Carsten Brockmann

Coastal management of estuarine environments: Application of remote sensing

Abstract

Proper management of estuarine environments requires appropriate management plans as well as tools to carry out these plans. This paper reviews the use of remote sensing as a valuable tool in monitoring of estuarine ecosystems. One problem with respect to monitoring of estuaries is that a small pixel size is required, but an overview of currently available space born sensors show that a number of satellite sensors provide the required spatial resolution. Another difficulty with the interpretation of optical remote sensing images is that they contain a mixture of signals originating from different origins, i.e. from mud, water, microphytobenthos etc. Decomposition of the composite signal into its components by Linear Spectral Unmixing provides good results for intertidal areas. It is concluded that the best way to monitor estuarine environment is by a combination of available methodologies, including remote sensing.

Introduction

The proper management of estuarine environments requires a) the appropriate policy directives and b) the necessary tools to carry out these directives. The increasing number of multilateral environmental treaties and EU Directives since the 1972 Stockholm Conference is an encouraging sign and testament to man's increasing concern and commitment to protecting particularly sensitive environments. However, because of this proliferation in the number of directives and treaties there is also a concomitant growing need for more information relating to the health of ecosystems, in order to better understand the biogeophysical processes involved and the socio-economic consequences which global, regional and national policies can have on these systems.

The growing acceptance of remote sensing data in the contribution to our understanding of coastal systems – in a visually compelling way – reflects the development which has taken place in the algorithm development necessary to properly process these data. A global assessment of ecosystems without such data is next to impossible and this is realized by scientists and policy makers alike. The use of remote sensing data to assist in environmental problems is mentioned in no less than 8 paragraphs and 11 sub-paragraphs in the recent Earth Summit on Sustainable Development - Plan of Implementation in Johannesburg in September, 2002. Most notably is the statement in Paragraph IV; 'Protecting and managing the natural resource base of economic and social development' subparagraph 35(c) which states:

> '*An integrated, multi-hazard, inclusive approach to address vulnerability, risk assessment and disaster management, including prevention, mitigation, preparedness, response and recovery, is an essential element of a safer world in the twenty-first century. Actions are required at all levels to*: *…………Strengthen, the institutional capacities of countries and promote international joint observation and research,* ***through improved surface-based monitoring and increased use of satellite data….***'

The following contribution will provide examples of how remotely sensed data can be used as an integral part of measurement, monitoring and management strategies for tidal flat areas. This will be illustrated using examples of results from two EU-funded projects, namely BIOPTIS (Assessing the Biological and Physical Dynamics of Intertidal Sediment Ecosystems: A Remote Sensing Approach) [BIOPTIS] and HIMOM (A System of Hierarchical Monitoring Methods for Assessing Changes in the Biological and Physical State of Intertidal Areas) [HIMOM].

Coastal management requirements

The management of estuarine and tidal flat environments requires, on the one hand, the monitoring of a multitude of parameters, on a multitude of spatial and temporal scales while on the other hand, the necessary tools to translate this scientific knowledge into facts which can be used in decision making. These tools help translate science into decisions, however, it should be clear to the scientists, who make the measurements, which parameters are of most importance in terms of the long-term sustainability of the system and how to structure these measurements to assist in long-term monitoring strategies. Tidal flat areas such as the Wadden Sea are a unique heritage which need careful management if they are to have long term sustainability. This is why the governments of Holland, Germany and Denmark place such emphasis on the advice and guidance of the Trilateral Monitoring and Assessment Group (mostly scientists) which laid down guidelines for what parameters are of importance to monitor to safeguard the future sustainability of this ecosystem [TMAP 2001].

A healthy ecosystem can be viewed as having the correct balance between productivity and biodiversity. The cornerstone of most aquatic ecosystems in terms of productivity has been shown to be the algae i.e. the phytoplankton and microphytobenthos. Berger *et al.* (1989) for instance estimated a two to five fold greater production in shelf areas compared to what occurs in open oceans. Postma (1982) concluded that the productivity of the phytoplankton in the Wadden Sea was about three times greater than that of the adjacent North Sea. This is a dramatic difference between a tidal flat area and the open ocean. Considering just the Wadden Sea alone, Asmus *et al* (1996) found that the productivity of the plants species (excluding macroalgae) can be divided between the phytoplankton contributing to 52 % of the total, microphytobenthos to 45% and the seagrasses to 3% These results illustrated the enormous importance of the microphytobenthos to the overall productivity of tidal flat areas in the Wadden Sea.

However, the authors of the Trilateral Monitoring and Assessment Programme Evaluation Report (TMAP 2001) noted that the large majority of the parameter groups could be implemented but gaps still existed in the Common Package Parameters. It was noted that the TMAP provides no information for calculating the primary production of the benthic microalgae, which was considered to be a serious gap. It was noted that several gaps, which include information on the development of the coastline or mapping of habitat parameters of salt marsh areas, were not included in the Common Package (Figure 1) and that these gaps could be filled in using remote sensing techniques.

Solutions – current and future practices

Monitoring requirements of the various parameters, e.g. as in the TMAP Common Package, differ in their spatial and temporal resolution, which has a strong impact on the most suitable technique to use. Today most measurements are made by ground sampling with subsequent laboratory analysis. Only points are sampled and the selection of measurement points is biased by the accessibility of the area. Because of this time consuming procedure, large areas such as the Wadden Sea can only be sampled sparsely.

Common Package of TMAP parameters		
Chemical Parameters • Nutrients • Metals in sediment • Contaminants in Blue Mussels, Flounders and birds eggs • TBT in water and sediment	Biological Parameters • *Phytoplankton* • *Macroalgae* • *Eelgrass* • Macrozoobenthos • Breeding birds • Migratory birds • Beached birds survey • *Common Seals* • *Benthic microalgae*[*] [*]…addition after TMAP evaluation, Esjberg 2001 *Italic = potentially measurable by remote sensing (direct of indirect)*	Human Use Parameters • Fisheries • Recreational activities • Agriculture • *Coastal Protection*
Habitat Parameters • *Blue Mussel beds* • *Salt marshes* • *Beaches and Dunes*		General Parameters • *Geomorphology* • *Flooding* • *Land use* • *Weather conditions* • *Hydrology*

Figure 1. Parameters included in the TMAP Common Package. Parameters which can potentially be measured by remote sensing techniques are printed in italics.

Temporal monitoring requirements as laid down by the Water Framework Directive, the Habitat Directive or the TMAP, are ranging between daily to weekly measurements, e.g. for algal bloom monitoring (SISCAL), up to 5 year surveys for coastal morphology. The requirements for microphytobenthos, as formulated in the TMAP, are in the order of a seasonal assessment. In some cases the time for taking the measurement is event driven, i.e. triggered by natural circumstances, such as the evolution of a spring bloom. The spatial monitoring requirements vary between the decimetre/meter scale, e.g. for microphytobenthos, over a scale of 10-50 m, which is a typical resolution for a large scale assessment of primary productivity up to a scale of 1 km for monitoring water quality parameters. Today, several remote sensing systems which match these requirements are in operation (see Table 1).

Optical remote sensing instruments measure the sunlight backscattered from the sediment surface or from the euphotic zone of a water body. The light is spectrally resolved in several spectral bands. Methods are available today to qualitatively and quantitatively derive parameters from these measurements, which are requested by the monitoring programmes. The instruments can be operated from airplanes and are included on satellites. Satellites have the advantage of providing a larger overview and regular overpasses over an area of interest, while airplanes have the advantage of higher spatial resolution and are less dependent on cloud coverage. As an example, a Landsat 7 ETM image of the Sylt-Romo Bight in the North Frisian Wadden Sea is shown in Figure 2 as a black and white composite. In the Wadden Sea the vegetated areas are highlighted. The data have a spatial resolution of 30 m.

Every image pixel is the measurement of the sunlight reflected from an area at the surface covering 30 m x 30 m. This area is generally not uniform but a mixture of sediment of a certain grain size, vegetation of one or more species, and more or less water coverage. As a consequence, the signal measured at the sensor is a mixture of the reflectances of all different elementary surface types. Methods exists to decompose this measured signal into its components, one of these being the Linear Spectral Unmixing (LSU) (Adams *et al.*1989) which provides good results in intertidal areas (Stelzer *et al.* 2004). As a result, the portion of each elementary surface type in every image pixel is derived. The resulting image then shows, for example, the sand and mud fraction or the water coverage (Figure 3). This can be further calibrated with ground truth points in order to derive a quantitative image.

This is only one example of the contribution which remote sensing can provide to fulfil coastal monitoring requirements. On the smaller spatial scale, i.e. in the range of 1-5 m resolution, systems such as Ikonos have been available for quite a few years, which provide less spectral information but much higher spatial resolution compared to the Landsat ETM image described above. These data are combined with vector data in order to monitor coastal morphology, beach nourishment, area and position of dunes etc. Also a rough estimate of vegetation cover can be derived, but a sophisticated delineation of elementary surface types is not possible due to the lacking spectral information.

The monitoring of phytoplankton has been part of the TMAP from the beginning and is gaining more attention due to the EU Water Framework Directive. Remote sensing techniques to measure the chlorophyll-a concentration in the ocean have been

Table 1. Spatial and spectral characteristics of space borne remote sensing instruments

Sensor	Ikonos PAN	Quick Bird	IKONOS	SPOT	IRS	LANDSAT	MERIS FR	NOAA AVHRR	SeaWiFS	MERIS RR
Spatial resolution	1 m	2.4 m	4 m	20 m	23 m	30 m	300 m	1000 m	1100 m	1200 m
Swath width	11 km	16.5 km	11 km	60 km	140 km	183 km	1345 km	3000 km	2800 km	1345 km
Spectral resolution	Pan	4 (vis, nIR)	4 (vis, nIR)	4 (vis, nIR)	3 (vis, nIR, thIR)	7 (vis, nIR, mIR, thIR)	15 (vis, nIR)	4 (vis, nIR, mIR, thIR)	8 (vis, nIR)	25 (vis, nIR)
Temporal resolution	2.9 days		1.5 days	26 days	24 days	16 days	3 days	2-4 days	1 day	3 days
Price	25-98* $/ km2	25$/km2	18-98* $/ km^2	1900€ 53€/100km^2	2700 € 13€/100km^2	600-1500 € 2-5€/100km^2				

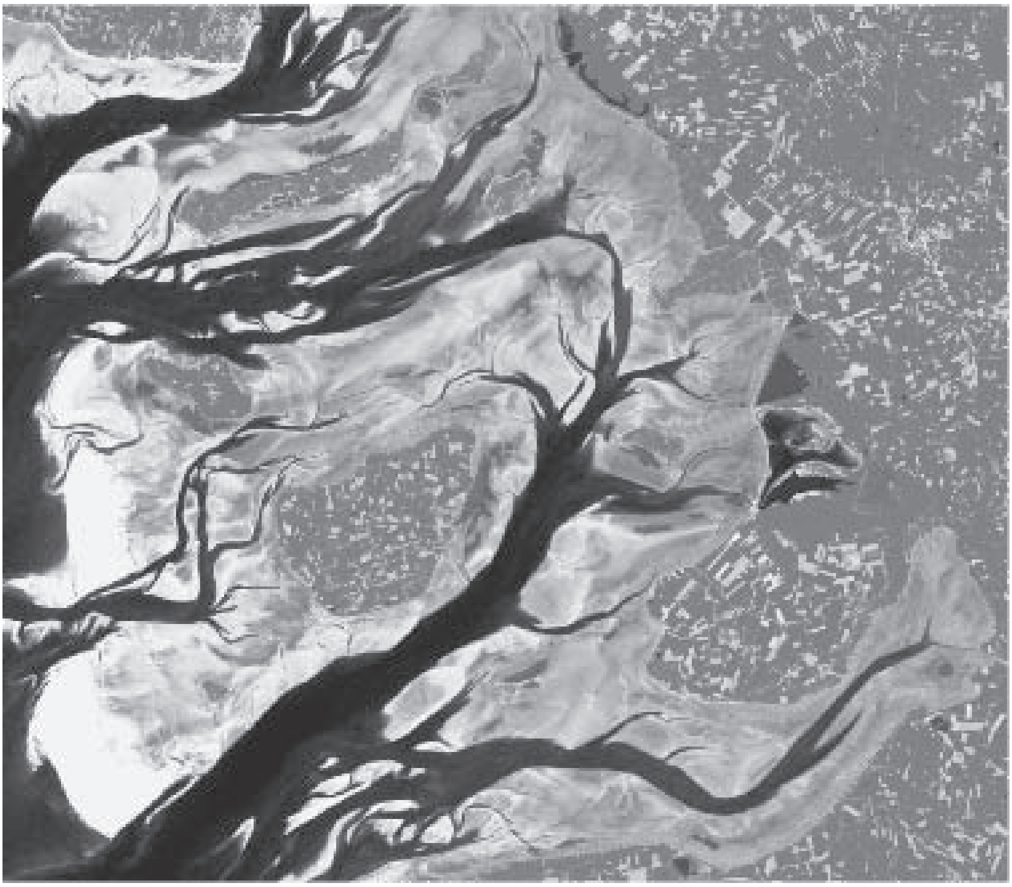

Figure 2. Example of a Landsat-7 ETM scene of the North Frisian Wadden Sea, 15.7.2002. Stelzer 2004. Landsat 7 ETM © Eurimage 2002

developed since the early 80s (Gordon and Morel 1983), and since the mid 90s space borne instruments dedicated to measuring the sea surface reflectance, such as SeaWiFS and MERIS, are in operation. In coastal waters, the retrieval of the chlorophyll-a concentration is particularly difficult due to the non correlated co-existence of suspended matter and yellow substance, which both have a strong influence on the measured signal. However, new retrieval methods are available (Doerffer and Schiller 1997) and weekly mean chlorophyll concentration maps of important European waters are now available on an operational basis (Marcoast).

An analysis carried out for the environmental ministries of Lower Saxony and Schleswig-Holstein in Germany (Stelzer 2004) has shown that the determination of the area and location of features and patterns of the following parameters, which are essential parts of the TMAP as shown in Figure 1, can be especially improved by using remote sensing techniques. These include:

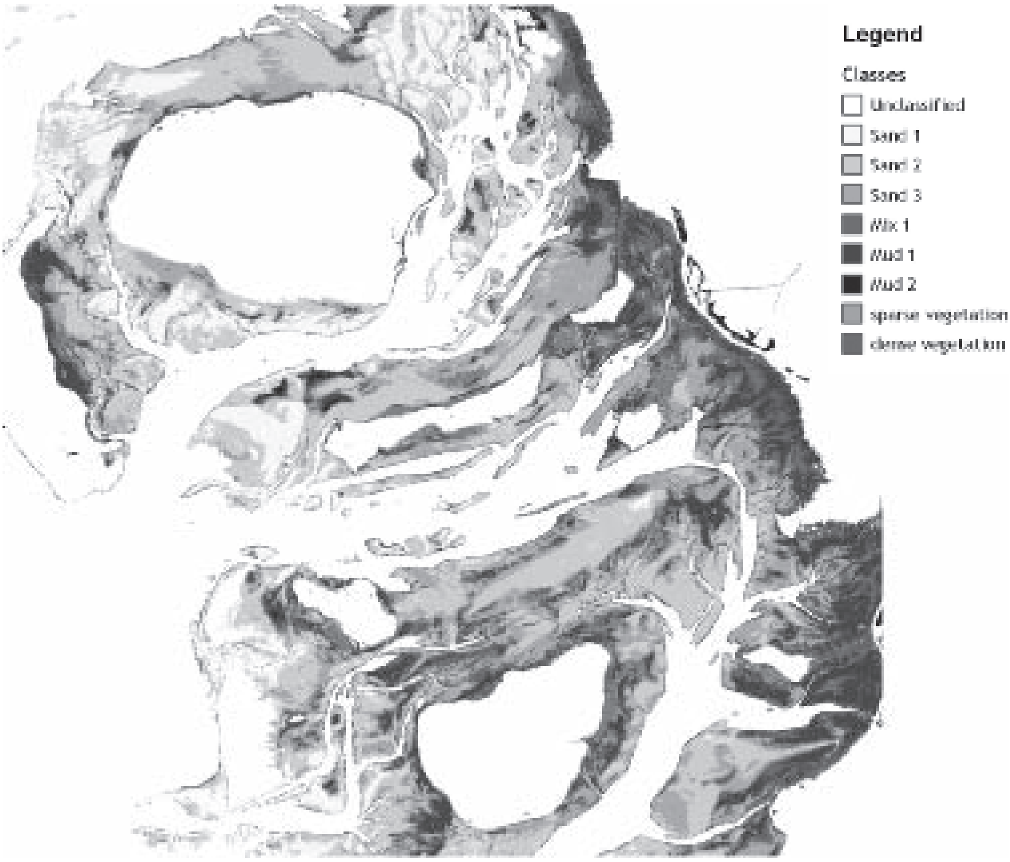

Figure 3. Result of the LSU (sediment classes) applied to the ETM image of North Frisian Wadden Sea. Stelzer 2004

- sediment type
- macrophytes
- phytoplankton
- blue mussel beds

Conclusion

The need for monitoring of coastal zones and in particular intertidal areas and coastal waters has become more urgent in the past decade due to European regulations, which themselves are a response on the high anthropogenic pressure being exerted on our coastal environments. Traditional techniques, namely the combination of intensive field survey and subsequent laboratory analysis, are high quality and well established methods, however, they are labour intensive and costly, and they cannot provide large scale assessments at reasonable frequencies. The need for new, more appropriate methods has been expressed for quite some time now, and in this respect, considerable expectations have been put on remote sensing.

Thanks to the availability of suitable instruments, both on air and space borne platforms, and due to the development of new evaluation procedures, it could be shown that some key parameters, such as sediment type or location and area of macrophytes, can be derived from these measurements. Satellite data are available at acceptable costs and are significantly cheaper compared to field surveys. However, the availability of space borne data is very much limited by cloud coverage in northern latitudes, and the spatial resolution, which is in the order to 30 m, is at the lower end of what is required by coastal managers. Airborne data overcome these limitations, however, they are much more expensive and the costs for one campaign can be compared with that for an extensive field survey.

The best way to proceed will be in using a combination of all available methods. Space borne remote sensing is beneficial for establishing references for key parameters and for monitoring large areas at a low frequency. Such data can also be used as a planning tool for airborne and field campaigns. Areas which are unambiguously mapped by space borne remote sensing can be left out, enabling more time to be spent, or an airborne campaign to be undertaken, in areas where for instance the macroalgae could not be differentiated from seagrass.

Acknowledgement

Part of this work was co-funded by the European Commission Research Directorate General XII, for the Project HIMOM (Contract No. EVK3-CT-2001-00052). We would like to thank the HIMOM project team, particularly Rodney Forster, for their support to the remote sensing work. We also thank Arfst Hinrichsen for the critical assessment of the study on high resolution imaging and provision of the vector data of the Amt für ländliche Räume.

References

BIOPTIS – Assessing the Biological and Physical Dynamics of Intertidal Sediment Systems: a Remote Sensing Approach. EU co-funded research project. Project reference MAS3970158. Homepage: http: //www.st-andrews.ac.uk/~serg/research/BIOPTIS/

HIMOM – A system of hierarchical monitoring methods for assessing changes in the biological and physical state of intertidal areas. EU co-funded research project. Project reference EVK3-CT-2001-00052. Homepage: http: //www.brockmann-consult.de/himom

Trilateral Monitoring and Assessment Group (2001). TMAP Evaluation Report. The Trilateral Monitoring and Assessment Program (TMAP). Common Wadden Sea Secretariat, Wilhelmshaven.

Berger, W.H., V.S. Smetacsk and G. Wefer. 1989. Productivity in the Ocean: Past and Present. Life Science Research Report, Vol 44, Chichester: John Wiley and Sons.

Postma, H. 1982. Hydrography of the Wadden Sea: Movements and properties of water and particulate matter. Report 2 of the Wadden Sea Working Group, 75 pp.

Asmus, R., M.H. Jensen, D. Murphy and R. Doerffer. 1998. Primary production of the microphytobenthos, phytoplankton and the annual yield of macrophytic biomass in the Sylt-Rømø Wadden Sea. (In German, English abstract) In C. Gätje and K. Reise (edts.) Ökosystem Wattenmeer – Austausch-, Transport- und Stoffumwandlungsprozesse. Springer-Verlag Berlin Heidelberg, pp. 367-391.

SISCAL – Satellite-based Information System on Coastal Areas and Lakes. EU co-funded research project. Project reference IST-2000-28187. Homepage www.siscal.net

Adams, J.B., Smith, M.O, & Gillespie, A.R. 1989. Simple Models for Complex Natural Surfaces: A Strategy for the Hyperspectral Era of Remote Sensing. Proceedings IEEE Int. Geoscience and Remote Sensing Symposium, New York, 1, 16-21

Stelzer K., Brockmann C. and Murphy D. (2004). Using Remote Sensing Data for Coastal Zone Monitoring. RSPSoc 2004. Mapping and Resources Management. Aberdeen, 7.-10.9.2004. Proceedings

Gordon, H. R. and A. Morel. 1983. Remote assessment of ocean color for interpretation of satellite visible imagery. A review. Lecture Notes on Coastal and Estuarine Study, Vol. 4, Springer Verlag.

Doerffer, R., Schiller, H. 1997. Pigment Index, Sediment and Gelbstoff Retrieval from directional Water-leaving Reflectances using Inverse Modelling Technique. Algorithm Theoretical Basis Document. http: //envisat.esa.int/instruments/meris/pdf/atbd_2_12.pdf

Coastwatch – a coastal information service for the European coastal environment. Homepage www.coastwatch.info

Stelzer, K. 2004: Potenzial der Fernerkundung im Küstenraum für die Umsetzung der EG-Wasserrahmenrichtlinie, TMAP und FFH. www.brockmann-consult.de/english/projects/projects