrations from the images; it will be robust, relatively insensitive to the sediment characteristics and applicable with a minimum of ground truth/calibration points. The BELCOLOUR project (http://www.mumm.ac.be/BELCOLOUR) brings together three Belgian teams (ULB,MUMM and VITO) to improve the theoretical basis and the software tools for applications of suspended particulate matter and chlorophyll products from remote sensing data of coastal waters.

In this paper we briefly look at the first results obtained in the ORMES project. In the framework of this project an AHS-160 hyperspectral airborne campaign took place over a test site following the Scheldt river in Belgium on the 15th of June 2005. Simultaneously to the airborne overpasses water samples were collected and field measurements of water leaving reflectance and turbidity were made.

2.4.2 Results

The retrieval of suspended sediment concentrations from the AHS data was tested on the in situ reflectance measurements, resampled to the AHS bands using different empirical algorithms from the literature. The highest correlation coefficient between measured and calculated SPM concentrations (0.78) was obtained using the SPM algorithm of Matthews et al. (2001). This algorithm was used to obtain a first suspended sediment map of the Scheldt test site. Figures 5 and 6 show the preliminary results for an image taken at 08:44 UTC time and 11:13 UTC time respectively. On the day of the flight, the highest water level was measured at 08:58h UTC time. Hence, the image was taken close to the tidal maximum what explains the low current speed and the low concentrations of suspended sediment, as can be seen in figure 5. At 11.13h (Figure 6), the concentrations are clearly higher because the outgoing tide causes much higher current speeds. Note also that the highest sediment concentrations are found along the erosive outer banks of the river; lower concentrations can generally be found in the middle of the stream and at the sedimentary inner banks. The eroded material is taken in suspension and transported downstream. These processes are clearly visible in Figure 6.

The next goal is to modify the existing algorithms by using the image spectra instead of the in situ reflectance measurements. Linear and logarithmic relationships between in-situ SPM/turbidity and image reflectance will be tested and a hydro-optical model will be calibrated for this specific location.

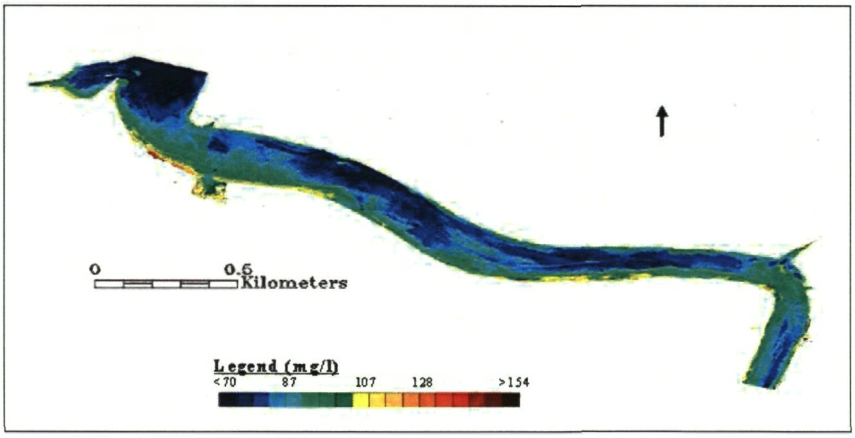

Figure 5: SPM concentrations (mg/l) in the river Scheldt - 08:44h (UTC)

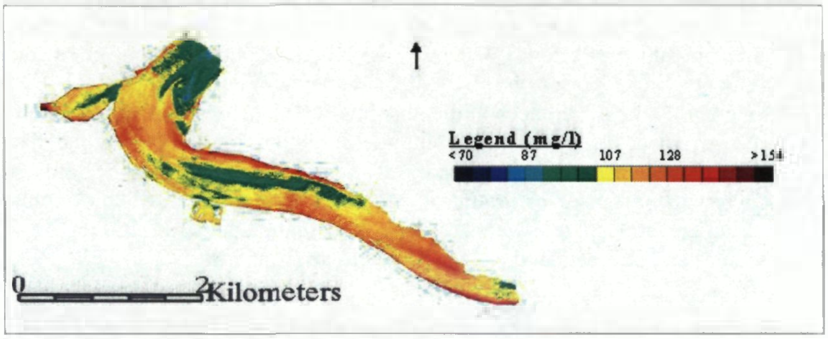

Figure 6: SPM concentrations (mg/l) in the river Scheldt - 11:13h (UTC)

2.5 Atmospheric and air-interface correction above water bodies

2.5.1 Introduction

Atmospheric correction is essential for adequate extraction of water quality information from remotely sensed data. The effect of scattering and absorption by the atmosphere can be substantial. Due to the high absorption and transmission of water bodies the reflected radiation level is low compared to land. To extract this small signal from the other radiance components such as path radiance, a very accurate atmospheric correction algorithm is required. Therefore a specific atmospheric correction, WATCOR, has been developed to account for the atmospheric conditions as well as the air-water interface (STERCKX and DEBRUYN, 2004).

2.5.2 Results

The WATCOR algorithm was applied to CASI data acquired from the North Sea in the framework of the BELCOLOUR project (see chapter 2.4). To estimate the visibility during the time the CASI data were acquired two different approaches were evaluated. In the first methodology the visibility was estimated using MODTRAN-4 radiative transfer simulation combined with the sun photometer aerosol optical depth measurements. This procedure is similar to the approach given in (KELLER, 2001) and is based on the fact that at 550 nm the aerosol optical depth is independent of the aerosol type and atmospheric model but only varies with the visibility. The second method is an adapted dark target approach and assumes that there is a pixel in the deeper water regions for which the water-leaving radiance is negligible in the near-infrared. Detailed information can be found in STERCKX and DEBRUYN (2004). The first approach resulted in an average visibility of +/- 20 km. The average visibility derived with the adapted dark target approach was a bit lower +/- 18.8 km. Based on these results it was decided to set the visibility to 20 km for the correction of all the flight lines. The results are in close agreement with the visibility (20 km) reported by the airport of Ostend.

Figure 6 shows the result of the atmospheric correction. In the green, red and NIR parts of the spectrum a good correspondence between the corrected airborne data and in-situ reflectance spectra is obtained. Seaborne reflectance measurements were performed by MUMM using TRIOS and SIMBADA spectrometers. Some differences in the absolute reflectance values can be due to the time difference between the in-situ measurements and the airborne data acquisition. Possible causes of the larger reflectance difference below 500 nm are inaccuracies in the sensor calibration (spectral calibration error visible around 430nm), in the atmospheric aerosol characterization (standard MODTRAN-4 models used) and/or errors in the skyglint due to sea roughness.

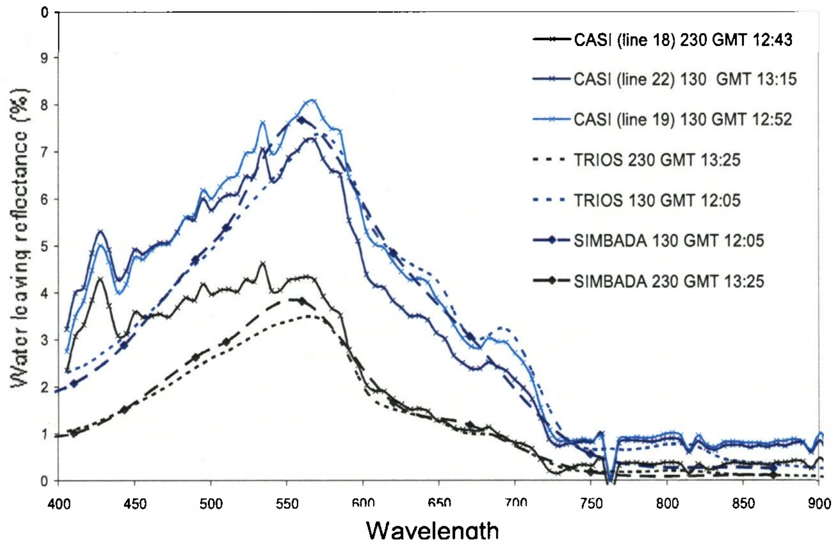

Figure 7: Comparison of water-leaving reflectance from CASI images, after the WATCOR correction, with in-situ measured spectra (130 and 230 are two measurement points).

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