The use of Remote sensing as a monitoring tool for coastal defence issues in the Wadden Sea

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Samenvatting

Grote delen van Nederland liggen onder zeeniveau. De Waddenzee, met de ervoor liggende eilanden, is een belangrijke natuurlijke barrière die de noordelijke kuststrook beschermt tegen de Noordzee. De Waddenzee is een ondiep dynamisch en troebel ecosysteem met veel bij laagwater droogvallende platen.

Het Delta Programma Waddenzee behelst de Waddenzee, de Wadden eilanden, het Eems-Dollard estuarium en de (Wadden)kustzones van Noord Holland, Friesland en Groningen. Klimaat verandering kan leiden tot verhoging van het zeeniveau, meer extreme weersituaties leidend tot hogere stormvloeden, meer zoetwaterafvoer, frequentere stormen en veranderingen in de richting van de golfaanval. Daardoor kunnen de eilanden sterker eroderen en droogvallende platen en kwelders, de natuurlijke beschermingszones voor de vastelandsdijken, kunnen verdwijnen. In hoeverre dat zal gebeuren en met welk tempo is nog onduidelijk.

Remote sensing kan een bruikbare en relatief goedkope methode zijn om specifieke karakteristieken van droogvallende platen waar te nemen. Het geeft de mogelijkheid om ruimtelijke en temporele variaties in sediment en biogene structuren te kwantificeren en te volgen. De techniek kan informatie uit metingen op enkele specifieke locaties vertalen naar een groter gebied. In aanvulling daarop kunnen historische beelden gebruikt worden om trends in ontwikkelingen over grote gebieden te detecteren. Er zijn beelden beschikbaar vanaf 1975. Zodoende kan het gedrag van belangrijke ecosysteemcomponenten over een lange periode beschreven worden

De toepassing van Remote Sensing in kustbeschermingsbeleid en –beheer vergt specifieke aanpassingen aan bestaande classificatie technieken. Het bepalen van relevante parameters in een troebel, zeer dynamisch ondiep systeem als de Waddenzee is een grote uitdaging. De doelstellingen van het huidige rapport, als onderdeel van de monitoring component in het Delta Programma Waddenzee, zijn het beoordelen van mogelijkheden en limitaties van de toepassing van RS als instrument voor het monitoren van variabelen die relevant geacht worden in het kader van kustveiligheid. Gedacht moet worden aan sedimentkarakteristieken, schelpdierbanken en dynamisch gedrag van geulen en prielen.
De studie haakt aan bij internationale Remote Sensing expertise en methoden en richt zich op aspecten die belangrijk zijn voor kustbeheer in de Nederlandse Waddenzee.

De vereiste resolutie, ofwel het oplossend vermogen, om sedimentkarakteristieken en kenmerken van droogvallende schelpdierbanken te kunnen bepalen moet beter zijn dan 30 meter. De beschikbaarheid van historische multispectrale satellietbeelden voor de Waddenzee, zonder wolken en bij laagwater, is beperkt. Meestal zijn minder dan 4 beelden per jaar beschikbaar. Voor het bepalen van trends in sterk variabele of hoog dynamische parameters is toepassing van Remote Sensing op basis van satellietbeelden daarom niet aan te raden. Voor relatief stabiele structuren zoals kwelder(randen) schelpdierbanken, geulen en prielen is RS zeer bruikbaar bij het volgen van ruimtelijke en temporele veranderingen

Historische Landsat beelden laten verschillen zien in sediment karakteristieken zoals vochtgehalte en zand/slib verhouding. De locaties en grootte van schelpdierbanken (mossel en oester) konden met redelijke nauwkeurigheid gevolgd worden op de beelden bij laagwater. De ontwikkeling van geulen en prielen in de richting van de kust kon in kaart worden gebracht waarmee mogelijk potentieel voor kustbescherming gevaarlijke ontwikkelingen tijdig zijn te detecteren

Mogelijke toekomstige toepassingen voor het monitoren van veranderingen en toepassingen voor beleids- en beheersondersteunende modellen wordt besproken.

Summary

Large parts of the Netherlands are below sea level. The Wadden Sea is an important natural barrier, protecting the northern coast of the Netherlands from the North Sea. The Wadden Sea is a shallow, partly intertidal, turbid and dynamic ecosystem. Climate change may, among others, lead to increased sea level rise, possibly causing drowning of the Wadden Sea and losing its protective function. If and how these changes occur and at which pace is still unclear.

Remote sensing can be a very useful and relatively inexpensive tool in detecting specific characteristics of emerging tidal flats. Remote sensing techniques offer an alternative option to track, detect and to analyse spatial and temporal variations in e.g. sediment characteristics and biogenic structures. The technique can be used to translate information on habitat characteristics from point measurements to a wider geographical area. In addition, Remote sensing databases of historic images, going back to 1975, offer the possibility for trend analyses of large areas as to provide valuable information on the behaviour of important components of the Wadden Sea area in the past.

The application of remote sensing in coastal defence policy and management requires very specific adaptations to existing classification techniques. Detection of relevant parameters from a turbid, highly dynamic shallow ecosystem as the Wadden Sea is a challenging task. The objectives of this report as part of the monitoring component in the Delta Programme Wadden Sea, is to assess the possibilities and limitations of the application of Remote sensing as a tool for monitoring parameters that are relevant to coastal defence objectives, i.e. sediment qualities, mussel and oyster beds and channel and gully dynamics. The study provides links to international Remote sensing expertise and methods. It also focusses on tools for testing Remote sensing applicability for answering questions related to coastal defence issues in the Dutch Wadden Sea.

The required resolution for detecting sediment qualities and mussel and oyster beds is 30 m or higher. The number of these medium resolution historical multi-spectral satellite images for the Wadden Sea is limited (up to four images per year). Satellite based Remote sensing of historical trends of highly dynamic and variable parameters are therefore not recommended. For structures like salt marshes, mussel and oyster beds, intertidal flats and gullies and channels, however, Remote sensing is highly applicable for measuring temporal or spatial changes.

Historical Landsat data showed different characteristics of intertidal sediments in terms of water content and sand and mud content. The locations of mussel and oyster beds can be fairly well detected on images acquired during low tide. Time series of satellite images showed progression of gullies and channels towards the coast, potentially endangering defence structures.

Future perspectives of using remote sensing for monitoring changes in the Wadden Sea and application in scenario and management support models are discussed.

Contents

1 Introduction

1.1 Delta Programme Wadden Sea

The Delta Programme Wadden Sea area addresses the Wadden Sea, the Wadden Sea islands, the Eems-Dollard estuary and the coastal zones of the provinces of North Holland, Friesland and Groningen that border the Wadden Sea and the Eems-Dollard estuary. Climate change may lead to increased sea level rise and a change to more extremes in the tidal amplitude, the atmospheric precipitation pattern and in the occurrence and timing of storm events and the angle of wave attack relative to the coastline. As a consequence it is expected that the North Sea side of the Wadden Sea island will experience other and increased coastal erosion and the intertidal mudflats and salt marshes in the Wadden Sea Area, the natural coastal defence of the mainland, could drown. If and how these changes occur and at which pace is still unclear.

The Delta Programme Wadden Sea Area aims:

- To develop an integrated routine which should secure the safety of the islands' and main land's coasts. The objective is to integrate water safety with other functions of the Wadden Sea Area, which are: nature, recreation and tourism, and sustainable economic activities.
- To monitor the effects of climate change on ecosystems and developments in the Wadden Sea Area.

For appropriate policy development it is important to know:

- If and which system changes are likely to occur in response to climate change and at what pace,
- If these changes negatively affect safety or natural and socioeconomic values,
- If these changes are disagreeable from a public opinion's point of view, and
- If moments in time can be signposted at which adaptive measures should be taken or beyond which changes are irreversible and other less appealing or expensive measures are required to meet at least the flood defence safety norm (adaptation tipping points).

1.2 Monitoring

The objectives of a Monitoring programme as one of the areas of attention in the Delta Programme Wadden Sea Area are (Stapel and Dankers, 2011):

- To create coherence between and optimisation of different monitoring activities and data information management (national and international),
- To integrate the long term measurements suggested from other areas of attention,
- To interpret data in order to answer the policy questions raised above and to contribute to the objectives of the Delta Programme Wadden Sea Area as a whole

The aim of monitoring is to detect and to monitor the effects of climate change on ecosystems and developments in the Wadden Sea area, which could have an impact on the coastal integrity.

Remote sensing is a cost-effective and time saving method to obtain measurements from large areas (altitude, sediment composition, channel and gully morphology, geological and biogenic structures, zonation and vegetation characteristics). Remote sensing techniques offer an alternative option to track, detect and analyse spatial and temporal variations in e.g. sediment characteristics and biogenic structures. The technique may be used to translate information on habitat characteristics from point measurements to a wider geographical area. In addition Remote sensing databases of historic images, going back to 1975, offer the possibility for trend analyses of large areas and provide valuable information on the behaviour of important components of the Wadden Sea area in the past in response to changes that are expected to continue in the future, some of and which may have effects on coastal defence structures, natural qualities and ecosystem resources and services

1.3 Remote Sensing

The aims of this fore sighting study are to assess the possibilities and limitations of using remote sensing as a tool for data monitoring relevant to the coastal defence objectives of the Delta Programme Wadden Sea area. The intention is to generate knowledge on how the historical satellite data can provide valuable information on developments of channels and gullies and sediment characteristics, in particular what methods are available and applicable to the Dutch Wadden Sea. The focus was to use satellite data on:

- classification of sediments
- identification and locations of mussel and oyster beds
- detection of temporal changes in gullies and channels, which is considered as potentially relevant for coastal defence issues in the Wadden Sea and for which remote sensing techniques and satellite images are already developed and available.

Trend analyses will also reveal shortcomings in data sets and monitoring gaps that should subsequently be addressed in the monitoring activities supporting the Delta Programme objectives. The advice on relevant future applications of remote sensing in highly dynamic coastal seas such as Wadden Sea, including new application of high resolution remote sensing, storm database and integrated model is discussed.

1.3.1 *Classification of sediments using satellite data*

The changes in sediment composition is considered to be strongly related to coastal erosion and climate change (Bartholdy and Folving, 1986; Gomez et al, 1995; Hommersom et al, 2010; Sørensen et al, 2006; Schmugge et al, 2002). Several studies using satellite Landsat data with a resolution of 30 meters dealt with mapping the spatial distribution of sediment types in the German and Danish Wadden Sea. However, methods were tested only in selected parts of the German and Danish Wadden Sea, which differ considerably in parameters such as sediment composition and sediment transport (Postma, 1961; Bartholdy and Folving, 1986; Sørensen et al., 2006).

1.3.2 *Identification and locations of mussel and oyster beds*

Mussel and oyster beds, creating hard three-dimensional substrates and reefs (Fey et al., 2008), are considered important for coastal defence by reducing wave energy. Mudflats and mussel beds are protected and recognised as useful for coastal defence along the Scottish part of the UK, as mentioned in a National Marine Plan resolution of the Scottish Government, adopted in 16 March 2011(Scottish Government, 2012). The National Marine Plan of Scotland is one of the main components of the Marine (Scotland) Act, setting the national marine strategy, ensuring sustainable economic growth of maritime industries, with taking the environment into account, and formulating policies on economic, social and marine ecosystem objectives.

The classification algorithm on the identification of mussel and oyster beds using Landsat satellite data developed by Brockmann Consult (Brockmann and Stelzer, 2008), is based on the habit of mussel and oyster beds to strongly reflect sunlight because of a distinct colour and tone (dark) and a rough structure of the surface, making these ecotopes very distinct from surrounding sediments.

1.3.3 *Detection of temporal changes in gullies and channels*

The temporal change in gullies and channels can provide information on coastal erosion processes (Knighton, 1998; Gomez et al., 1995) and other developments which may affect the coastal integrity. Detection of temporal changes using satellite images is based on the analysis of series of images, acquired by the same satellite, by the same sensor and in the same resolution. Only by doing so we will be able to compare the details shown in the images.

1.4 The research objectives of the study

1.4.1 *The general objective*

The general objective of this study was to assess the possibilities and limitations of Remote sensing techniques as a tool for data monitoring relevant to the objectives of the Delta Programme Wadden Sea. Additionally we wanted to explore the available expertise and knowledge on how historical satellite data can provide information on developments of channels and gullies, morphology and sediment characteristics.

1.4.2 *The specific objective*

The specific objective of this study is to answer the question what methods are available to provide information on sediments composition, location of mussel and oyster beds and developments of channels and gullies, which are considered relevant for coastal defence. The study specifically tests and identifies methods which are applicable for the Dutch Wadden Sea.

To reach this specific objective, the following tasks were implemented:

- Review of relevant literature, satellite missions and available satellite data (resolution, optical range), and properties of sediments, mussel and oyster beds, gullies and channels which can be detected on satellite images. These issues are described in Section 3.2, Application of Remote sensing in the Wadden Sea.
- Applying the Brockmann Consult method on classification of sediments and mussel and oyster beds, this is described in Sections, 3.3.1 Classification of sediments and 3.3.2 Classification of mussel and oyster beds.
- Detection of developments of channels and gullies, described in Section 3.3.3 Temporal change detection in gullies and channels.

1.5 The limitations of the study

As the scope of this study did not allow analysis of the whole Dutch Wadden Sea, one location from which sufficient ground data are available for a selection of the potentially relevant parameters was selected for a pilot study, The parameters considered are: sediment characteristics, mussel and oyster beds and temporal changes in gullies and channels. The analysis of the selected parameters started from selecting the most applicable and relevant images from available satellite missions. For this reason an overview was made of:

- Satellite missions
- Periods of operation
- Revisiting frequencies (imaging dates and time)
- Used wave bands

The scope of this pilot study did not allow analysis and processing of all available (cloud-free and low tide) images. Therefore it was decided to select the most representative images matching the dates of classified images by Brockmann Consult, to compare the results and to see whether classification of ecotopes in the Dutch Wadden Sea provided the same results, in the same way as had been done in the German Wadden Sea.

1.5.1 *Research methodology*

The focus of the Delta Programme determined the parameters selected for this study. The parameters must be relevant for coastal defence and be detectable by satellite sensors. In general, there are several satellite missions offering historical data from the Wadden Sea: Landsat (USA), ASTER (Japan), ERS (EU), JERS (Japan) and SPOT (France). The Landsat missions have the largest continuous historical coverage and resolution suitable to identify the selected parameters. One of the important preconditions for developing useful Remote sensing procedures as a monitoring tool is the possibility to validate the results of image interpretation with real ground data (ground thruthing). The current study employed a mixture of different methodologies to classify sediments and mussel and oyster bed and to detect temporal changes in gullies and channels from satellite images.

1.5.2 *Structure of the report*

Chapter 3 on Materials and methods provides an overview on historical missions of medium resolution satellites of Landsat, ASTER and ERS. The summary on mission's available, type of sensors and data is provided.

The sections on Classification of sediments, Mussel and oyster beds and Temporal developments in gullies and channels deliver a general overview of Remote sensing classification studies implemented in the Wadden Sea, the results obtained and experiences learned. The restriction of satellite data availability (weather and tides, and usability of satellite missions) is presented. The inventory of satellite images presents images of different years and under different tidal conditions with the purpose to provide an impression on how low and high tides images appear. The section on pre-processing of the satellite images gives information on atmospheric correction and Principal Component analysis of images from high and low tide. A test on Modified Soil Adjusted Vegetation index (MSAVI) is considered in relation to the algorithm of Brockmann Consult. The usefulness of this index is explained, pointing out that it is possible to detect mussel and oyster beds covered by macrophytes.

Chapter 4 describes the results of classifying sediment composition, mussel and oyster beds and temporal changes in channels and gullies.

Chapter 5 on Future applications presents new developments on Remote sensing, including high resolution WorldView- 2 image (2 meters in multi-spectral and 0.60 cm in panchromatic bands). The experience from other marine institutions working with satellite data like the French Research Institute for Exploration of the Sea (IFREMER) using historical radar ERS data, and a proposal for an Integrated decision support model using satellite data, are presented.

Finally, the discussion outlines challenges and experiences gained from the study. For convenience of the reader, Appendix 2 explains some technical terms used in Remote sensing science.

2 Assignment

The assignment of this study was to provide answers to:

- Safety issues related to sediment budget and climate change of the Delta Programme Wadden Sea, concerning the analysis of “Development of channels and gullies and sediment characteristics in the Wadden Sea based on an analysis of 30 years of satellite images and aerial photographs available. Creating links to international literature and provide sediment data”. The research question of this component concerned literature review of relevant studies on properties of sediments, mussel and oyster beds, gullies and channels which can be detected on satellite images and selection and testing of algorithms.
- “What are the opportunities for use of Remote sensing?”.

3 Materials and Methods

Remote Sensing can be used to detect a wide variety of properties in the atmosphere and on the ground. The development of image interpretation tools for specific parameters, which is a time consuming process, is beyond the scope of this pilot study. The materials and methods discussed in this report apply only to data analysed in relation to the objectives of the Delta Programme to assess the possibilities and limitations of Remote sensing as a tool for monitoring the system based upon long-term historical satellite data. The parameters selected to represent long-term changes in the Wadden Sea are sediment composition, mussel and oyster beds and temporal changes in gullies and channels.

In Section 3.1 an overview of satellite data from Landsat, ASTER and ERS missions is presented. The description on Period of operation, Resolution of the scene, Revisiting frequency, Purchasing details and Wave bands (spectrum) of each mission is presented in Tables 1 and 2. The overview on Application of Remote sensing in the Wadden Sea and the section on Classification describe methods used in Remote sensing studies implemented in German and Danish parts of the Wadden Sea. The Selection of pilot parameters and pilot area where the classification method was tested highlighted the Factors restricting satellite data availability. Pre-processing describes atmospheric correction of the images, which is important in order to remove the effects of atmosphere in order to reduce the spectral reflectance of sediments, mussel and oyster beds, and gullies and channels. To detect mussel and oyster beds covered by macrophytes, the Modified Soil Adjusted Vegetation index (MSAVI) was tested.

3.1 Historical medium resolution satellite data

Satellites providing historical medium resolution images of the Wadden Sea area include missions from the United States government agency National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). The data from NASA Landsat satellites are going back to the 1970s, providing long-term historical coverage of the entire globe (Figure 1- Landsat missions (NASA, 2011)). The European Space Agency has cooperation with NASA and other space agencies, providing its multi-mission ground systems to acquire, process, distribute and archive data from Landsat and other satellites, known as Third Party Missions (TPM). The data from these missions are distributed under specific agreements with the owners or operators of those missions, which can be either public or private entities outside or within Europe.

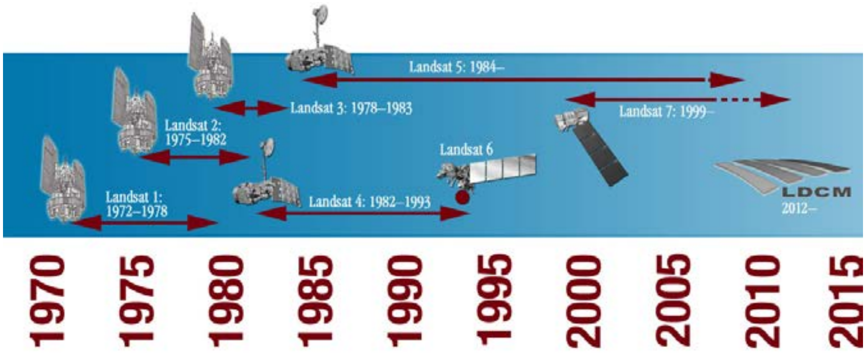


Figure 1- Landsat missions (NASA, 2011).

3.1.1 *Landsat*

The Landsat missions provide extended large coverage of 170 km (north-south) by 185 km (east-west) scenes on the ground. The revisiting time of satellite missions are every 18 (Landsat 1-3) to16 (Landsat 5-7) days over the same area (705 km altitude, sun-synchronous, so that at any given latitude it crosses directly overhead at approximately the same time each day). Landsat series were specifically designed to detect characteristics about terrestrial features and wet and dry areas on land. The spectrum of different bands ranges from visible blue (0.45-0.52 µm), green 4 (0.52-0.60 µm), red (0 0.63-0.69 µm) and near infrared (NIR; 0.77-0.90 µm) to middle infrared (MIR; 1.55-1.75 µm) bands. There are two additional thermal infrared bands (10.40-12.50 µm), measuring the radiant flux (heat) emitted from surfaces (land and water) and mid-infrared, recording long wave data (2.08 - 2.35 µm).

The Landsat missions employ among others MSS (Multi Spectral Scanner, Landsat 1-5), TM (Thematic Mapper, Landsat 4, 5) and ETM+ (Enhanced Thematic Mapper Plus, Landsat 7) sensors. The images from MSS have resolution from 80 to 120 meters in blue, green, red and near-infrared bands. The resolution of TM is 30 meters in blue, green, red, near and mid-infrared bands with an additional thermal band in 120 meters. The ETM+ acquires data in all bands of the TM sensor and an additional high resolution 15 meters panchromatic band. In addition, the ETM+ sensor collects information in two different gain settings (radiometry settings- image precision) in high and low mode. When brightness and reflection of land surface is high, the sensor collects information in low gain, aiming to reduce size of collected data. When surface brightness is lower, the sensor switches to high gain, in order to increase the capacity of the sensor to collect as much details as possible. Table 1 provides an overview of Landsat satellite missions. The main advantage of the Landsat (L4-7) mission is continuous temporal coverage over same area for many years, using the same sensor and spectral range in resolution of 30 meters, with a latest addition of 15 meters panchromatic band. The recent failure of Landsat-7 data mission closed provision of data in October 2011, however, a new mission of the Landsat-8 is planned in the next two years, which will continue global acquisition. The detailed technical characteristics of the Landsat data on acquisition dates and position of the sun, cloud condition and sensor parameters can be found in metadata files which are available for each image.

3.1.2 *ASTER*

ASTER is a cooperative effort between NASA and Japan's Ministry of Economy Trade and Industry (METI), in collaboration with scientific and industrial organisations in both countries. ASTER captures high spatial resolution data in 14 bands from visible to thermal infrared wavelengths and provides stereo viewing capability for digital elevation model creation. The ASTER satellite was launched in 1999 and can provide information in 15 meters resolution and as the Landsat satellite has global coverage with temporal acquisition every 16 days of the same area covering 60 km on the ground. The advantage of ASTER images is its high resolution, making it possible to enhance Landsat data, because of the same spectral and temporal resolution (Table 2).

Table 1- Overview of the Landsat satellite missions

Satellite	**Landsat 1-3 (RVB, MSS)**	**Landsat 4, 5 (TM, MSS)**	**Landsat 7 ETM+**
Period of operation	1972 - 1983	TM: 1982 – MSS: 1982 - 1995	1999 -
Resolution scene	57 x 79 m 170 x 185 km	30 m (120 m) 170 x 185 km	30 m (15 m, 60 m) 170 x 185 km
Revisiting frequency	18 days	16 days	16 days
Purchasing details	ESA: until 2010 free of charge for the scientific community.		
Wave bands (spectrum)	RGB (Red, Green, Blue) sensor 1:475-575 nm- B 2:580-680 nm- G 3:690-830 nm- R Multi Spectral Scanner (MSS) sensor 4:0.5-0.6 µm 5:0.6-0.7 µm 6:0.7-0.8 µm 7: 0.9-1.1 µm 8:10.4 – 12.6 µm (L3)	Multi Spectral Scanner (MSS) sensor 4:0.5-0.6 µm 5:0.6-0.7 µm 6:0.7-0.8 µm 7:0.9-1.1 µm Thematic Mapper (TM) sensor 1:0.45-0.52 µm 2:0.52-0.60 µm 3:0.63-0.69 µm 4:0.76-0.90 µm 5:1.55-1.75 µm 6:10.40-12.50 µm (120m) 7:2.08-2.35 µm	Enhanced Thematic Mapper Plus (ETM+) sensor 1: 0.45-0.52 µm 2: 0.52-0.60 µm 3: 0.63-0.69 µm 4: 0.76-0.90 µm 5: 1.55-1.75 µm 6: 10.40-12.50 µm (60m) 7: 2.08-2.35 µm 8: 0.52-0.90 µm (15 m)

3.1.3 *ERS*

The ERS-1 satellite is one of the oldest European satellites, with global coverage dating back to 1991. T Compared with the Landsat and ASTER missions, the ERS-1 satellite provided data in spatial resolution of 12,5 meters with coverage of 5 km by 5 km, with three planned repeat cycles of 35 days. The ERS-1 provided data in black and white mode, and compared with the Landsat and ASTER satellites, the data is not influenced by clouds and weather, because of the ability of radar system (pulse signal sending and receiving) to penetrate clouds and rain. The ERS-1 was joined in 1995 by ERS-2, providing tandem missions until 2000, finally stopping the ERS-2 satellite because of satellite control failure in July 2011. The archived data of the ERS-1 and 2 satellites are available from ESA, free of charge for the scientific community. An overview of ERS-1 and 2 satellite missions is given in Table 2.

Table 2- Overview of ASTER and ERS satellite missions

Satellite	**ASTER (NASA + Japan RS)**	**ERS-1 and ERS-2 (EU)**
Period of operation	1999 – to present	1991– 2011
Resolution (and coverage)	15 m (60 x 60 km)	12.5 m (5 x 5 km)
Revisiting frequency	16 days	Revisit depends from the area, starting from 3, 35 and up to 168 days. European area revisit time is from 3 to 35 days
Wave bands (spectrum)	Blue 1 (0.45 -0.52 µm) Red 3 (0.63-0.69 µm) Near infrared 4 (0.76 - 0.90 µm) Short-wave infrared 5 (1.55-1.73 µm) Thermal infrared 6 (10.4-12.5 µm)	Radar panchromatic images

3.2 Application of Remote sensing in the Wadden Sea

Brockmann Consult analysed 20 years of historical data of Landsat TM (60 and 30 meters resolution) starting from 1987, focusing on the German Wadden Sea and the province of Zeeland in the Netherlands. The surface mapping used data from high resolution ASTER images and measurements from an air plane (HyMap imager). The results were validated using in-situ measurements. The following characteristics of tidal flats were detected from satellite images with reasonable accuracy:
sediments composition (sand and mud)
changes in locations of vegetated areas (macrophytes) using multi-temporal images
location of mussel and oyster beds.

The Danish part of the Wadden Sea was mapped in 2006 using Landsat ETM+ (30m) data. For sediment classification, combinations of several bands were analysed, and best combinations were found in blue (0.45 -0.52 µm), red (0.63-0.69 µm), near infrared (0.76 - 0.90 µm), short-wave infrared (1.55-1.73 µm) and thermal infrared (10.4-12.5 µm) (Sørensen, et al, 2006). The final results showed a fairly good distinction of sediments in 4 main classes: mudflat, mixed flat (wet/moist), low (wet) sand flats and high (dry) sand flat.

Geospatial Data Service Centre (GDSC, Haartsen and Marrewijk, 2001) analysed temporal changes in movements of sandbanks and tidal channels in the Wadden Sea using Landsat MSS images recorded between 1975 and 1987. The satellite data were combined with in-situ measurements and an attempt was made to detect reflectance properties of sediments and biogenic structures (Curran and Novo, 1988; Schmugge et al., 2002).

NIOO-CEME implemented several studies on monitoring sediments grain size in the Westerschelde (southwest Netherlands), based on information from radar and optical Remote sensing (Van der Wal and Herman, 2007; Van der Wal et al., 2005; 2008). Three algorithms were combined exploring:
a) properties of radar images
b) reflectance properties of sediments in optical (green) and short infra-red bands
c) combination of these two methods with in-situ measurements.

Van der Wal et al. (2008) classified the distribution of intertidal macro benthos using Remote sensing and in-situ measurements. The aim of the study was to assess distribution of macrobenthos and sediments in relation to dynamic processes in the Westerschelde. The study stated necessity of validation and calibration in order to use this method in other areas.

Overall, Landsat images with 30 meters resolution (Landsat 4-7) were better in classification of sediments and location of biogenic structures, compared with images of lower MSS (60 meters) resolution (Landsat 1-3).

3.3 Classification

3.3.1 *Classification of sediments*

Bartholdy and Folving (1986), Haartsen and Marrewijk (2001) and Sørensen et al. (2006) described methods on classification of sediments using Landsat TM and ETM+. The methods are based on peculiarities of sediments with different composition of sand, clay, silt and water content to reflect distinct spectral signatures which can be recorded by satellites. The data processing in this case will do spectral unmixing for detecting and separating spectral signatures corresponding to each sediment type.

However, the method of spectral unmixing in the Wadden Sea is of limited use because of the high nonlinearity of sediment transport and gradients in sedimentation processes, patterns of high temporal and spatial variability, and tidal asymmetries (Stanev et al., 2007; Hommersom et al., 2010). The processes in the Wadden Sea produce non-correlated patterns of sediment mixtures, and it is different not only from one image to another, but even within one image. The spectral unmixing in this case is not always able to differentiate very precisely different objects and substances, potentially resulting in reduced classification accuracy and mismatches. Validation of final results with field data, ideally acquired during or within a very short time lag after satellite data acquisition, will be extremely important to refine classification. Classifying Wadden Sea sediments by grain size is limited in medium resolution satellite data (Bartholdy and Folving, 1986). The final classification created six main groups of water, mudflat, muddy or mixed flat, wet or moist sandflat, dry sandflat and high-sand, without going into further details.

Another limitation is temporal change detection using images from different dates. The satellite sensor records “momentum” states of tidal flats and each image has its own specific non-correlated pattern of temporal and high spatial variability, further complicated by the periodicity of the tidal wave. This means that “reusing” spectral signatures from one image to another is not always possible.

Brockmann Consult tested a spectral unmixing technique in German and Dutch parts of the Wadden Sea and in Zeeland. In addition, the method is enhanced by adding high resolution ASTER data and supplying textural information from ERS and TerraSAR-X (Germany) radar data. The advantage of the developed method is the possibility to do quantitative analysis of satellite images without prior knowledge of the area and to predict sediment composition (content of mud and sand) and location and size of areas covered with macrophytes, using spectral libraries from reference images.

3.3.2 *Classification of mussel and oyster beds*

Bartholdy and Folving (1986), Brockmann and Stelzer (2008), Fey et al. (2008) and Hommersom et al. (2010) described a classification method for mussel and oyster beds. The detection of intertidal mussel beds is based on spatial characteristics of mussel and oyster beds in tone and colour (dark appearance compared to bare sediment), shape (stretched patterns along the tidal flats), texture (rough surface), size (irregular rounded) and shadow (originated from sediment deposits from mussels and oysters). The Normalized Vegetation Index NDVI detects mussel and oyster beds covered by macrophytes. The method applied by Brockmann Consult used the same prediction algorithm described for sediment classification.

Textural information from radar images served as added information in delineation of mussel and oyster beds when beds are slightly covered by water or sediment.

3.3.3 *Temporal change detection in gullies and channels*

The location of gullies and channels and their movements in course of time can be detected using 30 meters resolution Landsat TM images. As revealed in studies by Postma (1961), Bartholdy and Folving (1986), Sørensen et al. (2006) and Hommersom et al. (2010), the composition of sediments and their transport and spatial distribution are different in every location of the Wadden Sea. In order to detect changes it is important to use satellite data taken in the same optical range. The algorithm for change detection computes differences between two images. The spectral values from the first image are subtracted from the second image. The next step is to compute statistical variability for both images and highlight differences ("change"). This algorithm used Landsat images from different dates.

3.4 Selection of Remote sensing classification method

Brockmann Consult, with support from the European Space Agency developed a prediction algorithm to detect sediment characteristics, changes in vegetated areas (macrophytes) on emerging tidal flats and locations of mussel and oyster beds from Landsat images using field information on water content and water coverage, location of mussel and oyster beds and sediment composition. The first step of the algorithm was to separate intertidal flats from water. The next step was to separate more details of intertidal flats. The core of the Brockmann algorithm followed a decision tree rule, with specific differentiation (Figure 2). To detect mussel and oyster beds covered by macrophytes, the method of vegetation indexing is tested.

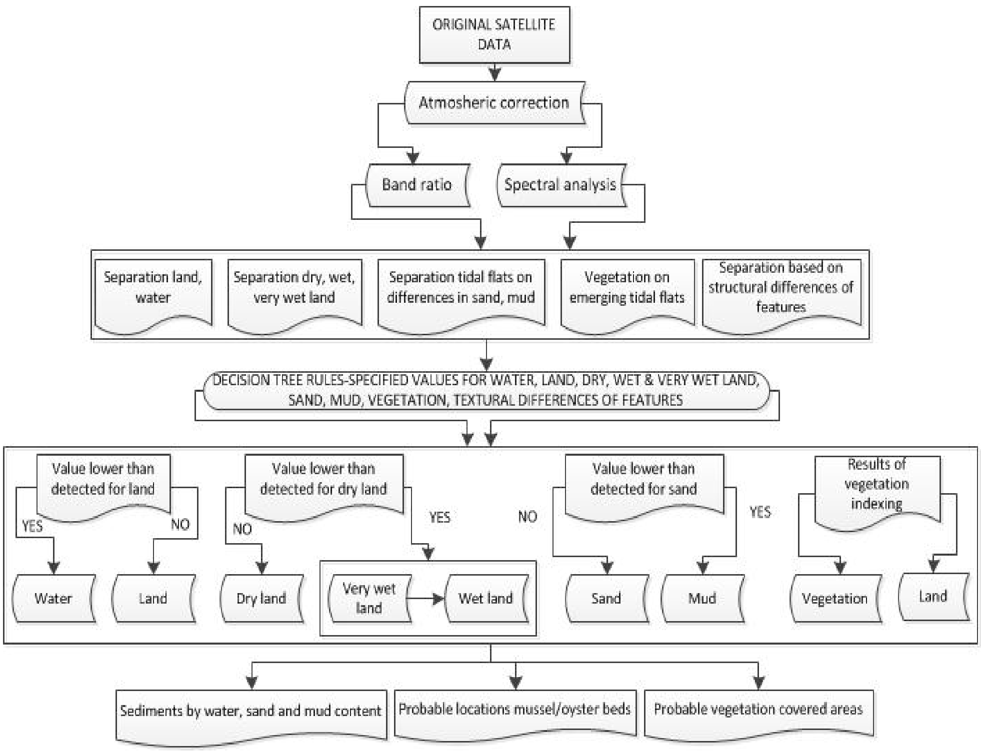


Figure 2- Brockmann Consult designed decision- tree rules

In cooperation with Brockmann Consult it was decided to use its available expertise and to apply its method to see whether it is also applicable for the Dutch part of the Wadden Sea

3.5 Selection of pilot parameters and pilot area

Sediment properties and sedimentation processes are important parameters in relation to coastal erosion and coastal defence issues in the Wadden Sea (Madsen et al., 2010). For the Delta Programme Wadden Sea, aspects affecting sediment dynamics are of particular interest. The selection of parameters for this pilot study considered features that are presumed relevant in terms of sediment budgets in the Wadden Sea. In addition, the parameters should be detectable by satellite sensor and field data should be availability for validation.

The changes in sediment composition, location of mussel and oyster beds and gully and channel development were considered as relevant for the Delta Programme Wadden Sea. Mussel beds can catch large amounts of sediment influencing its own and nearby surroundings. By doing so they act as sediment accumulating and storing systems and at the same time play a role in reducing wave energy during storms. The stored sediment may later become available for salt marshes (Oost, 1995). There are several satellite missions providing data acquisitions on global and regional scales, including the Wadden Sea. The medium resolution (30 meters) Landsat 5-7 missions over Wadden Sea started from 1984 and have continues acquisition till 2011. This allows comparison of different images taken in the same optical range and by the same sensors and sufficient time span between images to analyse temporal developments. The other satellite mission's data can serve as important supplementary information to verify and to improve the final classification results.

The Schiermonnikoog - Rottumeroog Islands area was selected as pilot location (Figure 3). The advantages of this area are:

- Relatively undisturbed environment (area closed for fishing since 1990s)
- Limited area: limited tidal variation
- Availability of temporal and spatial coverage of ground data for the selected parameters for
- validation
- Links to other DP-Wadden projects (sediment dynamics and system knowledge)
- Potential interest from e.g. other DP-Wadden project partners and Brockmann Consult.

It is assumed that the selected area is representative for the Wadden Sea and that the results and developed Remote sensing techniques may be extrapolated from this area to cover the whole Dutch part of the Wadden Sea, and beyond.

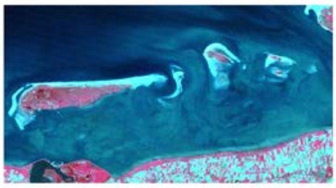


Figure 3-Location of pilot area (Rottumeroog and Schiermonnikoog islands) (Right- Netherlands map; satellite image of Schiermonnikoog and Rottumeroog Islands).

3.6 Factors restricting satellite data availability- weather and tides

The main requirements for using optical, multi-spectral satellite data for (intertidal) developments in the Wadden Sea are cloud free and low tide conditions. Climate data from station Lauwersoog showed that on average, there are 10 days per month with more than 50% maximum potential sunshine duration (data: KNMI).

The tidal differences measured at locations nearest to Schiermonnikoog and Rottumeroog islands at Huibertgat, Netherlands (53.5667° N, 6.4000° E), Lauwersoog (53.4167° N, 6.2000° E), Eemshaven, Netherlands (53.4500° N, 6.8333° E) and Borkum, Germany (53.5833° N, 6.6667° E) presented tide information for every image used in the study. The main challenge caused by tidal movements is the difference in harmonics of tidal waves within one image, affecting classification accuracy. Tidal movements over four stations in the investigated area are presented in Figure 4.

Although possibly these tidal predictions may be different from the actual sea level because of additional factors such as wind, atmospheric pressure etc, the information is still helpful to select potentially usable satellite images.

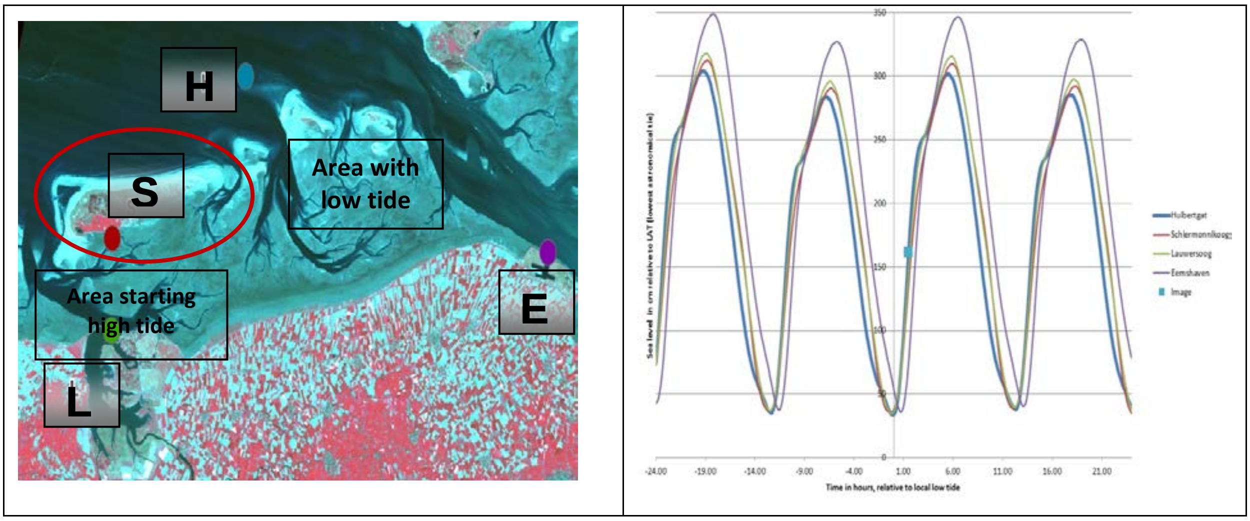


Figure 4 -Tidal movements over the stations of Huibertgat (H), Schiermonnikoog (S), Eemshaven (E).

3.7 Inventory of satellite images

Landsat revisits the Wadden Sea area every 16th day, in morning between 09.30am and 10.30 am GMT. Compared to the low water table, this means that all passages occur during daytime but less than 50% of the passages occur at low tide. Combining the satellite revisiting scheme and tidal charts with weather data, on average 4 low tide and cloud-free images are available from each satellite mission every year for the Wadden Sea. Landsat uses 233 paths (orbits) for total global coverage. Path numbers 197, 198 and 199 cover the eastern, middle and western parts of the Dutch Wadden Sea, respectively. A complete overview of available cloud-free and low-tide satellite images is given in Appendix 1.

3.8 Pre-processing

3.8.1 *Atmospheric correction of Landsat images*

The atmospheric correction of satellite images is necessary as it reduces the effects from moisture evaporation, haze and other disturbances generated by the atmosphere. The atmospheric correction removes effects from atmosphere using time and date, sun elevation, azimuth of sun illumination and azimuth angle during image acquisition, to make corrections for each wave band. The disturbance from satellite motion is reduced by applying corrections called gain offset.

The formula on atmospheric correction for Landsat images is (Chander and Markham, 2003):

$$L_\lambda = \left(\frac{\mathrm{LMAX}_\lambda - \mathrm{LMIN}_\lambda}{Q_{\mathrm{cal\,max}}} \right) Q_{\mathrm{cal}} + \mathrm{LMIN}_\lambda$$

Where: L_λ- spectral radiance (in Watt)
Qcal- quantized calibrated pixel value in Digital Units (DN)
Qcalmin- minimum quantized calibrated pixel value in Digital Units (DN), which is equal to 0 (zero).
Qcalmax- maximum quantized calibrated pixel value in Digital Units (DN), which is equal to 255 (two hundred fifty five).
LMAX_λ- spectral radiance that is scaled to Qcalmax
LMIN_λ- spectral radiance that is scaled to Qcalmin.

The atmospheric correction visibly improves contrast of the images (Figure 5).

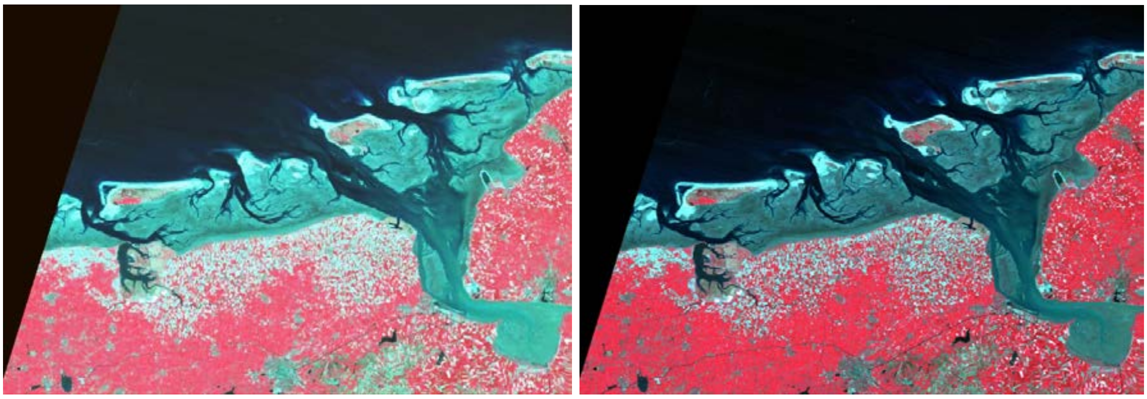


Figure 5-Landsat-5 (TM) image of Rottum island, date of acquisition- 1995-11-25, before (left) and after (right) atmospheric correction.

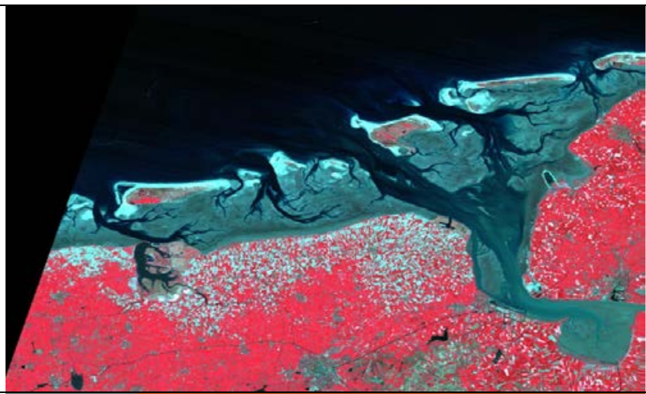
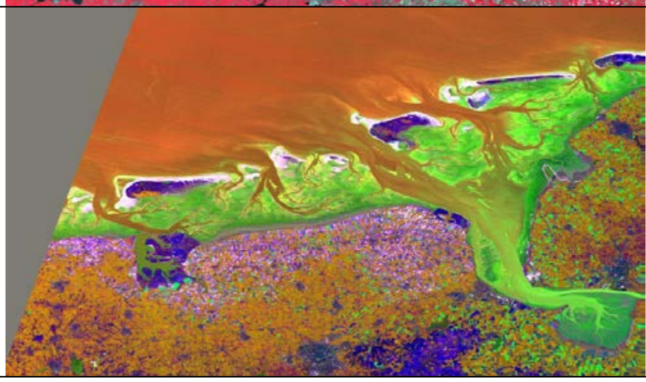
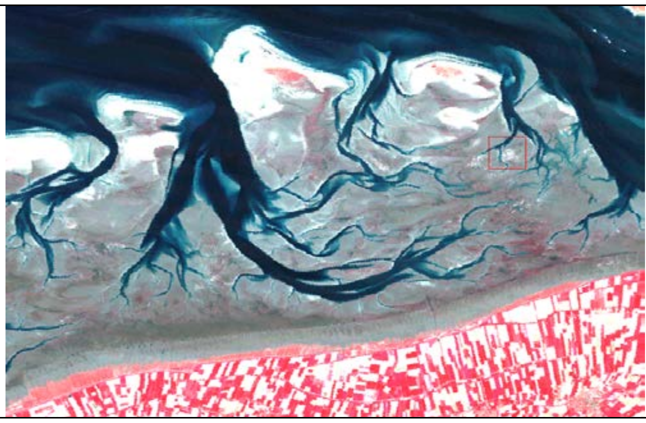
3.8.2 *Spectral analysis*

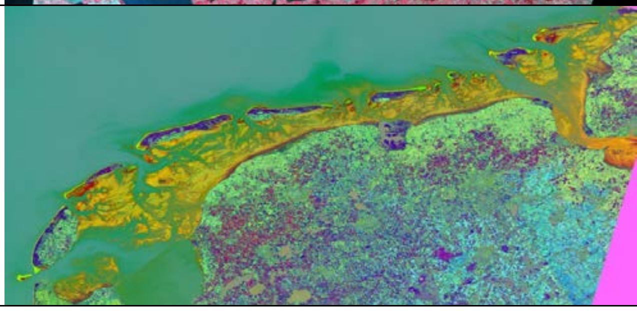
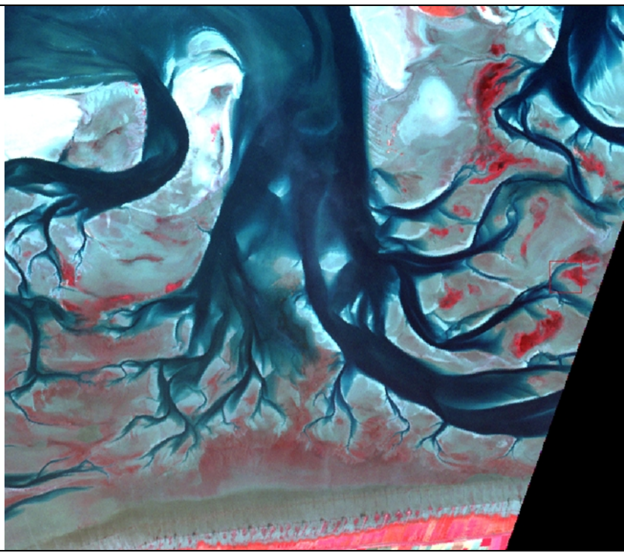
The spectral separability is analysed using the technique of Principal Component Analysis (PCA). In addition, Normalized Vegetation Index (NDVI) was derived to see if any biomass (vegetation) is covering emerged tidal flats. Figure 5 present results of PCA analysis. Differences in sediment concentrations and turbidity of the water can be seen around Rottumeroog island and in the Eems-Dollard estuary expressed in different colours. To see the differences in images from tide level, images in low and high tide were used. Images in low tide from 1995-11-25, 1990-03-05; 2000-05-13; 2006-09-12 and almost low tide from 2009-07-01; 2010-07-04 show detailed composition of tidal flats, expressed in variations of different colours. Two images were selected for classification, one from 1990-03-05 because it is showing large areas of dry tidal flats and one from 2006-09-12, because it is matching with classified images in the German Wadden Sea from Brockmann Consult. The images from 1995-11-25, 2009-07-01 and 2010-07-04 were used to detect changes in a long period of 15 years (from 1995 to 2010) and in short one year period (from 2009 to 2010).

Table 3 shows the scenes that were selected for this pilot study, images in low tide, with two images used in classification of sediments and mussel beds and Table 4 image in high tide, not used in classification. In order to analyse the effect from tidal level the spectral analysis (PCA) is presented both for images in low and high tide.

The images from high tide in Table 4 are given for general overview and PCA images are explains why images in high tide cannot be used for classification. However, images in high tide still can be used to detect changes along the main coast and coast of the islands.

Table 3-Images in low tide selected for this report

<table>
<tr><td colspan="2">Landsat-5 TM – Low tide
• Image acquisition date: 1995-11-25
• Tide information by station Lauwersoog (53.4167° N, 6.2000° E):
-Time of High tide- 12:02 PM CET/ 2.91 meters</td></tr>
<tr><td>Original image
In original image mainland and islands is shown in red color, because of reflectance of chlorophyll of vegetation in red and infra-red bands. The water from the North sea in deep blue color. The dry area of tidal flats in the Wadden Sea presented in brown and light blue color.</td><td></td></tr>
<tr><td>PCA image
The PCA analysis shows that there are disctict differences between major structures, like sediments (green), sea water (violet) and sandy beaches (very bright yellow).</td><td></td></tr>
<tr><td colspan="2">Landsat-5 TM - Low tide
• Image acquisition date: 1990-03-05
• Tide information by station Lauwersoog (53.4167° N, 6.2000° E):
- Time of Low Tide -9:50 AM CET /0.66 meters
- Time of High Tide- 4:06 PM CET /2.49 meters</td></tr>
<tr><td>Original image
One of the images selected for sediments classification. Sediments in a high contract with coastal land and from gullies and channels.It is one of the very few best images showing such high separability of sediments from coastal land and gullies.</td><td></td></tr>
</table>

<table>
<tr><td colspan="2">Landsat-5 TM - Low tide
• Image acquisition date: 2000-05-13
• Tide information by station Lauwersoog (53.4167° N, 6.2000° E):
-Time of High tide-6:59 AM CEST / 2.29 m
-Time of Low tide- 12:39 AM CEST / 0.26 m</td></tr>
<tr><td>Original image
The image covers large area of the Wadden Sea and low tide can be observed in part of Schiermonnikoog and Rottumeroog islands. The Texel island area showing situation of high tide. The image presents short time lag in tidal variations, which can be seen within the islands.</td><td></td></tr>
<tr><td>PCA image
The PCA analysis shows that there are disctict differences between major structures, like sediments (green), sea water (ligher green) and sandy beaches (very bright yellow).</td><td></td></tr>
<tr><td colspan="2">Landsat-7 ETM+- Low tide
• Image acquisition date: 2006-09-12
• Tide information by station Lauwersoog (53.4167° N, 6.2000° E):
-Time of Low tide- 8:24 AM CEST/ 0.19 meters</td></tr>
<tr><td>Original image
One of the images selected for mussel beds classification. The date of image acquisition matches with classified image in the German Wadden Sea by Brockmann Consult.</td><td></td></tr>
</table>

Landsat-5 TM - Low tide

- Image acquisition date: 2009-07-01
- Tide information by station Lauwersoog (53.4167° N, 6.2000° E):
- Time of High tide- 5:50 AM CEST / 2.32 m
- Time of Low tide- 11:44 AM CEST / 0.39 m

Low tide in the eastern part of the Dutch Wadden Sea, incoming tide in the western part

Original image

Image presents very high tide level in Texel island, with low tide in Schiermonnikoog and Rottumeroog islands. The mainland coast and islands are clearly delineated, with channels and gullies around Schiermonnikoog and Rottumeroog islands.

PCA image

The PCA analysis shows that there are disctict differences between major structures, like sediments (pink), sea water (greenish) and sandy beaches (very bright almost white). The cloud on top of the image is very light green).

Landsat TM-5- Low tide

- Image acquisition date- 2010-07-04
- Tide information by station Lauwersoog (53.4167° N, 6.2000° E):
- Time of High tide- 4:00 PM CEST / 2.50 m
- Time of Low tide- 9:47 AM CEST / 0.43 m

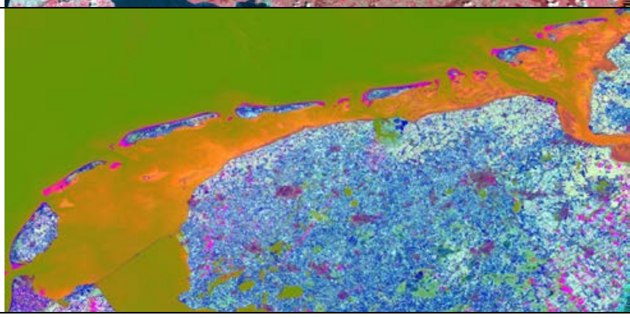
Low tide in the extreme eastern part of the Dutch Wadden Sea, more or less high tide in the western part

Original image

Image a bit distorted by haze from clouds, spread over islands. The distinction of mainland coast and islands are very clear and water in the Wadden Sea showing shallow areas of tidal flats.

PCA image

The PCA analysis shows that there are disctict differences between major structures, like sediments (pink), sea water (greenish) and sandy beaches (very bright almost white). The cloud on top of the image is very light green).



ASTER image- High tide

<table>
<tr><td colspan="2">

- Image acquisition date: 2007-06-08
- Tide information by station Lauwersoog (53.4167° N, 6.2000° E):
- Time of High tide- 8:34 AM CEST / 2.34 m
- Time of Low tide- 2:39 PM CEST / 0.52 m

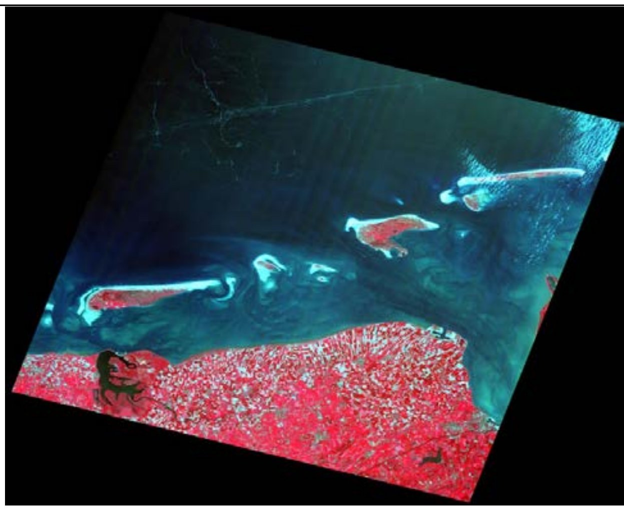
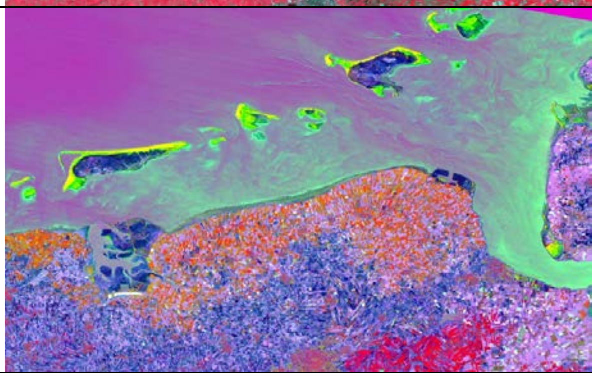
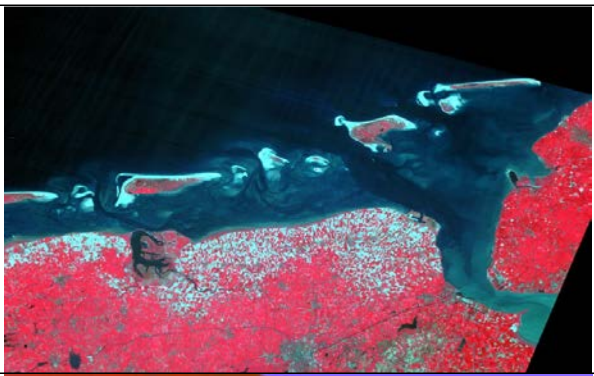
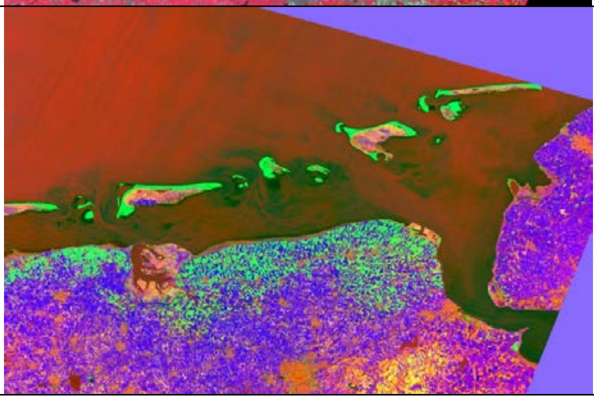
</td></tr>
<tr><td>Original image
The ASTER image is high tide, showing very clear the coast of mainland and islands. The tidal flats are completely covered by water and it is difficult to see channels and gullies development.
The PCA on ASTER image not done, because ASTER image in high tide and therefore it was not considered to use.</td><td></td></tr>
</table>

Table 4- Images in high tide, not used in the study

<table>
<tr><td colspan="2">Landsat- 5 image- High tide

- Date of acquisition- 1989-05-23
- Tide information by station Lauwersoog (53.4167° N, 6.2000° E):
- Time of High tide- 11:25 AM CET / 2.43 m

</td></tr>
<tr><td>Original image
Image in high tide showing high level of water around Schiermonnikoog and Rottumeroog islands. The delineation of mainland coast and islands are very clear. There are differences in color of the Wadden Sea and North Sea, which can be explained by bathymetry (deep in the North Sea) and shallow and turbid waters in the Wadden Sea.</td><td></td></tr>
<tr><td>PCA image
The PCA analysis shows that there are disctict differences between major structures, like sediments (green), sea water (violet) and sandy beaches (very bright yellow). However, tidal flats is completely covered by water and sediments expressed in green color are detected because area of the Wadden Sea is shallow and turbid.</td><td></td></tr>
</table>

<table>
<tr><td colspan="2">Landsat-5 image- High tide
• Image acquisition date- 1996-01-19
• Tide information by station Lauwersoog (53.4167° N, 6.2000° E):
- Time of High tide- 8:50 AM CET / 2.63 m</td></tr>
<tr><td>Original image
The channel and gullies development are not very well detectable. However, sandy beaches on islands and salt marshes along the mainland coast are clearly delineated.</td><td></td></tr>
<tr><td>PCA image
The PCA analysis shows that there are disctict differences between major structures, like sediments (green), sea water (violet) and sandy beaches (very bright yellow). The Wadden Sea is completely covered by high water and there is no much details are present.</td><td></td></tr>
</table>

The results from PCA analysis in one selected image show direct correlation of sediment reflectance and water content (caused by tidal differences). The scatterplot of the PCA image (Figure 6) shows highest amount of data in blue, (Band 1; 0.45 - 0.52 µm), green (Band 2; 0.52 - 0.60 µm) and red (Band 3; 0.69-0.83 µm), which is characteristic for water, wet soil and vegetation respectively.

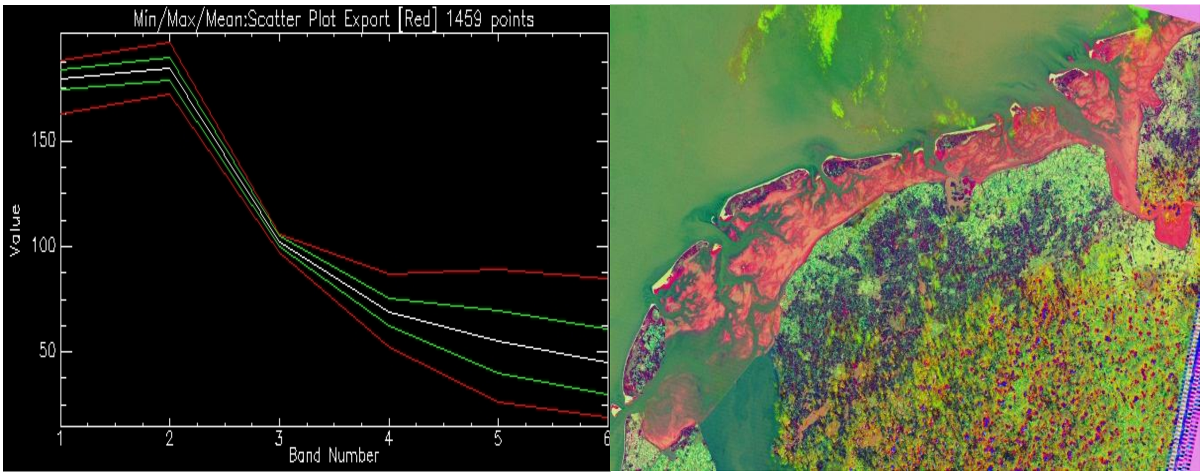


Figure 6- Scatter plot of PCA image (left) and corresponding PCA image (right)

Table 5 presents PCA statistic, with very high eigenvalues (PCA values) in first 3 bands and minimum values in band 6, which is mid-infrared band.

Table 5- Statistics of PCA analysis re Figure 6

Bands	**Min** (lower red line)	**Max** (upper red line)	**Mean** (grey line)	**Standard deviation** (green lines)	**Eigenvalue**
Band1	163	188	179.147361	4.921281	435.492695
Band2	172	197	184.440027	5.495821	83.351276
Band3	97	106	102.328307	2.674595	34.799761
Band4	52	87	69.113777	6.580676	10.199938
Band5	26	89	55.136395	14.800777	4.254306
Band6	19	85	45.261823	15.628093	0.084134

3.8.3 *Result from Modified Soil Adjusted Vegetation index*

The other spectral analysis on Modified Soil Adjusted Vegetation index (MSAVI), which is correlation of near-infrared NIR and red bands containing soil brightness correction factor. The difference between MSAVI and traditional vegetation and soil indexes, that MSAVI contain both indexes.

Equation 1- Soil brightness correction factor

$$L = 1 - \frac{2 * s(NIR - RED) * NIR - s * RED)}{NIR + RED}$$

Where: NIR- near infrared, RED- red bands; s- slope of soil line computed from plot of red versus near-infrared brightness values.

Equation 2- Modified Soil Adjusted Vegetation index

$$MSAVI = \frac{(NIR - RED)(1 + L)}{NIR + RED + L}$$

Where: NIR- near infrared, RED- red bands; L- soil brightness correction factor.

The index has values from minimum 0 (no contrast for soil, usually areas with water) to maximum 1 (depending from soil composition- mud, silt and sand content). Visually variations can be seen from very bright – high contrast, usually it is sandy and or very dry soil and very dark- low contrast- normally representing soil with high mud or water content. Results of MSAVI index in Figure 7. The image shows low contrast in soil values in emerging tidal flats (very dark grey) compare with high contrast sandy coast of the islands (very bright).

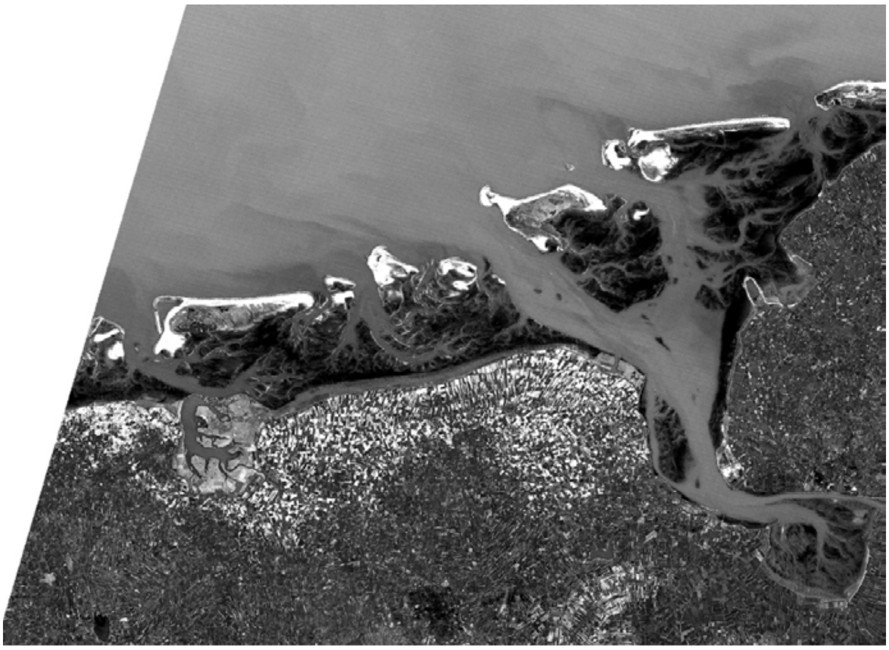


Figure 7-Landsat -7 ETM+; acquisition date- 2000-05-13

3.8.4 *Radar images*

The radar ERS data provides information on texture and roughness of surface features. The properties of ERS series satellites can provide additional information, for instance to verify classification results from Landsat data. One of the possible applications of radar data is image fusion. Images in lower resolution, e.g. Landsat 30 meters, can be merged at pixel level with ERS radar 12.5 meters data. As a result, a Landsat image will keep its multi-spectral properties which are useful in classification and will have an improved spatial resolution from 30 meters to about 20 meters. Figure 8 presents ERS-1 data of the Schiermonnikoog and Rottumeroog islands, compared to Landsat.

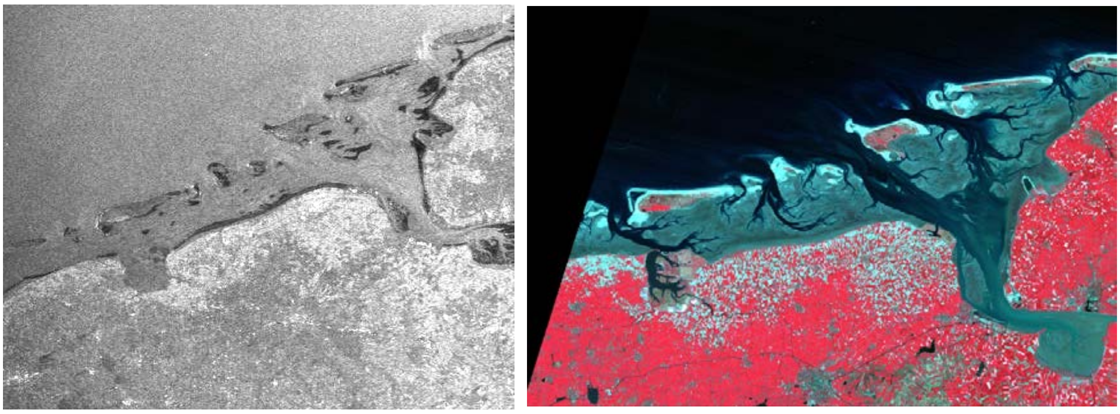


Figure 8-ERS-1 radar data of Schiermonnikoog and Rottumeroog islands. Radar image (left) with delineated area of islands. Landsat image on right, showing the same area.

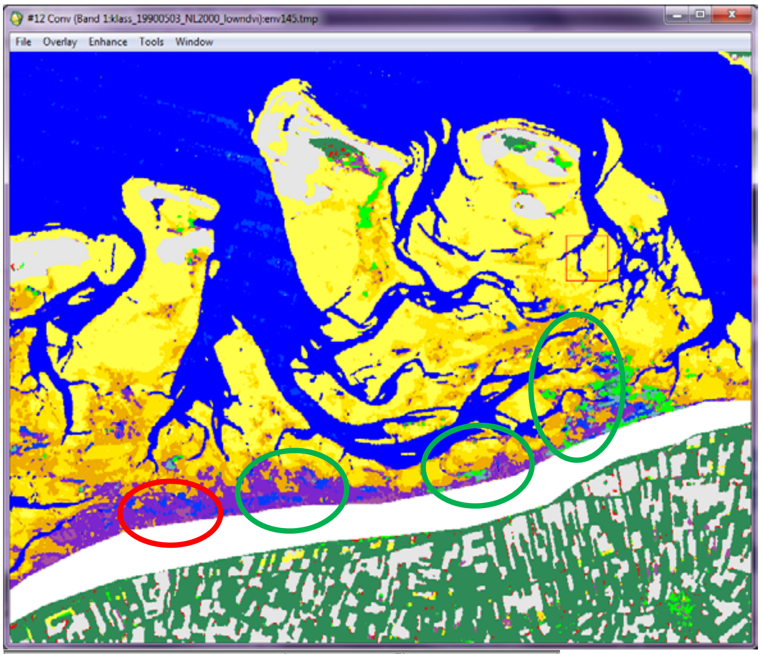
The radar image shows land in dark grey and water in light grey. Although the image is taken during low tide on 2003-10-28, the intertidal flats are not clear in the image.

4 Results

4.1 Classification

4.1.1 *Sediment*

The results of sediment classification using Landsat TM (30 meters resolution) data combined with ASTER and ERS (Figure 9) showed a clear separation between sand classes, mixed sediments, silt and silt mixed sediments and some mussel and oyster beds. The algorithm has been developed to predict sediment concentrations (content of mud and sand), location and size (area) of mudflats and areas covered with vegetation. The overall accuracy of the method comparing classified sediments with field data was nearly 80%.



Class_Names	Color	Area
		0
Sand		31932.4
Sand2 class		19099.4
Mixed sediments		13962.2
Silt sediments		8051.22
Silt sediments mixed		5153.67
Dense vegetated areas		7819.92
Dense vegetated areas 1		222944
Mussels/oysters		2247.21
Beach		28991.6
Water		282302
Unclassified		0
Other water features related		4204.26
Vegetation		2488.05

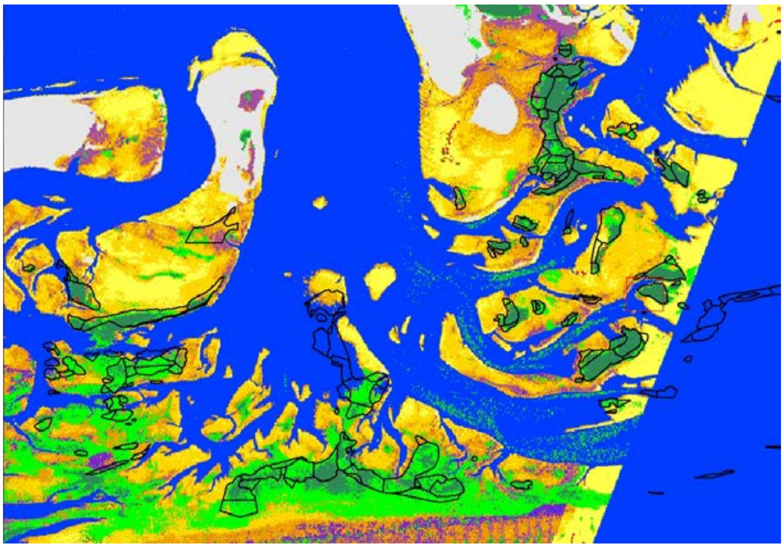
Figure 9-Sediments classification. Sediment types (in various colours) in the area between Rottumerplaat-Rottumeroog and the Frisian coast. Yellow = sand, purple = silt, green= vegetation, blue = water. Image date from 1990-05-03. Circles indicate locations for ground truthing. The red circle indicates a mismatch between the classification result and field data.

The table in Figure 9 shows the area size for each classified sediment type, expressed in hectares. The red circle in Figure 8 indicates a mismatch with field data. Very muddy areas with high water content can be mismatched with sandy areas also containing water, as they may appear similar. The dynamic of tidal movements and the water content of the sediment may also play role, since the area in the red circle (sandy according to field data) was already starting to fill up with water, whereas the areas indicated with the green circles were still dry. This means that satellite images have a high accuracy when there is a perfect match between low tide and the time the image was made. However, if there is a time difference the accuracy decreases and PCA images presented in Table 3 and 4 showing the distinct details in images in low tide and not much details in images in high tide.

The sediment image (Figure 8) dates from early May from 1990. Mussel beds were not present in that year. During early spring similarity in green colours in vegetated areas in the saltmarshes and some parts of sand and mudflats and arable land does not necessarily imply a similarity in chlorophyll, and/or vegetation biomass or coverage.

4.1.2 *Classification of mussel/oyster beds*

Figure 10 shows the result of a satellite image processed using the Brockmann algorithm developed to classify mussel and oyster beds. Superimposed over this image are the locations of mussel and oyster beds based on IMARES field data. The classified image from September 2006 shows mussel beds in a dark green colour. The black surrounded polygons in this figure represent a compilation of IMARES field data on the occurrence of mussel beds in 2005-2007, when large areas were covered with mussels. Mussel beds developed in this are from 1994 onwards after their disappearance in 1990 due to fisheries. A major expansion occurred in 2001 and after 2007 a gradual decline occurred. The light green colour may indicate fine silt which may cover parts of the bed area.



Class_ Names	Color
Unclassified	
Sand classes	
Sand classes 1	
Sand classes 2	
Sand classes 3	
Silt sediments1	
Silt sediments 2	
Probable mussel beds	
Mussel beds	
Other water features	

Figure 10- The location of mussel and oysters beds in the Simonszand-Frisian coast area (presented in dark green). Yellow = sand, purple = silt blue = water. Black lines indicate the maximum extension of mussel and oyster beds present between 2005 and 2007, based on IMARES field data. The satellite image represents the situation in 2006.

The Remote sensing classification result from 2006 shows a good match with the field data from 2005-2007. Some possible mismatches may be explained by tidal dynamics in one image, which may affect the appearances (spectral signatures) of the mussel and oyster beds. IMARES field data suggest that some mussel and oyster beds are located below the water line at the moment the image was recorded. In general the results are very promising.

4.1.3 *Temporal development of gullies and channels*

The intention of our study was also to generate knowledge on how historical satellite data can provide information on developments of channels and gullies and sediment characteristics, in particular what methods are available and what the applicability of such methods are to the Dutch Wadden Sea.
Gully and channel developments have been analysed by comparing two images using a change algorithm which can be used for historical monitoring of optical Landsat TM (30 m) images. The channel dynamics can be visualised and interpreted.

The main limitation of trend analysis specifically for the Wadden Sea is the high dynamics of tidal flats, recorded on satellite images as momentum state of non-correlated temporal patterns in high spatial variability, further complicated by the periodicity of tidal waves. The study by Hommersom et al. (2010) revealed that existing algorithms tested in the Wadden Sea are limited due to a high variation in concentrations of various substances and sediments. It is difficult and not always possible to precisely differentiate spectral mixes of different objects and substances present in one area. In this case a comparison of images for specific trend analysis of specific patterns in sediment composition is not possible. However, it is possible to see such trends in “hard” substances such as coastal land, which is clearly demonstrated in Figure 11, showing changes in the course of channels as well as changes in the shape of the sandy coastline on the northern shore of the island of Schiermonnikoog, Rottumeroog and Rottemerplaat between November 25, 1995 and July 1, 2009.

Especially the inner delta between Schiermonnikoog and Rottumerplaat shows strong changes in the running of channels as well as a widening of some channels. Early detection of such changes may be very helpful in detecting potential threats for coastal defence. Changes over one year are presented in Figure 12, comparing images of July 1, 2009 and July 4, 2010. The two arrows indicate erosion at Simonszand (east) and De Balg at Schiermonnikoog (west).

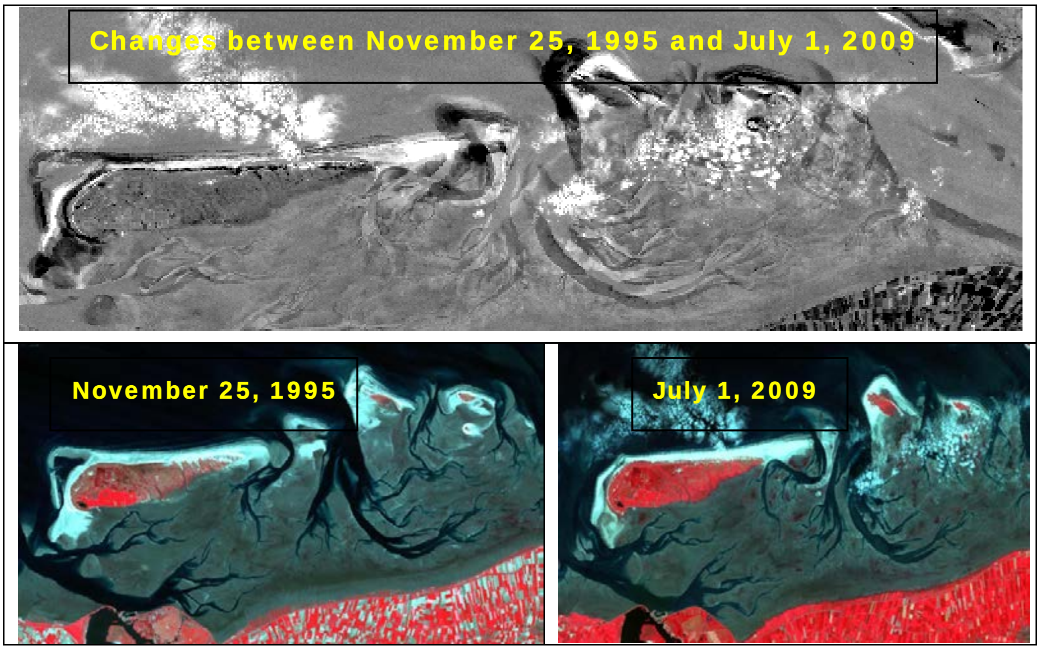


Figure 11-Upper image: changes in morphology between November 25, 1995 (lower image left) and July 1, 2009 (lower image right). The level of change is indicated by the amount of contrast. Grey areas indicate no change. Darker areas indicate features present in the past (i.e. 1995) and could point to erosion; lighter areas indicate features that were not visible in the past and could point to newly emerged intertidal areas.

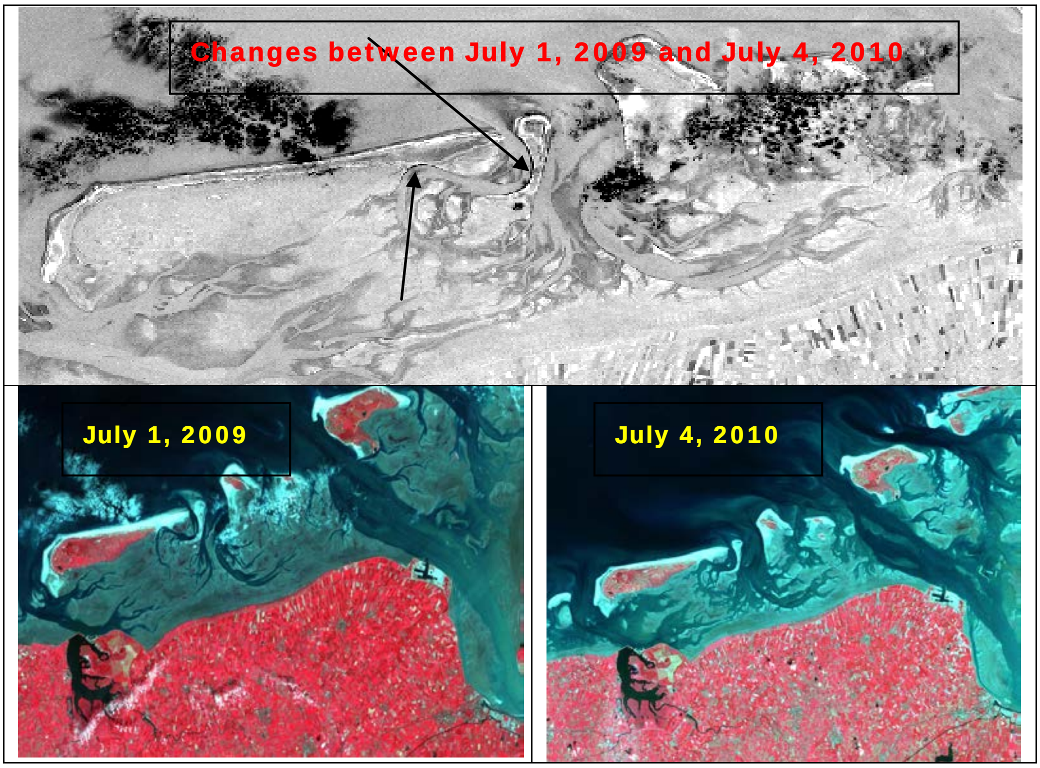


Figure 12-Upper image: changes in morphology between July 1, 2009 (lower image left) and July 4, 2010 (lower image right). The level of change is indicated by the amount of contrast. Grey areas indicate no change. Darker areas indicate features present in the past (i.e. 2009) and could point to erosion; lighter areas indicate features that were not visible in the past and could point to newly emerged intertidal areas.

5 Future applications

5.1 Storm database

An application with relevance for decision-making with respect to coastal defence is a storm database. IFREMER (the French Research Institute for Exploration of the Sea) developed a storm database based on historical Remote sensing data (ERS-1 and ERS-2) and information on storm history:

- date, time
- duration of the storm in hours
- strength of the storm: wind direction; wave height (maximum in meters); wind velocity (meters per hour); amount of rain (in mm)
- location and size of affected area, derived from historical ERS data.

The meteorological data are used for deriving a Storm occurrence index, estimated by statistical analysis of historical storms and storm forecasts. The Storm occurrence index shows the probability of future storms, and models areas to be affected. A storm occurrence index is very useful in combination with information on stability and resilience of coastal ecosystems which have a wave attenuating capacity such as mussel and oyster beds and salt marshes. Stability and resilience of these ecosystems in relation to storm occurrences (strengths, frequencies, direction of attack) determine the extent to which coastal defence strategies can rely on wave attenuation by salt marshes and mussel and oyster beds. A storm damage observation team (a saltmarsh resilience team or Quick Reaction Force) is recommended to gather field data on storm damage and subsequent recovery time for wave attenuating coastal ecosystems. A Quick Reaction Force has the objective of gathering relevant information and data on coastal damage as soon as possible after a (major) storm. Base-line data on coastline, dunes, locations and extents of mussel and oyster beds, salt marshes and channels and gullies, and elevation of intertidal flats and salt marshes need to be available before each storm event. Re-establishment needs to be monitored between storm events and calibration before the next storm event is necessary to reset the base-line data. Organisation of pre- and post-storm measurements will determine the pace at which relevant (eco) systems recover from storms and if the measures taken as to compensate for erosion are sufficient to meet the objectives of the Delta Programme and to uphold the pre-set safety levels. Measurements should comprise new dune and tidal marsh formation between two storm seasons as to determine the (semi) natural resilience of dune and tidal marsh systems to storm events. Remote sensing may prove instrumental to assess these data just before and immediately after each storm season.

5.2 Integrated model

Analysis of the past provides scenarios for future developments on which coastal defence strategies can be based. Remote sensing data and meteorological forecasting can be merged into an integrated model with the objective to predict possible extreme event (storm) damage to e.g. intertidal flats, mussel and oyster beds, salt marshes, dunes and beaches, etc. For the development of such a model the expertise and instruments of e.g. IFREMER, Deltares and IMARES can be combined (Strom index, FEWS- Water Level Forecast Early Warning System, IMARES Wave prediction mode). This integrated model can be updated each year with new information on the developments of gullies and channels, intertidal flats, salt marshes and mussel and oyster beds, fine-tuning the short term predictions and extending long term projections. Such a decision support tool will be a powerful instrument for coastal managers as to evaluate the effectiveness and longer term sustainability of their management practises and if and when adaptations are necessary to meet certain coastal defence policy standards. The proposal on an integrated model is presented in Figure 13.

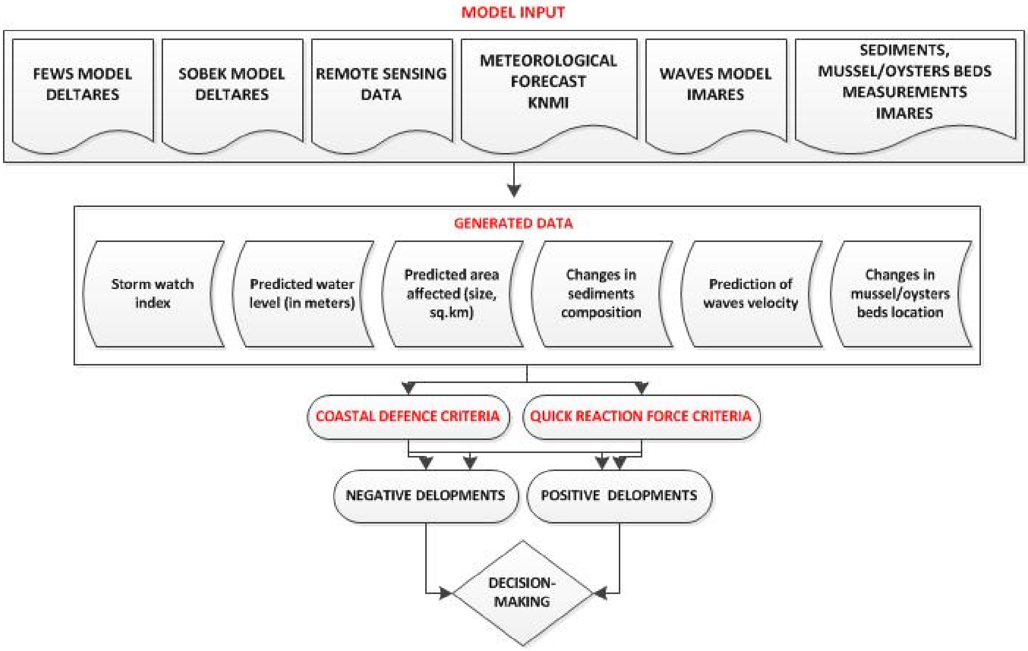


Figure 13-Proposal of integrated decision support model

5.3 High resolution satellite data

The new generation of high resolution satellite missions include sensors with imaging capability in resolutions better than 10 meters. The WorldView-2 images cover the Frisian community of Dongeradeel and the north-western part of Groningen, De Marne and partly of the islands Schiermonnikoog, Rottumerplaat and Rottumeroog islands (Figure 14).

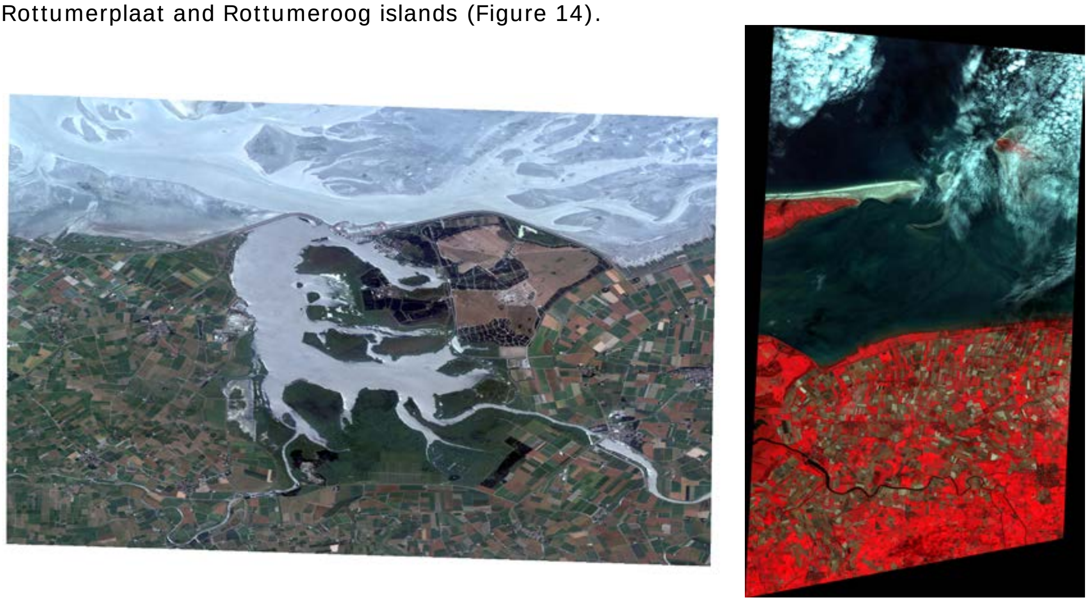


Figure 14-WorldView-2 images

High resolution WorldView-2 images contain information in blue, green, red and infra-red bands with an additional panchromatic very high resolution (0.60 cm) band. The data is supplied by the commercial company Digital Globe (USA). The standard image product contains radiometrically corrected pixels.

Further corrections for atmospheric and other effects are necessary. An overview of sensor characteristics is given in Table 6.

Table 6- Sensor characteristics of the WorldView-2 satellite product information

Product	
Multispectral (4-bands)	Resolution-2,4 meters Bands- Blue, Green, Red, NIR1
Panchromatic band	Resolution- 60 cm
Spectral resolution	
Multispectral (4-bands)	*Optical range*
Blue	442 - 515 nm
Green	506 - 586 nm
Red	584 - 632 nm
NIR1	765 - 901 nm
Panchromatic band	447 - 808 nm

Compared with medium resolution data (e.g. Landsat), high resolution WorldView-2 data has shorter extents in blue, green and red spectrums, meaning that collected information is less comparable with the Landsat sensor, but this is compensated by the advantage of high resolution. The 0.60 cm panchromatic band is ideal for visual interpretation, especially to identify and to locate mussel and oyster beds.

An automated detection algorithm for location and size of mussel and oyster beds and sediment composition is being developed by IMARES (submitted for publication). The algorithm is based on building libraries of spectral signatures of sediments and mussel and oyster beds, taken from one area. In the next step the collected spectral signatures are used and extrapolated to a wider area (Figure 15).

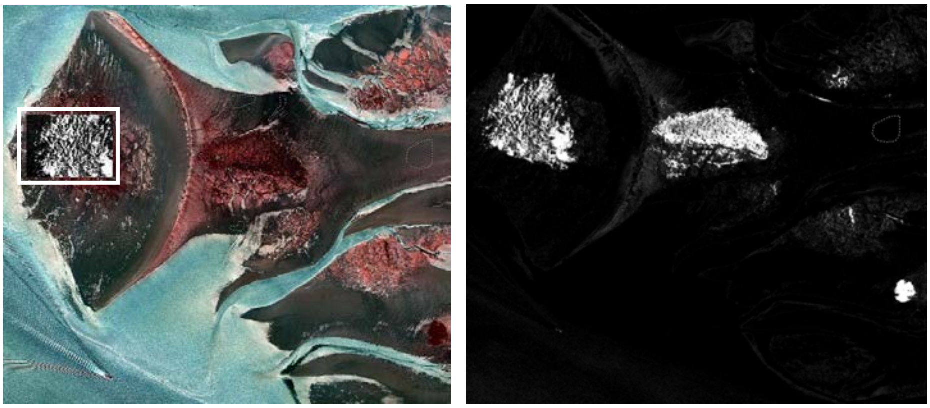


Figure 15- Result of a mapping of habitat types using the IMARES algorithm. Satellite image with detected mussel/oyster beds (black and white picture). Left: step 1 relating spectral signatures of different types of sediment and mussel/oyster beds in a selected area with known locations of mussel beds and sediment composition. Right: step 2 extrapolation of the results from left picture to a wider area. Image resolution- 2 meters.

Figures 16 and 17 shows images that can be used for mapping areas where changes in salt marshes occur, by showing developments in the occurrence of pioneer vegetation, changes in areas with cliff erosion, changes in vegetation coverage, etc. Regular flooding of salt marshes delivers sediment to the system which results in vertical growth and vegetation change. This function of salt marshes is an important ecosystem service which can be included in coastal defence strategies. Algorithms for high resolution salt marsh zonation mapping still need to be developed.

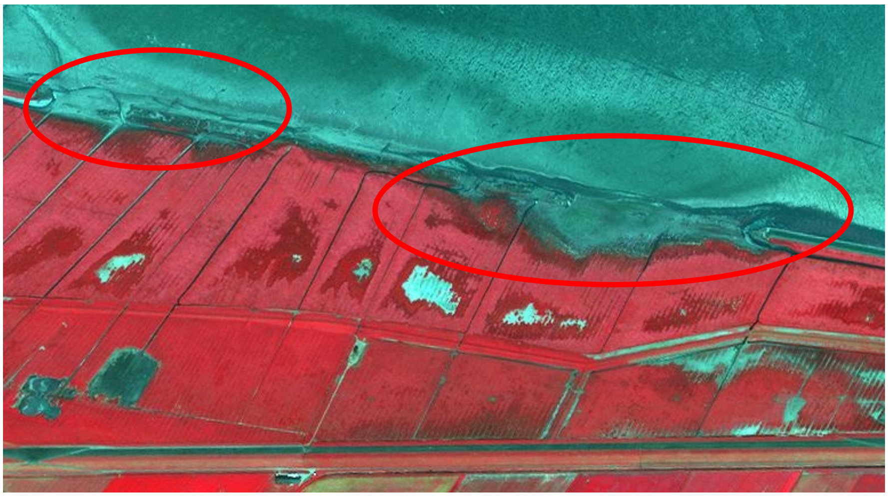


Figure 16- Salt marshes along the coast (Peazemerlannen, Friesland). Levee breaks Breaches in dikes bordering the former summer polders (1976) are highlighted in red circles (image date: October 2006). The flooded area behind the broken dike level increased towards the coast. In these areas salt marsh rejuvenation occurs. Date: October 2006

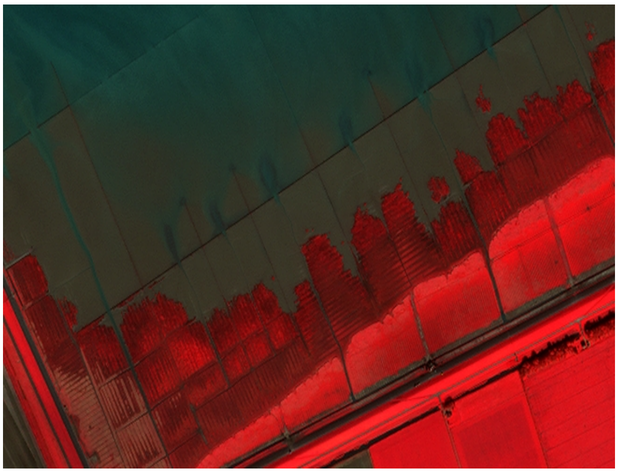


Figure 17- Salt marsh zones (Westpolder, Groningen) in bright red (high salt marsh), dark red (lower salt marsh and pioneer zone) and brown (diatoms and/or pioneer zone). Date: July 2011.

6 Discussion

Remote sensing can be a very useful and relatively inexpensive tool for detecting specific characteristics of emerging tidal flats. Detailed detection of the properties of these characteristics requires satellite data taken during cloud free weather and low tide. For each historical satellite mission, on average four images per year are available for the specific parts of the Dutch Wadden Sea. Considering the limitations on usability of historical satellite data mentioned in Section 3.6. the number of images which can be used for trend analysis and any other related analysis of sediments and mussel and oyster beds, is limited.

The historical Landsat data showed different characteristics of intertidal sediments in terms of water content and sand and mud content. The locations of mussel and oyster beds can be fairly well detected on images acquired during low tide. However, due to tidal variation even over small distances, additional algorithm calibrations are necessary to increase classification accuracy and need to be developed. In order to cover the total Dutch Wadden Sea area, multiple satellite images are needed, each targeting specific sections of the Wadden Sea within a rather narrow low tide window. This may offer considerable challenges when attempting to analyse dynamic developments for the whole Dutch Wadden Sea based on series of images from different years and from different months. The use of radar images that do not require cloud free conditions may prove useful to add information to multi-spectral data, for instance to enhance the spatial resolution of 30 meter Landsat images to 20 meter and 15 meter ASTER images to 12 meter. This enhances visibility and detection of mussel and oyster beds and will possibly improve the sediments classification. Another contribution from radar images is provision of information on surface texture and roughness, which can be used in verification of areas that are not clearly classified at multi-spectral images.

Time series of satellite images showed progression of gullies and channels towards the coast, potentially endangering defence structures. Combined with hydrodynamic models the application of Remote sensing techniques may also provide information on (future) current and wave climates and angles of attack on coastal defence structures. Gully development in combination with mapping of specific characteristics of intertidal flats may provide additional knowledge on gully behaviour, e.g. in relation to locations of mussel and oyster beds.

Because of the limited historical number of (medium resolution) multi-spectral satellite images available for the Wadden Sea (up to four images per year) satellite based Remote sensing of temporal trends of highly dynamic and variable parameters (such as diatoms) is not recommended. For structures like salt marshes, mussel and oyster beds, intertidal flats and gullies and channels, however, Remote sensing is highly applicable for measuring temporal or spatial changes, which can be seen in Section 4.3.1 on Temporal developments of gullies and channels. Especially newly developed automated high resolution classification algorithms mentioned in Section 5.3 and those determining temporal changes on specific locations (c.f. Figure 10-11) are very promising for application in future monitoring programmes. Remote sensing may be especially beneficial for applications in relation to a Quick Reaction Force which should gather field data on storm damage and subsequent recovery time, as well as for monitoring of indicators for change.

Potential indicators for drowning or rising intertidal areas in the Wadden Sea must be found in parameters that show little natural variation, that are relatively unaffected by changes (natural variation) in other ecosystem parameters, that are unaffected by drivers forcing changes in external, but interconnected, systems, and that do not show sudden shifts within the ecosystem. From a management point of view these indicators must be easy to measure and assess, and it must be possible to subject mechanisms forcing indicator change to management practises. Available techniques to measure the elevation of tidal flats and developments of channel dimensions do not yet have the required accuracy for early detection of significant changes. However, detailed knowledge exists about the habitat requirements for the development of salt marsh pioneer vegetation. Monitoring of the total area of pioneer vegetation in the Wadden Sea, relative to the total area of salt marsh and of intertidal flats at a given water reference level may be a useful indicator for changes in tidal flat elevation and could be easily detected by Remote sensing. The rate at which the pioneer area is developing or disappearing, or a maximum and minimum ratio between pioneer, total salt marsh and total intertidal area could be taken as critical boundary conditions for management adaptations. These so-called Adaptation Tipping Points are defined as moments in time when the magnitude of change due to sea level rise or erosion of the Wadden Sea is such that the current management strategies, aiming to maintain conditions to fulfil coastal defence functions, will no longer meet the coastal defence policy objectives (Deltares and IMARES, 2012).

Conclusions:

- Historical coverage.

Historical coverage of medium resolution multi-spectral satellite images over the Wadden Sea is almost 30 years. These data are useful as a primary source to detect spatial and temporal changes. Field data on sediments in (specific parts of) the Wadden Sea are available for calibration between 1980 and 2001 (not every year). Field measurements on locations and changes in areas of mussel and oyster beds are conducted every year since 1995, and each area of mussel/oyster bed is revisited every year. Sometimes because of weather condition (storm) and not accessibility to the bed by ship (water condition), then mussel/oyster beds which were not visited, will be visited next year.

- Synoptic view.

The Landsat satellite covers an area of 170 x 185 km on the ground, providing a synoptic overview over selected areas, including areas difficult to reach.

- Cost effectiveness.

Historical Landsat data is available at no cost and continuity of the Landsat mission is foreseen with the launching the Landsat-8 satellite. The new application of high resolution data and design of automated algorithms to detect e.g. mussel and oyster beds and salt marshes zonation can substantially reduce monitoring expenses.

- Resolution.

A resolution of 30 meters is quite accurate in sediment (up to four to six classes) and oyster and mussel bed classification and in detecting temporal and spatial changes in coast line and channels and gullies.
New applications for high resolution satellite data provides precision of details up to 60 cm on the ground, allowing to directly zoom into areas of interest where observed changes can be studied in detail.

- Promptness of information.

The Landsat images can be directly viewed after acquisition. Even without pre-processing, changes along the coast and in channels and gullies can be quickly and easily viewed and detected. It may serve well as a Quick Reaction Force tool.

- Presentation of the results.

The satellite images can be directly printed and viewed, and information contained on images is easily understood by the general public, local communities and decision-makers.

- Data integration.

The satellite data can serve as additional input in integrated models, including hydrodynamic and wave models, as to assist decision making.

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Quality Assurance

IMARES utilises an ISO 9001:2008 certified quality management system (certificate number: 57846-2009-AQ-NLD-RvA). This certificate is valid until 15 December 2012. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V. Furthermore, the chemical laboratory of the Environmental Division has NEN-AND-ISO/IEC 17025:2005 accreditation for test laboratories with number L097. This accreditation is valid until 27 March 2013 and was first issued on 27 March 1997. Accreditation was granted by the Council for Accreditation.

Justification

Report number C057/12
Project number: 4308602005

The scientific quality of this report has been peer reviewed by the a colleague scientist and the head of the department of IMARES.

Approved: Marcel Rozemeijer, Dr.
Scientist

Signature:

Date: 27 June 2012

Approved: F.C. Groenendijk, MSc.
Head of Department

Signature:

Date: 27 June 2012

Appendix 1 – Complete overview of available cloud-free and low-tide Landsat satellite images

Information source:

1. U.S. Earth Resources Observation and Science Center (EROS) (http://glovis.usgs.gov)
2. EOLi (Earth Observation Link) catalogue from European Space Agency (http://earth.esa.int/EOLi/EOLi.html)
3. U.S. Geological Survey, Landsat missions (http://landsat.usgs.gov/)

Table 1- Landsat image acquisition dates

N	**Date of image acquisition**	N	**Date of image acquisition**	N	**Date of image acquisition**
1.	1984-06-19	42.	1997-08-10	83.	2008-05-11
2.	1984-11-01	43.	1998-05-16	84.	2008-09-09
3.	1985-03-25	44.	1998-05-18	85.	2009-03-20
4.	1985-04-26	45.	1999-07-30	86.	2009-04-03
5.	1986-06-16	46.	1999-10-18	87.	2009-04-20
6.	1987-05-02	47.	2000-04-10	88.	2009-05-30
7.	1987-07-05	48.	2000-04-20	89.	2009-07-01
8.	1987-07-14	49.	2000-05-06	90.	2010-06-02
9.	1984-08-20	50.	2000-05-13	91.	2010-06-27
10.	1987-07-05	51.	2000-08-18	92.	2010-07-04
11.	1987-07-14	52.	2000-08-26	93.	2011-01-28
12.	1987-10-02	53.	2001-01-17	94.	2011-01-28
13.	1989-04-30	54.	2001-05-07	95.	2011-02-22
14.	1989-05-16	55.	2001-05-23	96.	2011-04-11
15.	1989-05-23	56.	2001-05-25	97.	2011-05-12
16.	1989-07-03	57.	2001-12-10	98.	2011-09-02
17.	1990-03-05	58.	2002-01-04		
18.	1989-08-20	59.	2002-09-24		
19.	1989-09-21	60.	2003-04-20		
20.	1990-03-16	61.	2003-09-18		
21.	1990-03-30	62.	2003-09-19		
22.	1990-04-01	63.	2004-04-23		
23.	1990-10-26	64.	2004-09-15		
24.	1991-04-04	65.	2005-04-01		
25.	1991-09-02	66.	2005-04-24		
26.	1992-05-22	67.	2005-05-26		
27.	1992-05-24	68.	2005-05-28		
28.	1993-03-15	69.	2005-07-14		
29.	1993-05-11	70.	2006-05-06		
30.	1993-10-18	71.	2006-06-30		
31.	1994-05-14	72.	2006-07-02		
32.	1995-05-01	73.	2006-07-16		
33.	1995-08-12	74.	2006-07-17		
34.	1995-11-25	75.	2006-07-18		
35.	1996-04-24	76.	2006-09-11		
36.	1996-07-22	77.	2006-09-12		
37.	1997-03-03	78.	2006-09-13		
38.	1997-03-10	79.	2007-04-15		
39.	1997-05-13	80.	2007-06-02		
40.	1997-06-07	81.	2007-08-05		
41.	1997-08-08	82.	2007-08-06		

Appendix 2- Glossary of Technical Terms

- **Remote sensing**- can be defined as the collection of data about an object from a distance. Humans and many other types of animals accomplish this task with aid of eyes or by the sense of smell or hearing. Geographers use the technique of Remote sensing to monitor or measure phenomena found in the Earth's lithosphere, biosphere, hydrosphere, and atmosphere. Remote sensing of the environment by geographers is usually done with the help of mechanical devices known as remote sensors. These gadgets have a greatly improved ability to receive and record information about an object without any physical contact. Often, these sensors are positioned away from the object of interest, features (see Features) by using helicopters, planes, and satellites. Most sensing devices record information about an object by measuring an object's transmission of electromagnetic energy from reflecting and radiating surfaces. Features- features can be objects of nature- forest, land, water, etc. and artificial, man-made- e.g., urban structures, artificial mountains, structures in the sea, ships, platforms, etc. Objects of the nature and man-made objects can be detected from the space and recorded on satellite images, based on reflectance or spectral signature (see Reflectance).
- **Features**- features can be objects of nature- forest, land, water, etc. and artificial, man-made- e.g., urban structures, artificial mountains, structures in the sea, ships, platforms, etc. Objects of the nature and man-made objects can be detected from the space and recorded on satellite images, based on reflectance or spectral signature (see Reflectance).
- **Reflectance** (spectral signature) - when sun light hits any surface on earth, the sun light can be absorbed (for example by water), transmitted back (dry soil), reflected in full extent (house roof, ice and snow cover) or partially- forest, land, etc. The strength of the transmission, absorption and reflection is depending from the texture and type of the surface. The satellite sensors record the transmitted and reflected signals. Reflectance value (Spectral signature) is a number, presented in bits and stored as numerical values in the image.
- **Texture** (of the feature) - the real objects often do not exhibit regions of uniform intensities. For example, the image of a wooden surface is not uniform but contains variations of intensities which form certain repeated patterns called visual texture. The patterns can be the result of the physical surface properties such as roughness or oriented strands which often have a tactile quality, or they could be the result of reflectance differences such as the colour on a surface. In Remote sensing the texture of the surface is used in image classification.
- **Image**- image is representation of captured signal or sun light. The features are shown in colours if image is in colours (see Colours) or in black and white (see Panchromatic image). The image can be analogue- printed, or digital- stored in the computer. In Remote sensing, image has two dimensional functions- X and Y coordinates, and size of the image consists from Row and Columns (Height and Width). Such image is called a raster image.
- **Raster** (image) – raster (image) consists from the squares (grid). Each cell of the grid (see Grid) is represented by a pixel (see Pixel), also known as a grid cell.
- **Grid-** square in the image, representing the smallest element of the image. In Remote sensing, the grid is called Pixel (see Pixel).
- **Colors**- the colors are continuous range, starting from Black to Red, Magenta, Yellow, Green, Blue, Violet to White. The colours used in images represented in mixtures. Each feature can be identified by distinct colour.
- **Panchromatic image**- it is black and white image and image values (see Image) are represented in range from black (zero value) to the white. The image values from black to white are represented in shades of grey.
- **Multispectral image**- it is image containing several bands (see Bands) and it shows features in different colours, depending from bands combination.

- **Wavelengths**- are the distances between repeating units of a propagating wave of a given frequency. The light, microwaves, x-rays, and TV and radio transmissions are all kinds of electromagnetic waves. They are all the same kind of wavy disturbance that repeats itself over a distance called the wavelength.
- **Electromagnetic spectrum**- it is physical definition of wavelengths, expressed in nanometres (see Nanometres). The spectrum used in Remote sensing starts from infrared region (near, middle and far infrared), visible region (Red, Green, Blue) and thermal.
- **Nanometres**- a nanometre is 0.000000001 meters, equal to 10^{-13} meters.
- **Infrared** region of wavelengths- starts from 0,7 to 5,0 nanometres.
- **Optical range**- often referred as visible region (Red, Green and Blue light). The Blue region starts from 0,4 to 0,5; Green region from 0,5 to 0,6 and Red from 0,6 to 0,7 nanometres.
- **Satellite sensor**- is a camera mounted on satellite, which records reflected and transmitted reflectance of features in selected wavelengths. Every satellite has distinct range of electromagnetic spectrum to record.
- **Image Processing**- is a process which extracts information about features based on their reflectance, transmission and absorption property of the sun light.
- **Resolution** of the satellite image- is a broad term commonly used to describe the number of pixels you can display on computer, or area on the ground (in meters, centimetres, etc.), often called a pixel (see Pixel) represented in an image. The resolution is fixed for each satellite. For instance the resolution of the Landsat satellite is 30 meters.
- **Pixel**- it is area on the ground which represents is a single point on a raster image, or the smallest addressable screen element on a display device; it is the smallest unit of picture that can be represented or controlled. In satellite image the pixel is related with sensor resolution.
- **Spectral resolution**- the specific wavelength intervals that a sensor can record and it is fixed for each satellite. For example for the WordView-2 satellite, the spectral resolution is starts from Blue wavelength (see Wavelengths) and includes another blue wavelength, green, yellow, 2 red and 2 infrared wavelengths of the spectrum. Often these wavelengths are called bands of the image (see Bands).
- **Bands** (of image) - bands are recorded range of Electromagnetic spectrum by satellite sensor of reflectance's of the features. The range of the bands is expressed in nanometres and each satellite sensor has predefined range.
- **PCA- Principal Component Analysis**. The technique based to compress information, especially when image contain several bands. The so-called principal components are indicating where the most of the information is and in which bands.