Mapping of intertidal surface sediments using high resolution remote sensing (A study in the Westerscheldt Area, the Netherlands)

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ABSTRACT

The estuary of the Westerscheldt, the test area for the study discussed in this paper, is a dynamical tidal area. To maintain and control this unique delta area in the south-western part of the Netherlands amongst others regular information about sediment composition and distribution is needed. The conventional method of mapping the intertidal surface sediments involves extensive point sampling of particle size distribution on a regular spatial grid with cells in the order of 500x500 meters and interpolation.

The suitability of high spectral resolution remote sensing to map and monitor the spatial distribution of sediment types in intertidal areas was investigated. In the field a set of sediment samples was gathered at selected locations to determine the grain size distribution and high resolution field spectrometry was used to determine the spectral characteristics of the sediment at the sample positions. A Landsat TM image was included in the analysis. Furthermore data of the airborne imaging spectrometer CASI were collected. So spectral data were available on three different altitude and scale levels and with three different spectral resolutions.

The field spectra were used to investigate possibilities for differentiation of sediment types. Multivariate regression analysis and maximum likelihood classification were used to map the sediment distribution on the basis of remote sensing information.

It was concluded that real quantitative mapping of sediment type distribution with optical remote sensing is hampered by the fact that spectra of sediments with different compositions only show minor differences, while the influence of water content on colour is rather dramatic in the spectral range between 400 and 900 nm. Sediment type distribution can however be mapped in a qualitative way. Subdivision of an image in a number of sediment type classes can be done and offers a very helpful tool for management and research purposes.

A sediment classification based on a Landsat TM image offers a synoptic view and helps to get an insight in the sediment distribution of a certain area at a certain time. An airborne instrument is recommended for mapping and monitoring of sediment distribution in intertidal areas because of favourable spatial resolution, flexible band-setting possibilities and the fact that it can be flown whenever weather circumstances are favourable.

1. INTRODUCTION

Remote sensing (both from satellite and from aircraft) allows qualitative and quantitative information on the Earth's surface to be evaluated over wide zones. Remote sensing data can be of tremendous importance as one of the tools for monitoring processes on the earth's surface. The project described here was executed in the Westerscheldt area.

The estuary of the Scheldt in the south-westerly part of the Netherlands forms a natural transition from fresh water via brackish towards salt water with in all zones vegetated salt marshes, muddy and sandy flats and shallow water, all of them areas with great potentials for plants and animals. Accumulation and displacement of (fine) sediments are influenced by a number of factors. Besides hydraulic forces (tides and waves) and the availability of sediments, for instance salt marsh vegetation stimulates accumulation of fine sediments whereas diatoms increase critical erosion and enhance sedimentation of tidal flats. Human activities like dredging and dumping are important factors too.

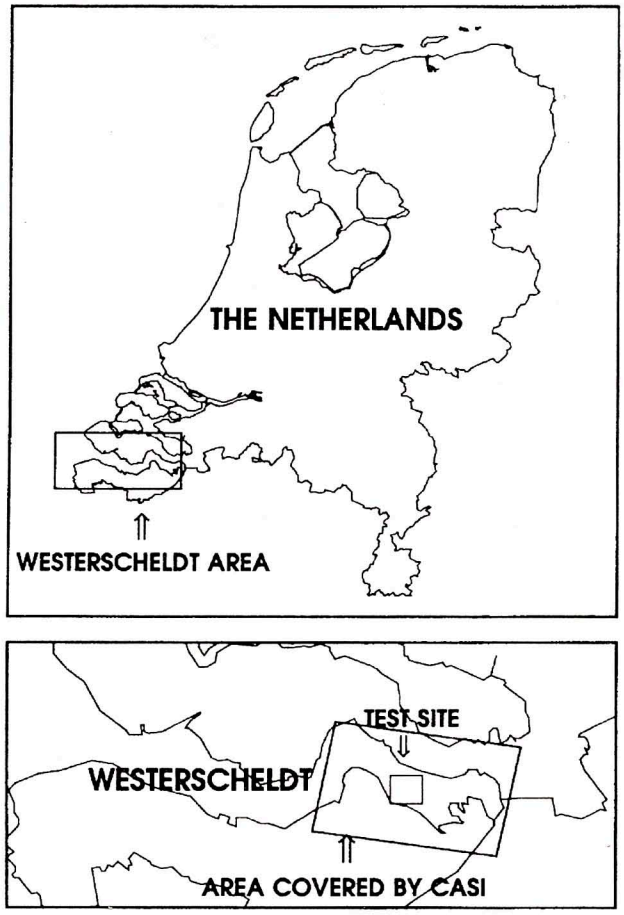


Figure 1 - The Westerscheldt area; test site indicated

The basin of the Westerscheldt has been widened by sand mining and dredging activities. Constant dredging has been necessary to maintain the economically important fairway to Antwerp. But also the ecological values of the area have to be preserved. The salt marshes in the brackish-water tidal area present unique ecological values. Dredging activities in the vicinity disturb the natural equilibrium and are a menace to this vulnerable region. Research results indicate that largely the same measures will have to be taken to achieve both a decrease of dredging activities and a restoration of ecological values. By taking appropriate dredging and dumping measures and by dereclamation a durable solution can be achieved.

To develop the best suited policy and to check results of measurements amongst others regular spatial information on sediment grain size composition and distribution is needed. Airborne and maybe space borne imaging spectroscopy could be a useful tool for perceiving this information.

The study reported here focuses on spectral discrimination of different sediment types as characterized by their grain size distribution. The selected flat for the study, Plaat van Walsoorden, is the highest one in the area with maximum (low tide) dimensions of 4x1.5 km and is indicated by the small rectangle in **Fig. 1** (approximate location 4°,07' E, 52°,23' N). It is mainly flat and exhibits parts that are predominantly sandy and others with a relatively large clay and mud content.

A data set was collected in the area around this test site, including both sediment grain size distribution data and spectral data, recorded at different altitude levels. Field spectrometer data and multispectral airborne and satellite imagery, almost simultaneously acquired.

2. THE AVAILABLE DATASETS

2.1 Field data

The field experiment on the Plaat van Walsoorden took place on 7 September 1993, a clear day, at least in the region of the test site, and also a day of Landsat 5 passage (track 199, scene 24). From 11.00 AM untill 15.00 PM spectral measurements of sediment samples were collected. On each sample location 5 reflectance measurements were averaged to give a spectral reflectance signature of that particular sample.

All samples were analyzed to give grain size composition as well.

2.1.1 Grain size distributions

23 samples were taken from the top 5 cm of the sediment, which were subsequently processed on a Malvern 2600 L laser particle size analyser using a standard technique developed by GeoSea Consulting. The instrument measures the diffraction pattern caused by sediment particles, suspended in water, being continually passed throug a laser beam. It uses lenses of different focal lengths to measure the concentration of particles. Three distributions are measured at each sample and the results averaged. Besides a size distribution also percentages of gravel (grainsize >.25 mm), sand (0.063-0.25 mm), silt (0.02-0.063 mm) and clay (< 0.02 mm) in each sample have been calculated and reported. None of the samples in this experiment contained gravel. Knowledge of the mud fraction (= silt + clay -> grainsize < 0.063 mm) is important because of the fact that mainly the fine sediment fraction is the carrier of contaminants.

2.1.2 PSII field spectrometer measurements

Reflectance spectra of all sediment samples were measured with the PSII field spectrometer. These were obtained by repetitive scanning of the target (the sediment surface) and a Lambertian reflecting reference panel. The reflectance in each channel of the PSII were calculated by ratioing these two measurements.

The field spectrometer used (PSII) is a plasma-coupled photodiode array with 512 elements and a contiguous nominal spectral range from 350 to 1050 nm with 1.4 nm dispersion and 4 nm spectral resolution. Data acquisition, real time display and analysis are combined in a single portable unit. The total weight of spectrometer and computer is 7 pounds. Photons are captured with a 3 meter long fiber optic cable with an acceptance angle of appr. 20° (10 and 5°). The instrument, ideal for field work, is capable to detect rather small absorption features within its spectral range. The PSII can also be used for simulation of present and future sensors, for modelling and calibration as well as for feasibility studies. By virtue of the capability to sum a number of adjacent channels one can simulate bands of existing or future sensors. Following this strategy e.g. best suited bands of a remote sensor for a certain goal can be defined and selected.

2.2 Imaging Spectroscopy data, acquired with CASI

The Compact Airborne Spectrographic Imager (CASI, see Babey and Anger, 1993) is a pushbroom imager with 288 spectral channels with 1.8 nm dispersion and bandwiths of 2.5 nm. The particular instrument we used has a spectral range from 380-891 nm. In the *casi* a 578x288 pixel CCD is used, resulting in an availability of up to 578 spatial bands.

The CASI offers the possibility to sum bands of adjacent channels and is thus capable to detect specific spectral features of the viewed target. The field of view of the CASI is 35.4° (swath) x 0.069° (along track).

Because of the rather short time span between the field sampling experiment (September 7) and the CASI flight we were not able to perform an extensive analysis on the spectral sediment data, as measured with the PSII and to define best suited CASI channels. In our experiment the data were acquired while flying in a twin engine Piper Navajo Chieftain at an altitude of 10,500 ft with an average ground speed of 100 knots. The CASI operated in spectral mode with a number of 12 bands programmed, resulting in pixels of appr. 4x4 m^2. A number of 12 contiguous bands with wavelength specifications as in **Tab. I** turned out to be the optimal choice with respect to boundary conditions (e.g. reasonable signal to noise ratios) and taking into account that an increase in the number of bands implicates an increase in the along track size of the pixels (because of a longer total integration time of the system). The full spectra, as measured by the PSII, can be well characterized using those bands, simulation of the first four bands of Landsat TM is also possible.

Table I - *casi* bandsettings for the sediment study

	casi SETTINGS 20/9/93	
BAND	**WAVELENGTH**	**BANDWIDTH**
1	420	80
2	485	50
3	525	30
4	555	30
5	585	30
6	610	20
7	630	20
8	650	20
9	680	40
10	720	40
11	760	40
12	815	70

21 CASI-tracks were flown, covering roughly the same area as the sediment sampling programme in the easterly part of Westerscheldt basin (as indicated by the larger rectangle in the lower part of **Fig. 1**). Sensor attitude and position were measured with a vertical gyroscope and a Global Positioning System (GPS). Roll, pitch and differential GPS data were collected. Even with the absence of a heading sensor the overall geocorrection is good when using dedicated software (Cosandier et al., 1992). The final conversion to UTM (Universe Transverse Mercator) was performed using ground control points and standard software available at the Survey Department.

2.3 Landsat TM

On the day of the field experiment, September 7 1993, Landsat TM passed over the area of interest. Although the image showed many cloudy areas, the part containing the Westerscheldt area appeared to be cloudless. Therefore also Landsat 5 Thematic Mapper data of track 199, scene 24, were included in the analysis.

2.4 Data used in the analysis

The analysis so far comprised only those data which covered the area of the Plaat van Walsoorden. Grain size distribution data and field spectrometer data of 23 locations on the flat were used.

Three adjacent CASI tracks covering the whole of the Plaat van Walsoorden were used; after geometric correction of the data (pixel size 4x4 m) the area of the sediment test site was mozaiced from those three tracks. This mozaïced image was subsequently analyzed.

Also the part of the Landsat TM image covering the test site was included in the analysis.

3. METHODS AND RESULTS

The CASI and Landsat imagery was used to map the finer sediment fraction (clay and silt), this fraction being the main carrier of contaminants. The dynamical range in the clay fraction turned out to be rather small (maximum in the samples used in the analysis ± 5.5%), whereas the dynamical range of the mud fraction (silt + clay) was much larger (maximum ± 55%). It is because of this fact that we have been concentrating on mapping of the mud content of the sediment when correlating sediment grain size with remote sensed radiance.

3.1 Analysis of the PSII spectral data

High spectral resolution data offer the possibility of analysis of narrow spectral features. Derivative reflectance spectroscopy is one of the techniques suited to do so. Phenomena like troughs, peaks and shoulders can be identified more precisely on the basis of derivative analysis. Chen et al. (1992) showed the applicability of derivative reflectance spectroscopy to estimate suspended sediment concentration. Results of Goodin et al. (1993) show that first order and second order derivative spectra can be used to discriminate between the effects of water, algal chlorophyll and suspended sediment. They indicate that spectral effects caused by water can be identified by taking the first derivative.

In **Fig. 2** two spectral measurements of the same sediment sample are presented. The upper curve is a measurement of the dry sediment, whilst the lower one is a measurement of the same sample with a 5 cm layer of water on top of it. The sample without water layer exhibits a monotonously increasing reflectance spectrum, which is the usual pattern for bare soils. There is a small trough evident around 680 nm, an absorption feature which is most probably related to the presence of algae colonies and the associated chlorophyll-a absorption. There were no measurements of algae or clorophyll per surface area. As can be seen from the figure, the presence of a small water layer (water plus possible constituents) influences the spectrum rather dramatically. This results in a 'darker' overall spectrum, a more pronounced through around 680 nm and the introduction of some additional (water) absorption features.

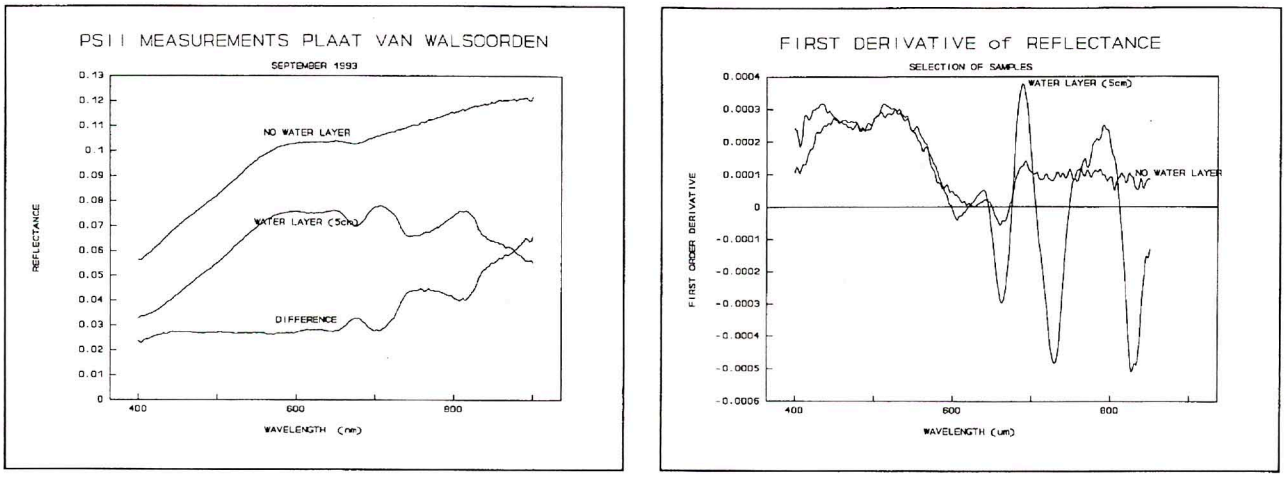


Figure 2 - The effect of a water layer on the reflectance of a sand sample from the test site
a. Reflectance spectra of sand with and without water layer + difference spectrum
b. First order derivative spectra

Some researchers identify distinct classes for dry and wet sediment (e.g. Yates et al, 1993), Hobbs and Shennan (1985) report that even then distinction between those classes can be cumbersome.

In **Fig. 3** reflectance spectra of 6 sediment samples are presented. The figure includes the spectra corresponding to the samples with minimum and maximum clay percentage. The spectral correlation of reflectance data with clay percentage is very poor (Pearson's correlation coefficient $|r| < 0.17$). This is partly caused by not taking into account the presence of water in the sediment samples.

First order derivative spectra were calculated of all the measured sediment reflectance curves, using a 5-point derivative calculation algorithm. The effect of using the derivative spectra for the analysis can be seen in **Fig. 4**. The spectral correlation of the first order derivatives with clay percentage of the associated sediment samples has improved (Pearson's correlation coefficient r amounts to -.62 for a wavelength of 627.5 nm.)

The precise nature of the througs and peaks in the sediment reflectance spectra should be further investigated. Of course the scattering and absorption properties of water are reflected in the spectra. Furthermore there is some evidence of the presence of algae, according to the apparent absorption maximum around 680 nm. Modelling experiments and maybe new measurements could clarify this issue.

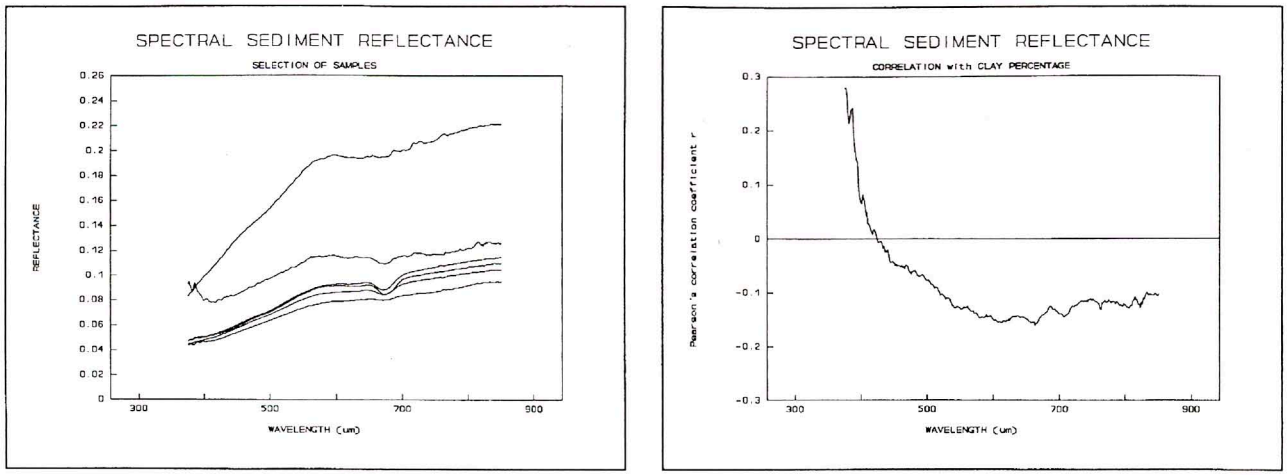


Figure 3 - Correlation of reflectance spectra with clay percentage.
a. Selection of reflectance spectra
b. Spectral correlation with clay percentage

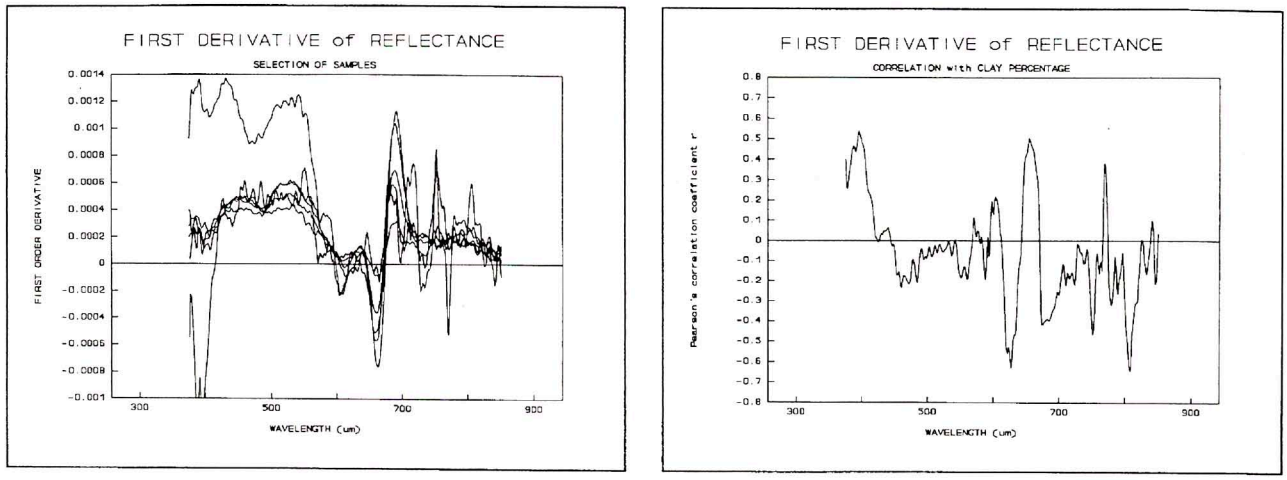


Figure 4 - Correlation of derivativ e spectra with clay percentage
a. Reflectance spectra of sand with and without water layer + difference spectrum
b. First order derivative spectra

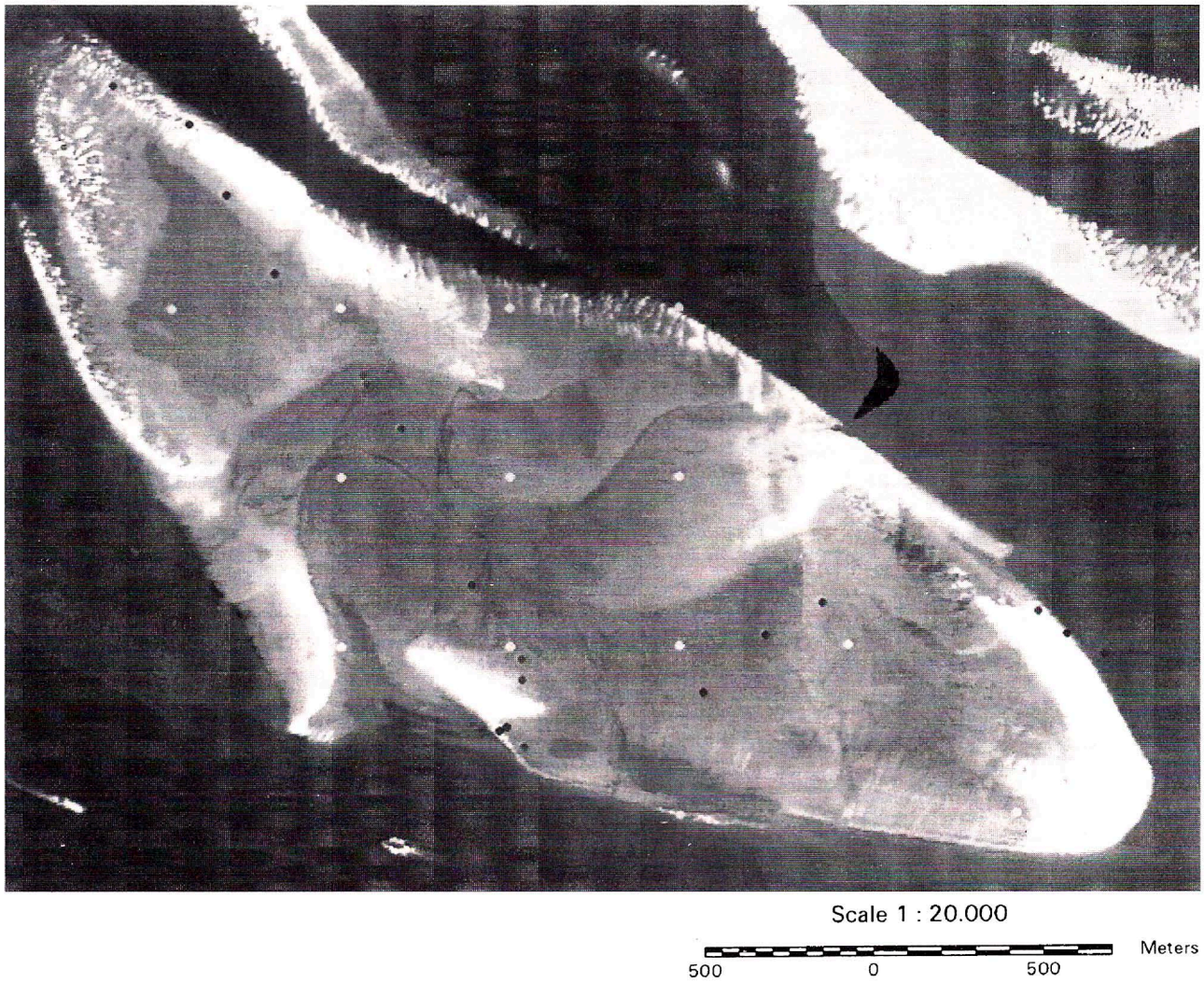


Figure 5 - Test area for the sediment mapping experiment: Plaat van Walsoorden
in red : sampling positions for grain size and spectral analysis
in yellow : sampling positions for grain size analysis on regular grid
true colour : R,G,B = 9,4,3

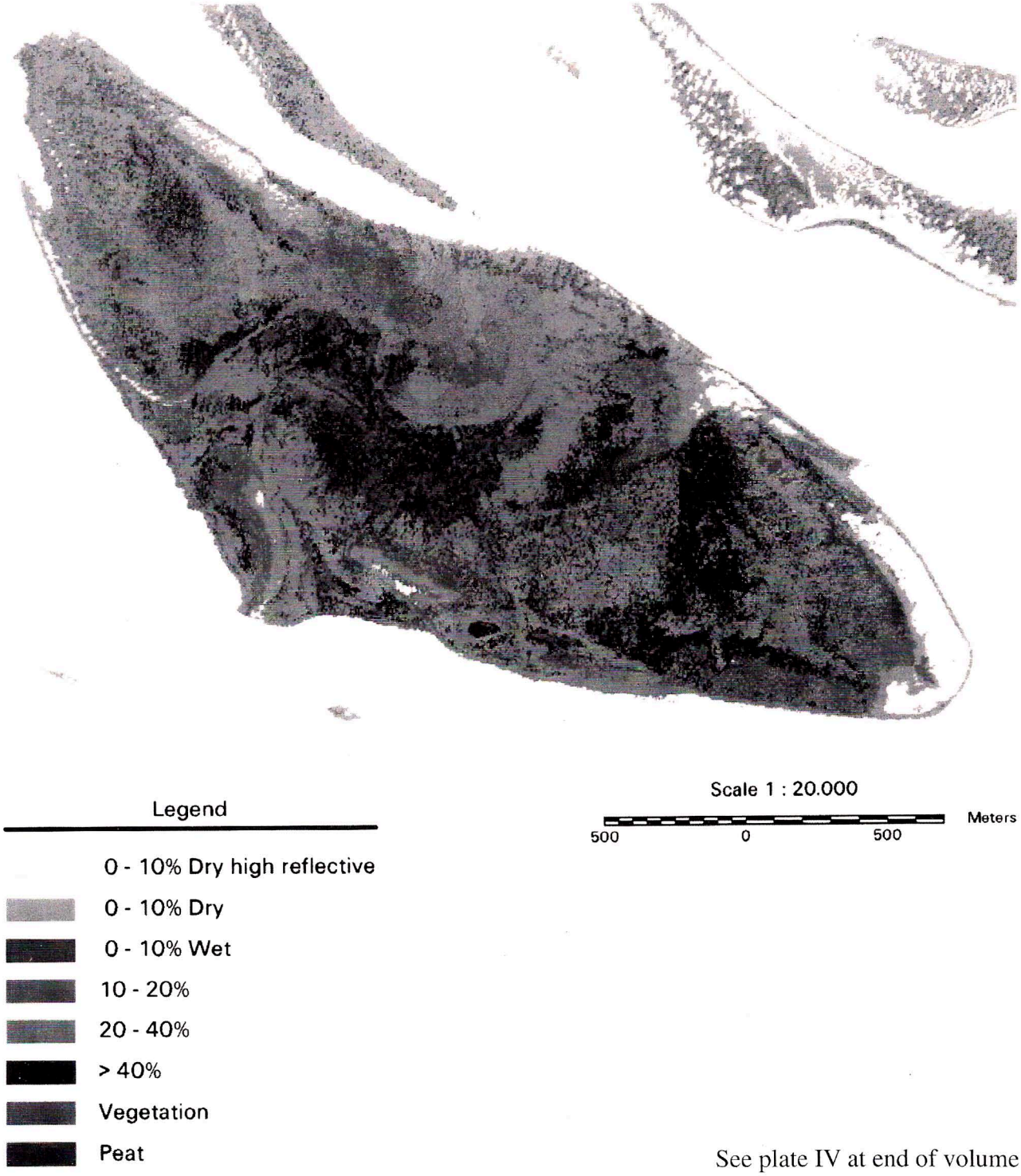
See plate III at end of volume

3.2 Classification of CASI data: Maximum Likelihood / Minimum Distance to Mean

Classification of remote sensing imagery is accomplished by selecting a classification scheme and combining it with image-interpretation techniques and field work. It is important to emphasize that the imagery is used to complement, improve, or reduce field work, rather than take its place.

Reference areas known to be of a certain sediment type were identified on the mozaiced CASI image of the test site. Those areas, indicated by red dots in the mozaïced image of **Figure 5** were located at and around the positions of the sample positions that were visited during the field campaign. For the Maximum Likelihood Classification (ML) a number of 8 classes was defined, based on particle size composition and the presence of vegetation and peat.

The mean and variance of the digital number values recorded in the imagery from pixels within the reference areas were used in the classification which was extrapolated to the whole test site. Data of another large-scale sample programme, not only covering the test sie but extending over the eastern part of the Westerscheldt and indicated by yellow dots in **Figure 5** were used for validation. By chec-



See plate IV at end of volume

Figure 6 - Maximum Likelihood Classification of the mozaiced CASI image, dirrerent colours representing different mud content classes

king how well the classification results of those points matched the observed sediment type it was possible to have an indication of how well the classification worked.

The results of the ML classification are presented in **Figure 6**.

The most sandy regions (0-10% mud) have been distinguished in three separate classes, which can of course always be grouped together (if the user wishes so). The idea was mainly to show the distinct differentiation that can be made between the very dry and high reflective sandy material, that occurs mainly along the north eastern

edges of the flat and the two other sub classes. The terms 'dry' and 'wet' are somewhat misleading; they should be interpreted as relative indications of water content (surely the dry sands contain some water).

Validation of the classification by inspection of the classification output on the sample positions on the regular grid revealed that only 25% of those positions have been classified correctly. If a misclassification of one class is permitted, than 75% of the validation samples stands the test.

In the case of Minimum Distance to Mean Classification (MDM) of the CASI mozaic with the same eight classes, 40% of the validation samples have been classified correctly, 75% if a misfit of 1 class is permitted.

No classification result of the Landsat-5 TM image has been calculated, because of the spatial variability of the sediment type distribution. The classification algorithm automatically uses a minimum training sample size of 3x3 pixels, which means an area of 90x90 m for Landsat (12x12 for CASI in this case). This would be tricky in this case; a 90x90 training sample size does not represent the class involved on many locations in our experiment.

3.3 Classification by Multiple Regression

Regression modelling seeks to capture the within-pixel variation in sediment particle size distribution by expressing sediment variables as a function of spectral reflectance. Both the mozaiced CASI image of September 20 and the Landsat-5 TM image of September 7 were processed. The dependent variable tested was the mean particle size. The independent variables were the mean digital numbers in each band. The SPSS/PC+TM package was used for the regression analysis (see Norusis (1986)).

As a measure of the amount of variation in the dependent variable that was explained by the independent variable, the r-squared values of the multiple regression models provided a means of verifying the accuracy of this method of classification. A further check was made by assessing how well a regression equation derived from a subset of 18 of the sample sites predicted the observed particle size distribution of the remaining sites. As in the MDM and ML classification the sub-set sites were the sites where hyperspectral field spectra were measured with the PSII field spectrometer.

Multiple regressions were calculated for both the CASI mozaic and the Landsat-5 TM image with 7 classes with somewhat different class boundaries than in the ML and MDM classification results. This makes qualitative comparison of the multiple regression results with those of ML and MDM difficult.

The multiple correlation coefficient r^2 amounts to .501 for the multiple regression of the CASI image using bands 4 (540-570 nm) and 12 (780-850nm).

In this case the Landsat-5 image could also be classified because we were free to choose the area which represents a certain training sample from the image. Only 1-4 pixels were used to represent a training sample. Bands 1 and 4 showed the largest information content, the multiple correlation coefficient was .821.

3.4 Reflections on optimal classification of intertidal sediment distribution

Most image classification techniques assign each pixel to a pre-defined class. This is of course appropriate if the area of interest can be partitioned into regions of homogeneous cover with well defined boundaries. However, when the observed surface is heterogeneous and has diffuse boundaries, processing methods that are able to estimate the proportion of surface components occurring within each pixel are more desirable. Intertidal surface sediments may often be homogeneous over large areas but by definition they will have diffuse boundaries. In the case of our experiment on the Plaat van Walsoorden we encounter both rather small scale variations and (of course) diffuse boundaries. Therefore it would be very advantageous to have a spectral mixture model operational, which on the basis of so called 'pure' input spectra of all sediment constituents would give as an output the percentage of surface extent of every individual constituent. The method would assume that each constituent contributes to the recorded radiance in linear proportion with its surface extent (see also Yates et al., 1993). Accurate spectral samples of all constituent sediment elements will be necessary to develop such a method. At least spectra of samples of pure water, pure sand (wet and dry), pure silt (wet and dry) and pure clay (wet and dry) and also of some algae species would have to be available.

There were too many predominantly sandy samples present in the data set. The sediment grain size data set would have to be extended with samples with a more muddy

character to see whether more definite conclusions about best suited bands can be reached.

The geometry of the CASI image is a factor, that introduces uncertainty, because the position of the sample location becomes uncertain. Cosandier et al. (1992) claim a maximum error of 4 pixels after geometric correction by their method. By inspection of adjacent CASI tracks it became evident that this is not the case for our mozaiced image.

The influence of water content in the sediment at the sample sites is evident and disturbs the classification accuracy.

4. CONCLUSIONS AND FUTURE PLANS

From this experiment it can be concluded that real quantitative mapping of sediment type distribution with optical remote sensing is difficult. There are no distinct spectral features present in sediment spectra which could be helpful in discrimination of sediment types. Apart from influences of water content and presence of algae sediment spectra show a monotonous increasing aspect. Spectra of sediments with different compositions only show minor differences, while the influence of water content on colour is rather dramatic in the spectral range between 400 and 900 nm.

However, sediment type distribution can be mapped using remote sensing, at least in a qualitative way. Combining remote sensing data and simultaneously acquired sediment grain size data a subdivision of an area of interest in a number of sediment type classes can be done and this can supply a very helpful tool for management purposes.

A sediment classification based on a Landsat TM image offers a synoptic view and helps to get an insight in the sediment status in a certain area.

If regular information about the sediment distribution in an area with the spatial dynamics of the Scheldt estuary is wanted, then it will be certainly advantageous to use an airborne scanner like the CASI. The CASI scanner has proven to be operational in the sense that it can be shipped to remote project sites and can be built in an aircraft within a few hours. The system allows flexible definition of bands and data processing of large data sets does not require a very long time (in the order of a few days). By virtue of its flexibility with respect to definition of bands and flight altitude a system like CASI can be very suitable for regular mapping of sediment types in the test area. It can be flown whenever meteorological circumstances permit so, which has to be viewed as a major advantage in view of Dutch mean weather conditions.

The classification results will be discussed with experts who know the region and a strategy for future work on this subject will be developed.

Major attention will be payed in the very near future to the technique of spectral unmixing, because it promises to be able to disentangle the within-pixel variations. By measurement of pure PSII spectral reflectance data of all possible constituents of sediment, including of course water and algae.

The use of a differential GPS is necessary to reach geometric correct images within 4 pixels accuracy.

5. ACKNOWLEDGEMENTS

This project was partly sponsored by the Netherlands Remote Sensing Board (BCRS). Special thanks to Cathy Wrightson and Glenn Farrington of ITS for providing us with CASI data. Kees Storm (Rijkswaterstaat) helped to arrange things for the field measurements and for guiding us on the Plaat van Walsoorden. Richard Powys (Geo Sea Consulting) performed the grain size distribution analysis very quickly. Finally Hans den Hollander of the Survey Department was responsible for the image processing.

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