Managing European Shorelines and Sharing Information on Nearshore Areas

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MONITORING AND MODELLING THE SHORELINE

Isle of Wight Council
Province of Ragusa

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North East South West INTERREG IIIC

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1 Introduction

1.1 The Purpose of Monitoring and Modelling Techniques

Shoreline monitoring is a vital element of planning and management of the coast in a sustainable way. Shoreline monitoring informs coastal managers of coastal evolution, change and processes as well as the rate of change. Monitoring provides an essential baseline against which the impacts of climate change on the coast can be assessed. Ideally coastal monitoring should take place across coastal process sediment sub-cells, sediment cells, and on a regional and ultimately a national scale; however in practice this is not always the case.

It is important to establish exactly what is to be achieved through monitoring and to choose the most appropriate methods. A major factor in this choice may be the financial cost, but other considerations such as the accuracy of data and the level of detail to be obtained are also important. Land ownership issues may impede some techniques. Monitoring is undertaken on a variety of spatial and temporal levels. The development of individual coastal defence schemes could require localized research including both pre- and post-construction monitoring programmes, while regional programmes cover a larger geographical area. Some monitoring may be sporadic or even take place only once, while other methods employed occur regularly and over a long time period. Historically there has been little co-ordination of monitoring undertaken in relation to the shoreline across Europe (Eurosion 2004).

Recommendations from Shoreline Management Plans (SMPs) and coastal strategy studies in the UK have consistently identified a requirement for development of coastal monitoring programmes (Bradbury, 2004). However, many other European countries have, in the past, failed to identify a need for coastal monitoring and as such, there is a lack of accurate information on the morphodynamics and hydrodynamics associated with many of these coastlines.

A number of case studies have been used in this report to reflect current monitoring practices throughout Europe and also on a global scale. More recently, steps have been taken in countries such as The Netherlands, Sicily, and Dubai, to create a standard and repeatable programme for coastal monitoring, similar to that set up on the south coast of England. In most cases, a combination of airborne, ship-borne and ground-based techniques have been used to develop sophisticated monitoring practices carried out on national scales.

CASE-STUDY N°1: Bournemouth Case Study – an example of a long-term local-specific approach to coastal monitoring.

Introduction

Bournemouth Borough Council currently operates coast protection policies established after many years of practical experience and maintenance, following close collaboration with the Government's research organisation, the Hydraulics Research Station, now operating in the private sector as H R Wallingford Limited. At present, DEFRA (previously the Ministry of Agriculture, Fisheries and Food (MAFF)) have grant-aided the Council's programmes of coast protection works and monitoring programmes.

Predictions of the state of the future coastline as a reaction to the changes in climate have lead to revisions in the future coast protection policies necessary to protect the Bournemouth coastline. In optimising the most economic solutions for the future coast protection of the coastline, alternative defences have been examined and costed, together with an assessment of the level of benefits if such defences were to be implemented (Bournemouth Borough Council Website, 2005).

A vital part of any coastal defence scheme is accurate monitoring data that allows for an understanding of current and earlier patterns in coastal evolution. This information is essential to inform shoreline management planning and design conditions for operational flood and coastal defence strategies. Long-term local coastal monitoring programmes as operated by Bournemouth Borough Council, have demonstrated considerable cost-savings, allowing greater confidence in efficient design of coastal works.

Geographical Outline

The Bournemouth coast lies on the South Coast of the UK between Poole in the west and Christchurch in the east. The Dorset and East Devon coast is one of the most significant earth science sites in the world, displaying a remarkable combination of internationally renowned features. As such, it has been designated as a World Heritage Site and is now known as the Jurassic Coast (Figure 1).

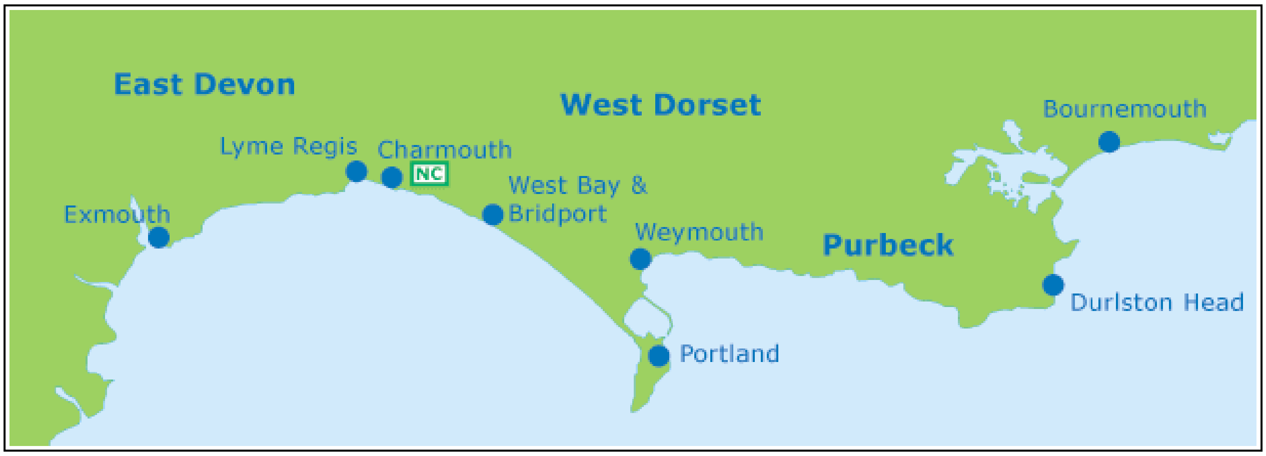

Figure 1. Location map of the Jurassic Coast.

It has a unique historical importance to the founding of geology and geomorphology and it remains at the forefront of modern earth science research. The features are displayed within an unspoilt and accessible coastline.

The Site displays a near continuous sequence of Triassic, Jurassic and Cretaceous rock exposures representing almost the entire Mesozoic era, together with outstanding geomorphological features such as landslides, a barrier beach and lagoon, cliffs and raised (fossil) beaches (Jurassic Coast Website, 2005).

Past and present monitoring techniques

Shoreline management methods have altered significantly during the past 10 years. Most sea defence and coastal protection schemes are now developed around dynamic elements, such as beach recharge or recycling, often in conjunction with beach control structures. The departure from hard engineering presents a complex risk management scenario that requires high quality information to support effective management; it relies heavily on an understanding of coastal processes at work and the effects that these processes have on shoreline evolution.

In the 30 years between 1970-2000 almost 2 million m^3 of sand has been used to replenish the beaches at Bournemouth and Poole. Since the predominant direction of longshore transport at Poole Bay is from west to east, new sand gradually feeds the beaches at Southbourne and Hengistbury Head to the east, and beyond into Christchurch Bay (Poole Bay and Swanage Beach Replenishment Website, 2006).

Poole Bay extends from Poole Harbour tidal inlet to the southwest and Hengistbury Head/Christchurch Ledge to the east. The Bournemouth component of this frontage has experienced a progression of protection measures to control erosion and safeguard the sandy beaches that are so vital to its tourist economy (Bray and Carter, 1995). A shift from a 'hard' engineering approach to a 'soft' engineering approach occurred in 1974 when one of the largest and longest running programmes of beach replenishment in the UK was established.

A pilot replenishment scheme, known as Beach Improvement Scheme 1 or BIS1, was carried out in 1970 whereby 84,500m^3 of dredged sand was positioned at Mean Low Water (MLW) along a 1.8km frontage (Elliott, 1989). Two further replenishment schemes followed with the fourth being carried out at present. The second scheme (BIS2) involved the importing and dumping of 1.4 million m^3 dredged sand at sites over 400m offshore the position of mean low water. Approximately 650,000m^3 of sand was then pumped ashore and re-profiled (Newman, 1978; Halcrow, 1980; Wilmington, 1982). The beach was intensively monitored thereafter by beach profiling and bathymetric surveys, which extended up to 450m offshore. Surveys were undertaken at frequent intervals along 38 survey lines between Alum Chine and Hengistbury Head. Comparison immediately before and after nourishment revealed that the intertidal zone had gained 725,000m^3 of sediment compared to the 650,000m^3 pumped ashore, thus suggesting onshore transport of 75,000m^3 of sand from dump sites during the operation (Lacey, 1985; Harlow and Cooper, 1994; 1996). Thereafter, the intertidal zone lost material, offshore and by littoral drift, but the nearshore and offshore zones continued to accrete. After 1979, all zones lost material and by 1982, the intertidal zone in many areas had returned to its pre-nourishment volume. A third replenishment scheme was undertaken in three phases from 1988-1990 involving the deposition of 998,730m^3 of dredged fill directly onto the beach. This material was pumped onshore above MHW and allowed to form its own profile. The coincidental dredging of the Poole Harbour entrance at the same time as the need for beach replenishment material substantial reduced the costs of BIS3 (Turner, 1994).

BIS4 was completed in late March 2006 and involved 1.1 million m^3 (1.65 million metric tonnes) of sand dredged from Poole Harbour channels and approaches, to replenish the beaches at Poole, Bournemouth and Swanage in order to protect them from erosion (Figure 2). Replenishment of Bournemouth's beaches began on Wednesday, 18th January 2006 at Double Dykes, Hengistbury Head and moved westwards to Boscombe Pier. The 600,000m^3 of beach material used was selected to match that naturally occurring on the beaches (e.g. a sand & shingle mix at the eastern end of the bay). A second contract to complete Bournemouth's beaches during winter 2007 will replenish from Boscombe Pier westwards to the Borough Boundary with Poole, using beach material dredged from commercial sources (Poole Bay and Swanage Beach Replenishment Website, 2006).

Pumping a 50/50 mix of sand and water through the onshore pipeline

Sand bunds create a 'lagoon' to retain new sand, and avoid losses to the foreshore

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Figure 2. Examples of beach replenishment methods being used at Bournemouth (taken from Poole Bay and Swanage Beach Replenishment Website, 2006).

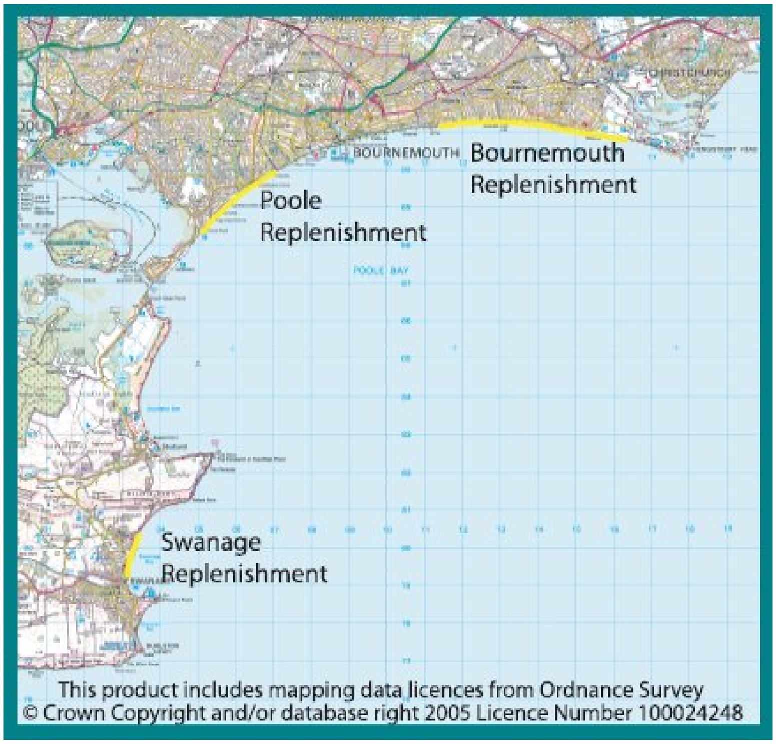


Figure 3. Location map indicating the areas of beach replenishment (Poole Bay and Swanage Beach Replenishment Website, 2006).

A daily diary was kept online on the project website (Poole Bay and Swanage Beach Replenishment Website, 2006) providing information regarding daily totals of material pumped ashore and averages for the weekly and monthly periods (Figure 4). These values were verified by a thorough topographic survey of the area pre and post replenishment. Profile lines were measured at 10m intervals using Global Real Time Kinematic Positioning System (RTK GPS) along the frontage. A calculation of the cross-sectional area of the beach allows for comparisons to be made to the figures quoted by the dredging team. An example of survey data collected by the contractors' survey department can be seen in Figure 4, with the red line representative of the pre-recharge profile, the green line representative of the theoretical replenished beach when the sand was first pumped ashore, and finally, the blue line serving as an indicator of the actual response of the beach following exposure to wind and wave attack.

DAILY DIARY

- Swanage diary
- Poole diary

Bournemouth - January/February 2006

Bournemouth statistics [1]	loads	m^3	metric tonnes	tons
Total pumped ashore to date	170	453,778	680,667	669,917
Average per day (26 days)	7	17,453	26,180	25,766

Bournemouth beaches are to receive 600,000m³ of new beach material; more than that will be pumped ashore to allow for various factors (more)

February		Daily Total (m^3)
12th	*'Countryfile'* on BBC1 this morning featured the beach replenishment and other stories from Poole Harbour. 4 loads pumped ashore	8,733
11th	Beach replenishment (5 loads)	11,323
10th	The *Waterway* completed her final discharge at 00:05 this morning, bound for Amsterdam. Beach replenishment (5 loads)	10,813
9th	Beach replenishment (7 loads)	20,950
8th	Beach replenishment (9 loads)	23,852
7th	The sinkerline was moved this morning, to the bottom of Gordon Steps at Southbourne, the BBC filmed aboard the *HAM 311* and 9 loads were pumped ashore - busy day!	24,015
6th	Beach replenishment (7 loads)	18,719
5th	Beach replenishment (8 loads)	21,845

Figure 4. Example of the Daily Diary from the project website.

The on-going need for beach replenishment was originally identified in the 1999 Shoreline Management Plan for the area, based on the outcome of the three previous beach replenishment schemes. A subsequent report by Halcrow (2004) suggests that a further 3 million m^3 will be required over the next 50 years in order to maintain protective beach levels and widths. It is essential that this stretch of coastline continues to be monitored as part of the Regional Strategic Coastal Monitoring Programme in order to provide highly accurate positional data on beach levels and sediment transport. The advantage of beach replenishment is that it can be adjusted to cope with unforeseen situations provided that adequate monitoring is undertaken (Stive *et al*, 1991). The availability of such a long-term monitoring record for Bournemouth both prior to the SRCMP and now within this programme is very rare and must be considered a valuable asset (Harlow and Cooper, 1996).

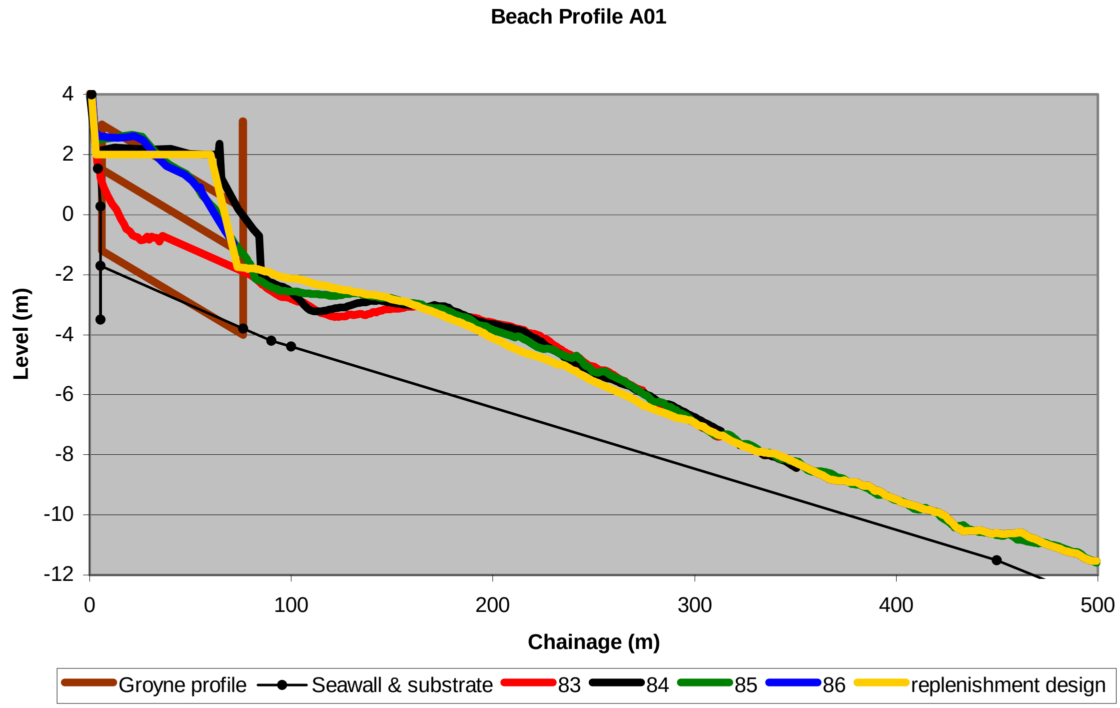


Figure 5. Example of profile survey data collected pre-survey and post-survey at Bournemouth. Survey 83 was carried out on the 18/1/06, Survey 84 was post replenishment on the 18/3/06, Survey 85 was on the 12/4/06, and Survey 86 was on the 13/6/06 (Bournemouth Borough Council, 2006).

Data Collection and Analysis

A bi-annual beach profiling survey was instigated in July 1974 and was maintained until 2002 when the Strategic Regional Coastal Monitoring Programme (SRCMP) took over. The SRCMP aims to provide a more holistic approach to coastal monitoring by creating a region-wide policy and a standardised methodology that each local authority or the lead authority should follow. Additional monitoring was carried out with regards to both particle size testing and real-time tide and wave data. Particle size testing of the beach material, twice annually to match the topographic surveys, was also undertaken at Bournemouth between 1974 and 2002. Sediment sampling does not form part of the SRCMP and so is still currently undertaken by Bournemouth Borough Council.

Annual aerial surveys from 1987 have also formed part of the monitoring of coastal evolution at Bournemouth. These aerial surveys are now undertaken as part of the SRCMP and also include photogrammetric profiling along the South-East coast.

Real-time tide data and wave data are collected by both the tide gauge on Bournemouth Pier and the directional waverider buoy located at Boscombe. Tidal data at Bournemouth has been recorded since 1974, although the original gauge fell into disrepair around 1990 and was only replaced by the present Proudman Oceanographic Laboratory (POL) gauge in 1995. In addition to this, daily weather records have been kept manually from 1974 until 1999, when electronic meteorological stations were installed. Finally, the littoral drift direction at each groyne in Poole Bay has been recorded from 1993 to date, in order to try and understand some of the complex responses of sediment transport in the area.

The collection and analysis of survey, LiDAR and wave data is now carried out as part of the SRCMP. Data collection from topographic surveys is collected using Global Positioning Systems. Kinematic GPS provides the opportunity to capture data with a vertical accuracy of approximately +/-2-3cm and horizontal positioning at approximately double the accuracy making it ideal for beach surveys. Further details about this technique can be found in section 2.3.4.

Techniques in current use at Bournemouth include both annual profiling and also continuous data collection of spot height data. Once every five years a baseline survey is carried out on all beaches within the South-East Strategic Regional Coastal Monitoring Programme area. These surveys provide a detailed topographical map of the beach through a combination of profile lines spaced at 50m intervals and continuous data taken every two seconds from shore parallel lines at 5m spacing. This combination allows a digital ground model (DGM) to be produced allowing profiles to be drawn at any location indicating changes in beach levels in comparison to previous surveys.

Subsequent surveys are determined by spatial and temporal factors. The profile interval varies from 100m-500m depending on the risk-based analysis of the area. Profiles spaced at 100m are generally in areas where barrier beaches run parallel to hold the line frontages at high exposure sites or where the beach has coastal structures where a high risk 'hold the line' beach management plan sites exists. Profile lines spaced at 500m are likely to be where a 'do nothing' option exists on a low-risk/low-exposure site.

Thousands of beach profiles will be collected during the course of the programme with some sites being surveyed as many as 4 times per year. Where possible data from historical programmes, such as that of Bournemouth, is incorporated within the data sets to provide information on longer-term changes in beach levels.

Data is downloaded and stored primarily in a GIS and database software programme known as SANDS (Shoreline and Nearshore Data System) produced by Halcrow (Figure 6 and 7). This programme provides a powerful facility through which input data can be analysed to establish correlations between forcing and response. It also allows weather and shore condition data to be entered, stored, inspected and compared. Through the analysis of both climatic and beach profile data, trends in coastal response can be detected. SANDS is also capable of storing, retrieving and analysing a wide range of environmental data, reports and records (Halcrow SANDS website, 2005).

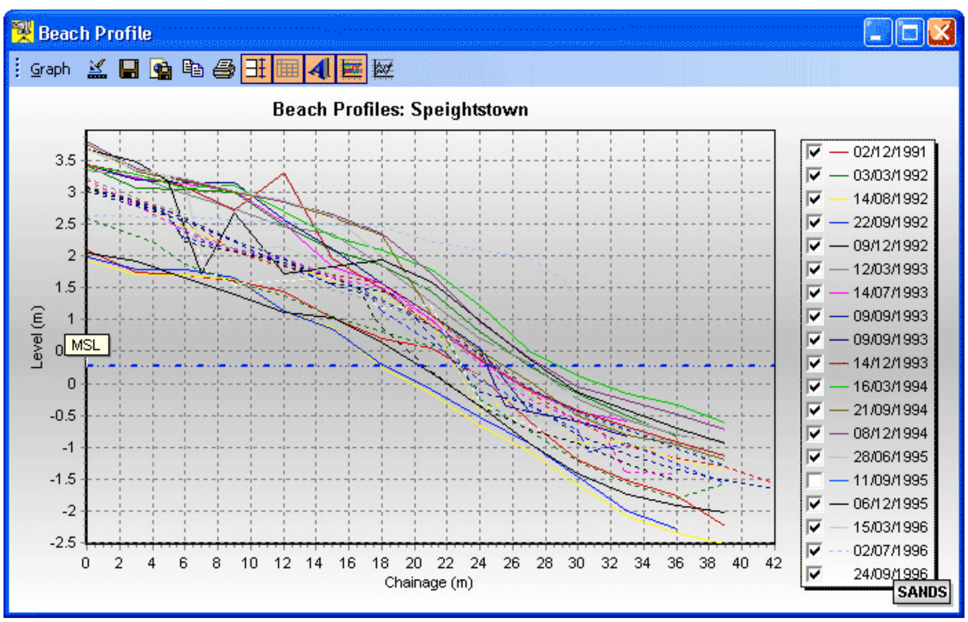


Figure 6. An example of beach profile data stored in SANDS.

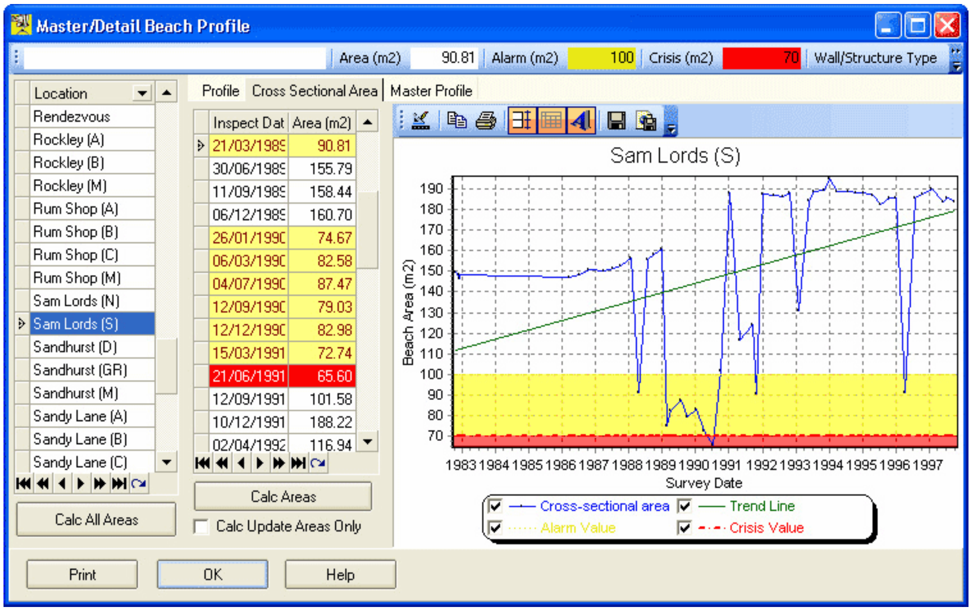


Figure 7. An example of cross-sectional area data derived from the master profile.

Conclusion

The monitoring data collected since 1974 in Bournemouth has provided an invaluable data source for coastal scientists and engineers alike. This stretch of coastline is one of the best documented in terms of monitoring data and this data has provided a basis for the design and development of coastal defence works in the area. Long-term local coastal monitoring programmes as operated by Bournemouth Borough Council, have allowed for considerable cost-savings to be made, providing greater confidence in efficient design of coastal works. The need for future replenishment schemes can now be predicted using the long-term monitoring data that is available, changing the management philosophy from a reactive to a pro-active one (Harlow and Cooper, 1996).

With regards to the specific replenishment schemes at Bournemouth (BIS1-4), these have been extremely successful, so much so that residents and tourist now take Bournemouth's excellent sandy beaches for granted. Future replenishment schemes could potentially be more effective as a protection measure if a coarse fill were used; however, this is undesirable from an amenity point of view. Not all future replenishments will coincide with the dredging of Poole Harbour, so an alternative 'borrow' source must be found. If the cost of, and demand for, beach fill increases in the future, emphasis will move towards more efficient conservation of sediments, with beach monitoring as a critical component of this strategy (Harlow and Cooper, 1996).

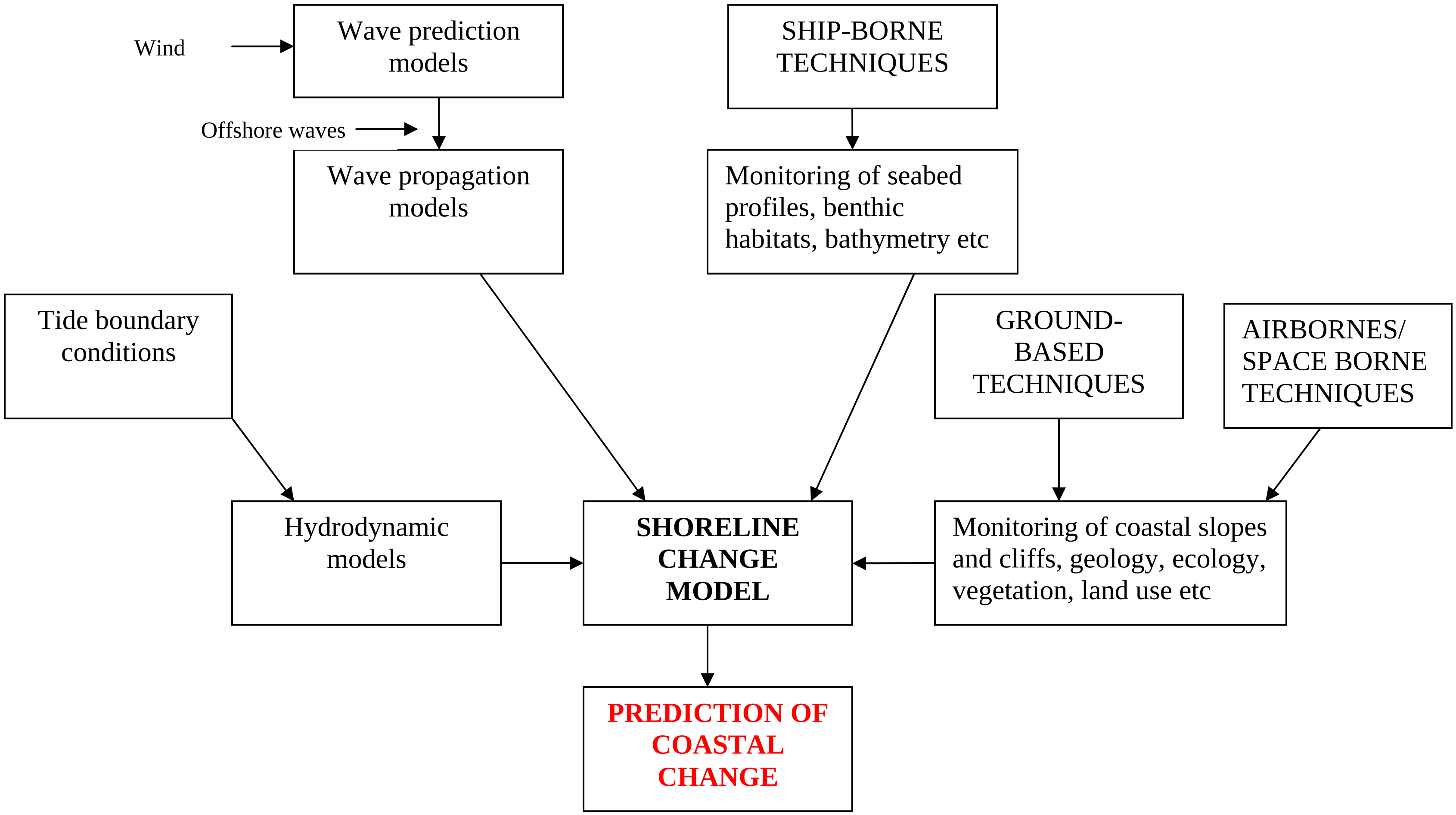
1.2 Outline of Monitoring and Modelling Techniques

There are a wide range of monitoring and modelling techniques available in the field of shoreline management. Many of these relate specifically to the coastline, while others have wider applications across a number of fields. Monitoring techniques can be categorized into airborne and space-borne techniques, ship-borne techniques and ground-based techniques. The type of information needed to assess shoreline change includes data on: waves, wind, tides, currents, coastal slopes and cliffs, geology, geomorphology, ecology, vegetation, bathymetry and land use (Figure 8).

Airborne and space-borne remote sensing techniques have been used to capture data at a variety of sites, to provide coverage of special features, or where these techniques are either more practical or efficient than land based methods (Channel Coastal Observatory Website, 2005). These techniques are often referred to as 'remote sensing' as they gather data from a distance beyond the immediate vicinity of the sensor device. The main airborne techniques used for remote sensing of the coastal environment include Interferometric Synthetic Aperture Radar (IfSAR or InSAR), LiDAR (Light Detection And Ranging), Airborne multispectral (MS) camera systems, Airborne thermal infrared radiometers (TIR), and Hyperspectral sensors.

Space-borne techniques refer to sensors that are mounted on-board a spacecraft (space shuttle or satellite) orbiting the earth. The main form of space-borne remote sensing is from satellite imagery, of which there are two main types, Moderate Resolution Satellite and High Resolution Satellite.

Figure 8. Flow chart showing the relationship between monitoring and modelling techniques in shoreline change.



Ship-borne techniques, for example bathymetric surveys, side scan sonar and grab sampling, are limited to the marine environment. They collect data on a number of variables, including: the changes and rates of change of dynamic sediments, below low water; changes and rates of erosion of fixed bedrock, below low water; the identification of small submerged small-submerged features, which may affect sediment transport processes; changes within offshore sediment sinks; and habitat mapping.

Ground based techniques take the form of topographic surveys, which provide elevation figures and, in some cases, three-dimensional XYZ co-ordinates, in relation to a known reference point. Topographic surveys can be undertaken via levelling, a total station theodolite or global positioning system (GPS), although the method used may vary from site to site. The most well developed long-term (>10 yr.) historical programmes within the south of the UK all include land based topographic surveying, in one form or another.

Once the raw data has been collected, numerous models are available to further analyse and predict shoreline change (Figure 9). Modelling techniques can either be in the form of a mathematical/numerical model for example the CERC Equation can be used to predict the volume of sediment transported alongshore as a function of the wave height, period and obliquity; or a computational model. Computational models can be used to analyse and predict sediment transport (e.g. UNIBEST TC, UNIBEST CL+, MIKE 21 ST and MIKE 21 MT). Other packages are available to model coastal change and erosion (e.g. ESTMORF, GENESIS, SBEACH and UNIBEST-DE.)

Computational hydrodynamic models (e.g. MIKE 21 HD) are site specific as oceanographic parameters vary around the UK. These range from lower resolution regional models to high-resolution local models. A hydrodynamic model could be run during extreme events to try to predict how sediments might move within a given area. The cells for the model can cover any extent providing there is sufficient data for the area. Programmes can be run to model waves, wind, current and tidal effects on sediment transport. Examples of wave models include MIKE 21 NSW, MIKE 21 BW, MIKE 21 EMS, MIKE 21 PMS, SWAN and STWAVE.

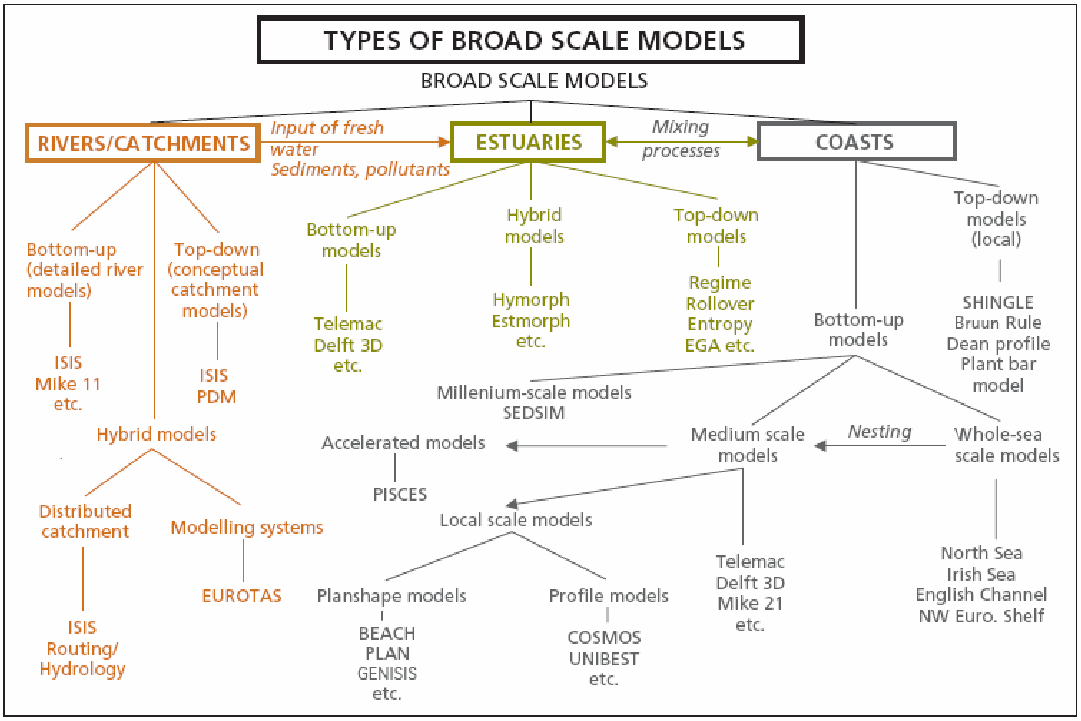


Figure 9. Types of broad scale modelling techniques used to predict flood and erosion risks (Defra, 2004.)

1.3 An Overview of Techniques used throughout the World

Monitoring Methods

A range of monitoring and modelling techniques have been used throughout the world. A study undertaken in 2004 by the European Commission on *'Living with coastal erosion in Europe: Sediment and Space for Sustainability'* found that monitoring techniques are still an exception in Europe and are not the general rule. There is a significant gap between northern and southern Europe in the systematic use of coastline monitoring techniques as part of shoreline management policies (Eurosion 2004). The United Kingdom, The Netherlands and Germany have established relatively advanced coastal monitoring programmes using mainly LiDAR, ship-borne techniques or locally applied ARGUS video systems as a means of shoreline monitoring. However, countries such as Portugal, Greece and France rarely implement coastal monitoring techniques or tend to use such methods for experimental research projects only.

South Carolina, USA, has a history of beach nourishment and replenishment, with the most recent nourishment project being completed in 1998. LiDAR survey techniques were used to gauge the success of beach nourishment efforts, the impact of shore stabilization projects, and the imprints left by a major storm. A large beach replenishment scheme is currently underway in Bournemouth, UK, with 1.1 million m^3 (1.65 million metric tonnes) of sand dredged from Poole Harbour channels and approaches being used to replenish the beaches at Poole, Bournemouth and Swanage to protect them from erosion. These values are being verified and monitored by a thorough topographic survey of the area pre and post replenishment. Profile lines are being measured at 10m intervals using Global Positioning System (GPS) along the frontage. A calculation of the cross-sectional area of the beach allows for comparisons to be made with the figures quoted by the dredging team.

Remote sensing has been used to detect shoreline changes along Rosetta promontory of the Nile delta in Egypt over the last two decades. The study focuses on using the geo-information technology for updating changes over the delta coast, in particular active stretches of the coastal area, by comparing existing configurations with ancillary surveys and studies, describing various changes, and attempting to establish existing and future classifications of different coastal activities. Multi-dates satellite data for the years, 1984, 1986, 1991, 1995, 1997 and 2000 were used (Ahmed, 2000). Along the northern coast of Egypt at Port Said City, investigations of shoreline change due to erosion and/or sedimentation were undertaken by analysing aerial images and comparing the results with that obtained from the ordinary methods of surveying (Elkoushy and Tolba 2004).

The South-East Strategic Regional Coastal Monitoring Programme primarily uses topographic data from both land and hydrographic surveys to determine sediment transport and changing beach levels. The programme is based on the use of Differential Global Positioning System (DGPS). Basic GPS is the most accurate radio-based navigation system and for many applications it is plenty accurate. However, DGPS allows for various inaccuracies to be corrected in the GPS system yielding measurements accurate to a couple of metres in moving applications and even better in stationary situations. Differential GPS involves the co-operation of two receivers, one that is stationary and another that is roving around taking position measurements. The stationary receiver measures the timing errors that result from atmospheric distortion and then provides correction information to the other receivers that are roving around. The accuracy and speed of data capture makes DGPS an ideal method for monitoring beach levels and shoreline change.

CASE-STUDY N°2: Dubai Case Study – An example of an International programme on Coastal Monitoring.

A comprehensive coastal monitoring programme has been set up for the Dubai coastal zone following extensive infra-structural development over the last 20 years. The Dubai coastal zone, and in particular the Jumeirah frontage, has been identified as a key element in the expected dramatic expansion of tourism to the region. Considered together with an expected 300% increase in population within the next 20 years, it is likely that the coastal resource will be under tremendous pressure (Smit, F. et al, 2003).

The Dubai Municipality has long since recognised that along with the desire to live and work by the sea come the difficulties of working with the dynamic forces of nature and, increasingly, the requirement to consider the natural environment (Dubai Coastal Zone Monitoring Programme, 2005). As such, an Integrated Coastal Zone Management approach has been adopted in order to provide a good understanding of prevailing coastal processes. This will inform recommendations of optimum development approaches whilst still maintaining protection for vulnerable areas.

Previous monitoring data has been collected on an ad hoc or a scheme-by-scheme basis. However, the need exists to capture coastal data in a more systematic manner to enable coastal planners and others to develop a full understanding of environmental conditions and how coastal developments will affect this process (Dubai Coastal Zone Monitoring Programme, 2005). The initial monitoring programme began in 1997 and involved bathymetric and topographic baseline surveys. In addition to this, a directional wave rider buoy was deployed to provide information on nearshore wave activity. Subsequent surveys were carried out regularly over the following years up until 2002 when the monitoring programme was considerably expanded to include whole extent of the Dubai coast, from Al Mamzar Lagoon in the north to the Jebel Ali coast in the south.

The Dubai Coastal Zone Monitoring Programme utilises innovative technology to assist Dubai Municipality with its management role in ICZM. The current initiative by the Municipality aims to build upon the existing data sets using industry recognised techniques, and will provide information required for the further development of its existing coastal zone management capability (Dubai Coastal Zone Monitoring Programme, 2005).

Geographical Outline

The Emirate of Dubai, is part of the United Arab Emirates, and is located on the South Eastern coast of the Arabian Gulf, with a coastline of approximately 105 kilometres (Figure 10).

Figure 10. Location map of Dubai.

In its natural state, the Dubai coastline consists primarily of long sandy beaches backed by dunes. However, the rapidly expanding tourist, trade and fishing industries has brought about extensive development which has interfered with the natural coastal processes of waves, tidal currents and sediment transport.

Coastal Zone Monitoring

As described in 1.4.2, the Dubai coastal monitoring programme began in 1997 when a baseline bathymetric and topographic survey of the Jumeirah coastline was undertaken. Additional data is now collected to supplement the original programme of measurements. Features of the current monitoring programme include regular topographic and bathymetric surveys, remote video monitoring of Dubai beaches, sediment sampling and analysis, nearshore directional wave and current recordings and intensive measurement exercises at selected locations using Acoustic Doppler Current Profiler (ADCP) equipment.

Bathymetric and Topographic Surveys

The Dubai coastal zone has been divided into units in order to facilitate the monitoring operations (Figure 11).

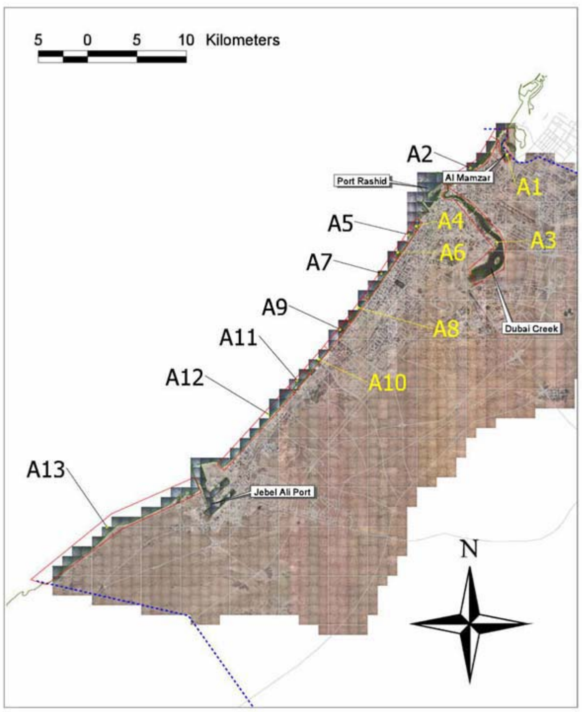


Figure 11. Management units of the Dubai coastline (Smit, et.al, 2003).

The frequency of surveys is determined using a risk-based approach, whereby those areas perceived to be at a greater threat from coastal erosion or inundation, are monitored more frequently than those seen to be less at risk. This risk assessment is reviewed on an annual basis in order to ensure the correct level of monitoring is being carried out within each unit.

The bathymetric survey element of the project involves full coverage of a 500m wide band along the entire coastline, with survey lines running perpendicular to the coast at 25m line spacings. Data is collected along pre-determined profile lines using a dual frequency echo sounder combined with the use of differential GPS in order to help position the survey vessel. Areas of particular interest or concern are re-surveyed as and when necessary to monitor changes over time. Comparisons between survey data sets assist in substantiating the existing understanding of the sediment budget and transport processes along the Dubai coastline (Dubai Coastal Zone Monitoring Programme, 2005).

Topographic surveys are carried out using a pre-defined set of profiles that run perpendicular to the shoreline down to mean water level +1.13m DMD (Dubai Municipality Datum). Scatter point surveys are also undertaken at 10 locations along the Dubai coast in order to produce a contour map of the beach by entering spot height data into a digital terrain model (DTM). Data is collected via a Real-Time Kinematic Global Positioning System (RTK GPS), which allows positional accuracies of up to 20mm to be recorded. A network of ground markers known as control points allows for all RTK points to be checked against a reference level in order to improve the quality control of the data.

Nearshore Wave Measurements

The Dubai Municipality has recorded directional wave information from January 1997 to February 2001 at a nearshore position just north of Jebel Ali Port in about 6 m water depth. Since 2002, a 1200 kHz ADCP with pressure sensor has been deployed at the same position. A second 1200 kHz ADCP has been deployed off the Jumeirah Public Beaches to provide directional wave information in the area of most immediate interest to the Municipality (Figure 12). This instrument provides a near real-time feed of wave information to the Municipality offices as well as being made available to the general public on-line. The instrument measures currents throughout the water column using the return echo of an acoustic signal transmitted by the instrument (Smit, *et al.*, 2003).

A pressure sensor was also installed behind the northern arm of the T-shaped breakwater to provide information on water levels within the sheltered embayment. Variations in water depth (pressure head) induce corresponding resistivity readings in a piezo-electric device in the instrument. The value of resistance measured is proportional to the depth of water (Dubai Coastal Zone Monitoring Programme, 2005). The data is used to gain an understanding of the hydrodynamic processes occurring along the coast, to calibrate and verify hydrodynamic models as well as to assess bather safety concerns. Over time, as a longer-term record is gathered, these will serve to update nearshore design wave and water level conditions for Dubai (Smit, *et al.*, 2003).

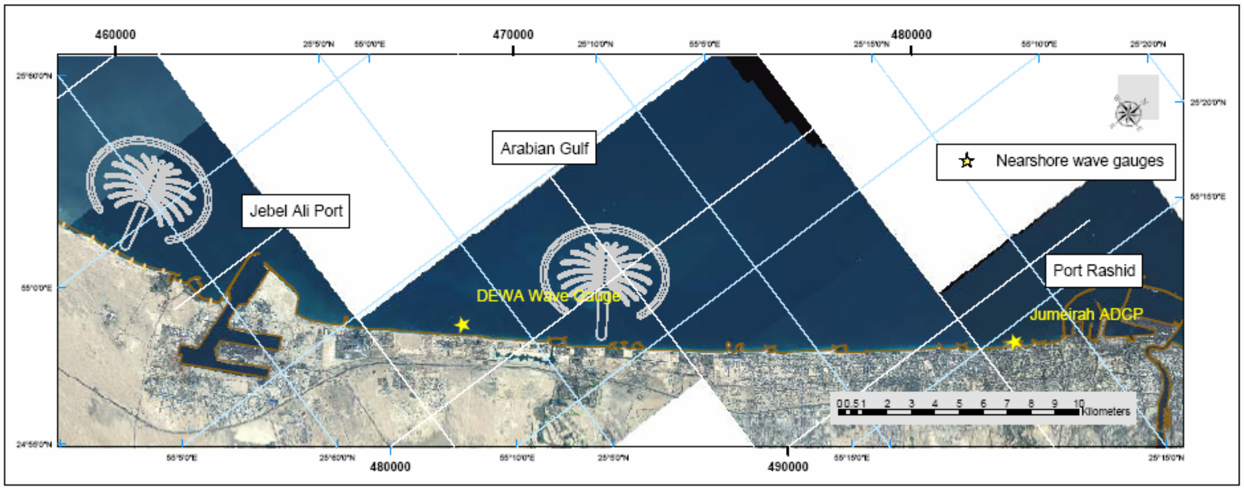


Figure 12. Location of nearshore wave gauges (Smit, *et al.*, 2003).

Video Monitoring

Two video cameras have been installed on the 34th floor of the famous Burj Al Arab hotel located offshore on the Dubai coastline (Figure 13). These cameras capture time-lapse imagery of the Um Sequeim and Palace Beaches, which are geo-rectified using GPS corrected control points. The images are then processed and the ground control points are used in order to return an hourly 'representative water line' (Dubai Coastal Zone Monitoring Programme, 2005).

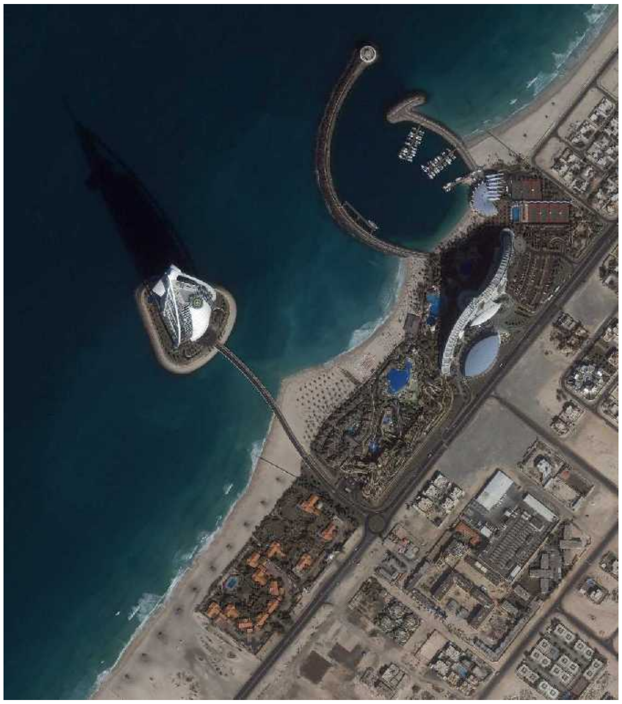


Figure 13. Aerial view of the Burj Al Arab Hotel

Analysis of data collected by the video camera has, until now, been used simply as a verification tool to compare extracted water levels from the images against real-time survey data. With verification complete, focus will now shift towards detailed analysis of water levels for the year's worth of images collected, the translation of these into profile dynamics and an investigation into bar dynamics and the extraction of nearshore current patterns using cross-image correlation (Smit, *et al*., 2003).

Meteorological Data

A meteorological station has been installed at the Jumeirah Open Beach to provide additional information on wind speed and direction, barometric pressure and air temperature (Smit, et.al, 2003). The monitoring station is controlled and managed automatically by a custom built software package "EDEMS" (EmuDome Dubai Environmental Monitoring System) (Dubai Coastal Zone Monitoring Programme, 2005). EDEMS allows real time data to be viewed by the client and project team and summary data to be processed and relayed to the project web site.

Sediment Sampling

Sediment samples were collected during the initial data collection exercise in 1997 along all the Dubai beaches and in the nearshore zone. A limited sample-gathering exercise has been undertaken to update this information. Samples are analysed with regard to grain size and fall velocity and provide input to the coastline evolution, sediment transport and morphological models set up for the region (Smit, *et al.*, 2003).

Coastal Monitoring of the Jumeirah Open Beaches

An area of particular interest to the Dubai Municipality is the Jumeirah open beaches. This area consists of two beaches known as the Jumeirah Open Beach and the Jumeirah Salient Beach, separated by a 'T'-shaped breakwater (Figure 14).

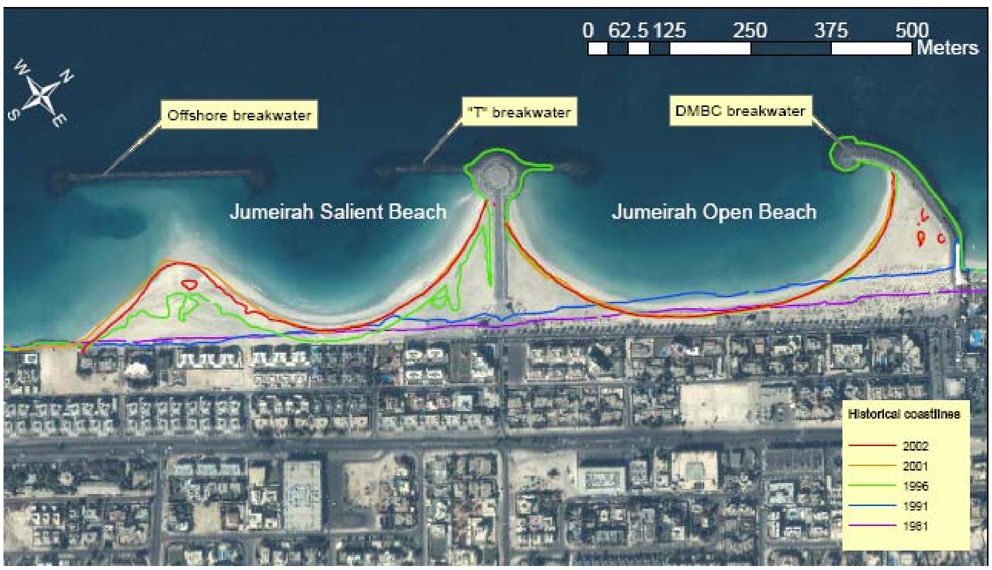


Figure 14. Aerial view of Jumeirah Open Beaches with historical coastlines indicated (Smit et al, 2003).

Prior to the construction of both the 'T'-shaped breakwater and the DMBC breakwater on the eastern side of the bay, the beaches were of a linear formation. The beaches then responded rapidly following the construction of the structures in 1994/1995 and assumed their present crescent shapes (Figure 15). A large amount of material accumulated in the salient with initial volume change figures somewhere in the region of 40,000m^3 per year. The situation settled slightly over the next 8 years although total volume increase over the period was estimated as 169,000m³, an average transport rate of 21,125m³ per year.

Ongoing monitoring suggests that the open bay area is relatively stable over the longer term with increases in volume of 10,165m³ over 8 years, of which 9,500m³ was from a nourishment exercise and approximately 1,500m³ from installed Softrock®. Essentially, there was a net loss of 835m³ over the 8-year period although this is deemed negligible as this would lie well within the obtainable survey accuracy over such an area (Smit, *et al.*, 2003).

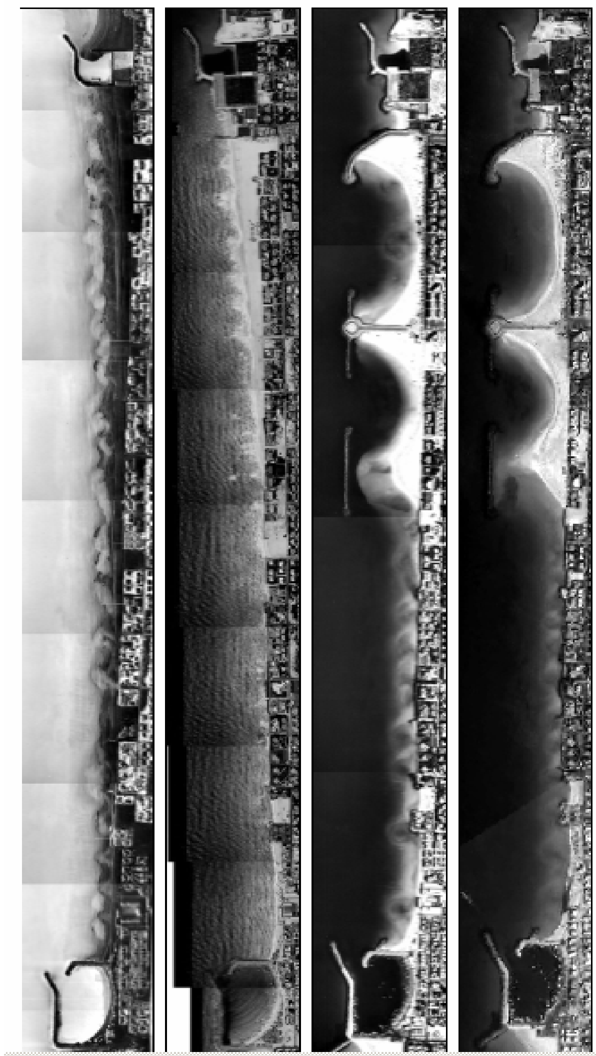


Figure 15. Aerial photographs showing changes in Jumeirah frontage for (top to bottom) 1981, 1991, 1996 and 2002 (Smit *et al.*, 2003).

Coastal Monitoring of the Palm Island Area

In 2001, one of Dubai's most famous coastal landmarks began to take shape (Figure 16). The Palm Islands are three artificial islands being built in shallow waters of the wide continental shelf found off Dubai, using millions of cubic metres of sand dredged from the approach channel to the Jebel Ali port (European Space Agency Website, 2006). *The Palm, Jumeirah* began construction in June 2001 and was originally expected to be completed in 2006. Due to design changes, the expected completion date now is 2008. Construction of *The Palm, Jebel Ali* began in October 2002 and expected completion time is late 2007. *The Palm, Deira*, set to be the largest of the three Palms began construction in November 2004.

Figure 16. Two of the Palm Islands (Dubai Waterfront Properties Website, 2006).

The construction of major coastal developments such as the Palm Islands has caused the Dubai coastline to respond rapidly over the past year or more. The construction of the Jumeirah Island adjacent to the harbour of Mina Al Seyahi has caused the coastline in the southwest shadow of the Island to grow rapidly (Figure 17). Wave models have indicated that the northerly waves are essentially removed from the nearshore wave regime at Mina Al Seyahi through the presence of Palm Island. With these waves removed the north-eastward directed net transport rate increased and the rapid build-up of the coastline occurred (Smit, *et al.*, 2003).

On the other side of Palm Island the opposite occurred. The coastline at this end had been steadily retreating as the harbour had effectively blocked sediment moving from the southwest and the net north-easterly directed transport had slowly eroded the beach. With the construction of Palm Island the nearshore wave regime changed as waves from a north-westerly direction are essentially removed and northerly waves assume a more prominent role. The net transport direction is effectively reversed with sediment now moving from the northwest to the southeast, resulting in the rapid build-up of sediment (Figure 17) (Smit, *et al.*, 2003).

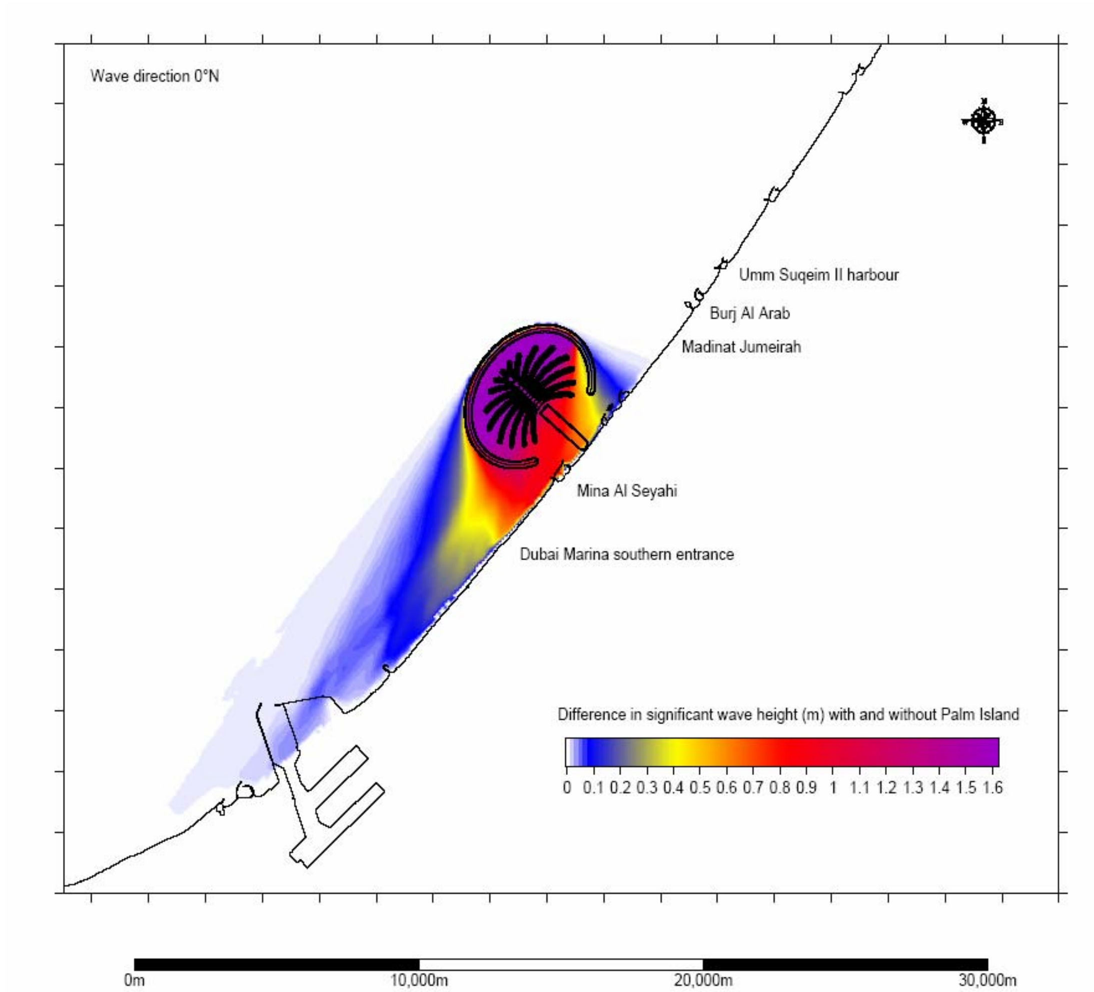


Figure 17. SWAN model showing the influence of Palm Island on the nearshore wave regime.

Data Analysis and Dissemintation

The data collected from the Dubai Coastal Monitoring Programme is subjected to rigorous quality control checks to ensure acceptable data quality. Following the checks, data is made freely available to all interested parties and the general public via the project website www.dubaicoast.org. Captured data from the Jumeirah Open Beach ADCP, pressure sensor and meterological station are uploaded to the website in near real-time. Wave and tide data, along with images from the video camera are also updated on a regular basis. Graphs for onshore and offshore tide levels and significant wave height, wave period and wave direction are displayed at 3-hourly intervals (Figure 18) and a summary of the most recent data is displayed on the homepage of the webiste. Historical data is also offered to coastal engineering consultants and other interested parties alike in order to provide a time-series account of coastal change.

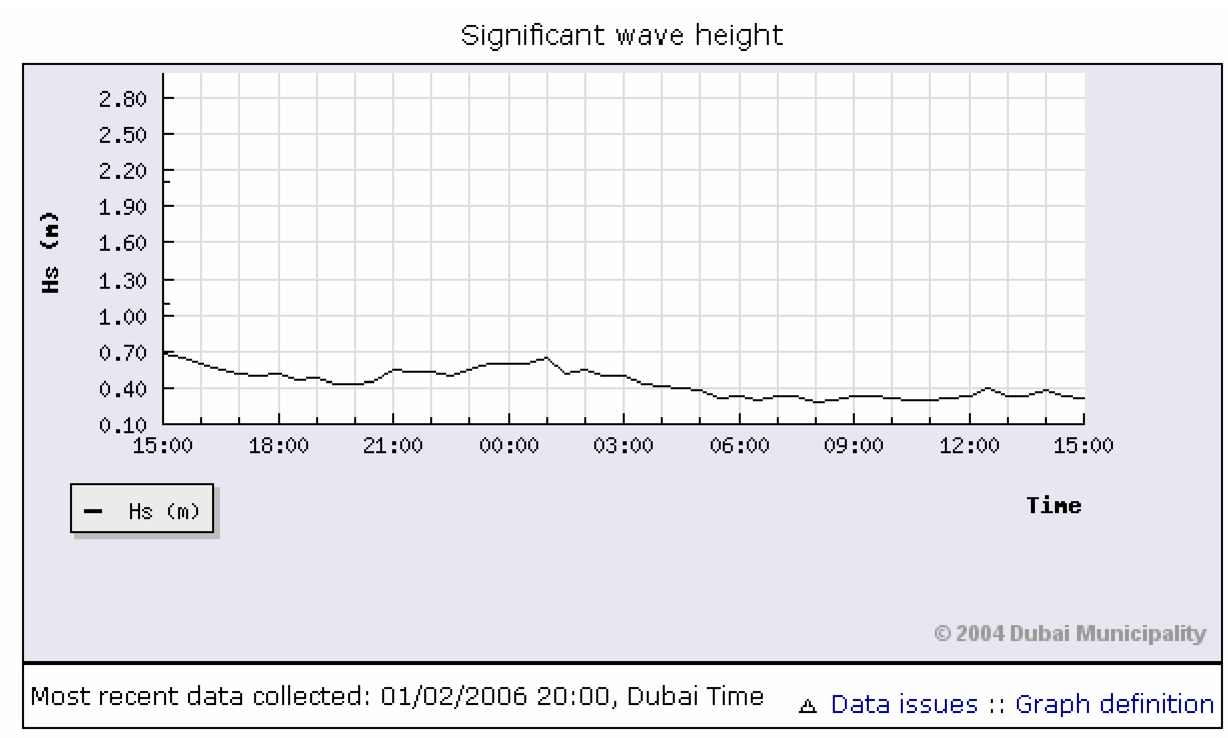


Figure 18. Example of the near real-time wave data.

Conclusions

A comprehensive coastal monitoring programme has been established for the Dubai coastal zone. With the aid of pioneering technology, accurate and reliable results have been collected for the coast of Dubai which offer a valuable tool for coastal engineers in terms of design and understanding the coastal processes occurring along the coast. The bulk of the work to date has focused on the implementation of the programme and assuring the accurate and timely gathering of the required information. Focus will increasingly shift towards more in-depth analysis of data and the feeding of results to projects initiated by the Municipality (Smit, *et al.*, 2003). With rapid development and construction occurring on the Dubai coastline, the need for a sound understanding of coastal processes is essential. It is hoped that with the data collected as part of the Dubai Coastal Monitoring Programme, the coastal dynamics of the region can be understood and predicted for both the short term and for the longer term in response to potential climate change and sea-level rise.

1.5.1 Modelling Techniques

Admiralty charts are a key source of bathymetric data for numerical modelling of wave climate, sediment transport and tidal currents. Admiralty Standard Navigational Charts are produced in a range of scales for safe ocean navigation covering passage planning, harbours and nautical hazards, anchorages, coastal and offshore navigation. The National Oceanographic and Atmospheric Administration (NOAA), provides Nautical Charts in various formats: NOAA's Electronic Navigational Chart (ENC) is a vector-based digital file containing marine features suitable for marine navigation. It is based on the International Hydrographic Organisation (IHO) S- 57 standard; NOAA's Raster Nautical Chart (RNC) is a geo-referenced, digital image of a paper chart which can be used in a raster chart system; and finally, NOAA's Lithographic Nautical Charts which are the traditional paper charts.

Long-term wave monitoring around the UK coast is currently undertaken by DEFRA (Department for Environment, Food and Rural Affairs) in conjunction with the Environment Agency and the UK Met Office. The WaveNet project aims to provide a National wave monitoring network using a single source of real time wave data from a network of wave buoys located in areas at risk from flooding. Data from this network will be used to improve the management of flood and coastal erosion risk and to validate the UK Met Office wave model. The data will be used by Flood Managers, Local Authorities, Consultants, and other stakeholders in order to assess flood risk and on a longer timescale will be to help design improved flood defence schemes and to provide data for climate change studies (Centre for Environment, Fisheries & Aquaculture Science Website, 2006). Local initiatives to monitor the local inshore wave regime will continue to be implemented and maintained along with regional programmes monitoring nearshore wave data such as that of the South-East Strategic Regional Coastal Monitoring Programme.

A global wave model is also run by the Met Office and covers 80.28° N to 79.17° S on a regular latitude–longitude grid, with a resolution of 5/6° longitude by 5/9° latitude; it covers all sea areas, but the computational grid does not reach the poles and the model takes ice edge information from the global NWP model. The global wave model is run twice daily from 00 UTC and 12 UTC data times. Each run begins with a 'hindcast', starting from the wave conditions of 12 hours earlier and running forward with wind data from the NWP assimilation. The global model forecast is then run to five days ahead, using hourly NWP forecast winds. The winds from global NWP are at the same spatial resolution as the global wave model. Observations of wave height from the radar altimeter carried on the ERS-2 satellite are also assimilated into the global wave model (Met Office, 2005).

The Met Office also run a European wave model covering the areas from 30.75° N to 67° N and 14.46° W to 41.14° E (covering the north-west European shelf seas, the Baltic Sea, Mediterranean Sea and Black Sea) with a resolution of approximately 35 km. The European wave model is run twice daily from 00 UTC and 12 UTC data times and is run out to five days ahead, using hourly NWP forecast winds. At the open boundaries the model takes boundary data from the global wave model, allowing swell from the Atlantic to propagate in. The UK waters model has a much better resolution of the coastline than the European wave model, and includes the effect of time-varying currents on the waves, using currents forecast by the operational storm-surge model (Met Office, 2005).

The UK waters wave model covers the north-west European continental shelf from 12° W, between 48° N and 63° N at a resolution of 1/9° longitude by 1/6° latitude (approximately 12 km) (Figure 19). The model was introduced into the operational suite in 2000 and runs four times daily from 00, 06, 12 and 18 UTC (Universal Time Coordinated), taking hourly surface winds from mesoscale NWP

(Numerical Weather Predictions) to give a 48-hour forecast. A second run of the UK waters wave model is also made to give a 5-day forecast, this takes hourly winds from global NWP but does not include the effects of currents. The UK waters model additionally includes the effects of time-varying currents on the waves (Met Office Website, 2005).

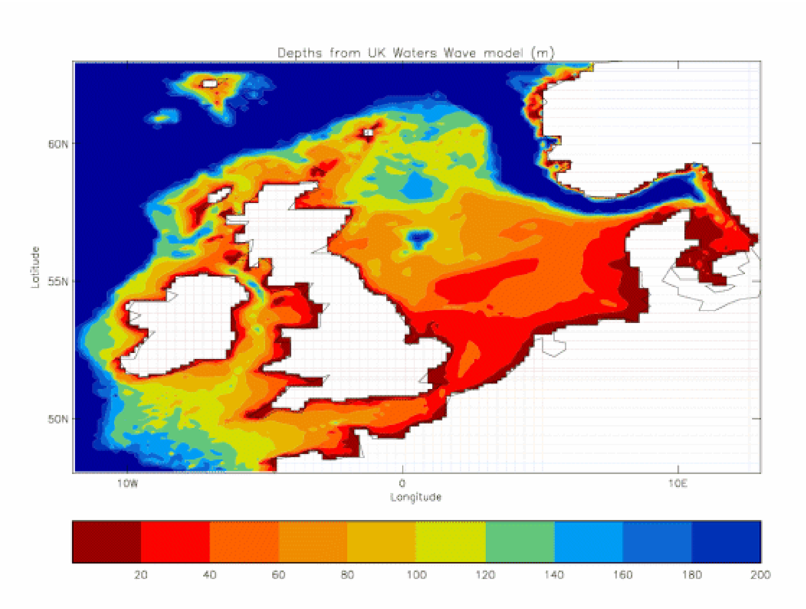


Figure 19. Depths and Land Sea Mask taken from the UK Waters Wave Model (Met Office Website, 2006)

A wide variety of tracers have been used to model sediment transport and dispersal for many projects all over the world. For example an offshore-onshore sediment exchange study at Helwick Bank on the Gower Peninsular, Wales was undertaken, whereby fluorescent tracers were used to track transport direction and magnitude for various particle size classes. In New Zealand an offshore-onshore sediment exchange (NOSEX) study in the Hauraki Gulf has also been undertaken (ETS 2004). Recent studies, such as that undertaken by *C.A. Booth et al., 2005*, have attempted to highlight the advantages of using mineral magnetic concentration data to indicate a correlation between magnetic concentration and particle size. The study suggests that there is considerable potential for using magnetic concentration data as a particle size proxy for particular sedimentary environments (*C.A. Booth et al., 2005)*. Given the speed, low-cost and sensitivity of the method, it may offer some advantages over other compositional signals (*C.A. Booth et al., 2005)*.

Another sediment transport study was undertaken on the south coast of England between Lyme Regis (Dorset) and Shoreham-By-Sea (West Sussex). The original study, produced in 1991, was commissioned by SCOPAC (Standing Conference on Problems Associated with the Coastline), a group of local and statutory authorities with responsibilities for coastal protection, sea defences and other aspects of coastal management (SCOPAC website, 2006). Since then, the study has been revised to contain information on sediment inputs (marine; fluvial; cliff/coastal slope/platform erosion; beach nourishment); littoral drift; sediment outputs (including offshore transport, estuarine outputs); beach morphodynamics; and sediment stores, of transport compartments (cells and/or sub-cells) along the south coast. Figure 20 illustrates the interactive maps available for all sites within the region detailing sediment transport sources, pathways and sinks.

NE Isle of Wight (Old Castle Point to Culver Cliff: Sediment Transport Sources, Pathways and Sinks

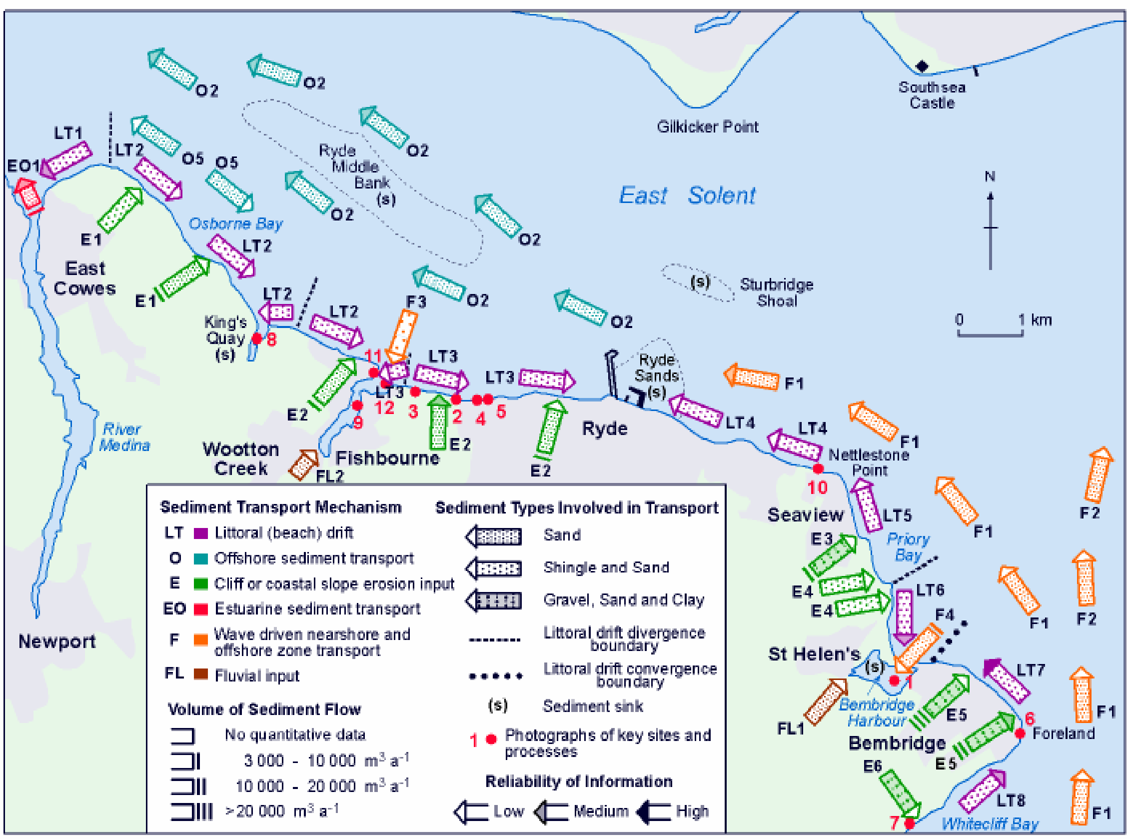


Figure 20. SCOPAC Sediment Transport Study (SCOPAC website, 2006).

2 Monitoring Techniques

2.1 Airborne/space borne Techniques

Airborne and space-borne remote sensing techniques have been used to capture data at a variety of sites, to provide coverage of special features, or where these techniques are either more practical or efficient than land based methods (Channel Coastal Observatory Website, 2005). Such techniques are referred to as Remote Sensing techniques as they involve the gathering of information at a distance via aerial photography, satellite imagery, acoustic data, and radar imagery.

2.2 Space-Borne Techniques

Moderate Resolution Satellite Imaging

2.2.2.3 Basic Principles

Remotely sensed data from satellites represents an important source of alternative data to those derived from *in-situ* measurements (Doody et al, 1998). Satellite data is similar to the data available from aircraft; however as satellites are in constant orbit, data is updated without the need to commission a custom survey (Millard, K. and Sayers, P. 2000). Satellites provide a means for looking at a very large area of the world within a very short time period. Satellite sensors create pictures of the Earth from space using electromagnetic radiation covering a range of frequencies, from radio waves to gamma rays (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

As electromagnetic radiation from the sun, or emitted from the satellite itself, hits objects on the Earth, a portion of that radiation is reflected back to the satellite. Sensors on the satellite measure the wavelength and intensity of the reflected radiation. Different objects do not reflect radiation in the same way: clear water, for example, will reflect light differently from turbid water (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006). Satellites can be fitted with both moderate and high-resolution sensors depending on the quality of imagery required. With regards to moderate resolution satellite imaging, there are two main types of sensors used, these being the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Landsat Thematic Mapper and the Enhanced Thematic Mapper (Landsat TM/ETM+).

Satellites can record accurate sea surface temperatures, which can be used for studying climate change. Radar systems fitted to satellites can observe the sea state recording surface waves, fronts, internal waves, currents and wind. Long-term data derived from satellites can be used to produce predictive models. Scientists can determine features such as the type of vegetation on the seafloor based on the signature pattern of the reflected signal.

Sea-viewing Wide Field-of-view Sensor (SeaWiFS)

The OrbView-2/SeaWiFs (Sea-viewing Wide Field-of-view Sensor) instrument is designed to monitor the colour of the world's oceans. Subtle changes in the ocean's colour result from changes in the concentrations of marine phytoplankton, resuspended sediment, and dissolved substances in the water column. Since an orbiting sensor can view every square kilometre of cloud-free ocean every 48 hours, satellite-acquired ocean colour data constitutes a valuable tool for determining the abundance of ocean biota on a global scale and can be used to assess the ocean's role in the global carbon cycle and the exchange of other critical elements and gases between the atmosphere and the ocean (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006). Used as a circulation tracer, spatial patterns in Chlorophyll-a concentrations, the green pigment found within plants and marine phytoplankton, often show a more detailed definition of the dynamic oceanic surface structure than is observed from spatial patterns in Sea Surface Temperature (SST). Many environmental monitoring programs require knowledge of Chlorophyll-a concentrations and changes in the magnitude and distribution of these concentrations in order to provide an understanding of the coastal environment on a global scale.

Landsat Thematic Mapper and Enhanced Thematic Mapper (Landsat TM/ETM+)

The Enhanced Thematic Mapper Plus (ETM+) is a multispectral scanning radiometer that is carried on board the Landsat 7 satellite. Multi-spectral sensing equipment on aerial or satellite platforms shows aspects not normally visible to the human eye. Satellites collect data by passing the reflected energy from the Earth through filters that separate the energy into small windows of the electromagnetic spectrum into discrete spectral bands. Satellites used in optical remote sensing typically collect data anywhere from the Ultraviolet (UV) to the Thermal Infrared (IR). By assigning any 3 spectral bands into the 3 colours (red, green, and blue), one can create a coloured image that gives us the ability to see data attributes that are not visible to the human eye (United States Geological Survey Landsat Website, 2006). The ETM+ instrument provides image data from eight spectral bands. The spatial resolution is 30 meters for the visible and near-infrared (bands 1-5 and 7). Resolution for the panchromatic (band 8) is 15 meters, and the thermal infrared (band 6) is 60 meters (United States Geological Survey Education Resources Website, 2006).

This technique has proven useful for benthic habitat mapping in some shallow water marine environments. For example, broad-spectrum bands of visible light (red, green, and blue) have been used to differentiate habitat types like sand, seagrass, coral, and hard substrate in coral reef environments where airborne imagery was unavailable (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

High Resolution Satellite Imaging

2.2.2.4 SPOT (Systeme Pour l'Observation de la Terre)

The SPOT system (Systeme Pour l'Observation de la Terre) began providing geographic data in 1986 with the launch of SPOT 1 and was enhanced by SPOT 2 in 1990 and two other sensors in 1993 and 1998. The SPOT-5 satellite, launched in May 2002, has been providing multispectral (MS) (sensors that collect data in two or more spectral bands of the electromagnetic spectrum, usually shown as a coloured image) and panchromatic (PAN) (sensors that are sensitive to all or most of the visible spectrum and show images in black and white) imagery since mid-July of 2003 (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006). The SPOT system currently includes three active satellites and numerous receiving and data processing facilities. SPOT-5 offers resolutions of 2.5 metres in black and white and 10 metres in colour. A study by Forghani *et al*, in 2003, aimed to evaluate the use of SPOT-5 imagery for topographic map revision in comparison to SPOT-2 and ETM+ (Enhanced Thematic Mapper Plus) imagery. The study concluded that SPOT-5 imagery improved the identification and delineation of problematic features and that the high-resolution data enhanced the interpretability of the imagery.

2.2.1.5 QuickBird

QuickBird, owned and operated by DigitalGlobe is a commercial satellite that collects high-resolution global imagery. QuickBird satellite provides the largest swath width, on-board storage, and highest resolution of any currently available or planned commercial satellite. QuickBird is designed to efficiently and accurately image large areas with extremely high geolocational accuracy (DigitalGlobe website, 2006). The QuickBird spacecraft is capable of acquiring over 75 million square kilometres of imagery data annually through panchromatic imagery at 60cm and 70cm resolutions and multispectral imagery at 2.4m and 2.8m resolutions. An example of such imagery is shown in Figure 21 taken less than four hours after the earthquake and moments after the tsunami impact on the south-west coast of Sri Lanka.

Figure 21. QuickBird natural colour, 60-centimeter pan-sharpened satellite image of Kalutara Beach, Sri Lanka (DigitalGlobe and Eurimage, 2006).

2.2.2.6 IKONOS

The IKONOS Satellite (derived from the Greek work for 'image') is a high-resolution satellite operated by Space Imaging. The IKONOS satellite was the world's first commercial satellite to produce 1m black and white (panchromatic) and 4m multispectral (red, blue, green and near infrared) imagery. Moving over the ground at approximately seven kilometres per second, IKONOS collects data at a rate of over 2,000 square km per minute, providing access to any location on the Earth's surface through the near fifteen, 98-minute journeys it makes around the globe each day.

Budgeting Monitoring Schemes

Various studies, such as that undertaken by Eurosion 2004 (Table 1), have aimed to estimate the cost of airborne techniques as a use of coastal monitoring techniques. However, it must be noted that these are rough estimates and that prices vary depending on the source of the image, the size of the area, and the level of processing involved.

Table 1. Unit costs for Satellite images for areas superior to 100 km2.

Satellite images	Resolution	Unit costs in Euros / km2
SPOT 5	2.5 – 5 metres	5-8
IKONOS	1 metre	10-13

Source: Eurosion (2004).

With regards to the use of OrbView-2/SeaWiFs, data is available as raw spectral values and as processed chlorophyll images. Both types are available from OrbImage with prices varying depending on the level of processing requested. Average costs for a single image are approximately €421 for a 512x512km image. Real-time data can be purchased at an annual subscription cost of approximately €84,000 per year based on a 2,200km radius.

The Thematic Mapper and the Enhanced Thematic Mapper Plus (ETM+) costs are based on the level of spatial and/or spectral correction ordered. There are three levels of processing; Level 0 Reformatted (L0R), whereby the data is simply reformatted raw data with no resampling or geometrical correction of pixels; Level 1 Radiometrically Corrected (L1R) where data is colour corrected and various system noise and image artefacts are characterised and corrected; and Level 1 Geometrically Corrected (L1G) where images are radiometrically and geometrically corrected. Prices range from approximately €400 for a single Level 0 scene (180km x 180km) to €500 for a L1R scene and €600 for a L1G single scene.

The level of processing (e.g., orthocorrection) and size of the scene are the primary factors affecting final cost of SPOT system imagery. A full SPOT-5 scene covers an area of 60km x 60km with entry-level images, offering 20-metre resolution multispectral images and 10 metres panchromatic images, priced at approximately €1,900. Core products at a resolution of 10 metres multispectral and 5 metres in panchromatic cost around €2,700 whilst high-end SPOT products, at a resolution of 2.5 metres in black and white coast around €5,400 — a cost of €1.5 per Km2 for a 3,600-km2 scene.

QuickBird image prices vary depending on the level of processing required and whether the image is archived or newly acquired. Archived geo-referenced images cost €30 per Km² with archived orthorectified images costing €44 per Km². Newly acquired geo-referenced images are priced at €44 per Km² and orthorectified images at €53 per Km² (Satellite Imaging Corporation (SIC) website, 2006).

IKONOS image prices, similar to that of QuickBird, vary depending on the level of processing the image age. Archived geo-referenced images cost €31 per Km² with archived orthorectified images costing €40 per Km². Newly acquired geo-referenced images are priced at €42 per Km² and orthorectified images at €48 per Km² (Satellite Imaging Corporation (SIC) website, 2006).

Limitations

Some limitations are present in satellite imaging techniques. Shorelines are often difficult to detect because reflection through the water produces signatures similar to those received from adjacent land (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006). Problems arise in the mapping of features below the water surface if there is a lot of material in the water column. Sub-surface remote sensing applications in turbid coastal environments are therefore extremely limited. In addition, coastal areas are prone to cloud cover, restricting the use of passive forms of remote sensing relying on reflected sunlight. However, increased frequency of satellites and availability of aircraft sensors can increase the number of images acquired. The use of radar sensors that can penetrate clouds and haze makes it possible to map and monitor coastal environments under all conditions.

Spatial resolution of satellite data is one of the most significant factors that restrict its wider use in coastal applications (Millard and Sayers, 2000). As the detail, or spatial resolution, increases, the area covered generally decreases. Higher resolution requirements often mean higher data costs and so it is essential that a cost-benefit analysis is carried out prior to purchasing the imagery. Possible licensing requirements or restrictions on data distribution, and associated expertise, hardware, and software needs are other factors that are likely to increase the costs of using such a method of monitoring.

The limitations associated with hyperspectral imaging include its relatively high cost and overall lack of availability to average users. Although this technique can achieve far better resolution than multispectral instruments, it is still primarily useful only in shallow, non-turbid water (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

Advantages

Satellite imaging is desirable because it can cover relatively large areas (spanning several kilometres) at relatively low cost. Remote sensing techniques are usually the most cost-effective means of getting information about areas that are inaccessible or are too large to effectively manage or assess with traditional surveying methods. Whereas surveying a large area with traditional methods can take weeks to even years to complete, remotely sensed data allows for an image to be collected at a specific moment in time. This ensures that no changes have taken place whilst the data was collected and means that the image can also be used in the future for comparisons of the same area over time.

Although it is seldom possible to acquire satellite imagery under the appropriate conditions for effective benthic mapping (such as low-tide or calm sea state), satellite imaging has proven useful in tropical, clear water environments for coral mapping. New high-resolution satellites are equipped with cameras that can distinguish objects as small as one-metre square, or about three feet in size, but such data are not yet widely available due to security and licensing concerns (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

2.3 Airborne Techniques

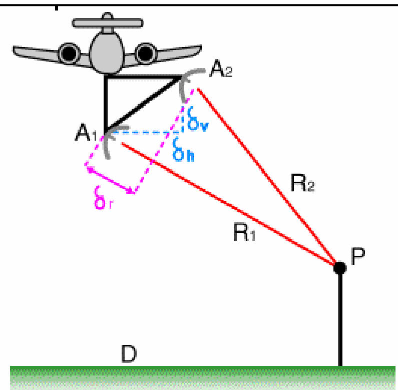
Interferometric Synthetic Aperture Radar (IfSAR or InSAR).

2.3.2.1 Basic Principles

Interferometric Synthetic Aperture Radar (IfSAR or InSAR) is an aircraft-mounted sensor designed to measure surface elevation, used to produce topographic imagery. Radar pulses are aimed at targets on the Earth, and the return ground signals are received by two antennae that record elevations (z) at specific ground coordinates (x,y). The ground coordinates are determined by Global Positioning System (GPS) and inertial measurement unit (IMU) technology. Post-processing of these data produces topographic information in the form of orthorectified radar imagery (ORRI). The ORRI are black-and-white (greyscale) 8- or 16-bit orthorectified radar imagery with a pixel resolution ranging from 1.25 to 2.50 metres (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

In interferometric synthetic aperture radar imaging, microwave pulses are transmitted by an antenna towards the earth's surface. The microwave energy scattered back to the spacecraft is measured. The SAR makes use of the radar principle to form an image by utilising the time delay of the backscattered signals. In real aperture radar imaging, the ground resolution is limited by the size of the microwave beam sent out from the antenna. Finer details on the ground can be resolved by using a narrower beam. The beam width is inversely proportional to the size of the antenna, i.e. the longer the antenna, the narrower the beam. The microwave beam sent out by the antenna illuminates an area on the ground (known as the antenna's "footprint"). In radar imaging, the recorded signal strength depends on the microwave energy backscattered from the ground targets inside this footprint. Increasing the length of the antenna will decrease the width of the footprint. It is not feasible for a spacecraft to carry a very long antenna that is required for high resolution imaging of the earth surface. To overcome this limitation, IfSAR/InSAR capitalises on the motion of the spacecraft to emulate a large antenna (about 4 km for the ERS SAR) from the small antenna (10 m on the ERS satellite) it carries on board (Crisp, 2001).

In SAR interferometry, two images are acquired of the same area by two spatially separated antennae. The antennae can be on the same platform, or the same antenna can be used twice during different passes. (This later scenario is called "two-pass" or "repeat-pass" interferometry.) If the antenna positions are separated in the range direction, i.e. orthogonal to the flight path, height information about the surface may be deduced; if separated in the azimuth direction, i.e. parallel to the fight path, surface motion can be measured for example ocean currents. In both cases, the two scenes are registered accurately and the phases corresponding to each pixel are calculated and differenced, resulting in an interferogram (Canada Centre for Remote Sensing Website, 2006).



A case of SAR interferometry for altitude measurement.
A_1, A_2 = two different antennas
δ_h, δ_v = horizontal and vertical separation of the antennas
δ_r = line of sight range difference ($\delta_r = R_1 - R_2$)
R_1, R_2 = line of sight distances from the two antenna positions to the target
P = target being imaged
D = datum

Figure 22. An example of SAR interferometry for height measurement (Canada Centre for Remote Sensing Website, 2006).

2.3.2.2 Limitations

There are a number of limitations in the use of IfSAR/InSAR that need to be taken into account when planning a monitoring programme. Despite having the major advantage of being able to produce topographic maps for remote areas, IfSAR X-band has difficulty mapping earth surfaces with dense vegetation. The X-band registers first-return signals from ground features that, in the case of densely forested areas, are return signals from the tree canopy, rather than the earth surface. However, P-band microwaves can penetrate dense vegetation with good results and provide an alternative solution for these harder-to-map areas. IfSAR/InSAR also has difficulty in mapping certain areas where it cannot see the earth's surface, such as the shadowed areas of mountains or buildings. This is a result of the angle of flight with respect to the target areas. These areas can result in voids in the DEM data, which are corrected, as best as possible, by interpolation modelling during the post-processing effort. It is possible to request from the IfSAR/InSAR provider a GIS layer where these voids were corrected, although to minimise potential voids, it is better to sample an area with multiple images.

Atmospheric effects represent one of the major limitations of repeat-pass interferometric synthetic aperture radar (InSAR) (Li *et al.*, 2005). This is, however, more common in space-borne IfSAR/InSAR than airborne imagery but nevertheless, is a factor that should be considered when determining which method of imagery is most valuable. Issues arise with regard to interference and refraction of GPS signals as they travel through the atmosphere. GPS errors can be minimised by reducing the distance between the reference control marker and the sensor, thus preventing an unwanted accumulation of distance-dependent errors.

Other limitations that occur with regards to IfSAR/InSAR are that certain materials (e.g., calm water) reflect radar signals away from the transmitter causing null elevations and that the vertical accuracy is not seen to be as accurate as the LiDAR system (Crisp, 2001). In addition to this, the military restricts the use of P-band frequencies around certain facilities and areas for security purposes making IfSAR/InSAR unsuitable for certain locations.

2.3.2.3 Advantages

One of the main advantages of using IfSAR/InSAR radar imaging systems is their ability to monitor ground displacements in real-time or near real-time. This allows for images to be used in the future for comparisons of the same area over time, making it ideal for monitoring shoreline changes. Other benefits of radar imaging include remote observation, day and night operability, and maximum flexibility in terms of viewing capacity and frequency of observation. IfSAR/InSAR can be an especially useful tool as it is not dependent on the weather and is less expensive than the LiDAR system (Crisp, 2001).

SAR interferometry has been demonstrated successfully in a number of applications, including topographic mapping, measurement of terrain displacement as a result of earthquakes, and measurement of flow rates of glaciers or large ice sheets (Canada Centre for Remote Sensing Website, 2006).

LiDAR

2.3.2.4 Basic Principles

LiDAR (LIght Detection And Ranging) is an airborne remote sensing technique that gathers millions of geo-referenced XYZ points on a single survey allowing for flood risk mapping, beach monitoring and cliff monitoring to be carried out. An active sensor, similar to radar, transmits laser pulses to a target and records the time it takes for the pulse to return to the sensor receiver, thus determining elevation.

Scanning LiDAR's acquire spatially dense data consisting of measures of elevation every few m^2 within a surveyed swath hundreds of metres wide (Sallenger *et al*, 2003). Systems with long baseline capability can survey hundreds of kilometres of coast in a few hours with a single GPS base station (Krabill *et al*, 2000). Surveys, typically flown at an elevation of 1000m, produce a swathe of data with a width of about 700m. This coverage is perfect for monitoring of the coastal zone. A vertical precision of +/-0.15m has been widely quoted; this relates to uncertainties in the altitude of the aircraft, but also relies upon a suitable projection and datum transformation to the local system. It is believed that transformation difficulties within the UK have (historically) resulted in rather worse data quality than is technically feasible (Bradbury, 2004).

In general, two types of LiDAR systems are used: bathymetric LiDAR that penetrates the water and provides measures of water depth, and topographic LiDAR that measures sub-aerial topography. In both instances it is vital that baselines can be flown for long stretches of coastline from one GPS base station in order to maximize the amount of data collected in one flight.

The Scanning Hydrographic Operational Airborne LiDAR Survey (SHOALS) system, amongst others, is a bathymetric LiDAR system used by the US Army. The system operates from a helicopter at approximately 200 meters altitude where the laser scanning system generates a swath width of just over 140 meters. System requirements dictate a laser operating at 200 Hz in both the blue-green wavelength for maximum water depth penetration and the infrared for surface interface recognition. Each laser shot strikes the water surface at a known location where its energy is partially reflected back to the receiver and partially transmitted through the water column. Transmitted energy undergoes scattering and absorption along its path to the bottom where the remaining energy is then reflected back to the receiver (Lillycrop and Banic, 1993)

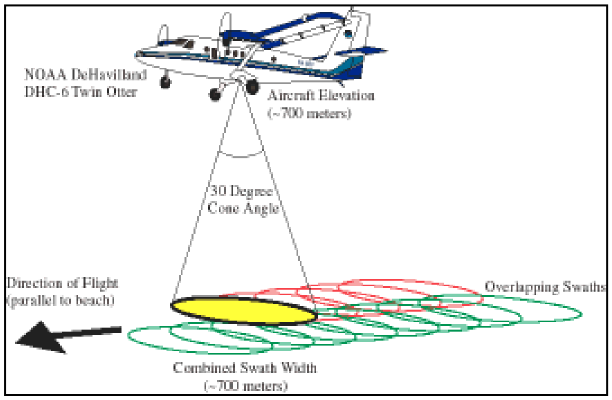


Figure 23. Diagram showing the elliptical scan pattern of NASA's Airborne Topographic Mapper (ATM) operated from a NOAA Twin Otter (http://coastal.er.usgs.gov, 2006).

2.3.2.5 Limitations

The LiDAR system, whilst operational for certain monitoring applications, has not yet reached the stage where confidence is sufficiently high to rely on it for beach monitoring at a strategic operational scale. A study by Sallenger *et al*, evaluated the use of airborne topographic LiDAR against three other ground-based measurements; differential GPS mounted on an All-Terrain Vehicle (ATV) measuring from the shoreline to the dune (approximately 3km), a human roving GPS antenna attached to a rod surveying a 100m stretch of beach and finally, a second ATV surveying a 70km stretch of coastline. The results concluded that the spatial density of topographic LiDAR data can resolve the dominant natural scales of beach variability yet accuracy is not sufficient to monitor smaller scale changes such as storm damage.

This LiDAR system is costly. However, when consideration is given to the resources and time it would take to gather information of similar accuracy using conventional geo-technologies, the benefits may outweigh the costs. It is however, essential for a surveyed ground reference marker to be installed prior to the flight adding time and money to the overall project. In addition to this, as with most technologically advanced equipment, improvements and upgrades will occur over the coming years that will result in additional expense in the future.

Weather conditions can affect the running of the LiDAR system with water vapour and/or droplets distorting the signal. It is also unlikely that LiDAR would be suitable for use in determining bathymetry in the turbid UK waters, although recent tests by the UKHO off the coast of Scotland found it to be extremely useful.

2.3.2.6 Advantages

The LiDAR system is useful for applications that seek to provide an overview, where the absolute vertical accuracy is less significant. Applications at a strategic planning level, for instance, allow assessment of relative water level changes over large areas and identify detailed relief of cliffs or saltmarsh systems. LiDAR has the potential to supersede conventional photogrammetric methods at some stage in the future, but does not appear appropriate at this stage (Bradbury, 2004). However, improvements in LiDAR systems have been driving down the overall cost while increasing the resolution, at the same time also decreasing file size; things that previously made LiDAR unfeasible as a solution (Romano, 2004).

A major asset of airborne LiDAR is the high spatial density. Measurements of elevation are acquired every few m^2 over regional scales of hundreds of kilometres. Hence, many scales of beach morphology and change can be resolved, from beach cusps tens of metres in wavelength to entire coastal cells comprising tens to hundreds of kilometres if coast (Sallenger *et al.*, 2003). In many cases, LiDAR is now proving to be more beneficial than photogrammetric methods.

Another major benefit of LiDAR is that it allows development of DTMs for large areas; these can be easily understood and interpreted within GIS to produce graphical representation of relief and changes in relief. Data can be presented in colour contoured isopachyte form, orby slope rate shading, and in 3-dimensions with the use of perspective views. Relief shading makes visual interpretation of the data very simple. Profile data can also be extracted from the data set, if required. The need to analyse multiple data sets in combination with topographical information, for shoreline management, seems certain to result in development of such an approach to data analysis and presentation. Typical practical applications may include flood risk mapping, beach monitoring and cliff monitoring (Bradbury, 2004).

The fact that LiDAR can be used at night is a huge advantage over other aerial methods of data collection.

Airborne Multispectral Systems

Airborne multispectral (MS) camera systems are complex systems that use multiple cameras for imaging terrain in three spectral bands whilst also allowing for navigational and positional readings to be collected via a Global Positioning System (GPS) receiver. These multispectral systems can collect stereo black and white, colour infrared, and true-colour imagery using a single pass at the required ground resolution. The systems were designed as an alternative to traditional film-based photogrammetric mapping cameras and offer both high accuracy and resolution. Most systems are designed around matrix (array) Charge Coupled Device (CCD) imaging elements to ensure rigid image geometry. This means that even if the GPS signal is lost and weather and turbulence are severe, images can still be collected at the required resolution.

The size of individual CCD cells (photosites) is approximately nine microns, which is a compromise between sensor spatial resolution and radiometric properties. A further decrease in the size of photosites would improve spatial resolving power of the sensor, yet would sacrifice the radiometric sensitivity. The spatial resolution of data products offered by the majority of systems is one metre (or higher) for visible and near infrared radiation and about four metres for medium and long (thermal) IR. This corresponds to flying altitude of approximately 1500 meters (5000 feet). Spatial resolution may be modified if application requires it. (Furh *et al*, 1999).

2.3.2.7 Limitations

To obtain multispectral image data with high spatial resolution, multispectral and panchromatic images have to be merged (pansharpening). Image transforms such as the Intensity-Hue-Saturation (IHS) or Principal Component (PC) transforms are widely used to fuse panchromatic images of high spatial resolution with multispectral images of lower resolution. These techniques create multispectral images of higher spatial resolution but usually at the cost that these transforms do not preserve the original colour or spectral characteristics of the input image data (Cetin, 2004).

Multispectral image data can be costly. Prices can vary depending on size of project, spatial accuracy, and project location. Costs may also increase based on additional product requests (i.e., DEMs, DTMs, contours, etc.), specific accuracy requirements, or licensing restrictions. It is therefore essential to budget for the level of processing and analysis necessary beforehand, to ensure the viability of the system with regards to shoreline monitoring.

2.3.2.8 Advantages

The position and reference data acquired by the GPS receiver and the attitude reference sensor can be used to register the multispectral image data with geographical coordinates, without need for predetermined ground reference targets. The image data is provided in the required coordinate system and can be easily integrated into an existing GIS database (Ehlers, 2004). Therefore, there is no need for users to have a thorough knowledge of GPS and GIS systems making multispectral imaging significantly more user-friendly than other monitoring techniques.

Unlike satellite-based missions, airborne data acquisitions, such as that of multispectral imaging, are significantly more flexible in terms of time schedules, flight line arrangements, calibration measurements, spectral/spatial resolutions, and acceptable weather conditions (Cetin, 2004). The user has a far greater influence over the mission offering a significant benefit over other space-borne techniques.

Thermal Infrared Radiometer

Airborne thermal infrared radiometers (TIR) are used to map and measure thermal characteristics of landscapes and seascapes. These instruments are often components of complex remote sensing systems that incorporate visible sensors, airborne inertial measurement units (IMU), differential global positioning units (DGPS), data storage devices, and specialised software for georeferencing. Thermal imagery can be collected at customer specified ground-resolutions and temperature ranges (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

Thermal infrared radiometers used in mapping applications are calibrated to maintain consistency among images collected during a mission. Midwave and longwave radiant energy (3 to 5 and 8 to 14 micrometers) emitted from the ground, water, and other objects is captured by airborne sensors on linear arrays or focal plane arrays and stored as digital numbers. Post-processing of the raw data produces temperature data that are applicable to a wide variety of mapping needs (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

Potential uses of TIR with regards to monitoring of the shoreline include pollution and wastewater mapping, marine mammal surveys and sea surface temperatures.

2.3.2.9 Limitations

TIR, like other forms of airborne sensor systems, is vulnerable to the effects of the weather. TIR imagery can be prevented by cloud cover and water vapour, restricting its use in certain climates. In addition to this, TIR can only record the surface temperature of the sea rather than subsurface measurements. This is because water is generally opaque to thermal wavelengths due to the vertical mixing of sediments within the water column.

Many time constraints are associated with TIR imagery collection and delivery. Flight schedules can be delayed due to seasonal restrictions, weather, and environmental factors, and project areas may be so large that multiple flights are needed (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006). Post processing can also be time-consuming with the production of additional deliverables delaying the delivery schedule whilst also increasing the costs.

2.3.2.10 Advantages

Despite a number of limitations, TIR is seen as an extremely reliable method of monitoring midwave and longwave radiant energy to produce temperature data applicable to a wide variety of mapping needs. It also has a wide range of uses not just specifically for coastal monitoring but for issues such as fire detection and mapping, law enforcement and search and rescue. It can be used day and night and advanced mapping grade TIR systems often include a separate digital video or frame camera that collects visible imagery to help interpret the thermal imagery.

Hyperspectral Systems

Hyperspectral sensors are passive sensors that acquire simultaneous images in many relatively narrow, contiguous and/or non-contiguous spectral bands through the ultraviolet, visible and infrared portions of the electromagnetic spectrum (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006). Hyperspectral information can be acquired via both aircraft and satellite platforms.

The difference between multispectral and hyperspectral imagery is the detail of the spectral signature. Most multispectral sensors take one measurement in a wide portion of each major wavelength band, such as visible blue, near infrared, etc. Hyperspectral, on the other hand, splits the visible and infrared light spectrum into many (greater than 100) narrow, adjacent bands. The sensor takes images from contiguous regions of the spectrum, typically with much finer resolution. As a result of this higher number of measurements, the hyperspectral signature is more detailed and contains more specific information.

Airborne Hyperspectral Imaging is an emerging technology for classifying benthic habitats in coastal zones. Since different substances reflect the various wavelengths differently, hyperspectral imaging analysis can be used to identify benthic habitats such as live coral, sand, and algae. Airborne hyperspectral technology can provide accurate base maps of reef communities and allow for change detection in near real time.

One of the most widely used hyperspectral imaging sensors is CASI (Compact Airborne Spectrographic Imager). CASI is a remote sensing tool that generates imagery by detecting the visible and near infra-red electromagnetic energy that is reflected from the earth's surface. The wavelengths of the reflected energy vary depending upon the surface type and therefore a digital image of ground classification can be developed. The CASI system can be installed and operated from a small aircraft and maps out a swath of the ground directly below the aircraft. The spatial resolution of the image can be varied from one to ten metres and is governed by the flying altitude. The aircraft is positioned and navigated using GPS, corrected to known ground reference points. This enables highly precise geo-referencing of the imagery. Data can also be integrated with LiDAR to provide 3 dimensional images, providing the same ground control network is used.

The CASI provides multi-spectral imagery in up to 288 bands for use in:

- Mapping coastal habitats and habitat change
- Land cover and landscape studies
- Algal biomass monitoring
- Monitoring vegetation productivity and health

A second-generation instrument, CASI 2 was developed in the late 1990's and since then the CASI 3, also referred to as CASI-1500, has been introduced. CASI 3, much like CASI 2, is a Charge Couple Device (CCD) pushbroom imaging spectrograph intended for the acquisition of visible and near-infrared hyperspectral imagery. The instrument combines the features of aerial photography and satellite imagery with the analytical potential of a spectrometer and the integration of GPS and high precision altitude sensors for precise position mapping. Pixel resolutions can vary from 25cm to 1.5 meters and can be programmed to operate in any two operational modes, spatial mode and hyperspectral mode. CASI 3 has a swath width of 1,500 pixels, while still retaining the 288 spectral channels. Moreover the CASI 3 images have a 14-bit depth instead of the 12-bits used in the earlier models.

The spectrograph optics of the CASI system image a line across the flight path of the CASI onto one axis of a two-dimensional sensor array. The image is spectrally dispersed along the other axis of the CCD, creating a complete spectrum for each point across the swath. Through the process of repetitively reading out the CCD data as the aircraft moves along the flight path, a two-dimensional scene image a high spectral resolution is acquired. Since all pixels are exposed simultaneously within each CCD frame, spatial and spectral co-registration are automatically archived. The across track resolution of the image is determined by the altitude of the aircraft above the ground and the field of view of the instrument, while the along-track resolution varies with the aircraft velocity over the ground and the frame rate at which the CCD is read out. The CASI system can be programmed to operate in any one of three modes to effect different types of CCD readout; spatial mode, hyperspectral mode and full frame mode. In all modes data is digitised (Itres, 2002).

2.3.2.11 Limitations

Airborne hyperspectral sensors are often very expensive due to the fact that their limited spatial coverage necessitates multiple flight lines to cover a study area. Also, data processing is usually complex and can cause problems (Cetin, 2004). There are numerous issues regarding how to display and analyse hyperspectral imagery and this complexity makes it unsuitable for average users. Post processing can be time consuming and producing additional deliverables can delay the delivery schedule.

Another disadvantage of this technique is that it requires an image with at least one distinctive linear feature, or the technique becomes inapplicable. In some circumstances, multiple minor linear features can be intelligently merged as a major linear feature in order to make this technique applicable. This requires a user to have more knowledge of image processing and more flexible computer skills in data manipulation (GeoComputation Website, 2006).

Hyperspectral imaging systems that operate at visible through near-infrared wavelengths, typically rely on solar illumination meaning that cloud shadows can be problematic with such systems. Flight schedules can be delayed due to seasonal restrictions, weather, and environmental factors, thus decreasing the flexibility of the system as a tool for shoreline monitoring.

2.3.2.12 Advantages

There are numerous advantages to using airborne hyperspectral imaging systems where highly accurate and geo-referenced image data is required. Data collection from hyperspectral imaging systems such as CASI is available 'on demand' and can provide real-time processed images with geometrically and radiometrically corrected data. This data is spatially accurate within several inches by using Differential Global Positioning System (DGPS) and can provide 100% coverage of the ground surface to approximately 1 metre pixel resolution. Airborne DGPS does not require a ground control and data collected is GIS-ready saving both time and money on preparation and post-processing.

The CASI system has a higher spatial resolution and greater flexibility, and a wide spectral range and greater spectral resolution than most satellites. It can image under low light conditions and has programmable spectral bands and pixel sizes. Its imagery has a wide dynamic range and high signal to noise ratio. CASI can be fully calibrated to provide consistent scene brightness values. The system also has full geometric corrections incorporating differential GPS, precision aircraft rotations and terrain height information. The integration of CASI data with GIS analysis allows a client to achieve improved data organisation and data results. The CASI system can often efficiently identify things, which are difficult or impossible to detect by satellite imagery, aerial photography, or even ground photography (Itres, 2002).

2.3.2.13 Budgeting Monitoring Schemes

Collection of airborne remotely sensed data can be extremely expensive. Costs vary with most types of airborne data depending on the size of project, environmental constraints, spatial resolution, spectral resolution and level of post-processing. In instances where a large area of land needs to be covered, the cost-benefit ratio is often in favour of using an airborne imagery system. High-density ground sampling would be both costly and time consuming in order to cover the same area covered by airborne techniques.

The average cost range for LiDAR *x*, *y*, *z* point data is approximately €820 to €1640 per square mile for 2 to 3-metre grid density. This cost includes flight, LiDAR collection, post processing, and delivery. Cost can vary depending on size of project, horizontal postings (point density), and project location. Cost does not include additional products (i.e., Digital Elevation Models, Digital Terrain Models, contours, etc.), specific accuracy requirements, or licensing restrictions (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

Hyperspectral imagery, such as that collected via CASI 3, uses DGPS/IMU systems with a pushbroom line scanner in order to provide spatially accurate data. However, this adds considerably to the cost of the overall scanner system. A sum of between €25,000 and €165,000 is needed to cover the cost of the DGPS/IMU component of a single system. Currently the Canadian *Applanix* company (now owned by Trimble) is the dominant supplier of the high-quality DGPS/IMU units that are required to carry out high-precision photogrammetric work with pushbroom scanner images. These lie at the top end of the price range. However, some multi-spectral and hyperspectral pushbroom scanners have used lower performance systems that lie at the lower end of the price range such as the C-MIGITS-III system from BEI Systron Donner since the images are mainly used for thematic mapping where the requirements for geo-referencing will often be lower (Department of Geographical and Earth Sciences, University of Glasgow, 2006.

Various studies, such as that by Eurosion 2004, have been undertaken to estimate the cost of using airborne techniques. The table below illustrates the approximate costs for airborne laser altimetry. However, it must be noted that these are coarse estimates.

Table 2. Unit costs for Airborne Laser Altimetry for areas superior to 100 km2.

LiDAR	Resolution	Unit costs in Euros/ km2
Airborne laser altimetry	0.1 metre	500-700

Source: Eurosion (2004)

Aerial Photography

Aerial photography is used widely in coastal monitoring programmes for interpretation of geomorphological changes and assessment of coastal erosion and accretion. Typical applications include; beach profiling from photogrammetry; habitat mapping; contact prints for visual interpretation; production of digital orthophotos or georectified photos; detailed topographic mapping from photogrammetry; and updating of OS mapping. Bunker *et al* recommend that good quality aerial photographs are best taken at low water of spring tides at a scale of 1:10,000. Photographs taken at a larger scale may not show enough detail to be useful.

Digital aerial photography consists of two types of imagery, georectified and orthorectified photographs. In both cases high-resolution (600-1000 dpi) scans of aerial photographs are produced. Georectified digital images are produced from scanned images that are transformed to the local co-ordinate system, by warping the digital images to fit either a map base or an air triangulation model (developed using ground control). Data can be viewed or plotted from within a GIS, at scales of better than 1:500 (from 1:5000 photography), without a significant loss of image quality. However, a higher level of plan shape accuracy can be achieved by mapping from surveys at a lower level. This photo-scale appears to be optimal, for production of scanned georectified images for use in strategic planning; it produces less reliable plan shape data and vertical resolution of profile generation from photogrammetry, than is needed for analytical operational purposes. Plan position accuracy achieved varies according to the variability of ground surface elevation, altitude and the tilt of the aircraft during photography. Plan position is usually found to lie within 1-3m, however, without full orthorectification, the expected accuracy may be no greater than +/-10m. Change detection based upon this method is therefore limited. This accuracy may be acceptable at a regional level over long temporal intervals, but is inadequate for generalised operational shoreline management purposes, especially when rates of change need to be established over relatively short periods (e.g. five years). Time series analysis can be conducted by scanning old data sets, but control on plan shape (which would be derived mainly from OS data sets) is likely to be less accurate than that derived from ground control derived specifically for the survey. Mosaic tiles produced in TIFF files, have been found to produce the most versatile images for manipulation within GIS (Channel Coastal Observatory Website, 2006).

Orthorectified photos are generated using photogrammetrically based techniques; this requires the production of a good quality digital elevation model (DEM). This may be derived from the OS Landline Profile Landform data, which provides a grid of interpolated levels at 5m intervals, but this is not ideal. A photogrammetrically derived DEM will provide much better resolution; this may allow orthophotos to be produced with a plan position accuracy of approximately +/-1m. Similarly a DEM derived from LiDAR can produce an excellent model (Channel Coastal Observatory Website, 2006).

2.3.2.14 Limitations

Photographs can be useful for visual comparison of changes through time although such results are not quantifiable and are open to interpretation. In addition to this, on sediment shores features can shift over a short time scale (between tides in some cases) and this will affect the accuracy of maps produced. The technique is also limited to detection of elevations above water level and confined to low water periods. Suitable lighting and no cloud cover are also essential for this type of survey and therefore there can be seasonal restrictions. Like satellite imagery, aerial photography is limited by environmental conditions, including water turbidity (from local runoff, plankton blooms, and material suspended in the water column), sun angle (sun glint or shadows), cloud cover, haze, and surface waves. However, by careful mission planning, the effects of these conditions can be minimised (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

Additional limitations include the relatively low spatial resolution data from aerial imagery and the inability to identify individual vegetation species. The vertical accuracy is worse than land survey techniques, and problems exist where rapid data collection is unable to be transferred and stored during acquisition unless sophisticated and expensive computer systems are used. The timing of the operation is limited by air traffic control and there are unsolved camera calibration issues due to the lack of fast and reliable in-flight camera calibration procedures.

2.3.2.15 Advantages

The main advantages of using digital aerial photography include the wide area of data coverage, readily obtainable photographs that provide sufficient resolution for detecting subtle submerged features and resolving features smaller than one metre, and results that are easily integrated into the coastal management process. In addition to this, images are available instantly and there is a quick turnaround from acquisition, through processing to distribution to end-users. Imagery is transferable over the internet and there is no need for expensive digitising.

There are also significant benefits in orthorectified photography over geo-rectified images, but there are also significant variations in cost. Orthorectified photography has the potential to be more accurate. The main benefits are of improved accuracy, particularly where there is high relief across the area e.g. cliffed coastlines. Accuracy is strongly dependant upon the accuracy of the DTM (Bradbury, 2004).

Digital raster aerial photos offer tremendous advantages, when compared with ordinary contact prints, and with conventional large scale OS maps. When correctly geo-referenced, the data sets can be used within GIS in combination with vector map data (typically from the OS) for many shoreline management applications. Digital images offer the following additional detail, relative to conventional large scale OS mapping:

- Geomorphological structure
- Geology
- Sediment type
- Saltmarsh morphology
- Land use
- Defence detail
- Beach plan shape
- Recent shoreline position
- Vegetation coverage
- Increased detail at large scale
- Evidence of nearshore sediment plumes
- Location of nearshore submerged sea bed features

Digital geo-referenced aerial photographs provide an excellent analytical medium, which can be used conveniently in combination with other types of geo-referenced survey information. In particular, the images provide the opportunity for valuable interpretation of morphodynamic changes measured by reference to geo-referenced profile data in combination with geomorphology. Such data sets are strongly recommended for use in shoreline management planning. This technique is economical for large frontages and allows for near instantaneous capture of data over long frontages on a single tide, including areas that are difficult to access e.g. MOD sites (Bradbury, 2004).

2.3.2.16 Budgeting Monitoring Schemes

The tables below illustrate broad cost estimates for the use of aerial photogrammetry for different unit lengths. Table 3 is taken from the Eurosion 2004 project and provides costings for a 100km² area. Tables 4 and 5 are taken from Bradbury 2004, and estimate the cost of this technique for a 500km frontage.

Table 3 Unit costs for Aerial Photogrammetry for areas superior to 100 km2.

	Resolution	Unit costs in Euros / km2
Aerial photogrammetry	0.1 metre	300-400

Source: Eurosion (2004)

Table 4 Relative photogrammetry cover for various photo scales, based upon a survey of 500km length.

	Photo-scale		
Variable	1:8000	1:5000	1:3000
Survey length	500km	500km	500km
Spacing needed between primary ground control points	2190m	1380m	825m
Expected vertical accuracy (+/-RMS)	0.3m	0.15m	0.1m
Cost /km aerial photography	£70	£90	£150
Cost /km photogrammetric profiling (200m line spacing)	£70	£90	£150
Length covered on photographic contact print	1.8km	1.14km	0.68km

Source: Bradbury (2004)

Table 5 Total and Annual Estimates of Cost.

	Cost per Survey	Annual Cost Estimate (every 3-5 years)
Digital Orthophotos	£150,000	£50,000

Source: Bradbury (2004)

2.4 Ship-borne Techniques

Ship-borne techniques, for example bathymetric surveys, hydrographic surveys, side-scan sonar, and grab sampling, are limited to the marine environment and collect data on: the changes and rates of change of dynamic sediments below low water; changes and rates of erosion of fixed bedrock below low water; the identification of small-submerged features that may affect sediment transport processes; changes within offshore sediment sinks; and habitat mapping, to name just a few.

Bathymetry is the underwater equivalent to topography. A bathymetric map gives the depth contours of the soil, rock, sand, etc. at the bottom of a body of water such as an ocean or a lake. In addition to this, a bathymetric chart provides navigational information. Hydrographic measurements on the other hand include the tidal, current, and wave information of physical oceanography. In addition, bottom measurements, with particular emphasis on those marine geographical features that pose a hazard to navigation such as rocks, shoals, reefs, and other features that obstruct ship passage are included. Unlike oceanography, hydrography will include shore features, natural and manmade, that aid in navigation. A hydrographic survey will therefore include accurate positions and representations of hills, mountains and even lights and towers that will aid in fixing a ship's position as well as the aspects of the sea and seabed and is thus seen as a mariner’s tool. Bathymetric charts on the other hand are best representations of the actual seabed, as in a topographic map, for scientific and other purposes.

Bathymetric Surveys with Admiralty charts

2.4.2.1 Basic Principles

Admiralty charts are a key source of bathymetric data for numerical modelling of wave climate, sediment transport and tidal currents. A Nautical Chart is a graphic portrayal of the marine environment showing the nature and form of the coast, the general configuration of the sea bottom including water depths, locations of dangers to navigation, locations and characteristics of man-made aids to navigation and other features useful to the mariner.

The United Kingdom Hydrographic Office (UKHO) is the main provider of accurate marine navigational information across the world. Both the United States National Oceanographic and Atmospheric Administration (NOAA) and the UKHO provide Nautical Charts in various formats: Electronic Navigational Chart (ENC) is a vector-based digital file containing marine features suitable for marine navigation. It is based on the International Hydrographic Organization (IHO) S- 57 standard; Raster Nautical Chart (RNC) is a geo-referenced, digital image of a paper chart, which can be used in a raster chart system; Lithographic Nautical Charts are the traditional paper charts.

2.4.2.2 Limitations

The source of bathymetric data for numerical modelling of wave climate, sediment transport, and tidal currents is often from Admiralty Charts. Periodic updates are made to Admiralty Charts, but these provide minimal detail in shallow water, particularly away from major shipping routes. Nearshore surveys are generally beyond the remit of the UKHO, although a new project has recently been established to examine nearshore requirements (www.coastalhydrography.com). Since this zone is of greatest significance, in terms of wave transformation processes, such a lack of detail presents a considerable problem. Offshore sand and shingle bank systems present significant challenges to numerical modelling, particularly when they are highly mobile. Modifications to the bathymetry, over periods of several years, may have a significant effect on the performance of numerical models. The model grids may require periodic updating to reflect these changes. The resolution of Admiralty surveys is rarely, if ever, of suitable density for production of detailed fine grid numerical models. Since most decision-making within shoreline management planning is developed from numerical models of coastal processes, there is a requirement to produce regular and detailed bathymetric surveys for the purpose of maintaining the validity of the models. Sediment mobility may occur to a considerable depth, depending upon local wave and current characteristics. There is a need therefore, for bathymetric data to some considerable depth (often more than 10m) (Channel Coastal Observatory Website, 2006).

Analysis of existing beach data in many regions fails to provide a mass balance of erosion and accretion. In order to understand sediment circulation and sediment transport within the system, there is a need to identify and monitor potential sediment sinks. Such monitoring will help to provide an understanding of sediment circulation and may also provide possible opportunities for sources of beach recharge materials, which may be recycled to the coast, on a sustainable basis. Bathymetric surveys are particularly valuable in these areas; this particular aspect of bathymetric monitoring has been neglected completely in most areas until now (Channel Coastal Observatory Website, 2006).

The intention of beach profile surveys is often to quantify changes in beach cross-section area. Land or aerial based techniques are satisfactory in circumstances where the active beach ends abruptly on a shore platform, which dries at some state of the tidal cycle. Dispersion of a thin veneer of sediment can occur across a wide foreshore: large volumetric inaccuracies may occur, if imprecise surveying techniques are used to monitor this zone. The mobile beach toe may never be exposed at many sites. More importantly, a zone of high volume change may (often) occur immediately below low tide level; this zone needs to be monitored since it may represent a considerable proportion of sediment movement. The lack of mass balance arising from topographic surveys may be accounted for, if topographic and bathymetric data are combined (Channel Coastal Observatory Website, 2006).

2.4.2.3 Advantages

The advantages of bathymetric surveys are dependent on the type of survey instrument used. Single-beam bathymetry is a simple method of running a survey to check if there has been a marked change in the depths in a selected area, for example, a dredged channel. This could then be further examined by a more detailed survey using a multibeam sensor. Single-beam bathymetry is simple and relatively inexpensive to use. It also has the advantage of requiring minimum operator training. Multibeam sonar on the other hand is an instrument that can map more than one location on the seabed with a single pulse and with higher resolution than is possible with a single beam echo sounder. High-resolution multibeam systems can accurately detect and define bottom features as small as one metre in diameter and can quantify changes and rates of change of dynamic sediments below low water. It allows for the production of detailed surveys for design and updating of numerical and physical models, of nearshore wave climate and sediment transport, whilst also enabling planning, design and construction of new works, in the near shore zone.

Sidescan and Multibeam sonar

2.4.2.4 Basic Principles

Side scan sonar is a specialised sonar (SOund for NAvigation and Ranging) system for searching and detecting objects on the seafloor. Side-scan sonar differentiates between types of surface sediments and identifies the direction of sediment movement. Multibeam sonar systems provide 'fan shaped' coverage of the seafloor similar to sidescan sonars, but the output data is in the form of depths rather than images (NOAA, 2002).

Sidescan sonar uses ultrasonic waves to locate objects and record bottom structure in a swath on one or both sides of its sensors. The sound pulses are usually on frequencies between 100 and 500 KHz. A higher frequency gives better resolution but less range. The sound pulses are most commonly transmitted from a towed unit called a towfish, but there are also hull-mounted versions. The pulses are sent in a wide angular pattern down to the bottom, and the echoes are received back in fractions of a second. It is designed to look sideways and at a downward angle from both sides of a towfish. The seabed and any objects in the water above this reflect sound waves back to the towfish and this produces an image. However, side-scan sonars only measure features on the seafloor and cannot collect bathymetry data.

Side-scan sonar systems are very accurate for imaging large areas of the seafloor. They are capable of producing continuous characterisation information of the seafloor at all depths. Lower frequency systems (around 100 kHz) provide wide swath coverage and are used to create mosaics of the entire survey area. Higher frequency systems (300 kHz and above) can provide higher resolution images. These data reveal detailed information of distinct objects or features on the seafloor. These higher frequencies have shorter ranges and are generally used to image a particular feature or area of interest. Some side-scan sonar is very sensitive and can measure features on the ocean bottom smaller than 10 centimetres (less than 4 inches).

Multibeam sonar systems provide 'fan shaped' coverage of the seafloor similar to side-scan sonars, but the output data is in the form of depths rather than images. As such, multibeam systems produce bathymetry whereas side-scans give a 'photograph' of the seabed. The multibeam sonar instrument can map more than one location on the seabed with a single pulse and with higher resolution than is possible with a single beam echo sounder. Effectively, the function of a narrow, single beam echo sounder is performed at many different locations on the seabed at the same time. These bottom locations are arranged so that they map a contiguous area of the bottom - a strip of points in a direction perpendicular to the path of the survey vessel. This area is called a swathe (Coastal Hydrography Report, 2004). Instead of continuously recording the strength of the return echo, the multibeam system measures and records the time for the acoustic signal to travel from the transmitter (transducer) to the seafloor (or object) and back to the receiver. Multibeam sonars are generally attached to a vessel, rather than being towed like a side scan. Therefore, the coverage area on the seafloor is dependent on the depth of the water; typically two to four times the water depth. Search patterns usually are run as a series of parallel lines that ensure overlapping coverage of the sidescan or multibeam sonar. Under certain circumstances 200% coverage is obtained by running a second search pattern perpendicular to the first over the same area (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2002).

2.4.2.5 Budgeting Monitoring Schemes

The tables below illustrate coarse cost estimates for the use of bathymetric surveys for different unit lengths/areas. Table 6 is taken from the Eurosion 2004 project and provides costings for a 100km² area. Table 7 is taken from Bradbury (2004), and estimates the cost of using swathe (multibeam) bathymetry.

Table 6. Unit costs for areas superior to 100 km2.

	Resolution	Unit costs in Euros/ km2
Multibeam sonar	0,1 meter	150-250

Source: Eurosion (2004)

Table 7. Total and Annual Estimates of Cost.

	Cost per Survey	Annual Cost Estimate (5 year rolling programme)
Swathe Bathymetry	£750,000	£150,000

Source: Bradbury (2004)

2.4.2.6 Limitations

The limitations associated with multibeam sonar are mainly related to the backscatter data. Most of the signal processing and bandwidth are dedicated to making a very accurate depth determination. As a result, the quality of the backscatter has generally been poorer than that produced by side-scan sonar. New systems are improving on this. Another potential limitation from a user's perspective is the large size of the files produced by multibeam sonars; however, with proper data management this problem can be mitigated (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

Another limitation of multibeam technology is the difficulty in collecting multibeam data in shallow or complicated areas such as estuaries and bays. Despite swaths up to eight times the water depth, in shallow areas it is often not economical and sometimes technically difficult to produce comprehensive data. In very shallow waters, the signal may return too quickly for the transducer to record it, so false depth values (or none at all) are recorded. False values may be indicated by depths that are twice what they are expected (signal bounces twice before recorded) or by abnormally high values in known shallow waters. This is complicated further by the fact that with the significant infrastructure requirements of multibeam sensors, often boats that can support the sensors have difficulty navigating in in-shore areas (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

Multibeam sonar equipment is expensive to buy and requires a high level of operator training to ensure correct operation and interpretation of data. The equipment produces very large quantities of data, requiring considerable computer capacity and special software to process and store.

With regards to side-scan sonar, only features on the seafloor are measured and bathymetry depth data cannot be collected. Unless used in conjunction with underwater acoustic navigation systems, such as GPS, positions of detected features are approximate. Additionally, the risk of loss of the towfish is a very real consideration when selecting areas where the unit can be deployed due to the relatively high costs associated with the equipment. Therefore equipment is not suitable for use in areas where obstructions can be reasonably expected as, for example, in areas of concentrated static fishing gear (Coastal Hydrography Report, 2004). In addition to this, some see the fact that the side-scan sonar produces huge datasets to be limitation as post-processing of data can be extremely time consuming.

2.4.2.7 Advantages

There are few limitations on using multibeam sonar technology for either bathymetric surveying or backscatter imaging because of the capability of a multibeam system to calibrate for water column characteristics and compensate for vessel attitude during data collection. This allows data to be produced that is comparable to earlier or subsequent surveys (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006). In addition to this, large areas of the seabed can be mapped quickly and easily enabling continuous coverage of the seafloor.

Side-scan sonar systems can identify different types of seafloor, such as mud, smooth sand, rippled sand, rock outcrops, and canyons. Dense objects such as rocks, coarse sand, and metal will reflect strong signals. Soft features such as silt, mud, or fine sediments absorb sonar energy and produce lighter acoustic returns. Side-scan systems are very useful in turbid water conditions, but as with the other acoustic methods, some field verification using physical sampling or imagery is necessary.

Sub-bottom Profiling

2.4.2.8 Basic Principles

Sub-bottom profiling systems identify and measure various sediment layers that exist below the sediment/water interface. These acoustic systems use a technique that is similar to simple echosounders. A sound source emits a signal vertically downwards into the water and a receiver monitors the return signal that has been reflected off the seafloor. Some of the acoustic signal will penetrate the seabed and be reflected when it encounters a boundary between two layers that have different acoustical properties (acoustic impedance). The system uses this reflected energy to provide information on sediment layers beneath the sediment-water interface (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

Acoustic impedance is related to the density of the material and the rate at which sound travels through the material. When there is a change in acoustic impedance, such as the water-sediment interface, part of the transmitted sound is reflected. However, some of the sound energy penetrates through the boundary and into the sediments. This energy is reflected when it encounters boundaries between deeper sediment layers having different acoustic impedance. The system uses the energy reflected by these layers to create a profile of the sub-bottom sediments (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

Several sonar parameters (output power, signal frequency, and pulse length) affect the instrument performance. An increase in output power gives better penetration into the sub-bottom layers. This will usually provide deeper penetration into the sub-bottom layers. Sometimes however, if the bottom is very hard or not very deep, the increase in power will cause more signal to be reflected back off the seafloor. The signal might then be reflected off the sea surface, leading to multiple reflections and "noise" in the data. Signal frequency also has an effect on system performance. Higher frequency systems (2 to 20 kHz) will produce high definition data of the upper seafloor sediment layers. These higher frequency signals have shorter wavelengths, and they are able to discriminate between layers that are close together. Lower frequency systems will give greater penetration but at a lower resolution. Longer sound pulse length transmits more energy and yields deeper seabed penetration. However, a long pulse length may decrease the ability to discriminate between adjacent reflectors, thus decreasing the system resolution (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

2.4.2.9 Limitations

Sub-bottom systems are limited by a narrow swath width, so continuous coverage of the seafloor is time-consuming and expensive to obtain. As with other single-beam acoustic methods, the footprint is relatively small and dependent on depth (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

2.4.2.10 Advantages

Sub-bottom profiling systems can be useful for characterizing benthic habitats, since they provide information about sub-surface sediment structure. No other acoustic techniques provide this type of information, and only physical sampling via cores or in-situ photography via sediment profile imaging will allow for characterization of subsurface structures. Sub-bottom profiling systems may penetrate as deep as 30 meters (approximately 90 feet) into the seafloor, which is much deeper than most cores and Sediment Profile Imaging (SPI) can penetrate. However, the penetration depth depends on the hardness of the overlying layers and the presence of gas deposits, such as methane (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

Acoustic Seafloor Classification Systems

2.4.2.11 Basic Principles

Acoustic seafloor classification systems (ASCS) process the acoustic return signals from standard single-beam echosounders, and can be used to make qualitative estimates of the seabed composition. They gather information about bottom type, bottom sediments, and aquatic plants. Different seabed bottom types can be discriminated by extracting data on bottom roughness (that is, irregularities in topography) and hardness (that is, type of substrate – rock, sand, mud, and so forth). There are several commercially available acoustic seafloor classification systems, such as the RoxAnn™ and QTC View™ systems (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

Acoustic seafloor habitat characterisation requires field verification. This can be done through either physical sampling of the bottom using sediment cores or grabs, or through visual observations by divers or underwater cameras. All types of substrate encountered must be verified to interpret the data accurately and link the acoustic signatures to the seabed classification scheme. Extensive fine-scale sampling may be required, especially where the seafloor is complex. Additionally, these systems require initial calibration in each unique study location in order to interpret the signal returns and classify benthic cover types (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

2.4.2.12 Limitations

These systems are highly dependent on field calibration, so the data they produce are very difficult to interpret without physical sampling, video, or imagery collection. Additionally, their narrow swath width makes continuous coverage of the seafloor difficult, and their acoustic "footprint" is relatively small and dependent on depth (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

2.4.2.13 Advantages

There are some advantages to using an acoustic seafloor classification system. These systems are commonly available at relatively low cost. They are portable, have minimal power requirements, and are also capable of collecting data quickly.

Waverider Buoys and Tide Gauges

Information on tidal currents, levels and wave patterns is essential for use in coastal defence studies and for the validation of numerical wave models. Historic wave data can provide information for use in climate change studies and near real-time wave data can be used for coastal flood forecasting and warnings. Wave measurements are often made through a network of nearshore wave recorders and the deployment of wave buoys, typically in a minimum water depth of 10-12m. Data is then telemetered by radio link to a nearshore base station.

Waverider Buoys can be categorised as two types, directional and non-directional. Directional buoys send wave height and direction data in bursts to an onshore receiver whereas non-directional buoys send only wave height data. As a buoy is raised by each passing wave, its vertical acceleration is measured and processed. In addition to this, most buoys will also measure sea temperature whilst also providing accurate positional information via an internal GPS system.

Directional and non-directional Waverider buoys measure vertical acceleration and displacement by means of an accelerometer. The directional buoy measures horizontal acceleration using two accelerometers and an onboard compass to give the directional displacement in two horizontal axes. With this information, the north-south and east-west directions are calculated (Queensland Government Environmental Protection Agency Website, 2006).

Tidal data is needed to provide estimates of extreme water level conditions; this aids the determination of standards of service of flood defences. Lengthy and reliable data sets are needed to provide the information required for provision of reliable forecasting of extreme water levels and determination of mean sea-level changes. Data is also needed to provide validation and development of storm surge warning models (Channel Coastal Observatory Website, 2006). Tide gauges measure the sea level relative to a fixed reference height called Chart Datum. It can be considered as a local variable, defined as a level so low that the tide will not frequently fall below it, and which is very close to the Lowest Astronomical Tide (LAT).

A permanent tide gauge network was set up in the UK in 1953. The UK Tide Gauge Network records tidal elevations at 44 locations around the country whilst programmes, such as The South-East Strategic Regional Coastal Monitoring Programme and the National Tidal and Sea Level Facility (NTSLF), allow for real-time tidal data to be downloaded from the project websites.

2.4.2.14 Budgeting Monitoring Schemes

Directional waverider buoys cost approximately £45k (€65k) each plus installation (Bradbury, 2004).

Pressure Recorders

Bottom Pressure Recorders measure vertical movements of the seabed whilst Acoustic Extensometers measure horizontal ground movements of the seafloor. Bottom Pressure Recorders (BPRs) precisely measure the pressure from the overlying ocean at a specific site. Since the pressure is a function of the height of the water column above them these instruments can measure vertical movements of the seafloor, after the predictable variations from ocean tides are removed. Thus, if the seafloor moves up or down, then the instrument measures that there is less or more pressure, respectively. Acoustic Extensometers on the other hand measure horizontal distance between two fixed points using sound waves. The speed that sound travels in seawater can be precisely calculated if you know the temperature, pressure, and salinity. The extensometers measure distance by carefully recording the travel time of acoustic pulses between pairs of instruments (and the water temperature) (Pacific Marine Environmental Laboratory, 2006). If the time and the speed are known, then it is possible to calculate the distance. In many coastal monitoring practices, pressure recorders tend to be used more to measure wave and tide levels.

Laser Line Scan Imaging

2.4.2.15 Basic Principles

Laser Line Scan (LLS) imaging is a high-resolution technique for viewing benthic habitats. The system is towed as laser beams are transmitted and reflected through a 70° sector. As it moves through the water, the laser illuminates individual spots, no bigger than the diameter of a pencil, on the seafloor. The two-dimensional visual image created is then displayed on the operator's console screen. As each new scan line appears at the top of the screen, the bottom line disappears. This provides the operator with a detailed view of the seafloor in real time. Resolution and area covered change with water clarity and instrument height above the bottom. LLS images can be saved and viewed in video, still, or photographic hard copy form. Current applications of LLS include testing interpretations of sections of side-scan sonar data, underwater search and recovery, and assisting with habitat and fisheries assessments. Because it can be used in deeper water than SCUBA techniques and provides more coverage than cameras attached to submersibles or remotely operated vehicles (ROVs), LLS imaging offers great promise as a useful tool for mapping benthic habitats (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

2.4.2.16 Limitations

While the resolution of LLS (millimetre to centimetre scale) is higher than that of side-scan sonar, LLS does not have the ability to cover as much area. However, it can provide greater coverage (two to five times) than video, although with somewhat lower resolution. Unfortunately, LLS imaging is expensive and not yet widely available (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

2.4.2.17 Advantages

LLS imaging bridges the gap between broad-scale approaches such as side-scan sonar and fine-scale video and still photography. Unlike acoustic techniques, LLS is capable of distinguishing fish and invertebrate species within a given habitat. In addition, the relationships of these animals to their habitats can be observed (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

Sediment Profile Imaging

2.4.2.18 Basic Principles

The sediment profile imaging (SPI) system is designed to photograph the sediment-water interface without creating disturbance. A sharp-edged prism cuts cleanly into the sediment to a depth of 15 to 20 cm. The camera is mounted in the top of the prism, and a mirror is used to reflect the sediment image to the camera from the vertical faceplate. Since the sediment is right up against the faceplate, lack of water clarity is never a limitation on this optical method (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

2.4.2.19 Advantages

Sediment profile imaging is a useful tool for rapidly collecting data and analysing a suite of seafloor parameters. These include: sediment grain size, camera prism penetration depth (an indirect measure of sediment density), roughness of the sediment-water interface, transition between oxygenated surface sediments and underlying sediments with little or no oxygen (called the apparent redox potential discontinuity layer), biological successional stage, and presence of methane gas bubbles, burrows, fauna, and dredged material (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

Photography and Videography

2.4.2.20 Basic Principles

Plan-view photography provides still images of small areas of the seafloor surface, generally less than one square meter. Plan-view cameras can be used in shallow water or deeper water with the appropriate housing: a large frame for deep sampling and a lighter frame for shallow sampling. The shutter on the camera can be released either manually from shipboard or automatically using an internal trigger mechanism. This technique is often used in conjunction with sediment profile imaging (SPI) to provide detailed information regarding sediment composition and biological activity. With this approach, a downward facing camera is mounted on the same apparatus as the SPI device. The plan-view photograph is taken just before the SPI prism penetrates the sediment (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

Video data can be used for detailed assessment of biological conditions in the water column and on the seafloor. It is especially useful in areas with hard substrates such as rocks or reefs, where sediment cores, grabs, and sediment profile imaging cameras may not be able to penetrate the seafloor. Video imaging can also be used in searches for specific items, such as marine organisms (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

Underwater video footage can be collected in a variety of ways. Cameras can be vertically dropped from the ship, towed, hand-held by divers, or mounted on remotely operated vehicles (ROVs). All of these methods are subject to negative effects due to poor water clarity. The specific method employed is determined based on water depth, water clarity, size of survey area, purpose for survey, and costs of operating the equipment (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

2.4.2.21 Limitations

Plan-view photography is limited by water clarity and a small image footprint. All of the techniques used for collecting video images are limited in the spatial coverage they provide. Therefore, mapping methods with a wider range of coverage (such as side-scan sonar and other acoustic techniques) are often employed first. Areas to be sampled by video can then be determined and specific transects can be planned. Additionally, data collection from video is time-consuming and labour-intensive, so it is not practical to obtain comprehensive coverage in a large study area.

2.4.2.22 Advantages

Plan-view photography can provide still images of small areas of the seafloor surface. Underwater videography presents a number of advantages over other benthic habitat mapping techniques. It is preferable to direct diver-collected data for several reasons. First, it can be used in areas that are too cold, deep, or dangerous for divers. Second, the data collected is permanently, objectively recorded and therefore not subject to the diver's interpretation. Video data can be viewed later and manipulated (paused, magnified, and so forth) to provide a more comprehensive view of the habitat. Unlike acoustic, satellite, or aerial methods, underwater video has high enough resolution to identify individual plant and animal species. This type of information may then be a further indicator of habitat health and characteristics. For example, the amount of encrusting or epiphytic algae can be an indirect indicator of the extent of nutrient loading (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

Grab Sampling

2.4.2.23 Basic Principles

Sediment sampling is an excellent way of determining the sediment quality and the current state of benthic habitats within the sea floor. Information on such characteristics provides an insight into the physiology and ecology of the organisms sampled.

Grab sampling is a common technique used to examine the surface sediment (from about 10-15 cm deep). Different grab samplers are used depending upon the type of substrate being sampled (soft or hard) and the size of the sample required (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006). The sampler is lowered to the seafloor where it penetrates the sediment-water interface and takes a sample before closing and being raised to the surface. Sediment samples can be tested for a variety of chemical (that is, toxicity, organic content, oxygen concentration) and physical (that is, sediment type, grain size) parameters in the laboratory. If knowledge of the biological composition of the sampled area is desired, grab samples may be washed and sieved to separate organisms from the sediment. The organisms are then identified and enumerated (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

2.4.2.24 Limitations

The process of sediment collection means that sediments are disturbed during sampling, so grab samples will not yield information about sediment structure. Grab samplers are designed for soft sediments so hard bottom or reef structures cannot be sampled effectively using grab samplers. Additionally, grab sample analysis can be time-consuming and relatively expensive since samples must be analysed by taxonomists in the laboratory.

2.4.2.25 Advantages

Grab samplers are relatively light and easy to operate and offer an opportunity to visualise and analyse an area not normally accessible to humans. The process of extracting and analysing grab samples allows for benthic habitat maps to be produced and to offer a form of validation to imagery interpretation from other methods.

Sediment Cores

2.4.2.26 Basic Principles

Sediment corers are another method for obtaining sediment samples for both historical and present day mapping. Cores provide a vertical cross-section of the sediment column indicating changes in environmental conditions and physical and biological processes.

There are several different techniques for sediment coring including piston corers, hand corers, gravity corers, vibracorers, and freeze corers. Depending on the coring technique that is used, cores can vary in length from 10 cm - 6 m. The type of corer used depends on substrate material, interval of interest, and volume of material required. For typical sediment cores, a hollow tube is driven into the sediment and taken up to obtain a continuous, undisturbed cross-section of the seafloor. This core can then be split and sub-sampled for the analysis of chemical, biological, and physical properties (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006).

2.4.2.27 Limitations

Unfortunately, sediment coring is a time-consuming and gear-intensive technique, so cores can be expensive to collect and process. In addition, analysis of sediment samples is both a lengthy and labour-intensive process, often requiring specialist knowledge of marine habitats and their species.

2.4.2.28 Advantages

Sediment cores can provide a great deal of information about the composition of the sediment column and the study area. A history of the area can be determined through analysis of sedimentation rates, magnetic properties, total organic carbon, grain size sampling, trace metal concentrations, and organic pollutants (The National Oceanic and Atmospheric Administration Coastal Services Centre, 2006). Analysis of the fauna within the sediment cores can provide an historical account of issues such as sea-level change. Certain micro-organisms within the sediment called foraminifera can allow for the mapping of current and historical sea levels based on knowledge of their habitats. Two types of foraminifera exist, calcareous and agglutinated, the first of which is associated with marine environments and the latter with freshwater habitats. Changes within core sediments of these two species can indicate if sea levels were previously higher or lower. For example, if agglutinated species are succeeded by calcareous species within the core, then sea levels are likely to have risen providing favourable conditions for the calcareous species to populate.

2.5 Ground-based Techniques

The most well developed long-term (>10 yr.) historical programmes within the region all include land based topographic surveying, in one form or another. The survey techniques used vary from site to site; these can include the use of kinematic GPS, total station theodolites and levels (CCO 2004). Bradbury (2004) has estimated the cost of using such a technique, the results of which can be seen in Table 8 below.

Table 8 Total and Annual Estimates of Cost.

	Cost per Survey	Annual Cost Estimate (3 per year reducing to 2 after 5 years)
Topographic Surveys	£170,000	£510,000

Source: Bradbury (2004)

Levelling

2.5.2.1 Basic Principles

A common approach to monitoring surface movements is the use of ground surveys by triangulation and trilateration. Fixed survey markers are established and the horizontal and vertical co-ordinates of each are calculated through successive surveys.

Levelling of profiles, with an automatic level, provides the basis for development of most of the existing long-term beach survey programmes. Profiles can be measured by recording elevations relative to a fixed reference datum, in conjunction with a rope or tape, to determine chainages. Differences in elevation are recorded by measuring vertical distances directly on a graduated rod with the use of a levelling instrument such as a Dumpy level, transit or theodolite (Figure 24.) This method is called direct levelling or differential levelling (Queensland Government Environmental Protection Agency Website, 2006). Repeat surveys are conducted from a constant zero co-ordinate and, at a constant bearing angle. Zero co-ordinates are determined by traverse or re-section with a theodolite (Bradbury, 2004).

2.5.1.2 Limitations

Profiling by this method can introduce an error, based upon the fact that on shingle beaches, the slope distance is measured as opposed to the horizontal distance; this represents a greater problem on steep shingle beaches, with frequent changes in slope angle, than on relatively flat sand beaches. This is mainly as a result of levelling on shingle beaches rather than being an inherent problem in the instrument. The method is generally satisfactory at the scale required, but significant differences have been demonstrated when compared with alternative technologies. The vertical accuracy achieved is expected to be better than +/-0.05m, whilst the horizontal accuracy

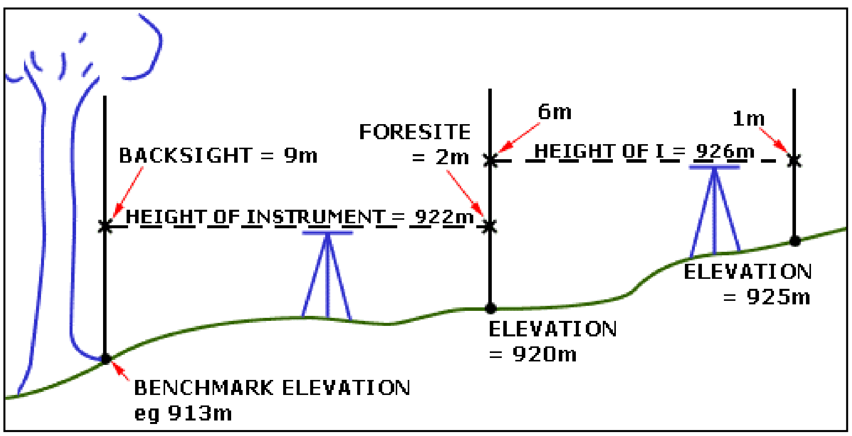


Figure 24. Diagram to illustrate the process of Differential Levelling (Queensland Government Environmental Protection Agency Website, 2006).

depends upon the slope angle and slope changes. This system is well suited to measurements on beaches with limited vertical range, since the instrument must be reset many times over large vertical ranges. Processing of the data takes longer than other methods, since all recording and generation of profiles has to be carried out manually.

Many of the programmes have now changed to use more advanced technology (GPS) (Channel Coastal Observatory, 2004).

2.5.2.3 Advantages

Levelling has the advantage that it can be conducted with cheap and simple equipment; it is generally reliable and properly maintained equipment rarely fails to perform (Channel Coastal Observatory, 2004).

Theodolites

2.5.2.4 Basic Principles

The primary function of theodolites is the accurate measurement of horizontal and vertical angles where measurements are made by reading veneers etched on glass circles. Theodolites are capable of high precision and accuracy and are compact and lightweight. There are four types of theodolites: repeating theodolites; directional theodolites; electrical digital theodolites; and total stations. With repeating theodolites the design enables horizontal angles to be repeated any number of times and added directly on the instrument circle. With directional theodolites the angles are obtained by subtracting the first direction reading from the second direction reading. Electrical digital theodolites automatically read and record horizontal and vertical angles and eliminate the manual reading of scales on graduated circles. A total station theodolite is an electronic digital theodolite and an electronic distance measurement instrument in one integral unit.

2.5.2.5 Budgeting Monitoring Schemes

Table 9 is taken from the Eurosion 2004 project and estimates the cost of this technique. However, it must be noted that these are coarse estimates.

Table 9. Unit costs for areas superior to 100 km2.

	Resolution	Unit costs in Euros / km2
Beach profiling using total stations or GPS	0,1 metre	100-200

Source: Eurosion (2004).

2.5.2.6 Limitations

The system is still restricted by line of sight from the instrument to the measuring staff and accuracy degrades with distance from the instrument. Low light conditions present operational problems; this is often significant when surveying over low water periods in early morning or evening. Vertical accuracy is generally marginally worse than levelling but better than RTK GPS, although this depends on the distance of observations.

2.5.2.7 Advantages

The advantages of theodolites are that the speed of data acquisition is faster than for levelling, since the instrument generally has to be set up less frequently. Systems that are operated in conjunction with a data logger have the advantage that no manual recording of data is required; those operating with manual booking systems are somewhat more laborious. Total stations have the advantage that XYZ co-ordinate data can be collected; profiles can be located in 3-dimensions. As true plan positions are determined, the accuracy of slope position is generally better than that derived by levelling. The method provides more flexibility in terms of both data acquisition and data analysis than levelling and the technology is well proven, and is still an efficient and appropriate method for collection of beach data (Channel Coastal Observatory Website, 2006).

Table 10. The advantages of the four main types of theodolites (adapted from Purdue University Website, 2006).

Types of Theodolites	Advantages
Repeating theodolites	• Better accuracy obtained through averaging • Disclosure of errors and mistakes by comparing values of the single and multiple readings
Directional theodolites	• Reads "directions" rather than angles • Angles are obtained by subtracting the first direction reading from the second direction reading
Electrical digital theodolites	• Circles can be instantaneously zeroed, or initialised to any value

	• Angles can be measured with increasing values either left or right • Angles measured by repetition can be added to provide a total larger than 360° • Mistakes in reading angles are greatly reduced • Speed of operation is increased • Cost of instruments is lower
Total stations theodolite	• They can automatically record horizontal and vertical angles and slope distances from a single set-up • Slope distances can be reduced to horizontal and vertical components instantaneously • Given initial data they will display positions and elevations of sighted points

Global Positioning System (GPS) and Differential Global Positioning System (DGPS)

2.5.2.8 Basic Principles

The Global Positioning System (GPS) system is a worldwide radio-navigation system comprising a network of 24 satellites orbiting at 20,000km above the Earth's surface. Ground-based GPS receivers analyse the phase/timing difference of radio signals transmitted from these satellites in order to determine the distance of the satellite from the base. By comparing how late the satellite's pulses (known as a Pseudo-Random Code - PRC) appear compared to the receiver's code, it is possible to determine how long it took to reach earth, therefore enabling the distance to calculated.

A minimum of four satellites is required to provide precise positional accuracy via GPS. Three satellites are used for triangulation purposes to determine positions, and a fourth is used to correct timing errors created as signals pass through the atmosphere. Both the satellite and the receiver need to be able to synchronize precisely their pseudo-random codes to make GPS work. The fourth satellite acts as a cross-check to the previous three measurements and determines the error in timings between all four satellite pseudo-random codes. The receiver looks for a single correction factor that it can subtract from all its timing measurements that would cause them all to intersect at a single point. That correction brings the receiver's clock back into sync with that of the satellites and enables accurate positional measurements to be transmitted. However, in addition to this, the US Department of Defence (DoD) monitor the orbit of the satellites and send any information on orbit errors to the satellites themselves, to transmit to the receivers along with the timing signals. The satellite's predicted position is transmitted from earth-based tracking stations within the DoD to the satellites, and relayed back to the GPS receiver.

Basic GPS is the most accurate radio-based navigation system ever developed. And for many applications it is quite accurate. However, Differential Global Positioning System (DGPS) can offer even higher accuracies making it ideal for monitoring small-scale beach movements. The use of DGPS as part of the South East Regional Strategic Coastal Monitoring Programme has allowed for topographic beach information to be collected with accuracies of +/- 30mm. Kinematic GPS provides the opportunity to capture data with a vertical accuracy of approx. +/-2-3cm and horizontal positioning at approximately double the accuracy; it is generally ideally suited to beach surveying (Channel Coastal Observatory Website, 2006).

Differential Global Positioning System (DGPS) system involves the cooperation of two receivers, one that is stationary and another that is roving around making position measurements. The stationary receiver is the key. It ties all the satellite measurements and timing errors into a solid local reference and then provides correction information to the other receivers that are roving around. By setting up on a known/fixed, previously surveyed point, the receiver can then act as a reference station. It receives the same GPS signals as the roving receiver but, instead of working like a normal GPS receiver and using timing signals to calculate its position, it uses its known position to calculate timing. It works out what the travel time of the GPS signals should be, and compares it with what they actually are (Trimble Geomatics Website, 2006). The difference is an 'error correction' factor that is transmitted to the roving receiver via a radio signal.

2.5.2.9 Budgeting Monitoring Schemes

GPS equipment can be expensive to purchase. The use of DGPS requires a base station and a minimum of one rover receiver. Average costs for base stations are around €29,000 and approximately €17,000 for a rover kit.

The financial estimates that arose from the consultation period on the South-East Strategic Regional Coastal Monitoring Programme quoted annual figures of €738,000 for purchase of equipment and provision of 3 topographic profile surveys per year for the South East frontage, including the Isle of Wight. An additional one-off cost of €580,000 was identified for the provision of an in-depth baseline survey of all frontages along the South East coast.

2.5.2.10 Limitations

One person can operate the system, although this is not appropriate in a hazardous environment, such as the coast. Two mobile systems used together can provide adequate safety and also double the rate of data acquisition; these can both operate from a single base station. Experiences have demonstrated that GPS systems are more limited in terms of coverage below water level, than either levelling or total station, since the systems contain electronic components that cannot be submerged. GPS surveying may not be well suited to sites where high, near vertical, cliffs back onto the beach; this can generally be overcome with careful timing of the surveys relative to the geometry of satellites. GPS can also be susceptible to technical problems, which are less easy to overcome than with alternative technology (Bradbury 2004).

2.5.2.11 Advantages

The main advantage of GPS over other techniques is in the speed of data capture. Kinematic GPS is particularly well suited to repetitive surveys, since fairly long stretches of coastline can be surveyed from a single base station set up. The system is well suited to low light conditions and can be used in complete darkness. It is well suited to measurements of slope stability in areas of unstable terrain, since no control is required within the zone of instability. Control surveys can be conducted considerably more efficiently than using optical techniques. The same system can also be used in conjunction with bathymetric surveys (Bradbury, 2004).

CASE-STUDY N°3 The use of GPS as a monitoring tool on the Sicilian Coast (adapted from Biondi, G. 2006).

Introduction

Sicily is the biggest island in the Mediterranean and has a very varied coastline, which covers almost a thousand kilometres (Randazzo and Scrofani, 1996). The east coast, bordering the Ionian Sea, extends for about 160 kilometres between Cape Peloro and Cape Passero: 55% of this coast is made up of beaches (Amore *et al.*, 1996). The east coast can be divided into two areas separated by the south-western Etna lava fluxes. These have reached the sea and formed the piers of Catania's port. The beaches of the north coast, crossed by steep streams (*fiumare*), are characterised by sand, grit and pebbles mainly of metamorphic origin. The south coast is mainly rocky and its inlets are often characterised by small beaches with medium and thin carbonaceous sands (Amore *et al.*, 1990; Amore *et al* 1992).

Almost 900,000 inhabitants live within the radius of influence of coastal erosion in Sicily, which makes Sicily the fourth most exposed Italian region in terms of population at risk, after Veneto (1,200,000 inhabitants), Tuscany (950,000) and Campania (915,000). However, Sicily comes just after the Veneto region in terms of urbanised area at risk (250 km2 within the radius of influence of coastal erosion) which is mainly explained by the presence of densely populated coastal settlements along the coasts such as the cities of Palermo, Messina, Catania, Syracuse, or Taormina. Moreover, the coastal urbanisation growth rate in Sicily (about 30%) between 1975-1990 is among some of the highest rates in Europe and it is estimated that Sicilian coasts shelter about 315 km2 of areas of high ecological value which are at risk of coastal erosion (Eurosion report, 2004).

In July 2001, a joint study was undertaken by the Regional Province of Ragusa and the University of Messina (Department of Earth Sciences). The study looked into sedimentological and morphological monitoring of the Hyblaean coast. Topographic and bathymetric surveys were carried out along the coast along with the collection of shoreline sediment samples at 29 locations. These locations were divided up into coastal sedimentary cells based on morphological-sedimentary features and land usage. A total of 405 topographic profiles and 61 bathymetric-topographic profiles were recorded in the zones of Arizza

– Spinasanta, Scoglitti – Punta Zafaglione, Punta Zafaglione – Mouth of the River Dirillo and bordering areas. In addition to this a total of 1288 surface and sub-surface sediment samples were collected and analysed.

The seasonal monitoring of the Hyblean coast was carried out taking into account the following time schedule:

- Summer 2002 to establish the origins of the profiles
- Fall 2002 (survey of the emerged beach)
- Winter 2003 (survey of the emerged beach)
- Spring 2003 (survey of both emerged and submerged beach)
- Summer 2003 (survey of the emerged beach)
- Fall 2003 (survey of the emerged beach)
- Winter 2004 (survey of both emerged and submerged beach)
- Spring and winter 2005 (survey of submerged beach)

The results of the seasonal surveys were collected and stored separately before later being compiled into a final technical paper. The paper was presented at a national meeting organised by the University of Messina – Department of Earth Sciences with the Osservatorio Coste, in Ragusa on the 24th June 2005.

Topographic surveys were conducted in all seasons, and shoreline samples taken. Due to prolonged bad weather conditions in the spring of 2003, only a bathymetric survey and the collection of shoreline samples were undertaken. A further survey was conducted in the winter of 2004, comprising topographic and bathymetric studies along with shoreline sample collection.

Both the bathymetric surveys and the shoreline sampling were conducted in the zones of Arizza (Spinasanta and Scoglitti), Punta Zafaglione, and Punta Zafaglione (Mouth of the Dirillo River and surrounding areas). These three areas were seen to be of great importance by the local administrative body and given priority for defensive works in these areas.

The entire Hyblaean coastline was initially divided into 22 sections, for geo-morphological purposes. In the preparation of the final report this section separation was revised, and the subsequent division was into 29 coastal sedimentary cells (Table. 1 and Figure. 1) both according to the morphological-sedimentary features of the area and with regards to land use. A total of 81 profile sections were identified, each containing 5 profile lines (a total of 405 profiles), along the coastline perpendicular to the shoreline.

An initial document recorded 81 benchmarks, for which a special benchmark notebook was prepared during the first survey season.
With regards to the bathymetric analysis, during the Spring of 2003 and the winter of 2004, 21 and 40 bathymetric-topographic profiles were recorded respectively, in the zones of Arizza (Spinasanta, Scoglitti), Punta Zafaglione, and Punta Zafaglione (Mouth of the river Dirillo and bordering areas).

Samples were taken of both the emerged shoreline using a bailer and on the submerged shoreline using a bucket. A total of 1288 samples were taken and analysed for the various seasons. The present document, as well as containing the results of the previously collected data, also contains all the information collected relating to the character of the coastal and maritime environment.

Table 11. Information on the 29 coastal sedimentary cells.

Zona	Celle Sedimentarie Costiere (CSC)				
	N°	Limiti geografici (da Est verso Ovest)	Orientamento corda	Lunghezza corda (in m)	Lunghezza linea di costa (in m)
Orientale	01	Le Grotticelle - P. Castellazzo	N 98°	4087.0	5454.9 (1431,30 tratto provinciale)
	02	P. Castellazzo - P. Ciriga	N 80°	1736.9	2142.8
	03	P. Ciriga - Solarino	N 100°	1403.2	1530.0
	04	Solarino - C.zzo S.M. del Focallo	N 125°	7094.2	7308.4
	05	C.zzo S. M. del Focallo - Abitato di Pozzallo	N 81°	4720.7	5000.7
	06	Abitato di Pozzallo - Molo di Levante Porto di Pozzallo	N 54°	541.9	747.8
	07	Molo di Levante Porto di Pozzallo - P. Raganzino	N 64°	1084.0	1110.7
	08	P. Raganzino - Abitato di Maganuco (C.da Cindari)	N 73°	1629.2	1976.1
	09	Abitato di Maganuco (C.da Cindari) - Punta Religione	N 70°	2216.0	2376.3
	10	P. Religione - Abitato di Marina di Modica	N 133°	1135.8	1806.2
	11	Abitato di marina di Modica - Fornace Penna	N 91°	1298.4	1212,45
	12	Fornace Penna - Promontorio di Sampieri	N 109°	2332.2	3122.6
	13	Promontorio di Sampieri - Sampieri (C/da Costa)	N 109°	763.4	1109.3
	14	Sampieri (C/da Costa) - Punta del Corvo	N 79°	1646.7	1949.2
	15	Punta del Corvo - Punta d'Aliga	N 112°	2003.7	2357.5
Centrale	16	Punta d'Aliga - Punta Bruca	N 150°	803.1	1081.0
	17	P. Bruca - Plaja Grande	N 123°	8195.4	9115.2
	18	Plaja Grande - Spiaggia Americana	N 114°	2010.4	2133.7
	19	Spiaggia Americana - Scalo Trapanese	N 101°	3128.3	3431.4
	20	Scalo Trapanese - Serbatoio Gesuiti	N 120°	138.9	274.1
	21	Serbatoio Gesuiti - Punta di Mola	N 81°	1541.4	1649.7
	22	Punta di Mola - Punta Caucana	N 112°	1886.7	2222.6
	23	Punta Caucana - Capo Scalambri	N 84°	922.2	1006.5
Occidentale	24	Capo Scalambri - Camping dei Coralli	N 136°	4220.0	5212.7
	25	Camping dei Coralli - P. Braccetto	N 116°	614.7	1020.7
	26	P. Braccetto - Maghialonga	N 168°	3069.4	3701.2
	27	Maghialonga - F. di Cammarana	N 162°	3616.1	3985.3
	28	F. di Cammarana - Punta Zafaglione	N 152°	5760.2	6254.8
	29	Punta Zafaglione - Porto di Gela	N 136°	23127.9	27760 (11519.0 tratto provinciale)

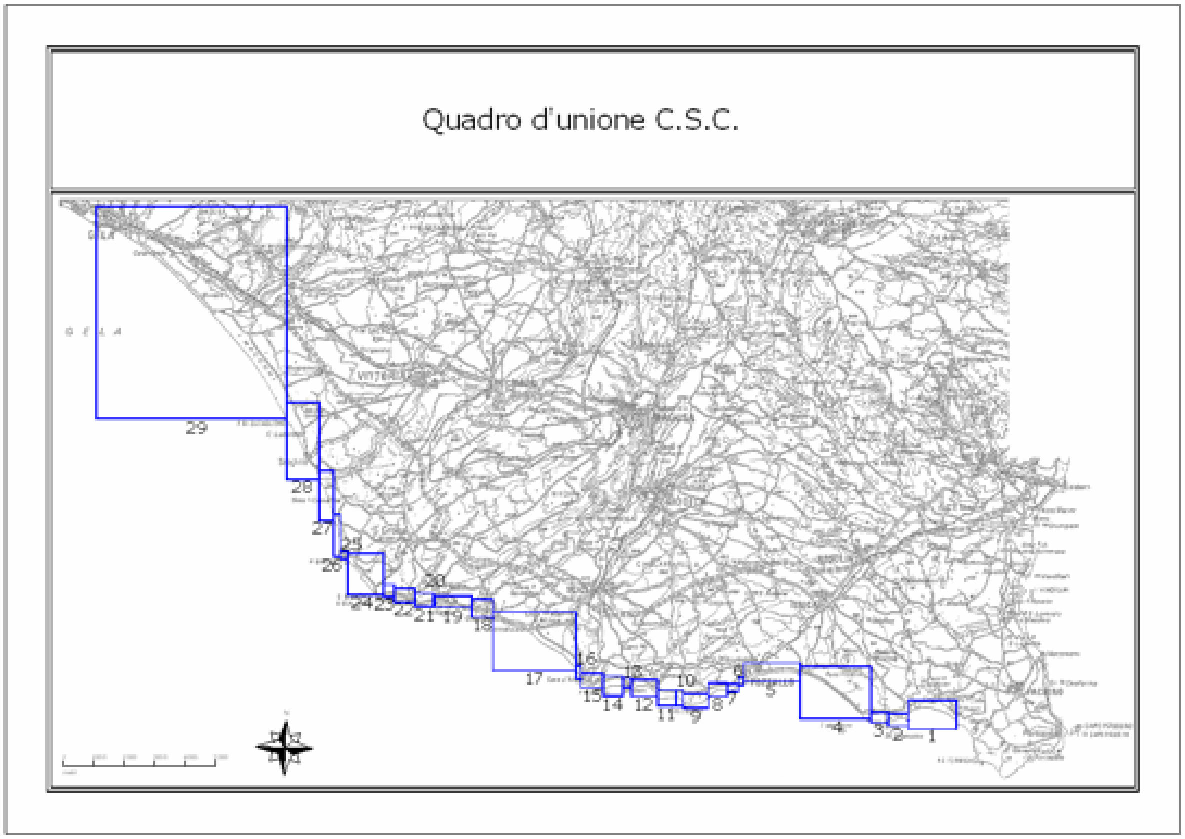


Figure 25. The location of the 29 coastal sedimentary cells.

Geographical Outline

The coastline of Ragusa extends for a total of 87 km between the mouth of the River Lavinaro Bruno to the East and the mouth of the river Dirillo to the North-West, with a fairly undulating course, due to a series of wide crescents edged by rocky projections.

The coastal stretch comprises eight administrative districts (comuni) which are part of the province of Ragusa. However, out of these eight districts, only the town centre of Pozzallo lies directly on the coast, while the others are linked to the coastline by seaside hamlets, mainly made up of second homes.

The low coastlines account for 64% of the entire coastal section, sometimes edged with dunes which in certain sections are fairly extensive (≈ 2,60 km in S. Maria del Focallo, ≈ 0.4 km Special Natural Biological Reserve of the Forest Scrub of the Irminio river, ≈

0,45 km Caucana - Casuzze, ≈1,00 km Punta Braccetto – Randello, 4.48 km in the Dirillo mouth – Macconi area) and still largely untouched, while in other sections intense urbanisation has caused serious deterioration and in certain cases has even caused complete flattening. The 56 km of low coastline consists of sandy and pebbly beach (the latter to a much smaller extent), and is alternated with 31 km (36%) of rocky coastline with cliffs of maximum height of no less than 5 m. The deepest beaches are mainly to be found in the vicinity of ports where values of over 100 m have even been recorded.

The rocky headlands mainly consist of the sedimentary formations of the Irminio member of the Ragusa Formation with a variation of calcarenite and marne limestone (Burdigaliano sup - Langhiano inf.), and terraced marine deposits (consisting of carbonated sand or conglomerates of a carbonate/sandstone clast dating back to the Upper Pleistocene era).

The entire coastal arc includes various hydrographic systems: the Modica stream, the river Irminio, the Biddemi stream, the Petraro stream, the river Ippari and the river Acate - Dirillo. The rivers present in the territory do not flow to the coast due to the fact that dams have been built on the main basins (S. Rosalia dam along the Irminio and the Ragoletu dam along the Dirillo – Acate).

Among the main infrastructures along the Ragusa coastline is the provincial road which runs directly along the coast from Punta Castellazzo to Marina di Ragusa. However, it is not a continuous stretch of road as it consists of various connecting roads (SP 67 Pozzallo - Marza, SP 66 Pozzallo - Sampieri, SP 65 Cava d'Aliga - Sampieri, SP 64 Donnalucata Cava d'Aliga, SP 63 Marina di Ragusa - Donnalucata), to the five port areas.

- The port of Pozzallo was built to promote the industrial development of the area, and is an extensive structure although lacking the services to permit a true conversion:

- The Port of Donnalucata is an ancient sea port, for which transformation is planned into a small-sized port partly to be used as a base for Civil Protection operations and partly as a small yachting area;

- The Port of Marina di Ragusa was built for commercial purposes and is expected to become the largest tourist port in the area;

- The Porto of Punta Secca, built in a totally archaic manner, is small and does not have any expansion potential, being adequate only to meet the needs of the local yachting sector.

- The Port of Scoglitti has always been a fishing port; it was originally small but functional, and has, during the years, been subjected to a series of development and salvaging operations to redress the gradual damage caused.

The natural layout of the Ragusa coastline has been drastically altered in recent years due to intense development and coastal squeeze. The building of numerous holiday homes (the urbanized areas accounting for 42 %) that form a continuous belt along the coastline, as well as extensive greenhouse cultivations (accounting for 37%) that have modified the traditional agricultural landscape, have both contributed to such change. The Ragusa territory has also been subjected to seaside tourism exploitation (11 %) mainly relating to local tourism.

Despite the high degree of coastal development, some unspoilt areas still exist, which are today protected as natural reserves and which account for 2 % of the coastal area. Only 1% of the coast has not been exploited.

In order to stop the increasing erosion of the beaches, numerous defence works were undertaken along the coast in the period between 1970 to the 1990, together with the damming and reclamation of the river courses.

The natural layout of the coast makes it possible to divide it into three parts: the eastern zone, the central zone and the western zone.

The **eastern zone,** which extends in direction N 96° for about 32 km, is bordered on the East by the Lavinaro Bruno stream and by the Punta d'Aliga to the west. It includes the coastal sections that form part of the administrative districts of Ispica, Pozzalo, Modica, and part of the Scicli area.

The coastal area features sandy beaches that extend for 24 km (S. Maria del Focallo, Pietre Nere, Maganuco, Marina di Modica, Sampieri) together with rocky coastlines (8 km) such as Punta Castellazzo, Punta Ciriga, Punta Raganzino, Punta Religione, Fornace Penna, Punta del Corvo and the Promontory of Sampieri. This coastal section includes the Modica stream, which is dry throughout the year.

The **Central zone** extends in direction N 112° from Punta d'Aliga up to Capo Scalambri, for about 21 km and partly includes the administrative districts of Scicli, Ragusa and S. Croce Camerina. This coastal section is characterised by a certain morphological diversity, with a low cliffed coastline extending for 16 km. The low coastline consists of sandy beaches, in the zones Arizza – Spinasanta zone, and sandy-pebbly beaches present in the RSNB of the mouth of the Irminio River and American beach. The rocky coastline that extends for 5km comprises low cliffs, to be found in the RSNB of the mouth of the Irminio River, at Punta di Mola and Capo Scalambri, and rocky pavements in the zone to the East of Marina di Ragusa.

The **Western zone**, bordered to the East by Capo Scalambri and the Mouth of the Dirillo River to the West, extends for 35 km in a N 161° direction. This coastal section includes the administrative districts of Acate and Vittoria and part of the coastal area of the administrative district of Ragusa and S. Croce Camerina. This coastal section features long, sandy curved sections which extend for 17 km, (Marina di Acate, Macconi, Scoglitti, Maghialonga), together with low cliffs (Punta Secca, Punta Braccetto and Punta Zafaglione). The Petraro stream, the Ippari River and the Birilli-Acate river all flow into this coastal section.

For the final version of the study, the Ragusa coastline was divided into 29 Sedimentary Coastal Cells (SCC) both on the basis of the morphological- sedimentary features of the area and the actual territorial function.

EUROSION defines the 'sedimentary coastal cell' as being a coastal compartment in which phenomena such as the positioning and movement of sediment, its transportation and deposit occur.

The edges of the cells define the geographic area in which the sedimentary balance is evaluated, thereby providing the outline for the quantitative analysis of both the erosion and sedimentation. These sedimentary coastal cells are in fact the most appropriate units for recording the Beach Balance Profile.

In practical implementation terms, the sedimentary coastal cell forms part of a more extensive sedimentary system comprising: the trapping system, the shoreline, and the marine environment facing the shoreline.

Materials and Methods

This chapter describes the survey and technical analysis methods used in the operations relating to the 'Volumetric, sedimentary, and morphometric monitoring of the entire Hyblaean coast' (Tab. 2).

The basic map used was the Technical Regional Map on a scale of 1:10.000, although for the purposes of the specific analysis of the evolution of the territory and for long-term comparisons of the shoreline, reference has also been made to the tables and quadrants of the Military Geographic Institute. The type of aerial photogrammetry used for the territorial shots and the support for the fieldwork was the Ortho-photograph, based on aerial shots taken in 1999, on a scale of 1:10.000.

The first field operation consisted of the positioning of the 81 benchmarks, first on paper and subsequently in the field; evenly distributed throughout the coastal area and falling within the administrative boundaries of the Regional Province of Ragusa.

The plane-altimetrical bench marks of the topographic sections were based on concrete structures (walls, boundary stones, etc.), lamp posts etc., in other words using any structure positioned near the coast, and from which the beach is visible and that cannot be modified in the short-term. The coordinates recorded using the satellite system of UTM (WGS84) type were converted into plane coordinates relating to the Gauss-Boaga system.

These clearly identified points were transferred onto the base map and all the measurements taken were made in relation to these fixed points. The sections were distinguished for each relative sector, using identification codes, and for each transect a transversal alignment was made in relation to the coastline to be seasonally surveyed in order to evaluate the variations in the evolution of the shoreline and relative volumes.

The coastline sections consisting of low sandy beaches, subject to phases of withdrawal or advance and seasonal changes were where the main monitoring activities were focused. The high coast sections were not monitored, as any variations are long term, and generally linked to isolated or sudden events.

The morphological, volumetric and morphometric study was conducted through surveys on the 81 sections located along the emerged beach, in relation to almost perpendicular alignments to the shoreline. On some of these sections (39) an expeditious topographic-altimetry survey was undertaken, while a topographic-planimetric survey was undertaken on the other 42 sections. This campaign data has been scaled down as necessary thereby permitting the topographic-altimetry profiles to be obtained.

As well as land surveys, submerged shoreline surveys were also made on the most pertinent sectors, the survey also being extended to include the respective bordering areas. The survey was undertaken with the aid of on-board instruments: a digital sonic depth finder, connected to the DGPS system and controlled by the Hypack navigation programme. It was thereby possible to compile the bathymetric maps of the various sectors examined.

The fact that two morphological entities of such a diverse nature in dimensional terms had to be represented (emerged shoreline and submerged shoreline together) made it necessary to apply different scale factors.

Profile overlaying was undertaken for the Autumn 2002- Winter 2003, Winter 2003-Spring 2003, Spring 2003- Winter 2004, Winter 2003 – Winter 2004 seasons, so that summer surveys were excluded from the comparative study due to the area and volume calculations being affected by the frequent, and often daily bathing disturbances. By the overlaying of two profiles, undertaken using the methods and in the seasons as indicated above, the areas of precise accretion or erosion were identified; the seasonal volumetric variations being calculated using the area of the individual profiles or the average of different profiles in a single cell.

The wind data was recorded by the Air Force for the stations of Gela and Cozzo Spadaro. The data provided by the Air Force relates to the observation period between 1954 and 2004 for the Cozzo Spadaio station and the period between 1965 and 2004 for the Gela station.
The basic data consisted of three-hourly speed recordings, expressed in nodes with the direction in degrees. Through the combined use of filters, this data was then recorded in eightieths, firstly in terms of direction and then in terms of speed categories. This collated data was then used to create convergent concentric cylinder graphs, of varying thickness according to intensity.

Sedimentary sampling on the emerged shoreline was undertaken, together with the topographic surveys, by following the same alignments of the profiles, taking about 500 g of surface material. Two samples were taken per section representing the two different deposit facies (beach and shoreline), with attention always being given to recording the distance from the benchmark or from the base point. In those sections that crossed shoreline edges with dunes, dune samples were taken on the peak, side and base of the dune using a three-metre rod. Texture analysis was of sediment samples was also carried out in order to characterise the environment studied and in order to understand the seasonal and annual variations.

Table 12. Table illustrating coastal sub-cells and profile frequency.

Zona	N°	Limiti geografici (da Est verso Ovest)	Campioni di sedimento	* Profili top.- plan. (spiaggia emersa)	** Profili top.-alt. (spiaggia emersa)	*** Profili top.-bat. (spiaggia emersa +sommersa)	****Profili bat. (spiaggia sommersa)
			Sezioni di riferimento				
Orientale	01	Le Grotticelle - P. Castellazzo					
	02	P. Castellazzo - P. Ciriga	A,B		A, B		
	03	P. Ciriga - Solarino	C	C			
	04	Solarino - C.zzo S.M. del Focallo	D,E, F, G, H, I	D, E, G, H, I	F		
	05	C.zzo S. M. del Focallo - Abitato di Pozzallo	L, M, N, O	L, M, O	N		
	06	Abitato di Pozzallo - Molo di Levante Porto di Pozzallo	P	P			
	07	Molo di Levante Porto di Pozzallo - P. Raganzino					
	08	P. Raganzino - Abitato di Maganuco (C.da Cindari)	Q,R,S	Q, S	R		
	09	Abitato di Maganuco (C.da Cindari) - Punta Religione					
	10	P. Religione - Abitato di Marina di Modica	T,U,V	T, V	U		
	11	Abitato di marina di Modica - Fornace Penna					
	12	Fornace Penna - Promontorio di Sampieri	Z, AA, AB	Z, AB	AA		
	13	Promontorio di Sampieri - Sampieri (C/da Costa)					
	14	Sampieri (C/da Costa) - Punta del Corvo					
	15	Punta del Corvo - Punta d'Aliga					
Centrale	16	Punta d'Aliga - Punta Bruca	AC,AD	AD	AC		AC, AD
	17	P. Bruca - Plaja Grande	AN, AO, AP	AN, AO, AP	AE, AF, AG, AH, AI, AL, AM	AE, AF, AG, AH, AI, AL, AM	AN, AO, AP
	18	Plaja Grande - Spiaggia Americana	AQ, AR, AS, AT	AQ, AT	AR, AS		AQ, AR, AS, AT
	19	Spiaggia Americana - Scalo Trapanese	AU, AV, AZ	AU,AZ	AV		AU, AV, AZ
	20	Scalo Trapanese - Serbatoio Gesuiti	BA		BA		BA
	21	Serbatoio Gesuiti - Punta di Mola					
	22	Punta di Mola - Punta Caucana	BB, BC, BD, BE	BB, BC, BD	BE		BB
	23	Punta Caucana - Capo Scalambri	BF, BG,	BF, BG,			
Occidentale	24	Capo Scalambri - Camping dei Coralli	BH,BI, BL, BM,	BH, BL,	BI, BM		BH,BI, BL
	25	Camping dei Coralli - P. Braccetto	BN, BO, BP	BN, BP	BO		
	26	P. Braccetto - Maghialonga	BQ, BR, BS, BT, BU	BR, BS, BT, BU	BQ		
	27	Maghialonga - F. di Cammarana	BV, BZ, CA, CB	BZ, CA, CB	BV		
	28	F. di Cammarana - Punta Zafaglione	CC, CD, CE, CF, CG, CH	CC, CE	CD, CF, CG, CH	CF, CG, CH	
	29	Punta Zafaglione - Porto di Gela	CI, CL, CM, CN, CO,CP, CQ, CR, CS, CT		CI, CL, CM, CN, CO,CP, CQ, CR, CS, CT	CI, CL, CM, CN, CO,CP, CQ, CR, CS, CT	

* Profili topografico-planimetrici
** Profili topografico-altimetrici
*** Profili topografico-batimetrici
**** Profili batimetrici

The submerged shoreline samples were taken during the seabed survey campaign and only for the areas of greatest interest, including the bordering areas. The samples were collected using a small bucket suspended at the end of a rope and made to slide by means of a pulley fixed to a metallic support projecting from the vessel. The bucket was sunk into the sea to the required depth as indicated by the sonic depth finder, while the GPS ensured the correct position. The sampling points were established beforehand on paper, and the route to be followed for this purpose was created using the Hypack navigation programme.

Samples were taken at the following characteristic points of the submerged beach: isobaths of -1m, -3 m, -5m, -7m, -10m, -12m e -15m. The samples taken were appropriately listed and taken to the Earth and Rock department of the Regional province of Ragusa and then taken to the Sedimentology laboratory of the Earth Science Department of Messina University for particle-size analysis.

Results of the Monitoring Programme

For the purpose of the final draft, the results of the geo-morphological-sedimentological monitoring of the Province of Ragusa, have been analysed based on the division of the coastline into 29 costal sedimentary cells (CSC). These divisions have been chosen due to both the intrinsic morphology-sedimentological features of the area and the purposes for which the territory is used.

As already mentioned EUROSION defines the 'coastal sedimentary cell' as a coastal division featuring aspects such as the positioning and movement of the sediment, its transportation and deposit. The cell limits define the geographic area within which the sedimentary balance is determined, providing a quantitative analysis of both the erosion and sedimentation that has occurred. In relation to this the coastal sedimentary cells provide a suitable unit with which to assess the shoreline balance profile and coastal resilience. In practical and management terms, the coastal sedimentary cell forms part of a more extensive sedimentary system relating to the catchment area, the shoreline, and the marine environment surrounding the waterline (MAP with indication of the CSC bench marks).

Within each CSC, the principal physical-morphological features have been defined (beach length, depth and position), the rocky sections of the beaches have been identified (high or low), and the percentage of purely coastal use has been calculated. The beach texture has also been defined and added.

Finally, monitoring has involved evolutionary assessment on three levels: the historic situation based on the available maps illustrating only a qualitative value and being based on data for which the season or the exact year of recording is not known, and data of seasonal-annual nature in which two subsequent shorelines were measures in a homogeneous manner. It is precisely this type of monitoring, which on sufficiently long cycles makes it possible to determine the cycles of erosion and/or seasonal advance, thereby making it possible to 'read' the evolution trends of the coastline in advance.

Eastern Zone

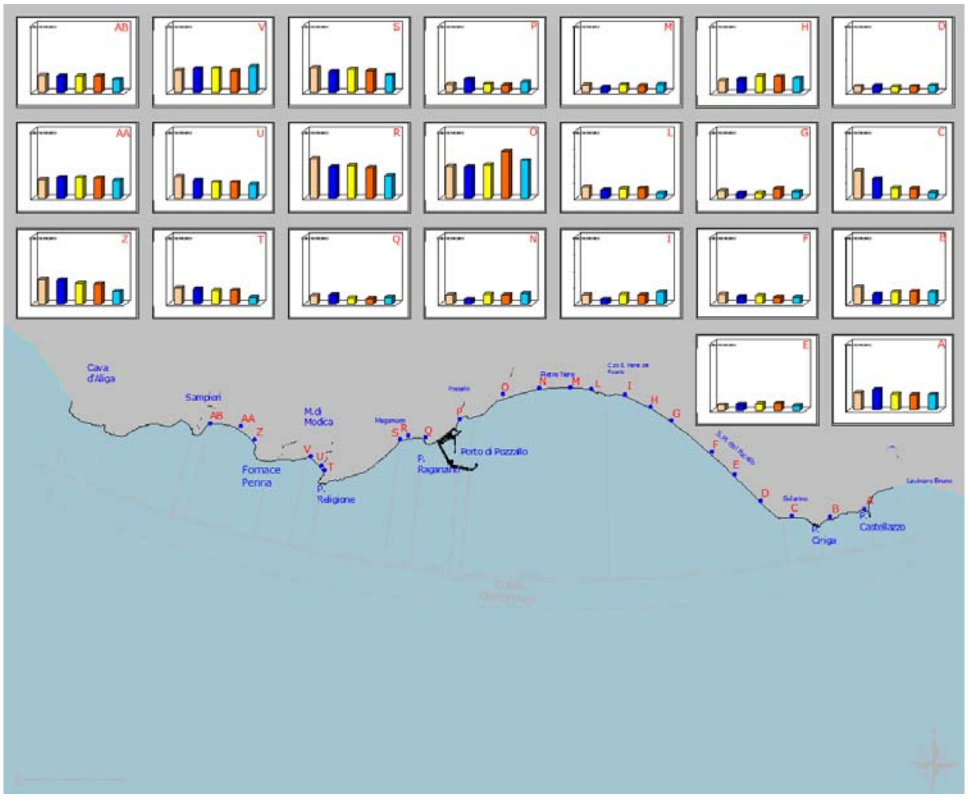


Figure 26. Map of the Eastern Zone indicating profile locations.

CSC 01 - Le Grotticelle – Punta Castellazzo

This section of coastline is bordered by Le Grotticelle on the east and by Punta Castelazzo in the West (the CSC is partially in the territory of Siracusa). The coastline section is located at N 98° and extends for approximately 1.431 m (considering only the part included in the province of Ragusa).

In this area the human impact has been fairly moderate with only 33% of the coastline having been developed, in particular by the construction of holiday homes. 49% of the coastline is undeveloped, while 18% is in a military zone to which access is not permitted.

Along the stretch of coastline under examination, sections have not been taken as there are only small pocket beaches present limited at the top by calcareous headlands.

CSC 02 - Punta Castellazzo - Punta Ciriga

This coastline section extends for 2.143km at an orientation of N 80°, and is delimited towards the West by the headland of Punta Castellazzo and by Punta Ciriga to the east.

The coastline is characterized by a morphology etched by small sandy beaches and pocket beaches interrupted by headlands composed of bio-calcarenite geology.

The limestone cliff of Punta Diriga, in which wave movement has etched a series of small caves, was, during the 70-80's, protected by four breakwater barriers, positioned sub-parallel to the coastline. This has promoted the formation of sandy outcrops as the result of the reduction in the circulation of the underlying water and the build up of sand in the caves.

This section of beach is approximately 1.04km in length with an average width of 44m (a maximum recorded width of 50m and a minimum of 38m), and is made up of fine sand.

The area has been densely urbanised (89%) mainly consisting of holiday homes, which delimit the top part of the coastline with their protective walls. CSC02 shows a phase of high erosion, especially in the central-western section. A comparison between the shoreline in 1999 and that of winter 2004 (the last monitoring season) shows a withdrawal of approx. -10,8 metres (-2,7 metres/ p.a) in the central-western sector and an equilibrium stage (+1,1 m) in the central-eastern sector; while if we consider the period of time between Autumn 2002 and winter 2004 (that is, the total monitoring period) the entire section appears to have eroded (despite being more evident in the central-western sector, in which values of -16 m have been recorded, as against the -4,6 m recorded in the central-eastern sector).

In the central-eastern sector of the CSC02 the highest negative variations have been recorded in the period between the winter and spring of 2003 with values of -12,8 m, while in the central-western sector, marked withdrawal values were recoded in the period between Autumn 2002 and winter 2003. Of particular note is the fact that a comparison between the recordings of 1999 and the first seasonal recording (Autumn 2002) highlights a situation of slight accretion of +5 m. As regards the volume analysis of the emerged shoreline, recorded in the period between winter 2003 and winter 2004, maximum volume levels have been recorded equivalent to -3.627 m3 in the western sector and values of -7.994 m3 in the eastern sector.

CSC 03 - Punta Ciriga – Solarino

This section of coast, located at N 100°, extends for approximately 1,530 m from Punta Ciriga in the east to Solarino in the west.

The coast generally features an undulating morphology, due to the presence in the most eastern sector of rocky limestone ridges, with rocky pavements to the east. The low coastline extends for 805 m (53%), with an average width of 43 m, and is principally made up of medium-grain sand and fine sand to a lesser extent. The upper coastline is delimited by the main road 67 between Pozzallo and Marza and is urbanised (100%).

This cell includes one of the sections most seriously affected by erosion, and in fact, during the period between 1999 and the winter of 2004, the coastline withdrew by –35.6 m (-8.9 m/per year) with an increased erosion rate, if we consider that a comparison between the coastline in 1999 and the first seasonal survey showed an advance of +28,6 m. In the course of the seasonal monitoring cycles, there is evidence of severe erosion especially in the period between autumn 2002 and winter 2003 and during the winter-spring of 2003 with the respective recorded withdrawal values being of -24,7 m and -27 m. During the spring-summer 2003 a phase of stability was recorded (-1,5 m), before a subsequent period of erosion that led to the loss of -11 m of beach. During the total monitoring period a total loss of –64.2 m was recorded.

CSC 04 - Solarino - Cozzo S. Maria del Focallo

This section of coast, located at N 125°, extends for a total of 7.308 m between the coasts of Solarino and Cozzo S. Maria del Focallo.

The coast is characterised by a series of headlands that jut out to sea, and has a predominantly straight morphology but tends to curve towards the extreme eastern part, delimited by a slightly protruding calcarenite crop.

The entire curved section consists of a single fine-sand beach, and extends for a length of 6,103 m (84%) and has a width of 25 m, with a maximum of 43 m and a minimum of 18 m. The central part of this section is characterised by the presence of a fairly continuous dune formation that extends for ≈ 2,60 km and reaches variable height levels of between 3 and 10 m. This area of dunes is predominantly non-vegetated and more consistent towards the side above the N 67 Pozzallo – Marza provincial road.

In the absence of the SP 67 road, which in this part of the coast is directly on the rear dune area, the dune formation is of a fairly dynamic nature, as illustrated by the regular road maintenance operations undertaken involving the clearing away of the sand. While just before the start of the summer season, the crossing points are also subject to maintenance as they provide access to the sea. These routes cross the dune and are marked by a series of bamboo fences of about 1.50 min height, which regularly become covered in sand during the non-bathing seasons. In the eastern zone the coast is strengthened in its upper part by the presence of main road N. 67 Pozzallo – Marza. This coastal section is 29% built-up while 71% of the area is dedicated to tourist – bathing purposes.

In terms of trends, the analysis of the seasonal data recorded in this area, shows a situation that we can generally define as stable, with a series of withdrawal and advance movements forming part of the naturally dynamic nature of the coastline itself.

A phase of stability has in fact been recorded in the eastern sector (+0.25 m), with a withdrawal of –5.1 m in the central sector and an area of accretion in the eastern zone with values of +6,1 m. The withdrawal movements were recorded in particular during the period between autumn 2002 and winter 2003 and mainly in the central and western areas, in the period between summer 2003 and winter 2004. While if we consider the coastline in 1999 and the last seasonal recording made, it is possible to note a general withdrawal situation with values of between –10.9 m (2.7 m/p.a) and –12.05 m (3.0 m/p.a) in the eastern and central sectors, and a phase of stability in the western sector (-1.15 m). This highlights the fact that the coast actually withdrew during the period between 1999 and 2002. As regards the volume analysis of the emerged shoreline, maximum volumes have been estimated of -14.983 m3 between the winter of 2003 and the winter of 2004.

CSC 05 - Cozzo S. Maria del Focallo – Inhabited area of Pozzallo

The coastal zone is delimited in the east by the section of beach adjoining Cozzo S. Maria del Focallo, and the inhabited area of Pozzallo to the west. This section of coast extends for 5,001m with an orientation of N 81°.

The coastal section has a curvilinear shape and consists of a single sandy beach extending for a length of 3,939 m (79%), characterised by a headland towards the west consisting of the Telluric formation (Serravalliano – Upper Tortonian.).

The fine-sand beach has an average width of approx. 45 m with a maximum of 108 m and a minimum of 21 m. The coast is delimited at the top by the fencing walls of the numerous summer residences, especially in the western zone.

During the summer of 2003 building work began to create a new parking area, bordering on the beach. This section has a high urban density (53%) due principally to the fact that it encompasses the community of Pozzallo, which is the only township in the entire province of Ragusa that has an inhabited centre that directly overlooks the coast. 47% of the land is dedicated to farming uses. Whereas in the more eastern section, a barrier of 150 m in length was built in the early 1980's in order to protect provincial road 67 and private buildings.

From the seasonal recordings, it is possible to denote a withdrawal in the eastern section (-16,7 m) with an advance in the central (+4.3 m) and western sections (+16.7 m). During a phase of consistent erosion, in the period between Autumn 2002 and winter 2003 (-8,2 m eastern section; -8.8 m central sector; -2 m in the western section), the beach underwent a stage of total general advance in the period between the winter and spring of 2003, with a subsequent stage of stability being recorded in period between spring and summer 2003, in the eastern and central sections, together with a strong accumulation stage which led to an increase of +41,4 m in the western sector. During the period between the summer of 2003 and winter 2004 a slight advance was recorded in the central sector (5.2 m) with a marked withdrawal in the eastern and western sectors with recorded values of –13.9 m and –28.3 m. respectively. A comparison of the shorelines in 1999 and the last seasonal recording shows a regressive tendency of the shoreline in the eastern sector which led to a withdrawal of –14.4 m, with a general stability in the central sector and an advance of +4.1 m (1,0 m/p.a) in the western sector. As regards the analysis of the emerged shoreline volumes, maximum volumes have been estimated as being of +75.546 m3 in the time period between winter 2003 and winter 2004.

CSC 06 – Pozzallo inhabited area – Eastern quay of the Port of Pozzallo

This area consists of a short coastal section located below wave level in relation to the eastern quay of the Port of Pozzallo and more specifically, from the inhabited part of Pozzallo, towards the east and up to the port quay to the West. The coastline extends for 748 m orientation N 54°. This short stretch of coastline has a curved form and consists of a short sandy beach.

The sandy beach extends for a length of 682m (91%), with an average width of 28 m, and is made up of fine sand. Its entire upper length is delimited by the local road. This section is also totally urbanised.

CSC06 shows a phase of almost total stability to exist, with a slight tendency to advance. A comparison of the shoreline in 1999 and that of winter 2004 shows a phase of general stability (3.7 metres), the period between the autumn of 2002 and the winter of 2004 shows an accumulation of sediment with values of +6 m. During the seasonal monitoring cycle there is evidence of a phase of advance between autumn 2002 and winter 2003 in which values of +15.1 m were recorded, followed by an erosion phase in the subsequent season with values of –13.9 m. During the spring summer season 2003 there was a period of stability (-2.7 m) while in the summer 2003 – winter 2004 period a new phase of increase was recorded which saw a +7.5 m increase in the beach. A comparison of the shoreline in 1999 and the first monitoring season shows a general stage of stability (-2.3 m).

CSC 07 – Pozzallo Port eastern quay - Punta Raganzino

This section delimits the port area of Pozzallo, identified to the east by the built up area of Pozzallo and by Punta Raganzino to the west. The area extends for 1.111 m, with a N 64° orientation.

The section of rocky coastline features a series of calcarenite rocks, which are located at the low cliff section in Punta Religione.

Sections were not analysed along the coastline in subject, due to the presence of a medium-low cliff section.

CSC 08 - Punta Raganzino – Inhabited area of Maganuco (C.da Cindari)

The coastal area is delimited to the east by Punta Raganzino and by Località Maganucoto to the west in the vicinity of Case Cindari. The coastal area extends for 1.976 m, with N 73° orientation.

The coastline has a slightly curving shape and is mainly made up of rocky coast that extends for 1.069 m (54%) and a low coast (907 m, 46%). The beach is mainly made up of fine sand, and medium particle sand to a lesser extent with an average width of 59 m with a maximum of 93 m and a minimum of 21 m. The eastern section of the CSC is bordered at the top by a dune formation of a variable height of between 2 and 4 m, and with scant vegetation.

The rocky coastline made up of low cliffs, of heights not exceeding 5 m, is made of calcarenite stone. This stretch of coastline has a low urban population density, mainly linked to tourist bathing use.

This cell is one of the most seriously affected by erosion, and in fact a comparison of the shoreline in 1999 and the winter of 2004 shows a withdrawal of –65.0 m (-16,2 m/p.a) in the eastern section, of –38.6 m (-9.6 m/p.a) in the central section and has been shown to be in a stable condition in the western section (+0.3 m); however it must be pointed out that a comparison between the shoreline in 1999 and the first seasonal monitoring in the eastern section shows marked withdrawal (-61.8 m) while the central and western sections show advances of +10.8 m and +21.9 m. During the period of seasonal monitoring there was a period of severe erosion recorded between Autumn 2002 and winter 2003, in the central and western sectors with values of –23.4 m and –12.0 m, respectively, while a phase of stability was recorded in the eastern section (+2.7 m). During the period between the winter and spring of 2003, the eastern section recorded a withdrawal of –8.0 m while the central and western sectors recorded an advance of +4 m and +8.0 m respectively. This was then followed by a period of more marked erosion in the period between spring-summer 2003 which resulted in the loss of –7.2 m and –5.3 m of beach in the central and western sections, while the eastern section recorded a period of stability. The monitoring undertaken between the summer of 2003 and winter 2004 confirms the regressive tendency of the shore in the central and western sections, with erosion rates of –23.0 and –12.3 m while the eastern sector shows an advance of +4.0 m. From an analysis of the monitoring data it appears that although the entire cell seems to be in a state of erosion, the central and western sections are those most seriously affected by erosion, in fact during the monitoring operations, losses of –49.4 m and -21.6 m of beach respectively were recorded. As regards the analysis of the shore face volumes, maximum volumes have been estimated of -342.923 m3 in the period between the winter of 2003 and the winter of 2004.

CSC 09 – Inhabited area of Maganuco (C. Cindari) – Punta Religione

Delimited to the east by the inhabited area of Maganuco (C. Cindari) and by Punta Religioneto the west, the coastal section extends for 2.376 m with N 70°orientation.

This coastline section is curvilinear in shape, becoming convex towards the sea, and is completely made up of rocky coast, with an alternation of low cliffs not exceeding 5 m and rocky pavements. This stretch of coastline is totally urbanised.

Sectional analyses were not made on this stretch of coastline due to the presence of a medium high cliff.

CSC 10 - Punta Religione – Inhabited centre of Marina di Modica

The area is delimited to the east by the promontory of Punta Religione and by the inhabited area of Marina di Modicato the west.

This coastline stretch extends for approx. 1.806 m with N 133° orientation.
The coast in question has a curvilinear form and consists of a shoreline that extends for a length of 867 m (48%) delimited at the ends by rocky coastal stretches which account for a surface area of approx. 939 m (52%) exclusively made up of calcarenite stone. The beach is of medium width 53 m, with a maximum value of 69 m and a minimum of 40 m, and is made up of fine and medium grain sand. The coastline stretch is delimited at the top, to the west, by the seafront, and to the east is delimited by a partially vegetated dune of approx. 5m in height. This coastline stretch that encompasses the urban centre of Marina di Modica, is 52% urbanised, especially its western sector, while 48% is given over to tourist bathing use, as this area is a popular holiday spot for the locals.

This coastline stretch has recorded a withdrawal in the east-central sections with values of –17.5 (-4 m/p.a) and –16.4 (-4.1 m/p.a) respectively, while an advance of +9.0 m (+22 m/p.a) has been recorded in the western section as can be seen by comparing the shoreline in 1999 with that in the winter of 2004. It must also be pointed out that a comparison of the shoreline in 1999 with the first seasonal monitoring results has revealed a situation of stability to exist, while in the eastern and central zones advances of +11.5 m and + 5.1 m. have been recorded.

During the seasonal monitoring a phase of erosion was recorded during the period between Autumn 2002 and winter 2003 in both the eastern and central sectors with values of –5.0 m and –11.9 m respectively, while the western sector recorded a progradation (+5.1 m); a state of regression was also recorded in the period between the winter and spring of 2003 in both the eastern (-4.2 m)< and central sectors (-4.6) while the western sector experienced a phase of stability (+0.9 m). In the period between the spring and summer of 2003 a phase of stability was recorded in the eastern and central sectors and a withdrawal of –7.9 m in the western sector followed by a regressive phase between summer 2003 and winter 2004 in the eastern and central sectors in which losses of –20.0 and –5.0 m of beach were recorded respectively; while the western sector experienced a period of progression with an advance of +13.9 m. From an analysis of these monitoring details it is clear that the CSC10 is experiencing a period of general erosion, especially in the eastern and central sectors (-29.0 m and –21.5 m). While as regards the analysis of the shore face, maximum volumes of –29,718 m3 have been estimated between the winter of 2003 and winter 2004.

CSC 11 – The inhabited centre of Marina di Modica - Fornace Penna

This coastline section is delimited to the east by the inhabited centre of Marina di Modica, and to the west by the promontory where the remains of the ancient Fornace Penna lie. The coastline extends for 1,212 m with N 91°orientation. It is of curvilinear form becoming convex towards the sea and entirely consists of a rocky coast made up of calcarenite stone.

The promontory on which the Fornace Penna is situated, and the cultural value of the remains, make this section of particular landscape interest. The coast is totally urbanised, although the eastern section is much more so than the western. Sectional analyses were not made along this coastal section as it consists of a medium-high cliff section.

CSC 12 - Fornace Penna – Sampieri promontory

The coastal area extends from the promontory on which the Fornace Penna is located right up to Sampietri, comprising a total of 3,123 m. The coastline has a N 109° orientation and has a curvilinear form and consists of a single section of beach delimited to the west by the rocky calcarenite promontory. The sandy beach extends for a length of 1853m (59%) with an average width of 53 m, with a maximum value of 59 and a minimum of 46 m, and is made of fine sand. In its central section the CSC12 is delimited at the top by a fairly stable and scarcely vegetated dune formation which extends for a length of approx. 227 m with a variable height of between 2 and 4 m. This section is 45% urbanised, 18% of the land is given over to tourist-bathing uses, whilst the remaining 37 % of the area is covered by a pine forest managed by the Forest Ranger Corp.

CSC12 corresponds to one of the areas most severely affected by erosion, and comparison between the shoreline in 1999 and the winter of 2004 shows a withdrawal of –51.6 m (-13 m/p.a) in the eastern sector, and of –14.5 m (-3,6 m/p.a) in the central part, with an advance in the western sector of +13.3 m; it must however be pointed out that a comparison between the shoreline of 1999 and a first seasonal monitoring survey in the eastern and central sectors has revealed strong withdrawal (-17.3 m and –12.6 m) while the western sector has registered an advance of +24.8 m. During the course of the seasonal monitoring operations there is evidence of erosion having occurred throughout the entire section, even if it appears more marked in the eastern sector, in which during the winter-spring 2003 period withdrawal values of –9.1 m were registered and of 21.4 m during the summer 2003- winter 2004 period. In the central sector the greatest withdrawal was recorded in the period between summer 2003 and winter 2004 with values of –6.0 m compensated for by the values recorded between Autumns 2002 and winter 2003 (+6.1 m); while in the remaining seasons only slight withdrawal of about 1 metres was recorded. The western sector is characterized by a certain stability during the first three seasonal surveys, with a more marked withdrawal in the last monitoring season in which a withdrawal value of –10.3 m was recorded. As regards the analysis of the shore face, maximum volumes of +15,247 m3 were recorded during the period between Autumn 2002 and winter 2003 and volumes of -32.409 m3 in the period between winter 2003 and winter 2004.

CSC 13 – Sampieri promontory – Sampieri (C.da Costa)

This area is a short section of coastline of approx. 1.109 m, delimited to the East by the Sampieri promontory and to the west by the neighbouring coastline area of C.da Costa. The coastline is has a N 109° orientation and a curvilinear morphology, consisting of a small beach, that extends for approx. 330 m (30%), delimited to the West by a calcarenite promontory.

The rocky coast that extends for 779 m (70%) consists of low cliffs not exceeding 3 m in height. Manmade intervention in this area is limited, although the entire section is urbanised.

Sectional analyses were not undertaken along this section of coast due to the presence of medium-high cliffs.

CSC 14 - Sampieri (C.da Costa di Carro) – Punta del Corvo

This coastline is delimited to the east by the part of the coast adjoining C.da Costa in Sampieri, and by Punta del Corvo to the West, it extends for 1,949 m with N 79°orientation.

The coastline is curvilinear in form and is characterized by a rocky coastline with an alternation of low cliffs that do not exceed 5 m and rocky pavements. This section appears to be 55% urbanized; it must be pointed out that this urbanization is linked to the presence of provincial road N 65 Cava d'Aliga-Sampieri; while 45% is given over to agricultural use and greenhouse cultivation in particular.

Sectional analyses have not been made on the coastline section in question due to the presence of medium-high cliffs.

CSC 15 - Punta del Corvo - Punta d'Aliga

The coastline which is delimited to the East by the rocky promontory of Punta del Corvo and by Punta d'Aliga to the west extends for 2357 m and has a N 112° orientation.

This coastline section is entirely rocky and has a curvilinear form convex towards the sea. The coastal morphology consists of low cliffs, of approx. 4m in height, almost exclusively made up of calcarenite stone. This stretch is 54% dedicated to agricultural use, and greenhouse cultivation is widely carried out; 46% of the area is urbanised. The urbanisation being linked both to the presence of the

SP N 65 Cava d'Aliga-Sampieri road, and due to the presence of housing, thinly scattered throughout the coastline.

There have been no sectional studies undertaken in this section of coastline as a medium-high cliff section is present.

Central Zone

CSC 16 - Punta d'Aliga – Punta Bruca

The coastline extends for approx. 1.081 m from Punta d'Aliga to the small promontory of Punta Bruca with a N 150°orientation.

The coastline is indented and forms two adjoining pocket beaches, extending for a total of 409 m. The beaches are delimited to the east by Punta d'Aliga and made up of calcarenite stone, in the central part by a very moderately prominent promontory that separates them, and by Punta Bruca to the west. The two beaches that extend for 272 and 193 m respectively (only taking into account the sandy sections) make up 38% of the entire CSC.

The beaches have an average width of 35 m with maximum width of 62 m and a minimum of 9 m and are characterized by both fine and medium grain sand. The section in question is totally urbanised and towards the interior is delimited to the East by the Cava d'Aliga shore, while to the West there is evidence of indiscriminate urbanization reaching right to the coastline, as highlighted by the area of the inhabited centre of Cava d'Aliga. The submerged shoreline is affected by the morphology of the emerged coastline section; the nearer isobaths up to a depth of -5 m would appear to be affected by the trends of the more coastal isobaths, while further in an adjustment is noted. In this area the seabed is sandy. The average gradient of the submersed shoreline being of between 0.8 e 1,1%.

In the coastal section between Punta d'Aliga - Punta Bruca, the data recorded during the monitoring period reveals considerable erosion. In fact, a comparison between autumn 2002 and winter 2004 shows a withdrawal of -30,4 m in the central-eastern sector and of –17.0 m in the central to western sector. During the course of the seasonal monitoring operations, a continuous phase of erosion can be noted, with the most significant values being recorded in the period between winter and spring in which withdrawal rates of –10.7 and –11.1 m were recorded and in the period between summer 2003 and winter 2004 during which erosion resulted in the loss of –21.4 m of beach in the central-eastern sector; whereas during the other monitoring seasons the erosion does not reach severe levels.

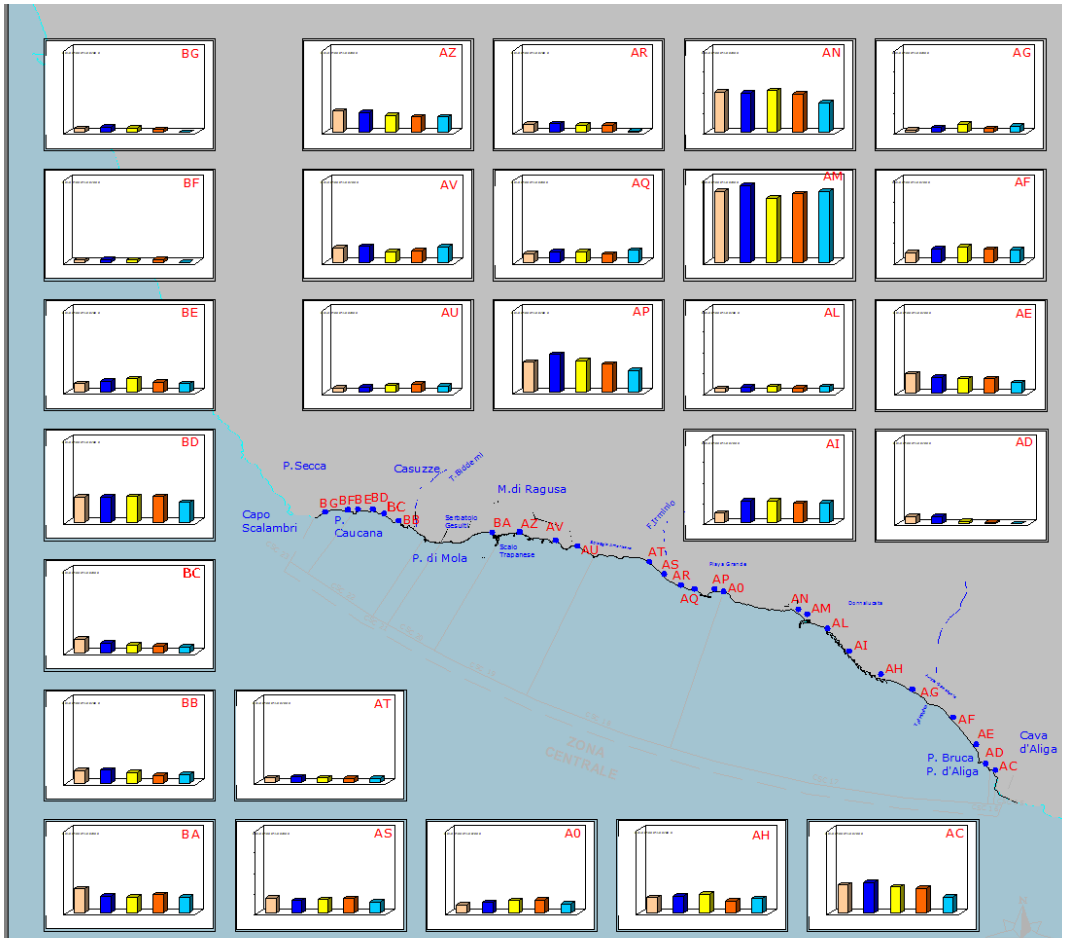


Figure 27. Map of the Central Zone indicating profile locations.

A comparison between the shoreline in 1999 and the first seasonal monitoring operation shows values of +4.7 m in the central-eastern section and of –14.9 in the central-western section, while between 1999 and 2004 values of –25.7 m and –31.9 m. were recorded. As regards the volume analysis of the emerged shoreline, maximum values have been estimated of -14.932 m3 in the period between Autumn 2002 and winter 2003 and volumes of -128.033 m3 between winter 2003 and winter 2004.

CSC 17 - Punta Bruca – Plaja Grande

Bordered to the East by the Promontory of Punta Bruca, and the inhabited area of Plaja Grande to the west, this extensive coastal section extends for 9.115 m and has a general orientation of N 123°.

It has a diverse morphology with a predominance of low cliffs which extend for 8.812 m (97%). The limited rocky section that extends for 303 m (3%) consists of yellowish calcarenite stone which extends towards the sea and forms Punta Bruca (the limit to the west of the cell.) The beach has an average width of 42 m, with maximum points of 170 m and minimum of 13 m, and is mainly made up of medium fine sand, and fine sand to a lesser extent. The eastern part of the beach is edged by a dune section, which extends in a discontinuous manner, for approx. 900 m, with a variable height of between 3 and 7 m. The dune is partially vegetated with the exception of the eastern part, where accumulations of sand occur in the non-bathing season, which are often several metres in height and which act to obstruct access to the sea by the houses located directly on the coast. This coastline section is 44% urbanised and is characterized by the presence of buildings that directly overlook the sea, especially in the areas of Donnalucata e Plaja Grande. Near the small seaside centre, the rear beach area is dominated by the marina and the S.P. N 89 Marina di Ragusa – Donnalucata road. While 54% is given over to agricultural use, particularly in the central area in which much greenhouse cultivation is undertaken. A great deal of coastal defence work has been undertaken in this coastal section, initially installed in the 1970's. A total of 17 breakwater barriers exist to protect the beach of Arizza and Spinasanta. The submerged beach morphology is affected by the morphology of the emerged coastal section; the nearby isobaths up to a depth of -5 m appear to be affected by the trends of the more coastal isobaths, while an adaptation is noted further out. The section between Porto di Donnalucata and Plaja Grande shows a diversified morphology with a deepening of the seabed in a saw-tooth style in the area not protected by any defensive works. Further out there is a widening of the isobaths as you travel westwards. The sea beds are predominantly sandy with some tiny concentrations of rocky material. In the area adjoining the beach of Spinasanta, a posidonieto has been found between isobath -9 m and isobath -12 m. The average gradients of the submersed beach vary from 1.4% in those areas nearest the coast to 0,6% towards the -7 m isobath.

Withdrawal has been noted in this coastline stretch in the eastern, central-eastern and western sections (-18,9 m, -39,1 m, -14,5 m), with evidence of a stage of stability in the central section and more marked advance in the central-western section with values of +37.4

m, as emerges from the comparison between the shoreline in 1999 and that of 2004.

A comparison between the shoreline in 1999 and the first monitoring season shows a predominant state of regression, with high withdrawal rates; such as –12.1 m in the eastern sector; 42.6 m in the central-eastern section and of 5.2 m in the western section: the central section has proved to be stable, while the central-western section has recorded an advance of +25.2 m.

However, during the seasonal monitoring a phase of stability was recorded in the central-eastern and central sections of 6.8 m and 9.3 m respectively. From the seasonal monitoring analysis it can be seen that in the season between autumn 2002 and winter 2003, a general advance was noted with a maximum value of +12.5 m in the western section. The following season also recorded a generalized advance with values of around –4 m with the exception of the central-eastern section where a withdrawal of 13.9 m was recorded. Between the summer of 2003 and winter 2004 there has been an advance in the central-eastern section (+6.2 m) and in the central-western section (+17.0m) with stability in the central sector and withdrawal in the other sectors with values of between –4.6 and 12.8 m. As regards the volume analysis of the emerged shorelines, maximum volumes of +38,8591 have been estimated between the Autumn of 2003 and winter 2004. While as regards the submerged beach volumes of 1,300,209 m2 have been estimated in the period between spring 2003 and winter 2004.

CSC18- Plaja Grande- American beach

The coastline extends for 2,134m and is delimited in the east by the inhabited area of Plaja Grande and by the American beach to the west. The coastline has a N114° orientation.
This coastline section includes the Special Biological Nature Reserve at the mouth of the Irmino river. The section is of undulating morphology with an alternation of concave and convex sections and is characterized by the predominance of low coastline that extends for approx.1,687 m (79%), found mainly to the west and the east, while the central area has a low cliff section not exceeding 5 m in height and made of semi-coherent material.

The beach has an average width of 21 m with maximum width of 32 m and minimum of 12 and mainly consists of fine and medium-fine sand with the presence of sunken pebbles. The coastline is not delimited by rocky promontories; however the choice of the cell has taken into account the presence of the reserve. The sandy beach is at the top delimited by a dune section covered with dense vegetation and Mediterranean scrub. The dune extends for approx 406 m and has a variable height of between 2 and 6m. The coastal section comprises various deposit areas: the mouth of the Irminio river, the sandy and pebbly beach and the dune. This area features the presence of the natural reserve of the Irminio river and is therefore an area of great environmental value, not only due to the flora that it contains but also by virtue of its unique coastal features and the variety of different environments present. The bathometric surveys show a diversified morphology with deepening of the seabed in a saw tooth form; while out to the sea a widening of the isobaths can be noted as we move west. The sea beds are mainly sandy with small pockets of rocky material. The submerged beach average gradient is of 1.4%, in the areas nearer the coast, and of 0.6% towards the - 10 m isobath.

This coastline section has been influenced by the erosion process which has caused a withdrawal of the shoreline by –22.2 m in the central sector and of 10.8 m in the western area (the eastern sector being stable), as can be seen by the comparison between 1999 and 2004. However, it must be pointed out that a comparison between the shoreline in 1999 and the first seasonal monitoring shows a period of total withdrawal throughout the CSC18 with beach losses of around 9m. During the course of the seasonal monitoring operations, there has been an advance in the eastern section (+4.1 m) and stability in the western and central sections in the period between Autumn 2002 and winter 2003, followed by a subsequent period of general stability. The recordings made between spring 2003 and summer 2003 also confirm the regressive tendency of the shorelines with a growing withdrawal which does not exceed the value of 9.5 m as recorded in the eastern section. During the period between summer 2003 and winter 2004 an advance of +9.5 m was recorded in the eastern sector, a withdrawal of –10.2 m in the central section and stability in the western section. Overall during the monitoring period there has been an advance of +7.9 m in the eastern sector and a withdrawal of 12.5 m in the central sector and a stability stage in the western sector. As regards the emerged beach volume analysis maximum values of –17,592 m have been estimated during the period between winter 2002 and winter 2004.

CSC 19- American beach – Scalo Trapanese

The coastal area under inspection is delimited to the east by the American beach and to the west by the quay of the Scalo Tranpanses, which extends for approximately 3,431 m and forms part of the comune of Ragusa. The coastline section is of N101 ° orientation.

This coastline section is generally straight with a predominance of low coasts (2,573 m, 75%)with an average width of 31 m, a maximum of 43 m and a minimum of 16 m, with mainly fine sand and rocky pavements. The area is totally urbanised (100%); urbanisation being linked to the presence of holiday homes. The bathymetric evaluations show a diversified morphology with deepening of the sea bed in a saw tooth manner. Further in, a widening of the isobaths can be noted as you go westwards. The seabeds being mainly sandy: between isobath .4 m and isobath –9 m a small posidonieto concentration has been found. The average submerged shoreline gradient is of 1.4%, in the areas nearest the coast, and of 0.5% bear the –10 m isobath.

A comparison between the shoreline of 1999 and the last seasonal survey (winter 244) reveals a condition of stability, with withdrawals of around a metre in the eastern sector and advances of about one metre in the central and western sectors. A comparison between the shoreline in 1999 and the first seasonal survey (Autumn 2002) shows erosion of the eastern beach with a withdrawal of –6.9 m, while the central beach remains stable, while the western beach shows an advance of +15.0 m. From this it emerges that during the monitoring period, the central and eastern sections have remained stable or slightly advanced, the seasons of regression being compensated for by seasons of progradation. In fact the eastern sector has shown a generalized phase of stability, while the central sector shows advances (4.3 m;10.0 m) and a withdrawal of –12.9 m recorded in the winter-spring season of 2003. While the western sector has shown a generalized period of stability throughout the monitoring period, with the exception of the winter-spring 2003 period, in which a withdrawal of –8.2 m was recorded. In total during the monitoring period advances of 5.8 m and 3.8 m were recorded in the eastern sector, with withdrawals of 13.3 m in the western sector. As regards the emerged beach volume analysis, maximum volumes of 14,408 m3 have been estimated in the period between the winter of 2003 and winter 2004.

CSC 20- Scalo Trapanses –Serbatoio Gesuiti

This short stretch of coastline is delimited in the east by the eastern quay of the Scalo Trapanses and to the west by the coastline section near the Serbatoio Gesuiti. It extends for approx. 140 m and has a N120° orientation.

This coastal section is curvilinear and consists of a sandy beach that extends for its entire length, delimited to the west by a rocky calcarenite ridge. The beach has a width of 44 m and comprises fine sand. This coastline section falls within the inhabited area of Marina di Ragusa, and its man-made influence is mainly related to its use as a sea resort. Bathymetric records show that it has a varied morphology, with saw tooth seabed deepening. Out to sea a widening of the isobaths can be noted in a westward direction. The sea-beds are predominantly rocky in nature. The average gradient of the submerged beach is of 1.8%, in the areas nearest to the coast, and of 0.6% towards the –12m isobath.

A comparison between the shoreline in 1999 and that of the winter of 2004 shows a withdrawal of approx. –4.4 metres (-1.1 m/p.a), although the period between Autumn 2002 and winter 2004 revealed severe regression with values of –19.5 m. During the course of the seasonal monitoring cycle it is possible to note a withdrawal stage between autumn 2002 and winter 2003 and in the period between summer 2003 and winter 2004 with recorded values of –18.1 m and –5.0 m respectively. The winter-spring 2003 season revealed a period of stability, while a state of advance was noted in the period spring-summer 2003, resulting in a +4.5m increase in the beach. A comparison between the shoreline in 1999 and the first monitoring season shows a considerable advance (+15.1 m). While as regards the analysis of the emerged beach volumes, maximum volumes of –702 m3 have been estimated, in the period between winter 2003 and winter 2004.

CSC21- Serbatoio Gesuiti – Punta di Mola

This coastal area extends from the area adjoining the Serbatoio Gesuiti up to Punta di Mola, it extends for a total of 1,650 m with a N 81° orientation.

The coastline features a curvilinear morphology, convex towards the sea, and is entirely made up of rocky coasts with an alternation of low cliffs not exceeding 3 m in height as well as rocky pavements made of calcarenite rock. The area is highly urbanised, and forms part of the inhabited area of Marina di Ragusa. The bathymetric readings show a varied morphology with saw-tooth seabed deepening. Further out to sea the isobaths begin to widen and shift westwards. The seabeds are predominantly sandy.

No sectional analyses were made on the coastline in question due to the presence of medium-high cliffs.

CSC 22- Punta di Mola- Punta di Caucana

This coastal stretch that extends for 2,223 m comes within Punta di Mola to the east and Punta di Caucana to the west. The coast has a N 112° orientation.

The coastline has a curvilinear form and is delimited to the west by a series of terraced marine deposits that make up the promontory of Punta Caucana. This coastline section is predominantly made up of generally extensive sandy beaches (1,846 m 86%) that alternate with rocky pavements (377 m, 17%). These beaches are characterized by the presence of medium-grain sand with an average width of 33m, a maximum of 59 m and a minimum of 21 m. In places the upper limit of these beaches is delimited by the presence of a rather discontinuous dune bar, that extends for a total length of 442 m and which has a variable height of between 2-3 m. The dune is poorly vegetated, and is over-steepened in the rear dune section as the result of the presence of holiday homes. This section is in fact highly urbanised, with an influx of population during the summer months, the urbanisation being largely related to the presence of holiday homes. The coastline section from Punta di Mola to Casuzze features a varied morphology with a saw-tooth seabed deepening. Further out to sea, it is possible to note a widening in the isobaths in a Westward direction. The seabed is predominantly sandy; there is a small posidonieto concentration. The average gradient of the submerged shoreline ranges from 1.3% in the areas nearest the coastline, at 0.6% towards isobath –7m.

In this coastal section the data recorded during the monitoring cycle show significant erosion; in fact a comparison between Autumn 2002 and winter 2004 shows a withdrawal of –9.8 m in the eastern sector and of –16.3 m in the central section with a stage of stability in the western sector. During the course of the various seasonal recordings there is evidence of continuous erosion with varied values in the different sectors and the various seasons. In the eastern part the greatest loss (-4.6m) is in the season between winter-spring 2003 and spring-summer 2003. The central section shows a predominantly stable phase, with the exception of the period between summer 2003 and winter 2004, in which a withdrawal rate of 8.3 m was recorded; in the western sector in fact we can see an advance of +5.3 m between autumn 2002 and winter 2003 which continued through to the subsequent season with slightly greater values (+6.7 m), while in the two subsequent seasons a withdrawal rate of –8.5 m was recorded and a phase of stability. If we compare the shoreline between 1999 and the first seasonal recording, regression can be noted with losses of –5.1 m in the eastern section, of –4.1 m in the central section and of –6.9 m in the western section. The analysis of the emerged shoreline volumes makes it possible to estimate maximum volumes of –21,709 m3 between Autumn 2002 and winter 2003, while in the period between the winter of 2003 and winter 2004, there has been a volume reduction of –597 m3.

CS3 23- Punta di Caucana – Capo Scalambri

The coastline section is delimited to the east by Punta di Caucana and by Capo Scalambri to the west and extends for approx. 1,007 m3. The coastline has a curvilinear morphology and N84 ° orientation.

The area is made up of low cliffs (371 m, 37%), consisting of an alternation of low and pocket beaches, with a series of intervening low cliffs (635 m, 63%) not exceeding 5 m and made up exclusively of marine terraces of the Pleistocene era (Capo Scalambi- Punta Caucana). The beaches have an average width of 10m, with a minimum value of 5 m and a maximum of 18 m and are made of fine sand. This coastline section has been subject to a protection operation, which has involved accretion using quarry material, the completion of the pre-existing cliff section and the initiation of 4 swashes. The area is of tourist-cultural value by virtue of the presence of archaeological sites situated on the marine terrace, and 34% of the area comes within the "Archaeological Park of Kaukana", while 66% of the area is urbanised. The bathymetry of the submerged shoreline generally reflects the general surrounding coastal morphology. The isobaths of between –1 m and –4 m have a curvilinear form parallel to the coastline. The nearer isobaths up to a depth of –8/9 m, appear to be influenced by the lie of the more coastal isobaths, while further out the isobaths tend to narrow. The submerged shoreline is predominantly sandy.

This area shows significant erosion, and the shoreline between 1999 and the winter of 2004 has withdrawn by –26.9 m (-6.7 n p,a) in the central-eastern sector and by 18.2 m (-4.5 m /p.a) in the central to eastern section. During the course of the seasonal monitoring operations there is evidence of a state of generalized stability, with the exception of the period between summer 2003 and winter 2004 in which a withdrawal was recorded with maximum values of 6-7 m and 6-9 m respectively. In general during the monitoring period a withdrawal of –5.8 m and –9.6 m was recorded; this highlights the fact that the greatest withdrawal was recorded between 1999 and the first monitoring season with values of 21.1 m and 8.6 m.

Western Zone

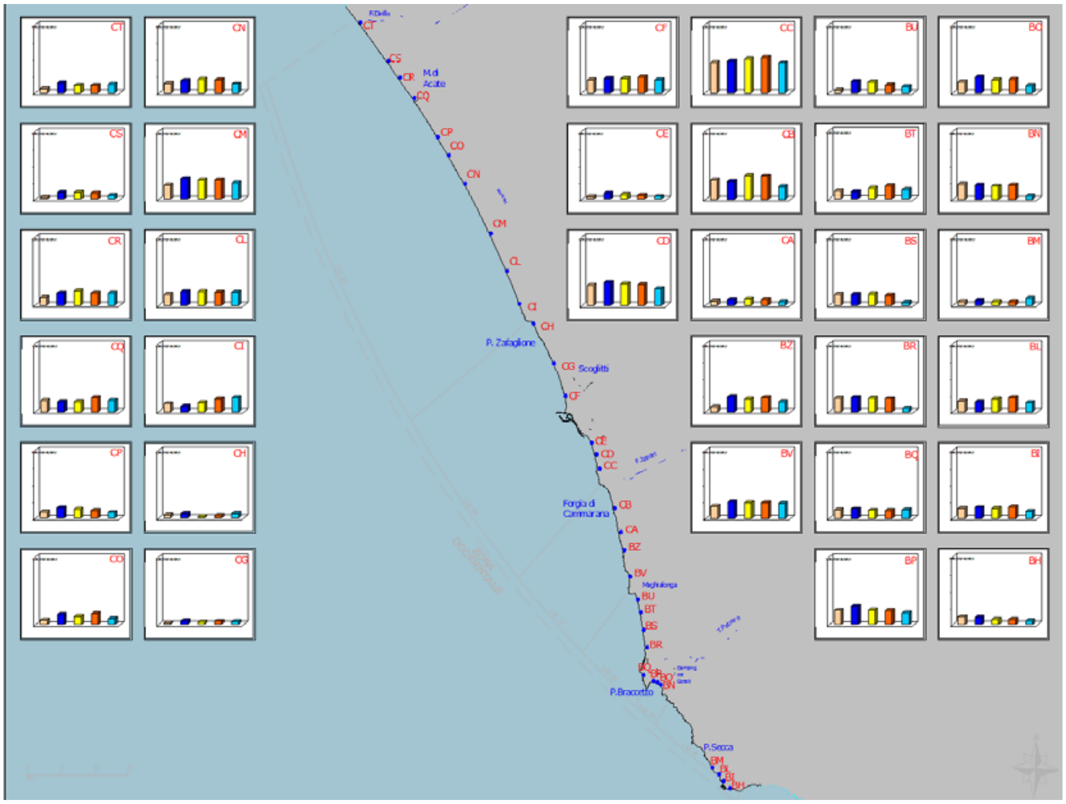


Figure 28. Map of the Western Zone indicating profile locations.

CSC 24 – Capo Scalambri- Coralli campsite

The coastline is delimited to the east by Capo Scalambri and to the west by the promontory located to the SE of Punta Braccetto and extends for 5,213 m with a N 136° orientation.

This section is rather indented and diversified, with a uneven morphology, with a predominance of rocky sections that project over the sea (2,377 m, 65%), alternating with short stretches of sandy beach (1,843 m, 35%).

The shorelines located in the more eastern area are made up of fine and medium fine sand with an average width of 26 m, maximum of 14 m and minimum of 34 m. In certain stretches the beaches are delimited by summer residences at the top which project onto the back beach area. The area is 19% urbanised, although the urbanisation level is high as it comprises the urban centres of Punta Secca and Punta Braccetto. 81% of the area is allocated to agricultural uses, as illustrated by the presence of many greenhouses. The submerged shoreline bathymetry generally reflects the surrounding coastal morphology. Isobaths from –1m to –4m follow a curvilinear pattern parallel with the coastline. The nearer isobaths up to a depth of –8-9m appear to be influenced by the trends of the more coastal isoabaths, while the isobaths tend to widen moving further out to sea.

The submerged shoreline is predominantly sandy. The average gradients of the submerged beach range from 1.6% to 0.9 %; the greatest gradients being between the –7 m isobath and the –10 m isobath and between the isobath of –12 m and that of –15 m.

This section of coastline shows a withdrawal in the eastern and central parts in the period between 1999 and 2004, with variations in the shoreline of –19.4 m (-4.8 m/p.a) and –9.75 m (-2.4 m/pa) respectively, while the western section shows a modest advance of +4.1 m (+1 m/p.a). A comparison of the seasonal recordings shows a withdrawal in the eastern section (-11.5m) and in the central section (-5.9 m) as well as an advance in the western sector (+9.2 m).

During the course of the seasonal monitoring operations a phase of stability can be seen in the period between autumn 2002 and winter 2003, in the eastern and central sections, and an advance of +4.2 m in the western section. The erosion tendency can be noted during the subsequent season in the eastern and western sections with values of –7.0 m and –5.4 m respectively, while the central sector has evidenced a period of stability.

The period between spring and summer 2003 showed a period of general stability followed by a further period of erosion during the period between summer 2003 and winter 2004, which led to a loss of –4.1 m in the eastern section, and of –13.2 m in the central section, while the western section showed a slight advance (+9.2 m). A comparison between the coastline in 1999 and the first seasonal recording shows a withdrawal with values of –7.9 m, -3.8 m and 5.1 m respectively; while the submerged shoreline volume analysis has provided estimated maximum volumes of +1,640 m3 during the period between Autumn 2002 and winter 2003. During the period between the winter of 2003 and the winter of 2004 a loss of –3,503 m3 was recorded.

CSC 25 – Coralli campsite – Punta Braccetto

The coastal area extends for 1,021 m and is delimited to the east by the Coralli campsite (SE of Punta Braccetto) and by Punta Braccetto to the west. The coastal orientation is of N116°.

This coastal section has a curvilinear morphology and consists of a sandy beach delimited to the east and west by terraced deposits. The beach extends for 405 m (40%) and is characterized by the presence of fine sand, with an average width of 38 m and with a maximum of 44 m and a minimum of 35 m.

The shoreline is also delimited at the top by holiday homes located in the back beach area. The coastal area is 54% urbanised, 26% being set aside for tourist-bathing uses, while 20% is used for local agricultural purposes.

This sector is in fact one of the coastline zones in which slight erosion has been recorded, and a comparison between the shoreline in 1999 and the winter of 2004 shows a generalised withdrawal of –31.7 m (-7.9 m /p.a) in the eastern sector, of 6.4 m (-1.6 m/p.a) in the central section, and of –9.1 m (-2.3 m/p.a) in the western section.

A comparison between the shoreline in 1999 and the first seasonal recording in the eastern and central sections shows a slight advance (+3.7 m and +4.0 m), while the western section shows a period of stability. During the period of seasonal monitoring a slight advance was recorded in the period between Autumn 2002 and winter 2003, in both the central and western sectors with values of +14.4 m and +11.0 m respectively, while the eastern sector shows a phase of stability, before changing into a state of total erosion in the period between the winter and spring of 2003, which resulted in the loss of 3.4 m, 8.8 m and 10.5 m of shoreline; while in the subsequent period a period of generalised stability was recorded.

The recordings made in the period between summer 2003 and winter 2004 further confirm the regressive tendency of the shore, showing an erosion of –32.5, 18.8 m and –5.6 m. An analysis of the monitoring data highlights the fact that the entire CSC 25 is in a state of generalised erosion, the eastern sector in particular, while an analysis of the emerged shoreline volumes has made it possible to estimate maximum volumes equivalent to –11.521 m3 in the period between winter 2003 and winter 2004.

CSC 26- Punta Braccetto – Maghialonga

This coastline section extends for 3,701 m from Punta Bracetto to the centre of Maghialonga. The coastline orientation is N 168°.

The morphology of this coastline is straight with a section of rocky coast that extends for 611 m (34%), in the Punta Braccetto zone, and also features a long sandy beach that extends for 2,458 m (66%). This beach is characterised by the presence of a beach of both fine and medium sand, and has an average width of 28 m, with a maximum value of 29 m and a minimum of 23 m. The top section of the beach is delimited by a dune section, that is thinly vegetated and which extends for approx. 2,071 m. This area is 40% urbanised, with only 5% allocated to agricultural uses, the remainder being covered by a pine forest which forms part of the Forest area of Randello.

An analysis of the seasonal data recorded in CSC26 shows a situation of marked withdrawal in the central-eastern and central sectors with values of −30.2 m and −22.5 m, with advances in the central-western sector (4.8 m) and in the western sector (10.0 m), while the eastern sector appears to be in a stable condition. The negative values that highlight a high level of withdrawal were recorded in the period between summer 2003 and winter 2004 in particular, especially in the central-eastern, central, and central-western sectors, in which withdrawal values of −28.8 m, -21.2 m and −10.7 m were recorded respectively. In the other monitoring seasons slight variations have been recorded which come within the stability values, with the exception of the advance figure of +25.9 m, recorded between autumn 2002 and winter 2003 in the western sector, +10.0 m in the winter-spring season 2003 in the central-western sector and of −8.5 m in the western sector in the winter-spring season 2003 in the central-western sector and of −8.5 m in the western sector in the spring-summer season 2003.

A comparison between the shoreline in 1999 and the last seasonal recording shows a situation of generalised withdrawal in all sectors (-8.1m −4 m/p.a; -21.7 m /-5.4 m /p.a;-23.3 m/-5.8 m/p.a) with the exception of the central-western sector in which an advance of +4.8 m was recorded (1.2 m p.a). As regards the analysis of the submerged shoreline volumes, the estimated maximum volumes are of −25,312 m3, between winter 2003 and winter 2004.

CSC 27- Maghialonga – Forgia di Cammarana

The coastal section is delimited to the east by Maghialonga and to the west by the mouth of the Ippari river (Forgia di Cammarana).

The coastline extends for 3,985 m and has a N162° orientation. The coastline morphology is predominantly straight and consists of sandy beaches that extend for 2,993 m (75%) as well as rocky ridges (623 m, 25%) that do not exceed 5 m in height.

The medium fine sandy beaches have an average width of 38 m, with a maximum value of 57 m and a minimum of 16 m. This area is predominantly given over to agricultural uses (58%), followed by tourism-bathing uses (28%), as the result of the presence of tourist villages. 14% of the area is of cultural-tourist importance as the result of the presence of archaeological sites (Kamarine necropolis).

This coastline section has been affected by an erosion process that has caused the withdrawal of the shoreline by –10.7 m and 35.7 m in the central and western sectors while the eastern sector shows signs of being in a phase of stability as confirmed on comparison of the 1999 recordings with those of the last seasonal survey. A comparison between the shoreline in 1999 and that of the first monitoring season also shows a marked withdrawal, with significant values having been recorded in all sectors (-6.0; -16.2 m and –16.8 m). An analysis of the seasonal recordings shows a progradation in the eastern and central zones, with values of +7.9 m and +5.5 m and a marked regression in the western sector (-18.9 m).

An analysis of the individual seasons shows a total state of advance with significant increases (+12.0 m. +16.4 m) in the eastern and central sectors, with a slight regression being recorded in the western sector (-3.3 m), in the period between autumn 2002 and winter 2003. The subsequent season shows a state of stability in the eastern and central sectors (-0.4 m and –2.1 m) and a marked advance in the western sector with a recorded increase of +17.5 m. A period of relative stability was recorded in the period between the spring and summer of 2003, while the subsequent season showed a considerable withdrawal of the entire coastal section with values of between –3.1 m and –9.6 m to 31\.3 m. The submerged shoreline volume analysis in the period between autumn 2002 and winter 2003 showed a volume increase of 15,308 m3, while in the period between winter 2003 and winter 2004, maximum volumes of equivalent to –6,889 m have been estimated.

CSC 28- Forgia di Cammarana – Punta Zafaglione

The coastline extends from the mouth of the Ippari river (Forgia di Cammarana) to the east up to Punta Zafaglione in the West. This section extends for 6,255 m with a N152 ° orientation.

The coastline is straight with mainly continuous sandy beaches that extend for 5,644 m (90%.). The sandy beach extends from East to West from the mouth of the Ippari river right up to the first of the 6 barriers that protect the sub-swash coastline of the Port of Scoglitti. Past the Scoglitti port area is a sandy beach, which in a discontinuous manner reaches the rocky ridge of Punta Zafaglione. The coastline consists of both fine and medium fine sand and has an average width of 38m, with a maximum value of 95 m and a minimum of 9 m. The section is delimited at the top by the road that flanks the coastline and goes through the town of Scoglitttti. The area is not heavily urbanised (approx.13%), and is mainly given over to agricultural uses (75%). The area also features the presence of several accommodation structures (7%) and a port area (5%). The area generally features a varied morphology, with the –1 m isobath showing a wavering pattern in the vicinity of the root of the port's northerly quay; this isobath tends to narrow at about 200 m from the port before re-extending as it approaches the shoreline in the area adjoining the Gela Riviera. Further out to sea the isobath tends to widen. The average gradients of the submerged beaches range from 1.8% in the sections nearest the coast, to 0.6% towards the –12 m isobath.

The seasonal surveys show this coastal section to be relatively stable, with negative values in the eastern sector (-5.4 m) and positive values in the central and western section with maximum values of +4.25 m. Following a progradation stage between autumn 2002 and winter 2003 with values of + 6 m, the beach underwent a slight advance (+1.7 m) in the spring of 2003 in the eastern section, and a withdrawal of –6.25 in the western section, with stability in the central section. Between the spring and summer of 2003 there was a generalised period of stability, followed by a stage of withdrawal in the period between summer 2003 and winter 2004, with values ranging from 4-9 m to 7.8 m and 14.8 m.

A comparison between the shoreline in 1999 and the last seasonal recording shows a phase of shoreline stability in the central and western section and a withdrawal of 13.5 m in the eastern section, while comparison between 1999 and the first recording shows considerable erosion throughout the entire CSC28. As regards the emerged beach volumes the period between autumn 2002 and winter

2003 shows an increase in volumes of +850 m3, while volumes have been estimated at –31.02 m3 in the period of time between winter 2003 and winter 2004. In terms of the submerged beach, values of +5,008,053 m3 have been estimated in the period between spring 2003 and winter 2004.

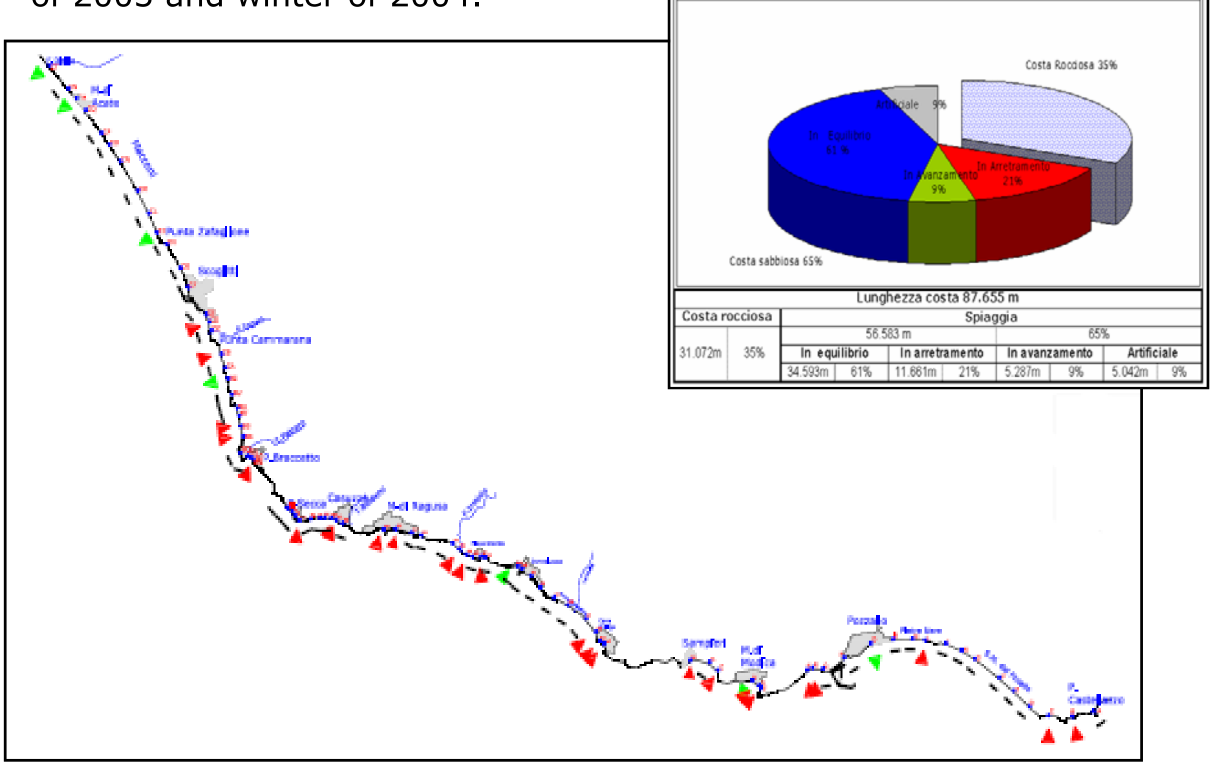
CSC29- Punta Zafaglione Gela Port

This coastal section extends from Punta Zafaglione in the east to the port of Gela and therefore comprises a very extensive coastal area which extends from the province of Caltanissetta. The description will refer solely to the coastal section that comes within the province of Ragusa, delimited by the mouth of the Dirillo river. The coastline extends for 11,520 m. The coastal section has a N136° orientation and has straight line morphology, with a low coastline. The section consists of a single sandy curved section extending for a length of 11,027 m (97%), that extends from Punta Zafaglione to the mouth of the Dirillo river. The coast has an average width of 31 m, with maximum values of 52 m and minimum of 15 m, with medium fine sand. Towards the top the beach is delimited by a dune formation which extends in a discontinuous manner in the vicinity of the mouth of the Dirillo river in the Macconi zone, with a total length of 4476 m. The dune is in a state of deterioration as the result of the mass dumping of plastic materials from the greenhouses and which are regularly buried by the sand that is annually deposited. This coastline is the most exploited part of the back beach area, and is an area with very extensive greenhouse cultivations (100%, which have had a detrimental effect on the landscape and has affected the rear coastline area of the dune. The area has a varied morphology in the vicinity of the wavering trend of isobath –10, from which it is possible to note a saw-tooth deepening with isobath widening. The average submerged beach gradient ranges from 2.2% in areas nearest the coast, to 0.2% towards – the 12 m isobath.

This area shows a general withdrawal state particularly in the central-western and eastern areas with values ranging from –10.3 m, to 5.0 m and 13.2 m and an advance stage in the eastern and central-eastern area with values of +15.5 m and +5.8 m as can be seen from a comparison of the shoreline in 1999 with that of 2004. A comparison between the shoreline in 1999 and the first monitoring season shows that all sectors are in regression with high withdrawal values such as –12.9 m in the central-eastern sector, –6.9 m in the central section and –22.8 m in the western sector as well as a slight advance in the eastern sector (+3.25 m).

During the course of the seasonal monitoring cycle we can see a generalised state of advance with maximum values of +12.3 in the eastern sector, and a slight advance of +6.9 m in the central-western sector and of +9.6 m in the western sector. If we analyse the individual stations it is possible to note an advance in the period between autumn 2002 and winter 2003 with values varying from 4.5 (central-western sector) to values of around +15 m in the other sectors, with the exception of the eastern sector in which a stage of stability can be noted. The subsequent season shows advance rates of around 4 m and withdrawal rates of not over –4 m; between the spring and summer of 2003 a period of stability can be noted; and advances of around 4 m, followed by the spring - summer season 2003, characterised by a phase of stability; and advances of around 4 m followed in the summer 2003 - winter 2004 season by a stage of predominant withdrawal along the entire coastal section with peaks of –10 m in the central-eastern and central sections.

As regards the analysis of the emerged shoreline volume, the period between autumn 2002 and winter 2003 showed a volume increase of equivalent to +45,866 m3, while in the period between winter 2003 and winter 2004, maximum volumes of around –38,397 m3 were estimated. While as regards the submerged shoreline values of +3,817,372 m3 have been estimated in the period between the spring of 2003 and winter of 2004.



Lunghezza costa 87.655 m									
Costa rocciosa		Spiaggia							
31.072m	35%	56.583 m				65%			
		In equilibrio		In arretramento		In avanzamento		Artificiale	
		34.593m	61%	11.661m	21%	5.287m	9%	5.042m	9%

Figure 29. Shoreline Evolution Trends (-10 m).

Conclusion

This study has permitted the Provincia di Ragusa to plan their interventions along the coastline for the next few years, while it has highlighted the most vulnerable areas, which will be covered with future monitoring.

Data Loggers

2.5.2.12 Basic Principles

Data loggers are often used to record and periodically transfer ground movement monitoring data to an operator. They can also be used to provide an early warning system if linked to telephone alarms when recorded ground movements exceed pre-set limits. They are ideal for use in coastal areas prone to landslides, where constant monitoring is required.

Total pressure cells

2.5.2.13 Basic Principles

Total pressure cells measure the combined pressure of effective stress and pore-water pressure. In general, pressure cells are used to verify design assumptions and to warn of soil pressures in excess of those a structure is designed to withstand. Typical applications include:

- Monitoring total pressure exerted on a structure to verify design assumptions.
- Determining the magnitude, distribution, and orientation of stresses (Durham Geo Website, 2006).

The total pressure cell is formed from two circular plates of stainless steel. The edges of the plates are welded together to form a sealed cavity, which is filled with fluid. Then a pressure transducer is attached to the cell. The cell is installed with its sensitive surface in direct contact with the soil. The total pressure acting on that surface is transmitted to the fluid inside the cell and measured by the pressure transducer (Durham Geo Website, 2006).

There are four types of pressure cells: Total Pressure; Cell Jackout Pressure Cell; VW Pressure Cells for Tunnels; and VW Stress Station. The Total Pressure Cell has a thickness to diameter ratio of 1:20 which helps minimize inclusion effects. A pneumatic version of the cell is also available. The Jackout Pressure Cell is designed for installation in cast-in-place structures, such as diaphragm walls. Its name is derived from the use of a hydraulic jack that is activated to keep the cell in contact with the soil during concreting. VW Pressure Cells for Tunnels are designed to monitor radial and tangential stress in tunnel linings. They are installed prior to shotcreting and pressurized after the shotcrete cures. The stress station is designed for boreholes in soil or soft rock. Stress stations are available with pressure cells oriented in one, two, or three axes (Durham Geo Website, 2006).

2.5.2.14 Advantages

To minimize bridging effects, the total pressure cell has a low profile and a modulus similar to that of a typical soil. Fluid in the cell is de-aired to maximise sensitivity. The total pressure cell is calibrated under fluid pressure in a custom-designed test fixture and therefore has accurate calibration. The total pressure cell is available in a pneumatic or vibrating wire version. The vibrating wire version can be read manually with a portable indicator or automatically with a data logger. The pneumatic version must be read manually (Durham Geo Website, 2006).

Settlement Cells

2.5.2.15 Basic Principles

Settlement cells are used to record ground settlement in soils at specific points. The system consists of a pressure transducer, liquid-filled tubing and a reservoir. The reservoir is fixed to a point outside of the area of settlement and acts as a reference point against which the pressure transducer, buried within the soil in fill or a borehole, is compared. The liquid-filled tubing connects the transducer to the reservoir, and the transducer measures the pressure created by the column of liquid in the tubing. This pressure reading is converted to millimetres or inches of liquid head to give a measurement of ground settlement. As the transducer settles along with the ground in which it is buried, the pressure increases and more settlement is recorded. It is important to correct for atmospheric pressure, which can have a very significant effect on the readings, and for this purpose settlement cells usually include an integrated barometer. Settlement cells are commonly attached to dataloggers to record continuous readings.

2.5.2.16 Limitations

Settlement cell systems require careful installation to minimize above-ground runs of cable and to minimize deviations in the upward slope of the tubing from cell to reservoir. Temperature changes in reservoirs and above ground tubing will affect the repeatability of readings and air bubbles are commonly cited as sources of error. Non-vented cells require corrections for barometric pressure (vented cells do not). Pneumatic cells take longer to read and generally should not be used with tubing lengths longer than 100 m (300 feet) (Durham Geo Website, 2006).

2.5.2.17 Advantages

The reservoir and readout station can be located away from the construction area whilst the cell and tubing are buried and do not interfere with construction activities. Vibrating wire cells can be automated. The vented version is the most precise settlement cell and automatically compensates for changes in barometric pressure. Tubing lengths of up to 300 m (1000 feet) are permissible with VW cells. Pneumatic cells are less expensive and a good choice in lightning-prone regions (Durham Geo Website, 2006).

Tiltmeters

2.5.2.18 Basic Principles

Tiltmeters are electrical devices used to monitor changes in inclination to a very high resolution. They are essentially precision bubble-levels forming a resistance bridge, with the bridge circuit outputting a voltage proportional to the tilt of the sensor. The sensor may be attached to any structure, but in the case of monitoring ground movement it is normally attached to a stake driven into the ground and housed within a protective cover. Changes in inclination are determined by comparing the initial current reading to all subsequent readings, and this comparison can yield continuous ground movement data when the unit is attached to a datalogger.

Hydrological studies – weather stations

2.5.2.19 Purpose

An investigation of hydrological conditions usually comprises an analysis of rainfall input to the slope, evaporation, infiltration and surface runoff. A study of these inputs, transfers and outputs helps to identify thresholds and the possible timing of slope failure in relation to climatic conditions. Rainfall can be monitored most effectively using a package weather station linked to a data logger. Weather stations monitoring rainfall and evapo-transpiration rates are used to determine the volume of water entering the ground, which can be a very significant factor in ground instability. Continuous data obtained in this way allows rainfall intensity and storm duration to be determined, enabling analyses of the development of slope failure over time.

Piezometers

2.5.2.20 Basic Principles

Piezometers are devices used to measure water pressures within boreholes, which are used as indicators of water pressure in the surrounding material outside of the borehole. A standpipe tube with a porous piezometer tip connected at its lower end is installed in a borehole, and bentonite and grout are then used to seal the borehole above the tip. This allows groundwater to enter the tube only via the tip. The water pressure is then read by using a dipmeter (a tape measure with a water sensing element on the end that emits a sound when it contacts water) and corresponds to the height of the water surface in the standpipe above the piezometer tip. This can be automated by installing a vibrating wire pressure transducer piezometer tip within the borehole, connected to a datalogger at surface.

There are different types of piezometers. The standpipe piezometer, which is installed in a borehole, consists of a filter tip joined to a riser pipe. Readings are obtained with a water level indicator. The pneumatic piezometer consists of a pneumatic pressure transducer and pneumatic tubing. It can be installed in a borehole, embedded in fill, or suspended in a standpipe. Readings are obtained with a pneumatic indicator. The vibrating wire piezometer consists of a vibrating wire pressure transducer and signal cable. It can be installed in a borehole, embedded in fill, or suspended in a standpipe. Readings are obtained with a portable readout or a data logger. The multi-level Vibrating Wire piezometer system is used to monitor pore-water pressure at multiple zones in a borehole. It consists of a number of Vibrating Wire piezometers in special housings, signal cable, a grout fitting, and some user supplied components (mainly PVC pipe). The system is grouted into a borehole. Readings are obtained with a portable readout or a data logger. The vibrating wire piezometer consists of a vibrating wire pressure transducer, a vented signal cable, and a desiccant chamber. It is designed for monitoring water levels in wells, stilling basins, and weirs. Readings are obtained with a portable readout or a data logger.

Limitations (Adapted from Durham Geo, 2004)

Type of Piezometer	Limitations
Standpipe Piezometers	Accuracy depends on skill of operator; remote reading not possible; slower to show changes in pore-water pressure.
Pneumatic Piezometers	Accuracy depends on skill of operator; difficult and expensive to automate; reading time increases with length of tubing; pneumatic tubing can be blocked by condensation if not frequently charged with dry nitrogen gas.
Vibrating Wire Piezometers	Must be protected from electrical transients.
Multi-Level Vibrating Wire Piezometer	Same as VW piezometers.
Vented Vibrating Wire Pressure Transducers	Electrical noise from a pump in the same well can interfere with operation.

Advantages

Type of Piezometer	Advantages
Standpipe Piezometers	Simple, reliable inexpensive, not electrical, no calibrated components.
Pneumatic Piezometers	Reliable, remote reading possible, not electrical, indicator can be calibrated at any time.
Vibrating Wire Piezometers	Easy to read, very accurate; good response time in all soils; easy to automate; reliable remote readings
Multi-Level Vibrating Wire Piezometer	Solves or avoids most of the problems with traditional multi-level piezometer installations.
Vented Vibrating Wire Pressure Transducers	Easy to read, accurate, and can be connected to data loggers. Requires no barometric pressure compensation.

Source: Adapted from Durham Geo (2004)

Inclinometers

2.5.2.21 Basic Principles

Inclinometers are used to measure ground deformation via deflection away from true vertical of specialised casing installed within a borehole. The system consists of the casing inserted and grouted into a borehole, and an inclinometer probe and logger. The casing is designed to move sympathetically with the ground, and to allow passage of the probe to measure this movement. The probe does this by employing two force-balanced servo-accelerometers that measure tilt. One accelerometer measures tilt in the plane of the inclinometer alignment, the other measures tilt in a plane perpendicular to the first. The probe is typically drawn up from the bottom of the borehole, stopping at half-meter intervals to measure tilt, which is recorded cumulatively along the length of the borehole. When the casing is first installed, an initial survey records the casing profile as a reference against which all subsequent readings are compared. Any deviation from this initial profile represents ground movement (after taking into account the measurement resolution of the probe).

Portable inclinometer probes are economical, since they can be carried from site to site. In-place inclinometer sensors are ideal for data logging and real-time, remote monitoring for critical applications such as construction control and safety monitoring. The costs for an in-place system are greater because the sensors are dedicated to a particular installation. A spiral sensor provides readings that can be used to correct inclinometer data obtained from spiralled casing. Spiral surveys are recommended when the installation is very deep, when inclinometer readings indicate movement in unlikely directions, or when difficulties were experienced during installation. A portable readout or a data logger is used to record the surveys. A data logger is used with in-place sensors. It monitors continuously and can trigger an alarm when it detects a change or rate of change that exceeds a preset value.

Vertical Inclinometers can be used for monitoring slopes and landslides to detect zones of movement and establish whether movement is constant, accelerating, or responding to remedial measures.

Horizontal inclinometers provide settlement profiles of embankments, foundations and other structures. They provide a useful settlement profile of the embankment or for a foundation, and give an indirect indication of how much the base of a structure may have deflected. In most cases in-place inclinometer sensors are connected to a data acquisition system that continuously monitors movements and can trigger an alarm when it detects change or rate of change that exceeds the present value.

Borehole Extensometers

2.5.2.22 Basic Principles

Borehole extensometers are used to monitor settlement, heave, convergence and lateral deformation in soil and rock. Typical applications include monitoring settlement or heave in excavations, foundations and embankments, monitoring settlement or heave above tunnels and other underground openings, monitoring convergence in tunnel walls and monitoring lateral displacement in slopes (Durham Geo, 2004).

Crackmeters are used to measure movement across joints such as tension cracks in soils and joints in rock, as well as the construction joints in buildings, bridges, pipelines, dams, etc. The instrument typically consists of a vibrating wire-sensing element connected to a spring, which is in turn connected to a connecting rod at its other end. When permanently placed across a dilating joint, the connecting rod is pulled out from the instrument body, and the spring stretches and causes an increase in tension, which is sensed by the vibrating wire element. The tension in the wire is directly proportional to the extension, which allows the amount of extension to by very accurately recorded.

There are a variety of Borehole Extensometers. Borros Anchor Settlement Point is used to monitor settlement of soil under an embankment. It consists of an anchor and two concentric riser pipes that are extended up through the embankment. Measurements are made with a graduated tape and optical survey. The Increx mobile extensometer is used in rock or stiff soils for high-resolution measurements of deformation along the axis of the borehole. It consists of a number of brass rings that are positioned at one-meter intervals along inclinometer casing, and a probe and readout that are used to measure the distance between rings. The magnet extensometer consists of a series of magnets that are installed with an access pipe. The magnets are anchored at specified depths. Measurements are taken by lowering a probe through the access pipe to detect the depth of the magnets. The Settlement hook is used to monitor settlement in telescoping inclinometer casing. Measurements are taken by lowering the hook device through the casing. The hook catches on the telescoping joints and a depth reading is obtained from a steel tape. The Sondex system consists of a series of rings attached to a flexible corrugated pipe. Measurements are lowering a probe through an inner access pipe to detect the position of the rings. The rod extensometer consists of anchors set at specified depths, rods inside protective tubing, and a reference head. Measurements are taken at the reference head by micrometer or by an electric sensor (Durham Geo, 2004).

2.5.2.23 Limitations

Type of Extensometer	**Limitations**
Borros Anchor Settlement Point	Provides only measure of total settlement; requires a man on site; extensions to pipe must be recorded carefully; top of pipe must be surveyed; anchor works best in soft clays, vertical installation only.
Increx Mobile Extensometer	Requires a skilled man on site; cannot be monitored remotely.
Magnet Extensometer	Requires a skilled man on site; not easily automated, difficult to install more than 15 or 20 magnets, vertical installation only.
Settlement Hook	Works only with telescoping casing. The inexpensive settlement hook requires a skilled operator.
Sondex	Requires a skilled man on site; cannot be automated, vertical installation only.
Rod Extensometer	Limited measurement range (50 to 100 mm).

Source: Adapted from Durham Geo (2004)

2.5.2.24 Advantages

Type of Extensometer	Advantages
Borros Anchor Settlement Point	Simple to install and inexpensive.
Increx Mobile Extensometer	Provides high-resolution measurements at one metre intervals, can be operated in any orientation, supplements inclinometer measurements.
Magnet Extensometer	Can monitor large settlements; works with inclinometer casing and can supplement inclinometer data, relatively easy to operate, indicates incremental settlements.
Settlement Hook	Works with inclinometer casing, nothing extra to install. The USBR-type settlement hook is easy to use and delivers reliable readings.
Sondex	Can monitor large settlements; works with inclinometer casing and can supplement inclinometer data, indicates incremental settlements, no limitation on number of measured rings.
Rod Extensometer	Can be automated, can be read remotely, works in any orientation.

Source: Adapted from Durham Geo (2004)

ARGUS video system

2.5.2.25 Basic Principles

An Argus monitoring system typically consists of four to five video cameras, spanning a 180º view, and allowing full coverage of about four to six kilometres of beach. The cameras are mounted on a high location along the coast and connected to an ordinary PC on site, which in turn communicates with the outside world using conventional techniques such as an analogue modem, ISDN, DSL, or a wireless LAN (Figure 25). Data sampling is usually hourly (although any schedule can be specified) and continues during rough weather conditions (CoastView Project Demonstration CD). Every daylight hour, a snap shot, time exposure and variance image are collected. During the night, data are transmitted to the central data archive by phone line.

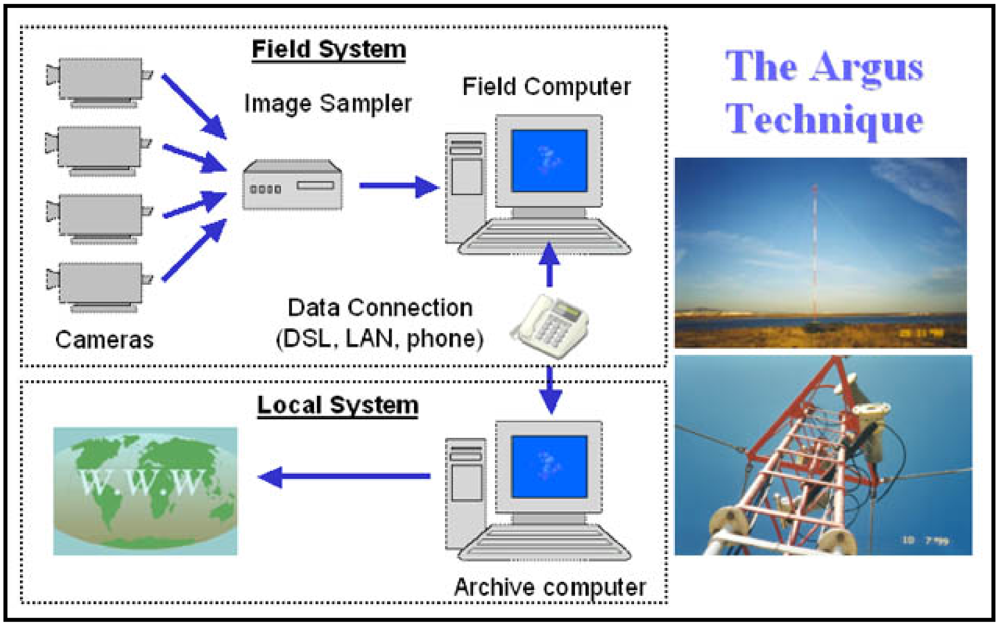


Figure 30. The Argus Technique (CoastView Project Demonstration CD).

Snap shot images are instantaneous oblique camera shots looking at a specific region of the beach, whereas Time Exposure Images (Timex) average the intensities seen by the cameras over a time period of 10 minutes. Typically images are recorded at a rate of one per second, therefore a ten minute Timex image is the average of 600 individual images. Regions where waves break frequently over shallow sandbars generating foam appear as bright white bands in the Timex images. The wave-breaking patterns highlighted in the Timex images can be used to infer the position and shape of sandbars, even though the bars are not visible above the surface (CoastView Website, 2006). The third type of image data collected is that of variance images. Variance images represent the variability in intensity seen in the image over the 10-minute period. Bright areas in the variance images highlight regions where the intensity has changed most rapidly. For example bright regions might include the waters edge (swash zone) where the beach is periodically covered and uncovered by water.

Making use of the theory involved within the field of photogrammetry, these oblique images can be projected on the ground plane, resulting in rectified images with real world co-ordinates. These rectified images allow for the quantitative interpretation of image features such as sandbar position, shoreline erosion, etc. If multiple oblique images are rectified simultaneously, so-called merged images can be obtained, which give a plan view of the nearshore zone (CoastView Website, 2006).

More recently, the ARGUS system has expanded its use of the time domain of optical signals, by rapidly sampling the intensity of individual elements of the image (pixels) providing pixel data. It is now possible to define an array of pixels in the image, which are treated as 'instruments' able to measure several moving oceanographic targets. Tests have shown pixels to provide potentially excellent measures of nearshore waves (direction, period & speed of propagation, etc) and surface currents (CoastView Website, 2006).

Currently, over 15 Argus stations have been installed worldwide.

CASE-STUDY N°4 - The CoastView Project – An Innovative Approach to Coastal Monitoring using Argus Video Technology.

The CoastView project focuses on the physical problems associated with sedimentary coasts and aims to provide information to coastal managers in a simplified form in order for appropriate management schemes to be implemented. By using video technology, a limited set of 'Coastal State Indicators' (CSIs), such as beach width, location and position of shipping channels and rip-current systems, and the rates of shoreline recession, is provided, upon which management decisions and policy can then be based. The provision of factual and easily accessible information via video remote sensing is becoming increasingly popular as a means of coastal monitoring, and has resulted in a shift away from direct nearshore measurements that often require expensive equipment that is logistically difficult to deploy and maintain.

The innovations resulting from the CoastView Project will help towards a simplified, cost-effective means of monitoring the coastal zone with a sampling frequency and duration that matches the time-scale of coastal evolution. A combination of the developments in video technology and the definition and implementation of CSIs will clarify coastal management tasks, facilitate better resource planning, improve project designs and allow better post-project evaluation. The high frequency, long-term video measurements will allow a more accurate evaluation of damage from extreme events and a better assessment of the implications for the long-term evolution of the coastline. The video-CSI system will allow effective detection of erosion 'hot-spots', long-term trends in coastal evolution and provide an early warning system for coastal flooding. The system will also facilitate a 'real-time' evaluation of coastal hazards (e.g. the location of sandbars in navigable channels) (CoastView Website, 2006).

2.5.2.26 Objectives

CoastView is designed to bridge the gap between science and management. In order to achieve such results the following two primary objectives are to be undertaken:

I) To develop resource-related 'Coastal State Indicators' (CSIs) for describing the dynamic state of the coast, in support of coastal zone management.

II) To develop and verify video-based monitoring methods and associated analysis techniques for estimating and interpreting these CSIs (CoastView Website, 2006).

2.5.2.27 Aims

The CoastView project aims to:

I) Simplify the task of the coastal manager by developing simple video-derived parameters (Coastal State Indicators or CSIs) that are directly related to management issues, and are informative about the current state and evolutionary trends of the environment. These Coastal State Indicators will have relevance to the fields of coastal protection, navigation, recreation and ecosystem protection.

II) Develop improved video systems for delivering CSIs promptly to the coastal manager at the appropriate temporal and spatial scales.

III) Develop algorithms for the estimation of CSIs.

IV) Conduct field measurements in order to provide ground-truth measurements and derive confidence limits for video-derived CSIs.

V) Produce schemes for the interpretation of CSIs and prediction of coastal state.

New video systems, theory and software for data collection and evaluation of CSIs were developed in the early stages of the project. Data for the verification of video-derived CSIs was collected from four environmental field sites each with clearly defined management problems typical of European Coastlines. These included continuous coastlines defended by nourishment/hard engineering and coastal inlets with single spits or multiple mobile sandbanks with navigational hazards, requiring dredging (CoastView Project Demonstration CD). The four selected field sites were Teignmouth on the South Coast of England, El Puntal within the bay of Santander on the North Coast of Spain, Egmond on the Holland Coast, and finally, Lido Di Dante located on the Emilia-Romagna coast of North-Eastern Italy (Figure 26).

A set of specific strategic and operational objectives were addressed for each site during the CoastView project. These objectives were dependent on current management practices and national policy on maintaining the coastline at each study location. For example, for the Teignmouth site the strategic and operational objectives were as follows;

Strategic Objectives (Source: CoastView Project Demonstration CD).

1.*To protect the developed areas of Teignmouth from flooding.*
2.*To maintain safe navigational access to the port of Teignmouth.*
3.*To maintain the safety, area and water quality of the bathing beach.*

Figure 31. Location map of CoastView European field sites (CoastView Project Demonstration CD).

Operational Objectives (Source: CoastView Project Demonstration CD).

a) To ensure that the dynamic navigation channel and hazards are adequately marked.
b) To ensure that effective dredging operations are employed under all conditions.
c) To inform the public of bathing hazards, danger areas and safe bathing zones.

Similar strategic and operational objectives were set out for each site with video solutions being introduced to meet the project requirements.

Solutions to meet the strategic and operation objectives for the Teignmouth area included; implementing an automated means of monitoring the location of channel marker buoys in relation to rapidly evolving sandbank morphology, video-monitoring the spatial distribution of dredging intensity by automatically tracking dredging operations in the channel, characterisation of the beach state through the identification of bathing hazards such as areas where bathers can be cut off on sandbanks during the rising tide or areas where strong tide- and wave-driven flows run vigorously. For the Netherlands study site, video solutions included; successive video-images to determine shoreline positions and intertidal beach volume evolution in order to allow for maintenance of the basal coastline, video-monitoring of the beach width, and finally, to identify areas of rip currents using time-series data collected by ARGUS video monitoring. At El Punta in Spain, techniques included video-monitoring the spatial evolution of the "El Puntal" Spit tip in order to protect the "public domain" and to monitor safe bathing zones by identifying hazardous rip-current positions on plan view Argus images. Finally, solutions to monitor the CSI's at the study site in Lido Di Dante, Italy, included estimating bathing hazards via video imagery, ensuring that the beach defence system works adequately by monitoring the maximum run-up in order to protect the infrastructure at the back of the beach, and ensuring that the beach defence system works adequately by monitoring beach width in order to protect the beach.

Using photogrammetric theory, the oblique images obtained from the study sites can be projected onto the ground plane, resulting in rectified images with real world co-ordinates. These rectified images allow for the quantitative interpretation of image features such as positions of bars, movement of the shoreline etc. If multiple oblique images, taken over time, are rectified and overlain for the same area of coast, merged images can be obtained which give a plan view of the nearshore zone (Richards *et al*, *2004*). Figure 27 shows an example of a merged rectified image from Egmond beach, the Netherlands, which shows the positions of sandbars as paler areas, due to the presence of breaking waves (The CoastView Project Website, 2006).

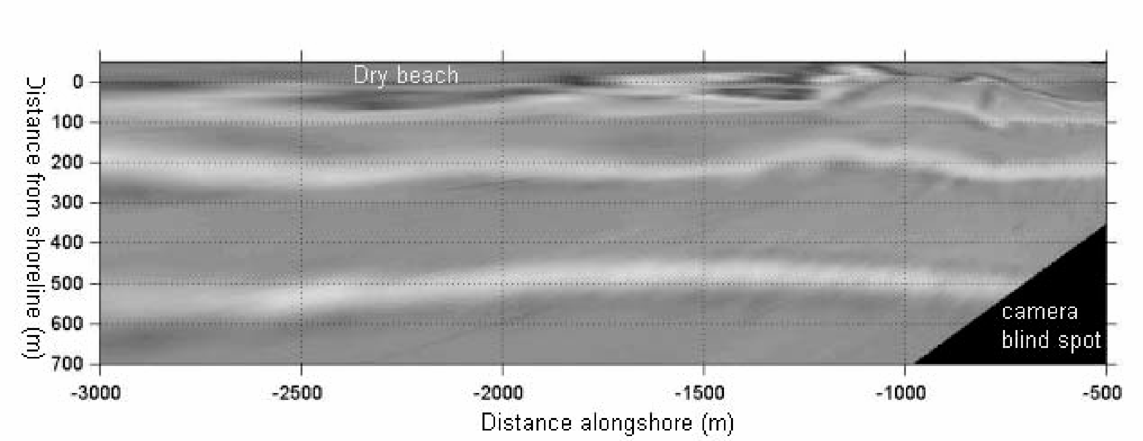


Figure 32. Example of a merged rectified image from Egmond beach, the Netherlands (The CoastView Project Website, 2006).

2.5.2.28 Conclusions of the CoastView Project

The objective of this project is to investigate the potential of video techniques to support coastal zone monitoring and management, by developing the use of the video systems, and thereby enabling the collection of the required data for the determination of CSIs. In the future the improved video systems will be capable of delivering specified CSIs promptly to the coastal manager at the temporal and spatial scales appropriate to monitoring coastal evolution. Fundamental to this is the development of new algorithms for the evaluation of the CSIs from the video data, and these will be developed and verified by comparison with measured data from four different coastal environments. The four sites selected across Europe have clearly defined management issues covering four distinct management contexts: coast protection, navigation, recreation and ecosystem protection (Richards *et al*, *2004*). From the data collected at the four different study sites, evidence had been provided to show that video imagery can prove an extremely useful and valuable means of indicating coastal processes and ultimately, CSIs.

The end-users likely to benefit in the future from the application of this technology are those responsible for all aspects of coastal zone management. It is essential to ensure the project remains focused on a national-scale and that coastal managers work alongside scientists within the CoastView consortium.

2.5.2.29 Budgeting Monitoring Schemes

As the process of data collection is fully automated, the marginal operating costs are virtually zero (CoastView Demonstration CD).

The Eurosion 2004 report estimates the cost of this technique, however, it must be noted that these are coarse estimates (Table 11).

Table 13. Unit costs for areas superior to 100 km².

Fixed remote sensing	Resolution	Unit costs in Euros/ km2
ARGUS video system	1 meter	20-30

Source: Eurosion (2004).

Tracers

2.5.2.30 Basic Principles

A variety of tracers can be used to monitor sediment transport. Tracers can be detected both with an in-situ, real-time laser optics system and by discrete sampling and analysis. The spatial and temporal distribution of Tracers provides invaluable information about the fate of the target species. The typical types of tracers that can be used are:

- Dye Tracers e.g. Rhodamine WT
- Fluorescent Dye e.g. Fluorescein
- Radioctive tracers
- Natural tracers
- Magnetic sands

Environmental Tracing Systems (ETS), amongst others, have developed a unique tracing capability, which involves environmentally benign non-toxic fluorescent tracer particles that mimic the size and density of a wide variety of target species including sediment, pathogens and sludge. This patented technology utilizes fibre-optic laser equipment to detect environmentally benign fluorescent EcoTrace and GeoTrace particles. EcoTrace particles are manufactured to mimic the size, density and surface charge of the target species for a wide variety of applications. GeoTrace particles involve coating a fluorescent signal on to natural sediment (silt, sand) collected from a study site (ETS 2004).

2.5.2.31 Advantages

Tracers can be non-toxic and environmentally benign; resistant and stable in high-energy environments; multiple tracers can be used for simultaneous monitoring; and are invaluable for numerical model validation for all marine, freshwater and process applications (ETS 2004).

CASE-STUDY N°5 - The use of Magnetic Concentration Data as an Innovative Method of Coastal Monitoring

The use of mineral magnetic concentration data as an innovative means of monitoring sediment transport and sediment properties in marine, estuarine and fluvial environments has been well documented in the past. Mineral magnetic measurements are now considered a routine form of analysis when investigating the compositional properties of rocks, sediments and soils (Thompson and Oldfield, 1986; Walden *et al*., 1999; Mather and Thompson, 1999).

Sediment-related analytical data can, however, be strongly affected by particle size effects. For example, it is often the case that the finer a sediment the greater its concentration of pollutants and thus its mineral magnetic concentration. In other words, high magnetic concentration measurements can be associated with large amounts of fine-grained sediments and an inverse relationship with coarse-grained sediments (C.A. Booth *et al.*, 2005). This irregularity in distribution of pollutants between different sediment types and compositions makes it necessary for a correction to be introduced in order to normalise the findings. The need for a correction factor to be introduced means that, generally, most methods of particle analysis are relatively time consuming and costly.

Recent studies, such as that undertaken by Booth *et al.*, (2005) have attempted to highlight the advantages of using mineral magnetic concentration data to indicate a correlation between magnetic concentration and particle size. The study suggests that there is considerable potential for using magnetic concentration data as a particle size proxy for particular sedimentary environments (Booth *et al.*, 2005). Given the speed, low-cost and sensitivity of the method, it may offer some advantages over other compositional signals (Booth *et al.*, 2005).

The study undertaken by Booth *et al*., (2005), was carried out within Carmarthen Bay, South Wales, U.K (Figure 25). The field setting included large areas dominated by marine (Carmarthen Bay), estuarine (Gwendraeth Estuary), and fluvial (Gwendraeth Fach and Gwendraeth Fawr Rivers) sediments.

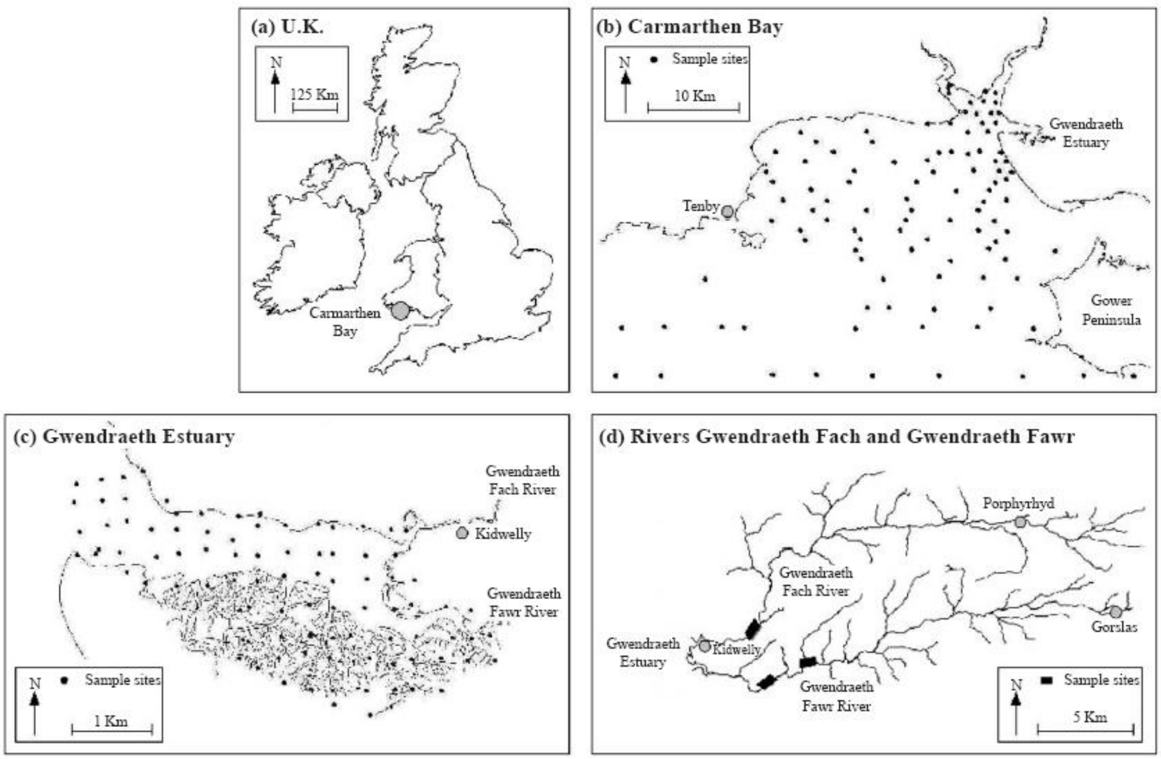


Figure 33. Location maps (a) U.K; (b) Carmarthen Bay; (c) Gwendraeth Estuary; and (d) the rivers Gwendraeth Fach and Gwendraeth Fawr (Booth *et al.*, 2005).

A total of 308 samples were collected and analysed at the different field locations. Marine samples were collected from Carmarthen Bay, estuarine samples from the Gwendraeth Estuary and fluvial samples from the Gwendraeth Fach and Gwendraeth Fawr rivers. The textural properties of the sediments were measured by laser diffraction in order to establish whether a relationship exists between mineral magnetic measurements and textural properties. Following this, a standard range of magnetic parameters was measured on all samples to determine their mineral magnetic concentration. The parameters used ranged from a low magnetic field to a saturation point where most mineral types will become saturated.

The results of the study indicate considerable variation between Carmarthen Bay, the Gwendraeth Estuary and the Fawr River although most exhibit a low to moderate concentration of magnetic minerals. However the Gwendraeth Fach River shows a moderate to high concentration of magnetic minerals (Figure 26).

Table 2
Mineral magnetic concentration data for Carmarthen Bay (n=113), Gwendraeth Estuary (n=95), Gwendraeth Fach River (n=50) and Gwendraeth Fawr River (n=50)

Sedimentary environments	Parameters	χ_{LF}	χ_{ARM}	SIRM
Carmarthen	Mean	0.86	0.09	114.55
Bay	S.D.	0.51	0.10	67.11
Gwendraeth	Mean	2.10	0.66	309.51
Estuary	S.D.	1.22	0.54	192.44
Gwendraeth	Mean	11.01	0.51	2013.99
Fach River	S.D.	6.10	0.25	1033.65
Gwendraeth	Mean	3.01	0.25	492.48
Fawr River	S.D.	0.50	0.02	112.46

Figure 34. Mineral magnetic concentration data collected from the three field sites. Taken from Booth *et al.*, (2005).

Following analysis by the Pearson's correlation coefficient, it was noted that significant negative correlations existed between each of the mineral magnetic concentration parameters and the percentage sand (i.e. the textural parameter; sand, silt or clay).

Both the Gwendraeth Estuary and the Gwendraeth Fawr River samples suggest modest differences in the concentration of minerals and could therefore be used, with caution, as a proxy for the proportion of sand. In contrast, both Carmarthen Bay and the Gwendraeth Fach River samples, as suggested by lower correlations coefficients, show greater scatter. Although the relationship between sand content and magnetic susceptibility is significant for the Carmarthen Bay sample set, the data distributions would not give high levels of confidence in susceptibility as a sand content proxy in either case (Booth *et al.*, 2005).

The results indicate that mineral magnetic data can be used as a particle size proxy. However, this should only be attempted with caution as the relationship between magnetic concentration parameters and particle size properties are not necessarily universal. The data demonstrates that the relationship between mineral magnetic concentration measurements and textural properties can be different for particular sedimentary environments even within the same overall sedimentary system and, in some circumstances, the mineral magnetic approach can be unsuitable as a particle size proxy. As a consequence, there is a need for a preliminary study to be undertaken for the particular sedimentary environment in question in order to validate the methodology. If such a study demonstrates that a strong correlation exists, mineral magnetic measurements can then offer considerable potential as a particle size proxy of use in geochemical, sediment transport and sediment provenance studies (Booth *et al.*, 2005).

A study currently underway is that of Holden (2005), which is looking at modelling the geomorphology and sediment dynamics of the North Sefton coast, UK. Recent changes in the sedimentation balance of the area have caused concerns, with an influx of mud in a southerly direction creating potentially significant implications for the future management of the area. It is hoped that by using environmental magnetic techniques, amongst other factors, past, present and future sea-level changes can be derived and management policies can be put in place as a result.

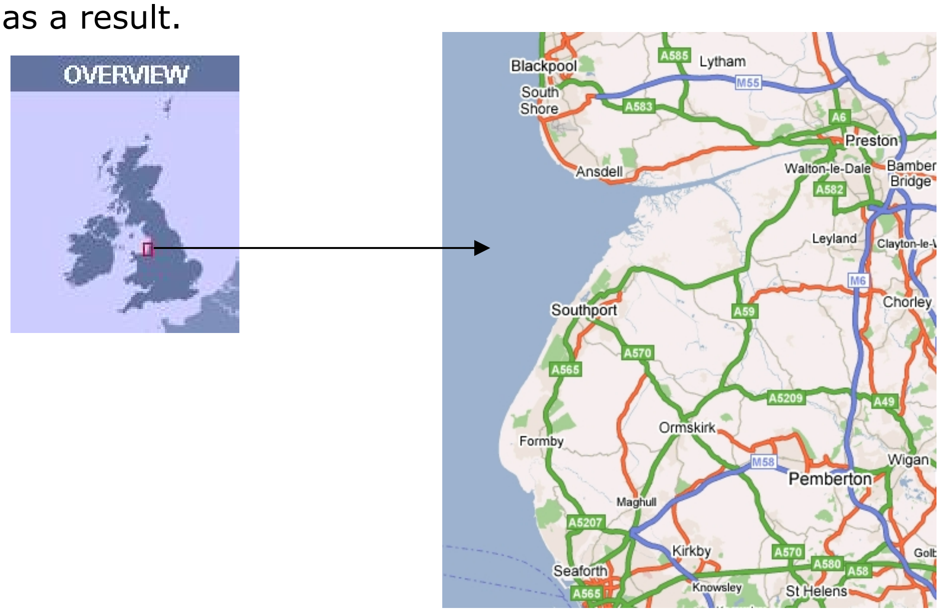


Figure 35. Location map of the North Sefton Coast and the Ribble Estuary (Google Maps Website, 2005).

The Sefton Coast lies between the estuaries of the Mersey and Ribble in north-west England. The sand dunes, beaches and marshes of the Sefton Coast are one of the most important areas for nature conservation in Europe. The Sefton Coast is also an important visitor destination with popular bathing beaches, open countryside, and the seaside resort of Southport (Sefton Coast Partnership Website, 2005). The study area in question covers the coastline north of Southport Pier into the southern part of the Ribble estuary. The research project aims to provide a high-resolution analysis of the contemporary coastal processes occurring on the north Sefton coast. Investigation of contemporary sediment characteristics will aid subsequent modelling of potential future changes.

A range of fieldwork-based data collection techniques are currently being employed to obtain primary sedimentological data via various analytical techniques (notably environmental magnetics); to monitor spatial accretion rates; and to determine the historical nature of the sediment (Holden *et al*, 2005). The contemporary sediment samples were collected and a sub-sample of the bulk sediment was retained from each sample to undergo environmental magnetics testing (Walden and Slattery, 1993). A portion of the remaining sample was separated into specific grain size fractions, namely sand (2mm to 63μm), silt (63μm to 4μm) and clay-sized (less than 4μm) materials. This was followed by a series of environmental magnetics tests on the bulk and individual size fractions of each original sample (Holden *et al*, 2005). Further sediment samples were also collected from other regional sources (marine-based samples from the Irish Sea, Mersey estuary, Liverpool Bay, Formby Point, Dee Estuary, and terrestrial sources from the River Ribble, the River Yarrow and the River Douglas). By fractionating these 'source' samples in an identical manner to the contemporary 'Southport' samples, and by then carrying out an identical set of magnetics measurements on these samples, it is then perceived that it will be possible to carry out a provenance analysis of the contemporary sediments from the salt marsh surface (Yu and Oldfield, 1993; Lees and Pethick, 1995; Walden *et al.*, 1997; and Lees, 1999). From there, it is envisaged that the origin of the contemporary sediments can be identified, allowing high resolution mapping of the sediment dynamics of the coastline (Holden *et al*, 2005).

Previous magnetic studies of coastal and estuarine sediments have noted significant correlations between magnetic susceptibility and particle size. It is also hoped that with current studies such as that of

Holden *et al* (2005), sediment transport, as well as morphology will be able to be accurately modelled and provide a useful tool to coastal engineers and planners when implementing Integrated Coastal Zone Management (ICZM).

The studies that have been described in this report indicate the value of the potential use of coastal magnetics in sediment transport and sediment morphology modeling. It is imperative that because of their social, economic and environmental significance, coastal sediment dynamics are fully explored and understood, and are therefore able to be included in the strategies of coastal engineers, commercial activities, and conservation management plans (Viles & Spencer, 1995; French, 1997; Haslett, 2000).

2.6 Large-scale Monitoring Systems

Global Wave Model

A global wave model is also run by the Met Office and covers 80.28° N to 79.17° S on a regular latitude–longitude grid, with a resolution of 5/6° longitude by 5/9° latitude; it covers all sea areas, but the computational grid does not reach the poles and the model takes ice edge information from the global NWP model. The global wave model is run twice daily from 00 UTC and 12 UTC data times. Each run begins with a 'hindcast', starting from the wave conditions of 12 hours earlier and running forward with wind data from the NWP assimilation. The global model forecast is then run to five days ahead, using hourly NWP forecast winds. The winds from global NWP are at the same spatial resolution as the global wave model. Observations of wave height from the radar altimeter carried on the ERS-2 satellite are also assimilated into the global wave model (Met Office, 2005).

European Wave Model

The Met Office also run a European wave model covering the areas from 30.75° N to 67° N and 14.46° W to 41.14° E (covering the north-west European shelf seas, the Baltic Sea, Mediterranean Sea and Black Sea) with a resolution of approximately 35 km. The European wave model is run twice daily from 00 UTC and 12 UTC data times and is run out to five days ahead, using hourly NWP forecast winds. At the open boundaries the model takes boundary data from the global wave model, allowing for swell from the Atlantic (Met Office 2005). Complete time series records of the model integrated parameters output have provided a region-wide hindcast at selected grid points since 1986. In 1994 formulation changed in line with the global wave model, to improve representation of wave growth at lower wind speeds and reduced dissipation of swell energy (Bradbury *et al*, 2004).

CASE-STUDY N°6 - Coastal Monitoring and Modelling in the Netherlands – A European Approach.

The Netherlands lies on the northern coast of Europe and is situated between Belgium in the southwest and Germany in the northeast. The Netherlands borders the North Sea which stretches from Cap Blanc Nez (France) to the north part of Jutland (Denmark) and is subdivided into three sections: the Delta coast, the Holland coast and the Wadden coast. The Holland coast forms the middle section of the Dutch coast and consists of a closed coast dune areas, varying in width from less than one hundred metres to several kilometres (Eurosion, 2003).

The Dutch coast is low-lying and thus extremely vulnerable to flooding and the potential risks of rising sea levels as a result of climate change. With 60% of the population living in low-lying areas and with 65% of the Gross National Product generated in coastal areas it is vital that coast protection and management are high on the national agenda.

On the 1st January 1990, the Dutch Government introduced a national policy to 'hold the line' in coastal areas in order to protect this low-lying land. Much of the Holland coast serves a key economic function, encompassing tourism, port industries, bulb growing, water abstraction activities and fisheries. Behind the dunes lie the political (The Hague) and economical centre (Amsterdam and Rotterdam) of The Netherlands. Where possible, soft engineering in the form of beach nourishment or beach recycling is used although in many cases, harder alternatives have been required.

The Government is currently making plans for long-term coastal monitoring and management alternatives through a policy of Integrated Coastal Zone Management (ICZM) but, with much of the general public unaware of the dangers they face as a result of coastal erosion and sea-level rise, the main priority is to educate and inform the nation. In the past, many coastal management initiatives have lacked the vision for the longer term and have concentrated on current and near-future threats. It is hoped by increasing awareness between stakeholders and the general public that a more holistic and long-term approach can be adopted.

The Netherlands forms part of Western Europe, bordering the North Sea, between Belgium and Germany (Figure 27).

Figure 36. Location map of The Netherlands (PHP Classes Website, 2005).

The Dutch coastline is formed primarily of sandy deposits as a result of the coastal and deltaic interplay between the North Sea and the rivers Rhine, Meuse and Scheldt. Successive fluctuations in climate change and sea levels since the last ice age (transgressive and regressive phases) have greatly influenced this formation and have resulted in the formation of a closed coast with dunes and sandy, multi-barred beaches (Heij and Roode, 2003).

The coastline is characterised as a wave-dominated coast and has been subdivided into three parts based on differences in morphological appearances and the dominance of related physical processes (Figure 28):

- The Delta coast – a delta/estuary coast in the south-western part of The Netherlands. The Delta coast consists of a number of former islands, separated by tidal basins, inlets and an estuary. After the major flood disaster of 1953 most of the tidal basins were closed or semi-closed by large constructional works (the Delta works).

- The Holland coast - an uninterrupted coastline in the central part of The Netherlands between the Hook of Holland (south) and Den Helder (north), with city areas close to the sea.

- The Wadden coast - a barrier island coast in the northern part of The Netherlands. The Wadden coast consists of barrier islands alternating with tidal inlets and their related ebb-tidal deltas at the seaward side. The lagoon area (the Wadden sea) between the barrier islands and the mainland consists of several connected tidal basins with extensive tidal flats. (Van Rijn *et al.*, 2002).

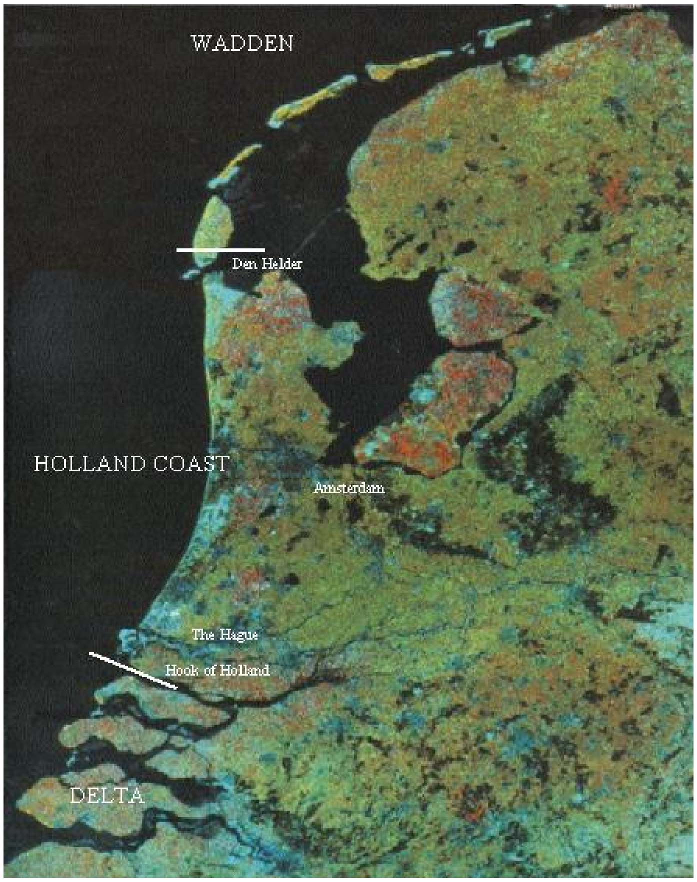


Figure 37. The three sections of the Dutch coast (Heij and Roode, 2003 Eurosion Report).

The geology of The Netherlands coastline offers a natural sandy defence to the sea yet is highly vulnerable to marine and fluvial flooding. The greater part of the country is low-lying and does not rise more than 30 m/100 ft above sea level. Substantial portions of the provinces of north and south Holland, the offshore islands in the mouth of the Scheldt, and the West Frisian Islands are near, or below, sea level but have been reclaimed from the sea over the centuries (BBC Weather Website, 2005) (Figure 29).

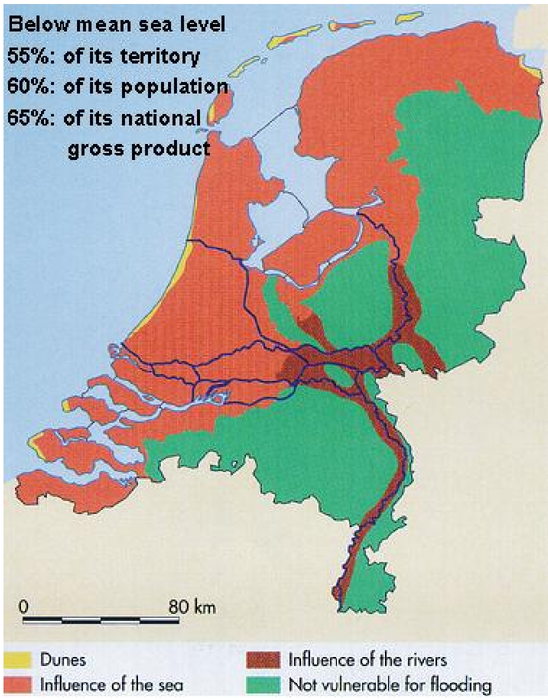


Figure 38. The percentage of The Netherlands below mean sea level (*Heij and Roode, 2003 Eurosion Report*).

The risk of sea-level rise as a result of climate change has placed an ever-increasing threat on the Netherlands coastline and, as such, the policy for the coast is dominated by safety demands. Coastal squeeze, where the coastal margin is squeezed between the fixed landward boundary (artificial or otherwise) and the rising sea level has occurred in The Netherlands as a result of both the intensification of economic and social demands on the landward boundary and sea level rise. In 2000 the national policy for the coast became one of Integrated Coastal Zone Management (ICZM) where the focus was placed on sustainable spatial quality, while maintaining safety (Roelse, 2002).

A significant component of ICZM, alongside other issues including coastal planning, coastal engineering and environmental protection and enhancement, is maintaining the quality of the built environment of the coastal zone. As 60% of the population of The Netherlands live below the mean sea level and a large proportion of the country's economy is tourism-based clearly this is an issue in which the government must address. Furthermore, by 2006 the government must put in place its response to the EU Recommendation on ICZM, which requires a national strategy to be in place for delivering effective coastal zone management.

2.6.2.1 Coastal Monitoring and Modelling Techniques

2.6.2.1.1 Coastal Defence

Since the 16th century much of the low-lying Dutch Coast has been reclaimed for residential and industrial purposes. By the 19th century, with advancements in drainage techniques, it became possible to reclaim large areas of land by using steam driven pumping stations to drain large polders. Due to this expansion in the coastal zone in social and economic demands, the majority of the coastline has, in one form or another, been protected from the threatening seawater.

In the past, much of the coast was protected by man-made, hard engineering structures like dykes and dams. It was hoped that these would provide a barrier against the encroaching sea and prevent flooding in the low-lying polders. However, it was soon realised that erosion was destroying these defences along with the majority of the Netherlands coast and so a softer engineering option was introduced whereby structures were built that worked with the natural depositional processes occurring at the coast. Groynes, known as a 'strandhoofden', and breakwaters were seen as the preferred option to build up beach and dune levels in order to offer a natural barrier to the sea. A policy of managed retreat, whereby nature is left to take its course to a large extent, was adopted around much of the remaining coastline of the Netherlands.

In 1990 Parliament adopted the envisaged policy of the Dutch government to stop further structural coastal recession. The Ministry of Transport, Public Works and Water Management established the 'basal coastline' as the position of the coastline on 1st January 1990 and determined that the coastline should be prevented from moving inland. The coastal policy of 1990 is referred to as 'dynamic conservation' and three goals were formulated (Heij and Roode, 2003 Eurosion Report):

- No further retreat of the coastline
- Preservation of valuable dune areas
- Preservation of the natural dynamic character of the coast.

To reach these goals, a number of instruments are available (taken from Heij and Roode, 2003 Eurosion Report):

- The annual coastal measurements and the acquired knowledge of coastal processes
- The basal coastline and annual assessment
- The technique of sand nourishment (beach nourishment and submerged nourishment). This technique can be described as *soft where possible and hard where necessary*. It is effective in stopping erosion, flexible, not expensive and the best way to preserve the valuable dune areas and the natural dynamic character of the coastline.
- An annual budget for coastline management of €40 million, which is 12 million m^3 of sand per year.
- Co-operation between Central Government, the coastal water boards, and Provincial Authorities/Consultative Bodies for the Coast (POK's). Responsibilities are divided as follows:
- Central Government safeguards the position of the coastline and combats structural erosion
- The coastal water boards maintain the sea defences
- Provincial Authorities are responsible for overall co-ordination and integration with other areas of policy such as physical planning

Every year the position of the coastline is measured and compared with the reference standard. If it looks as if the basal coastline will be breached by ongoing coastal erosion, preventive measures are taken in advance. In practice, this means that sand nourishment is carried out. The result of the annual measurements is used as a basis for the annual sand nourishment programme. In this way, dynamic preservation is put into practice.

Since sand nourishment was adopted in The Netherlands coastal erosion has been almost entirely prevented. In 1990 30% of the coast was landward of the 'basic coastline'. In 2000 this was reduced to 10%. Because some natural fluctuations are acceptable as long as safety is not at stake, this 10% can be regarded as the maximal result (Figure 30) (Heij and Roode, 2003 Eurosion Report).

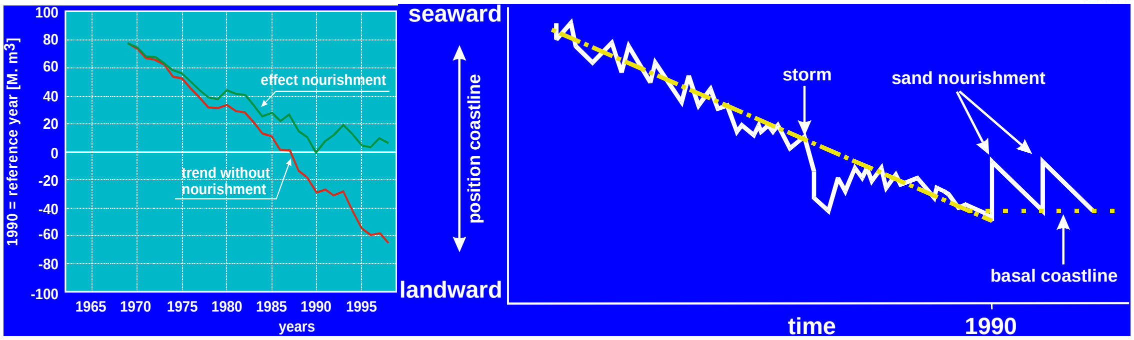


Figure 39. The effects of sand nourishment on the Netherlands Coast (Ministry of Transport, Public Works and Water Management (V&W), 1996).

2.6.2.1.2 Technical Measures

The Dutch coastline has been monitored for over a hundred years in order to establish the nature of change in the coastal morphology. Since 1967, an annual monitoring programme has been put in place where beach profile data is collected at intervals of 200 to 250 metres perpendicular to the coast. The results of these annual coastal measurements (known as JARKUS measurements) are stored in the Ministry's DONAR database (national database).

The 'wet' part of the profile is recorded by the Ministry's Survey Department or by water boards, using an automatic sounding system in combination with a computerised location system such as Global Positioning System (GPS). The 'dry' part of the profile is determined by using stereo photogrammetry. In the spring, the entire coastal strip is photographed from the air, each photograph overlapping the other by 60%. These photos allow the height of the topographical surface to be determined in 3D using precise spot height data as reference points. Since 1994 height measurements of the beach and the foredune have been taken using a laser scanner on board an aircraft. The laser scans a given area and the distance from ground to aircraft is measured many times a second. Analysis of the results produces a Digital Elevation Model (DEM) from which the height at the location of the reference sections can be determined. When height and depth data are combined, the end result for each section is known as the JARKUS profile (V&W, 1996).

As one of the six specialist services of the Directorate General of Public Works and Water Management, the Rijkswaterstaat Rijksinstituut voor Kust en Zee (RWS RIKZ) is the main department dealing with matters concerning the sustained use of estuaries, coasts and flood protection.

Prior to 2001, coastal monitoring in the Netherlands was undertaken on an ad-hoc basis along with a lack of knowledge on appropriate techniques and analysis methods. There had been problems with correlating data due to inconsistencies in measurement techniques and accuracy, meaning that very little analysis could be undertaken and conclusions were unable to be drawn. Since then, the RIKZ, along with other agencies, have aimed to co-ordinate and exchange knowledge to optimise the organisation of data collection and analysis, resulting in the establishment of a National Monitoring Programme based on a unified system. The programme was established with the intention of not only providing coastal information to coastal engineers and the public alike, but also as a means of educating those involved in the programme as to the background and aims of the programme, and the reasons for requiring high-accuracy survey data. By explaining these goals, it enabled the different agencies and partners to work together more successfully to create a standard and repeatable method of coastal monitoring.

The National Monitoring Programme has a budget of €44 million per year to cover the costs of all aspects of the programme, including data collection, analysis, consultation, recharge and scheme evaluation. This budget is solely used to monitor the requirement for replenishment at each study sight. However, with such a large budget, it is possible for the monitoring to encompass both offshore (to a depth of –20m) and foreshore areas. In order to maintain the basal coastline, as established by the Dutch Government in 1990, it is important to consider not only nourishment of the foreshore area but also replenishing the area up to -20m offshore.

The data collection aspect of the National Monitoring Programme is run by a working-group formed by local authority departments. All data resulting from this is then returned to RIKZ who then plan the overall programme and analyse and disseminate the data.

The current nourishing programme runs on a three-year cycle for each given site. Following the collection and analysis of data, a general nourishment proposal is drawn up and given to local government for comment. However, it is rare that any changes in the proposal occur as a result of this consultation with local government unless significant environmental factors, beyond the control of the department, have necessitated changes to the planned nourishment. For instance, extensive storm damage can exert a technical as well as a potentially political influence on planned nourishment. RIKZ make the decision as to whether a given site receives shore-face nourishment (i.e. replenishment to offshore areas which allow for the natural depositional processes occurring along the coastline to deposit material on the beach) or beach nourishment (immediate replenishment to the beach). Shore-face nourishment is often the preferred option as costs may be reduced since some handling and the installation of equipment such as pipelines, are avoided, while any ongoing recreation is no longer hindered (Spannhoff, 1998).

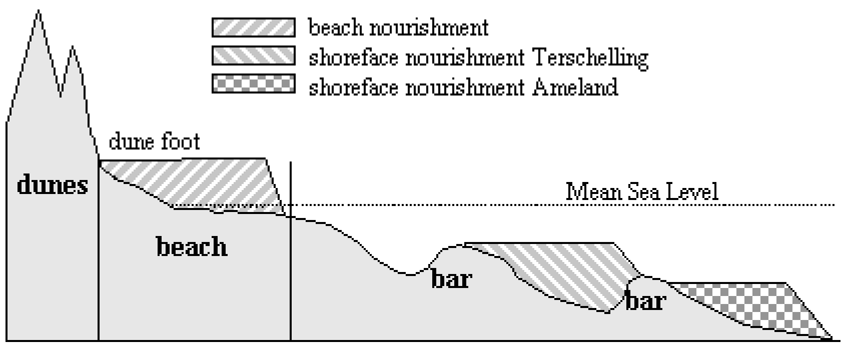


Figure 40. Approximate locations of beach nourishment and shoreface nourishment material (Spannhoff, 1998).

After this review, a site-specific plan is designed to illustrate the precise locations of replenishment works. The basis for decisions on areas that receive nourishment is solely based on the coastline position and does not take account of factors such as tourism requirements or the maintenance of wide beach as a means of coastal defence. Once the published plan is complete it is open to tender from dredging companies. These companies must have an inbuilt flexibility since amendments may need to be made as a result of issues arising from safety (for instance, emergency service access, storm damage, etc). Research in the past has shown that 12 million m^3 of sand, dredged from offshore, is required for beach replenishment at any given site. Usually, 6 million m^3 of this is used to replenish the beach and 6 million m^3 for the shore-face although this is a flexible division of aggregate. It is quite possible to vary the split of sand between shore-face and beach depending on local conditions and extreme storm events. Historically, 12 million m^3 has always proved sufficient or provided an excess of material. However, since the dredging is confined by fixed parameters, the total amount reclaimed is always in the order of 12 million m^3 regardless of how little is required. Of the 12 million m^3 of recharge material, a proportion of this can be used to replenish areas where modelling of monitoring data has indicated a need or a consistent pattern in sediment transport. This means that low beach levels can be pre-empted before problems occur resulting in long-term cost savings.

2.6.2.2 Monitoring of the Wadden Sea

Monitoring of the Wadden Sea, along with the entire coastline of the Netherlands, is seen of the highest national priority. In June 2006, plans for the Wadden Sea monitoring programme began. The main aim of this programme was to undertake geomorphological monitoring of this vulnerable stretch of coastline consisting of extensive tidal flats, the majority of which lie below mean sea level. The programme is based on a two-year cycle during which the previous year's data is validated, analysed, a new nourishment plan is drawn up, and a consultation period is provided.

Data on beach levels is collected via bathymetric, topographic and airborne techniques. Bathymetric measurements are taken to approximately 10m below mean sea level and topographic profile data to –0.5m below mean sea level. There is an overlap between all three methods of data collection with data from airborne laser scanning measuring from mean sea level to the first peak of the dunes. Once every five years measurements are also taken of the complete dune system. In total, 2049 topographic transects, 1959 bathymetric transects and 1986 airborne-topographic transects are measured on the Wadden Sea coast.

Transects are taken at intervals of between 200-250m in areas of relative instability and at 1000m intervals on stable coastlines. Problems exist with the bathymetric data due to the large offshore sandbanks often causing gaps in the survey data of the trench between the beach and the sandbank. This data is filled in on foot using topographic RTK GPS. The bathymetric soundings are corrected for tidal elevation and ship movements, and are interpolated to an area-covering map with a software package called DIGIPOL. The interpolation is linear, but DIGIPOL pays special attention to finding the optimal points in order to reproduce features like tidal channels as well as possible. The interpolation grid is oriented to the North within the national Rijksdriehoek (RD) coordinate system and has a grid size of 20 m. The interpolated map is stored into a database and is the standard monitoring product (ARGOSS website, 2006). Once every three years, a thorough baseline survey is carried out where transects are taken every twenty metres. This allows for a Digital Terrain Model (DTM) to be produced, indicating changes in sediment levels along the coast.

The monitoring of the Wadden Sea also focuses on the erosion, accretion and sediment transport occurring on the many small islands that characterise the Wadden Sea coastline. There is little management at these locations and natural processes are allowed to occur, causing some islands to erode yet others to build up naturally. Similarly, monitoring is also undertaken of the dykes erected following the floods in the 1950's. Whilst the river beds enclosed by dykes tend to become higher due to alluvia deposits, the floodplain level is becoming lower if it is no longer regularly flooded with new alluvia, and therefore the risk of dykes breaking increases. As such, dyke surveying is carried out to monitor the height of the dykes and the levels either side of the structure.

One of the main problems with the monitoring programme is the lack of communication between those carrying out the surveys and the programme designers. A lot of the time there is a misunderstanding of what is required from both parties and often the data may be unreliable as a result. Any monitoring option requires detailed surveys of, among other things, geology and topography. All this requires a lot of data collection over long periods and modelling many alternative solutions to understand how they work under different conditions. Choices have to be made by policy makers with the best of technological and scientific input and it is essential that these decisions be fed down to those carrying out the practical work.

2.6.2.3 Monitoring Techniques

The bathymetric survey element of the monitoring programme is carried out using Global Positioning System (GPS). This method of depth calculation has only been used in the past five years as, until then, the programme utilised soundings to calculate seabed depths. The difference between these measurements was approximately 18cm giving the impression of the seabed being deeper than initially thought. This level of inaccuracy resulted in huge difficulties when analysis of data using both methods was undertaken. As a result, the original data has had to be rectified in order to take account of this error. This correction is being introduced stage by stage to each area involved in the monitoring programme. The fact that the differences in levels are not uniform to each location makes rectifying the issue even more complicated.

Argus cameras were introduced by RIKZ five years ago although there is a long history (approximately 30 years) of Argus data for the area. Each year, the Argus data is analysed by an external consultancy such as HR Wallingford and analysed on a monthly basis. The data collected helps to gain an understanding of currents and sediment transport patterns and can be used to establish beach levels with and without nourishment. By using colour images from the cameras it is also possible to assess the drainage patterns occurring across the beach with both the wet and dry part of the beach being highlighted in the image. However, the one disadvantage of Argus images is that they fail to show the mechanisms behind the trends and as such RIKZ no longer use them for monitoring of the nourishment programme, as they offer more potential as a research tool and are also seen as both expensive and difficult to standardise. Despite this, they have been used for the local scale frequency monitoring and will be incorporated into the process in one or two other areas in a more innovative programme. For research purposes, it is thought that the Argus cameras would be of great use in researching design rules. For example, it is hoped that the cameras could be used to monitor the effects of underwater spot nourishment whereby individual heaps of sand are placed on the beach, or offshore, and transported and deposited through the natural processes occurring at that section of the coast. Similarly, Argus cameras were used at a study site in Egmond as part of a research tool for the CoastView Project (See Section 2.5.1.33). It is hoped that by using the Argus cameras, a more detailed picture of sediment transport patterns can be gained, proving to be a more effective form of monitoring and adding another dimension to the monitoring programme.

Monthly topographic quad bike surveys are also carried out as part of the programme. A GPS receiver mounted on the back of a quad bike measures beach levels at one-second intervals providing detailed coverage of the beach. These levels, when referenced to a base level, can determine the volume of sediment on the beach and can identify areas of erosion and accretion. By using a combination of methods of monitoring e.g. GPS surveys, Argus video imaging and bathymetric surveys, this brings added value to the overall programme.

Along with the monitoring and modelling of the physical processes occurring at the coast, the programme is also responsible for undertaking ecological monitoring. For each extraction site an Environmental Impact Assessment (EIA) is carried out. Additional EIA's are required for any further replenishment. Currently there is one EIA for all areas, but this may need to be more site-specific in the future. In addition to the ecological monitoring, the Eco-beach project has also been introduced into the National Monitoring Programme. This project, being undertaken by an external company, uses innovative methods to gain an understanding of the effects of drainage on beach levels and sediment transport. A pilot project has been established whereby a series of vertical tubes have been placed in the swash zone of two study areas, one of these being in the dynamic area of Egmond in the north-west and the other in a more stable area. It is expected that the beach will become drier and encourage faster run-up of seawater therefore depositing more sand on the beach. These pilot sites were tested against another reference site and against trials from a site in Denmark. The trials showed a high level of beach growth in the summer following the introduction of drainage and offered the option of using a more passive system of beach replenishment reducing the need for nourishment.

2.6.2.4 Modelling

Modelling is used by RIKZ to calculate future shoreline positions. As a result, models can be produced to indicate changes for up to 50 years ahead in order to inform planning for future replenishment schemes. Generally however, models are only used to try and innovate and make the replenishment more effective rather than for day-to-day interpretation or prediction of data patterns. Experts in RIKZ generally do not see models as being useful over a short time or even over longer time periods due to a lack of understanding of many of the modelling systems, resulting in an inability to create accurate predictions.

Despite a lack of confidence in modelling techniques and software with regards to short-term coastal evolution predictions, RIKZ are financing a separate research programme specifically based on modelling. Each year, a budget is set aside for the improvement and development of new models as a means of assisting long-term policy development. Other departments are able to utilise these models and are able to use such software for investigating long-term coastal change. This allows for a more systematic approach to be followed rather than having to finance modelling procedures in an ad-hoc way or as and when they are required. In addition to this, a couple of times a year there is also a local minor modelling programme to evaluate RIKZ efforts to manage a given part of the beach and also the effectiveness of the management of the channel. This procedure enables researchers to monitor, and to investigate in detail, the behaviour of the beach nourishment site, and to establish the success of the shoreface and offshore nourishment. This process gives a picture along the coastline of the success (or otherwise) of the nourishment and enables improved planning in the future.

Ultimately, the aim of the National Monitoring Programme is to establish universal design rules for the programme, taking account of the geographical aspects of each area whilst making sure all involved understand their wider role. However, this is not currently in place due to insufficient explanation and dissemination of the programmes aims and objectives. The standardisation of procedures is expected to assist with this although currently, there is no involvement at community level, and the programme will have to adapt in order to incorporate time for objections and the resulting amendments in the programme timeline that may result. Despite these downfalls, the programme has already offered many advantages to previous methods of monitoring. The standardisation of procedures has had the advantage of saving huge amounts of time previously spent on analysis. This means that data previously requiring four days to evaluate, now only requires four hours. Similarly, standardisation has allowed for the rationalisation of the number of computer programmes from fifty to less than ten. These steps have made the monitoring programme more efficient and less costly so that the budget can be used to best effect. As a result, much effort has gone into streamlining the processes in last few years and as such, there are now plans to focus on more scientific research and data dissemination. Moves have already been made to create a national data bank where quality-checked data is made freely available to interested parties. The National Water Boards already use the five-yearly data for research purposes.

In the framework of the Coast3D Project (1997-2001) a measurement campaign was conducted at Egmond, The Netherlands, during the spring of 1998. The Coast3D project is part of the European Commission's Marine Science and Technology Research Program (MaST-III). Within the Coast3D project (Coastal Study of Three-Dimensional Sand Transport Processes and Morphodynamics) field experiments at two locations were carried out, in Egmond (The

Netherlands) and in Teignmouth (UK). The Egmond site can be considered as a coastal stretch where in alongshore direction relatively uniform hydraulic and morphological conditions prevail, while the British site is typically a 3D site (Elias *et al*., 2000).

The main objectives of the study were as follows:

- To improve understanding of the physics of coastal sand transport and morphodynamics.
- To remedy the present lack of validation data of sand transport and morphology suitable for testing numerical models of coastal processes at two contrasting sites.
- To test a representative example of numerical models for predicting coastal sand transport and morphodynamics against this data.
- To deliver validated modelling tools, and methodologies for their use, in a form suitable for coastal zone management.

Data from the experiment included water levels, wave height and period, wave speed and direction, sediment concentration transport, bathymetric surveys, tracer movements, and meteorological parameters.

The data from the experiments at both sites allowed comprehensive tests to be made of hydrodynamic and morphodynamic numerical models (Soulsby, 2001). Five different Coastal Profile models were used by the COAST3D modelling partners to stimulate the hydrodynamics and morphodynamics of the beach at Egmond. The results indicated a reasonably high quality of model performance especially in relation to profile models simulating wave height, longshore and cross-shore currents and hydrodynamics. Coastal Area Models proved successful in predicting tidal flows and morphological changes. It is hoped that with a better understanding of the processes involved from the data collected at the two sites, further developments in the numerical models can be made so that there can be direct uses for coastal zone management.

In the Netherlands coastal defence actions are merely based on sand nourishments. The sand nourishment method has been chosen because it is a relatively cheap method and because it interacts with the natural characters of the Dutch coast (Heij and Roode, 2003 Eurosion Report). The technique is a flexible, soft engineering approach towards combating coastal recession of the 'basic coastline'. The sand is extracted from outlying sea bottoms of depths greater than 20 metres in order to minimize disruption of life on the sea bed and to ensure that the coast is not undermined. With suction-hopper-dredgers the sand is brought to the coast where pipeline connections make the nourishment possible (NORCOAST, 1999).

Since 1990, the basic coastline has been maintained using sand replenishment, preventing the structural erosion of the dunes. However, this form of maintaining the basic coastline cannot prevent incidental erosion, which occurs during extreme storms. Sand replenishments are also not entirely successful in slowing the movement of erosion lines inland as a result of rising sea levels. It is therefore necessary to have other methods of coastal defence and management in place should the need arise for further protection. As with the basic coastline, there are three options for addressing the situation: keeping pace with sea level changes by maintaining the current basic coastline, moving inland by letting nature take its course, and moving the basic coastline offshore by building artificial sandbanks or defence structures. In 1990, the decision was taken to keep pace with sea level changes by defining a basic coastline and this policy has been maintained ever since (Heij and Roode, 2003 Eurosion Report).

2.6.2.5 Conclusions

Coastal defence and coastal monitoring in The Netherlands is primarily based on soft engineering, in particular, sand nourishment. Since 1990 a new coastal policy (dynamic preservation of the coast) was introduced in which sand nourishment was, and still is, the major means of controlling coastal erosion. No structural erosion is allowed (the coastline of 1990 is the basal coastline which must be maintained), but the coastal area is to remain as natural and dynamic as possible. An evaluation of this coastal defence policy shows that coastal retreat can be stopped with sand nourishment. However, the realisation of the serious threat of sea-level rise and increased storm frequency as a result of climate change has encouraged new thinking on possible methods of maintaining the basic coastline. Developments in monitoring and modelling techniques as a result of the COAST3D programme will hopefully provide new answers on best practice in the coastal zone. The recent move towards Integrated Coastal Zone Management following the EU Demonstration Programme and publication of "Integrated Coastal Zone Management: A Strategy for Europe" in 2000, has encouraged a more holistic approach to coastal management taking into account physical, socio-economic, and political interconnections both within and among the dynamic coastal system.

UK Waters Wave Models

The UK waters wave model covers the north-west European continental shelf from 12° W, between 48° N and 63° N at a resolution of 1/9° longitude by 1/6° latitude (approximately 12 km). The UK waters model has a much better resolution of the coastline than the European wave model, and includes the effect of time-varying currents on the waves, using currents forecast by the operational storm-surge model. The model was introduced into the operational suite in March 2000 and runs four times daily from 00, 06, 12 and 18 UTC, taking hourly surface winds from mesoscale NWP to give a 48-hour forecast.
Waves in the tidal waters around the UK can be a combination of locally generated wind waves and remotely generated swell: both can be modified by tidal or storm-surge currents, which affect both wave height and wave period. Full wave energy spectra are routinely used in the wave model calculations but output is summarised as integrated parameters (H_s, T_z, θ) at each grid point. The total sea, wind sea, and swell sea are all calculated for each time step record (Bradbury *et al*, 2004).

The coastline is represented simply: by the land ocean boundary of the model grid. This physical limitation, together with the coarse grid bathymetry, provides for only coarse resolution of nearshore wave transformations. The nearest grid points to the land are generally too far away from the shoreline to be used directly in coastal process simulations. The grid resolution limits representation of parts of the south coast of England. For example, the Solent, which is a fetch limited basin that is only a few Km wide and is bounded to the south by the Isle of Wight, is not represented within the model at all. The sites used in the comparison are at the landward limits of the model grids (Bradbury *et al*, 2004).

Complete records of integrated parameters of the UK waters wave model have been archived for the period since 2000. Spectral files, which are not routinely archived by the Met Office, have recently been added to the regional archive data sets. The nearest grid locations to the wave buoys have been used as boundary conditions for input to finer resolution wave transformation models, to transform data to the buoy sites. The buoy and hindcast grid data are not generally suitably close that they can be termed truly co-located in this sense and direct comparison is limited to four of the buoy sites on this basis (Bradbury *et al*, 2004).

UK Sediment Transport Study

In 1990, SCOPAC (Standing Conference on the Problems Associated with the Coast) commissioned a Sediment Transport Study relating to the coastline of central-southern England between Lyme Regis (Dorset) and Shoreham-By-Sea (West Sussex). A thorough revision of this report was undertaken in September 2004, with the inclusion of additional research and information collated from a comprehensive search of sources and by contact with relevant organisations. It involved analysis of all available literature and information relating to sediment transport, beach behaviour and all aspects of the sediment budget of the successive coastal cells and sub-cells. The geographical scope of the study was also extended both westwards and eastwards. The Lyme Bay and South Devon Coastline Group commissioned the section relating to the coastline between Start Point and Lyme Regis, whilst the South Downs Coastal Group supported its extension from Shoreham-by-Sea eastwards to Beachy Head.

Within the study a sequence of transport compartments (cells and/or sub-cells) are used to measure the Sediment Inputs (marine; fluvial; cliff/coastal slope/platform erosion; beach nourishment); Littoral Drift; Sediment Outputs (including Offshore Transport, Estuarine Outputs); Beach Morphodynamics; and Sediment Stores.

CASE-STUDY N°7 - UK Regional Coastal Monitoring Programme

Introduction

Beach monitoring projects within the UK have often been confined to short stretches of coastline usually established in conjunction with individual beach recharge schemes. Effective planning and implementation of shoreline management requires high quality, long-term, time-series data sets, at appropriate spatial and temporal resolution, to predict long-term coastal evolution and to determine design conditions for coastal protection and flood defence projects (Bradbury et al., 2005).

Prior to the implementation of the UK South-East Strategic Regional Coastal Monitoring Programme in 2002, the traditional approach to coastal monitoring had generally been ad hoc, both with individual Coastal Groups and on a regional basis. A number of monitoring programmes in the UK had extended across the whole of a process unit sub-cell administered by individual coastal protection authorities. However, the fact that process units were covered in their entirety seemed to be coincidental due to the administrative boundaries of the local authority, rather than good practice (Bradbury, 2004). A few regional monitoring initiatives existed, such as the Environment Agency Annual Beach Monitoring Survey (ABMS), the Ministry of Agriculture, Fisheries and Food (MAFF) Coast Protection Survey of England and the Environment Agency Flood defence management system, yet there was a lack of confidence from both maritime operating authorities and consulting engineers in the standard and suitability of these schemes as appropriate tools for use at either Shoreline Management Plan level or operational level.

The Environment Agency Annual Beach Monitoring Survey (ABMS) was established in 1973 and, up until the introduction of the South-East Strategic Regional Coastal Monitoring Programme, was seen as the most comprehensive long-term systematic regional programme designed specifically for monitoring sea defence and coast protection (Bradbury, 2004). The ABMS survey programme provided annual aerial photography of 440km of coast (the Environment Agency's Southern Region), producing approximately 1300 aerial photographs; annual production of 2600 profiles, derived by photogrammetry; periodic overviews of the data set and annual dissemination of data and reports to contributing local authorities. However, there was a general consensus that more detailed and accurate data was required for operational beach management, and that the programme at the time did not offer good value for money.

The Ministry of Agriculture, Fisheries and Food (MAFF) Coast Protection Survey of England was originally commissioned in 1993 to gather information to help MAFF discharge its functions under the Coast Protection Act 1949 in regard to coast protection defences. The aim of the original survey was to gather data on the location, extent, nature, adequacy and state of repair of coast protection defences along the English coastline, with the primary purpose of identifying requirements for defence works within the next 3-5 years. Another aim of the survey included an examination of unprotected lengths of coast identified as 'significantly eroding', i.e. those with 'substantial (land) assets, which may reasonably require protection works within the next 10 years'. It was intended that data from the CPSE would help MAFF assess priorities for future expenditure on coast protection, and would inform discussions between MAFF's Regional Engineers and coast protection authorities about future programmes of capital works (The National Digital Archive of Datasets (NDAD) website, 2006).

The Environment Agency Flood defence management system (FDMS) holds data on flood defence system assets (e.g. sea walls, river banks, groynes, weirs etc.) relating to their location, description, size, condition and inspection record. Following the production of the business case for the South-East Strategic Regional Coastal Monitoring Programme, it was recommended that both the CPSE and the FDMS be combined and managed under a single project, using a standardized referencing system in order to provide a repeatable and cost-effective method of coastal monitoring.

Despite a general lack of structure with regards to coastal monitoring programmes in the UK, some local authorities such as Bournemouth on the South Coast of England, had already established effective local monitoring schemes. In the 30 years between 1970-2000 almost 2 million m^3 of sand was used to replenish the beaches at Bournemouth and Poole combined with extensive topographic surveys monitoring such schemes. Long-term local coastal monitoring programmes as implemented by Bournemouth Borough Council, Canterbury City Council and New Forest District Council, for example, have demonstrated considerable cost-savings, allowing greater confidence in efficient design of coastal works (South East Coastal Group Website, 2006).

Geographical Outline of the South-East Strategic Regional Coastal Monitoring Programme

The exposed coastline of southeast England is characterised by soft sedimentary geology that is vulnerable to erosion, and extensive areas of low-lying land and high coastal urbanisation that are vulnerable to flooding. Approximately 10% of the population and billions of pounds of infrastructure are at risk from flooding within southeast England, within a vulnerable area that exceeds 480km2. Annual damages averted by maintaining current levels of coastal protection and sea defence are estimated at £203m per year, whilst capital project investment on defences within the region exceeds an average of £30 million per year and annual maintenance costs exceed £4.3m (South East Coastal Group Website, 2005). The combination of low-lying land formed from soft sedimentary geology, along with extensive coastal development, means that the management of the coastal zone is essential. Shoreline Management Plans and coastal strategy studies have highlighted the need for a more standard approach to coastal monitoring in order maximise the use of data and to provide best value.

The coastline of England and Wales is subdivided into coastal cells for the purposes of shoreline management planning (Motyka and Brampton, 1993) of which the South-East Strategic Regional Coastal Monitoring Programme covers approximately 1000km within Coastal Cells 4 and 5 between Portland Bill and the Isle of Grain (Figure 31).

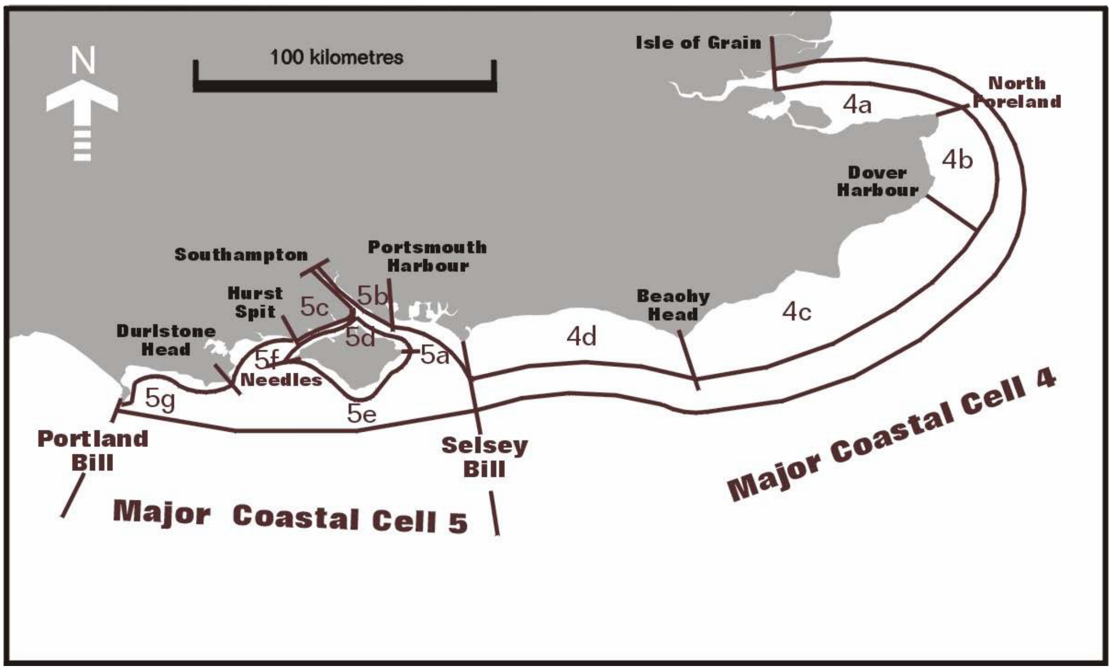


Figure 41. Major Coastal Cell and Sub-cell boundaries (Bradbury, McFarland, Horne and Eastick, 2001).

The recent approach to coastal monitoring has been both ad hoc and unsatisfactory within the southeast of England, and elsewhere in the UK; this is evident at both regional and local scales. Data collection and analysis methodologies have been inconsistent, and co-ordination has been poor. Region wide monitoring costs have been estimated at between £700,000 and £1.4m per year however. Although several region-wide monitoring programmes have been managed in isolation, results have not been integrated; either in context with each other, or with relation to regional aspects of shoreline management; this is contrary to best practice shoreline management principles.

The South-East Strategic Regional Coastal Monitoring Programme was introduced as a means of providing a standard, repeatable and cost-effective method of monitoring the coastal environment. It provides information for development of strategic shoreline management plans, coastal defence strategies and operational management of coastal protection and flood defence.

Aims

- Promote a standard, repeatable and cost-effective method of monitoring of the coastal environment.
- Promote, inform and integrate the operational monitoring requirements of: a regional overview; shoreline management plans; coastal strategies, and individual schemes, between the limits of the boundaries of regional cells 4 and 5 (Figure 31) (Bradbury, Beck, McFarland and Curtis, 2001).

Objectives (Bradbury, Beck, McFarland and Curtis, 2001)

- Examine the need for a hierarchy of tiers for coastal data collection and management
- Provide proposals for a coordinated regional hierarchy, including methods of integration of the various tiers.
- Define appropriate monitoring cells for each of the tiers. The extents of the regional scoping study area are major coastal cells 4 and 5. (Isle of Grain to Portland Bill).
- Examine the range of types of data collected within the coastal zone, on both defended and undefended coasts.
- Determine whether any further types of data should be collected which might benefit the understanding and management of the coastal zone.
- Discuss the range of spatial and temporal coverage required, for the various data types.
- Examine the range of operational survey techniques in current use.
- Provide guidance for regional baseline monitoring, at each of the defined levels.
- Examine current and best practice methods for data management, analysis and dissemination, and identify opportunities for regional collation and management of data
- Investigate methods of maintaining continuity and quality of monitoring programmes

- Examine techniques that might provide regional best value benefit, through economies of scale.
- Discuss methods of procurement and packaging of the monitoring programmes.
- Discuss options for the management of monitoring programmes and data.
- Discuss how the regional initiatives might be extended to a national level.

Background

Prior to the development of the South-East Strategic Regional Coastal Monitoring Programme, data collection programmes were seen as unsatisfactory both regionally and at a local scale. Although there are a number of extremely good local monitoring programmes in place in areas such as Bournemouth, North Kent, and Christchurch Bay, it was identified that a region-wide approach was necessary offering a standard and repeatable means of coastal monitoring.

The Environment Agency Annual Beach Management Survey (ABMS); an annual aerial survey programme generating beach profiles (approx. six per km) by photogrammetry of over 440km of coast, was, until now, the most comprehensive regional monitoring programme. A detailed review of the ABMS identified a regional consensus that it could be improved, to provide a product which could be used with some confidence, to inform both a regional overview and for strategic decision-making within SMPs and strategy studies.

The South-East Strategic Regional Coastal Monitoring Programme encompasses the older ABMS programme along with an extensive Global Positioning System (GPS) survey schedule and wave and tidal data. The programme is expected to cost approx £1.5m per year based on a five year funding period, but with an expectation that the programme will continue indefinitely. Funding commenced in August 2002 with the main funding source being DEFRA, Local Authorities and the Environment Agency. The programme will act as a regional pilot model that may later be used within other regions of England and Wales. Data is collected via a series of contracts and also by in-house local authority teams.

A specialist team has been established at the Channel Coastal Observatory within the National Oceanographic Centre, Southampton, to manage the programme and develop the data analysis, storage and dissemination procedures. Large quantities of data are currently being made freely available from the survey and analysis programme via the Channel Coastal Observatory website (Channel Coastal Observatory Website, 2005). It is hoped that this data will be useful to Local Authorities within the region, the Environment Agency, consultants in coastal defence, conservation management, academic research and for educational purposes.

Programme Design (taken from Channel Coastal Observatory, 2005).

A risk-based design approach has been adopted for the regional programme (Bradbury *et al.*, 2001), in order to optimise expenditure. Ideally, regular surveys of the various variables should be conducted at consistent (dense) spatial and (frequent) temporal scales. This idealistic approach cannot be sustained or justified financially however, and a reasoned method of sampling must be designed to provide best value for money. Coastal characteristics including geomorphology, shoreline composition and defence type, management strategy, exposure to wave attack and tidal range have all been considered within a weighted design framework developed from a conceptual model of data requirements. More data is generally required at those sites that are most vulnerable or heavily managed. Although the spatial and temporal coverage of data collection varies across the region, the risk-based approach has been applied consistently across the region (Channel Coastal Observatory Website, 2005).

The risk categories considered in programme design are:

- Exposure to wave attack
- Vulnerability to flooding
- Management strategy
- Coastal geomorphology and geology
- Defence type
- Application of GIS to development of risk model
- Limitations of risk model

Each of the risk categories has been considered separately, before drawing the data together within a weighted risk model. Extensive use has been made of a review of existing local and long-term programmes, to determine weightings. The well-developed programmes have been fine-tuned over a period of many years and demonstrate best value through their long-term development and use of the data in practical management of the coast.

The basic risk assessment model is very simple, but provides a clear separation of management risks and the relative need for monitoring at different sites. When considered together, the risk categories can be analysed in various combinations to determine those types of frontage where monitoring is most needed. A weighted approach, based upon the numerical indices derived for each category, was used to determine the most effective programme. Thresholds have been determined for each index category, and the required level of monitoring defined. The model has been validated against the existing long-term local programmes and has been further refined by consultation with each of the programme partners.

Examples of this risk-based approach are illustrated in the following examples. Exposed sites with active beach management and vulnerable features e.g. Medmerry (Sussex) shingle beach may require frequent and intensive monitoring. Low exposure, hard-cliff sites, with a do-nothing strategy e.g. Beachy Head (Sussex) need less intensive coverage, but some strategic data is needed to support other down-drift sites within the process unit e.g. Eastbourne (Sussex). Bathymetric surveys may be needed annually in areas of low tidal range and active submerged surficial sediments e.g. Bournemouth (Dorset), whilst areas that have a beach toe that dries at low water on a hard rock platform e.g. Hythe (Kent) will not benefit from frequent bathymetric surveys. Each site has been reviewed on the basis of exposure and the general dynamics of the local system.

Survey Techniques

The survey programme consists of a number of different survey techniques including both land-based and bathymetric surveys. In addition, the programme also undertakes airborne remote sensing topographic surveys.

Control Network

The wide range of survey techniques used within the programme requires a robust position-control network within which the surveys can be conducted. A single control network has been developed that will provide a framework for land surveys, aerial surveys, LiDAR and hydrographic surveys. Although the specific requirements for each element differ, the coordinate system and transformation methods must be consistent for all data to be integrated accurately and directly comparable. The basis for the network will be an ETRS89 GPS network transformed using standard OSTN02 and OSGM02 transformations to provide Ordnance Survey coordinates.

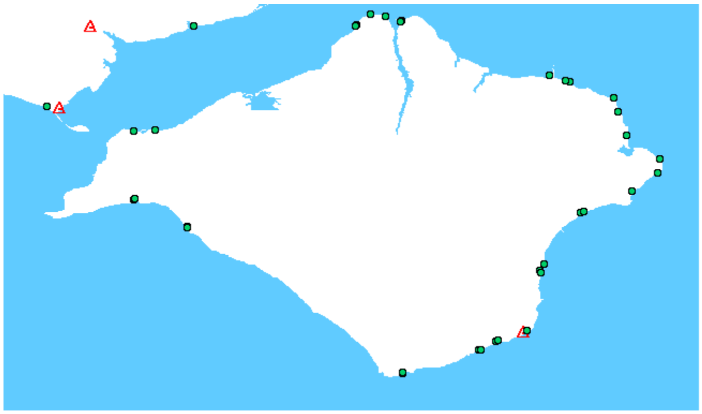


Figure 42. Isle of Wight Control Network (taken from Channel Coastal Observatory, 2005).

This process is already standard practice for EA LiDAR surveys and some local surveys. The historical ABMS programme and many other local systems require some modification to be relatively compatible. The figure below illustrates the locations of the control points for the Isle of Wight. In addition to the control points there are a number of less accurate Real Time Kinematic (RTK) points which allow checks to be made to ensure the base station is set up correctly and that surveys are measured in relation to this fixed point.

Land Based Topographic Beach Surveys

In the past, the majority of land based topographic surveys were carried out by levelling using an automatic level or by total station theodolite (usually in conjunction with a data logger). The technology associated with the total station theodolite is well proven and is still an efficient and appropriate method for collection of beach data. However, kinematic global positioning system (GPS) technology has advanced rapidly during the past few years. Kinematic GPS provides the opportunity to capture data with a vertical accuracy of approximately +/-2-3cm and horizontal positioning at approximately double the accuracy making it ideal for beach surveys. A minimum of two GPS receivers linked by a radio is required. One receiver acts as a base station, providing corrections, the other is a mobile station used for collection of data. The main advantage of GPS over other techniques is in the speed of data capture. Kinematic GPS is particularly well suited to repetitive surveys, since fairly long stretches of coastline can be surveyed from a single base station set up. The system is well suited to low light conditions and can be used in complete darkness. It is well suited to measurements of slope stability in areas of unstable terrain, since no control is required within the zone of instability. Control surveys can be conducted considerably more efficiently than using optical techniques. The same system can also be used in conjunction with bathymetric surveys (Channel Coastal Observatory Website, 2005).

Techniques in current use include both profiling and also continuous data collection of spot height data. Once every five years a baseline survey is carried out on all beaches within the South-East Strategic Regional Coastal Monitoring Programme area. These surveys provide a detailed topographical map of the beach through a combination of profile lines spaced at 50m intervals and continuous data taken every two seconds from shore parallel lines at 5m spacing. This combination allows a digital ground model (DGM) to be produced allowing profiles to be drawn at any location indicating changes in beach levels in comparison to previous surveys.

Subsequent surveys are determined by spatial and temporal factors. The profile interval varies from 100m-500m depending on the risk-based analysis of the area. Profiles spaced at 100m are generally in areas where barrier beaches run parallel to hold the line frontages at high exposure sites or where the beach has coastal structures where a high risk hold the line beach management plan sites exists. Profile lines spaced at 500m are likely to be where a ‘do nothing’ option exists on a low-risk/low-exposure site.

Thousands of beach profiles will be collected during the course of the programme with some sites being surveyed as many as 4 times per year. Where possible data from historical programmes is incorporated within the data sets to provide information on longer-term changes in beach levels. Figure 3 below is taken from a profile line within Colwell Bay on the northwest coast of the Isle of Wight. Survey data here dates back to 1998 and illustrates clearly how beach levels have changed over the years.

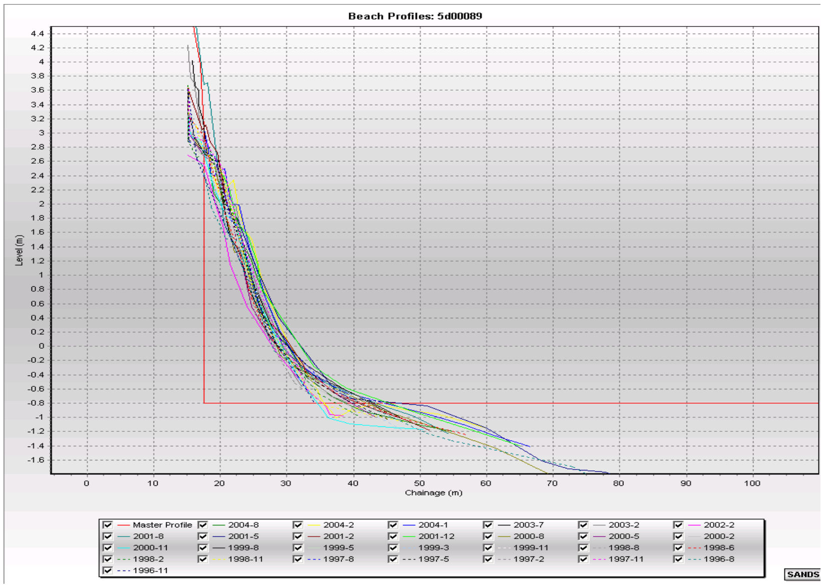


Figure 43. Beach profile graph for Colwell Bay (Southeast Strategic Regional Coastal Monitoring Programme Annual Report – Isle of Wight, 2004).

Provision has also been made for post-storm surveys. These surveys provide information on short-term changes as a result of storm events and allow for the effects of such an event to be measured.

Airborne Remote Sensing

Airborne remote sensing techniques are used to capture data at a variety of sites, to provide coverage of special features, or where these techniques are either more practical or efficient than land based methods. Surveys for a total of 530km frontage are monitored exclusively by remote sensing techniques. The whole of the programme area is also surveyed by airborne remote sensing methods to provide supplementary data to the land based techniques (Channel Coastal Observatory Website, 2005).

Digital aerial photographs (Figure 34) are also taken as part of the programme. Both orthorectified and georectified images are provided in order to allow measurements of shoreline position to be gained in inaccessible areas. Georectified images, once transformed to the local co-ordinate system can be viewed or plotted within a Geographical Information System (GIS). Digital georeferenced aerial photographs provide an excellent analytical medium, which can be used conveniently in combination with other types of georeferenced survey information. In particular, the images provide the opportunity for valuable interpretation of morphodynamic changes measured by reference to georeferenced profile data in combination with geomorphology (Channel Coastal Observatory Website, 2005).

Bathymetric Surveys

Bathymetric surveys are carried out in line with the topographic surveys with similar baseline and interim surveys being carried out. The majority of lines are measured at 50m spacing although in 'do nothing' frontages the spacing increases to 100m. The use of differential GPS enables survey points to be coordinated to within approx. +/-1m. This is generally considered to be sufficiently accurate. Kinematic GPS can be used to improve plan position, but such systems are not widely used yet. The alignment of the survey vessel track is also significant. Straight profiles can rarely be steered to an accuracy of better than 1-2m. The use of DTMs to produce profiles is advantageous in these circumstances, since survey error will be reduced. Vertical accuracy varies enormously, depending upon sea state, but is typically no better than +/-0.15m on the open coast. Bathymetric surveys tend to produce more scattered results across areas of irregular rocky seabed, by comparison with regular seabed (Channel Coastal Observatory Website, 2005).

Figure 44. Aerial photo of Yarmouth Harbour (Channel Coastal Observatory Website, 2005).

Environmental Mitigation Monitoring

In addition to the survey programme, a recent application has been made by the Isle of Wight Council for the South-East Strategic Regional Coastal Monitoring Programme to incorporate monitoring of Environmental Mitigation sites. DEFRA consents and planning consents require ongoing monitoring of flora and fauna for the lifetime of the project and it is hoped that this can be incorporated in the monitoring programme.

Analysis Programme – Annual Report

On the 30th September 2004 the first Annual Report was produced for each of the areas within the Regional Monitoring Programme. Analysis presented in this interim report provided an overview of beach changes and wave and tidal measurements since the commencement of the Southeast Strategic Regional Coastal Monitoring Programme.

On the Isle of Wight the first beach surveys took place during the winter of 2002 and changes are reported until spring 2004. This provides a short time base over which beach changes have been monitored. Detailed interpretation and decision-making is not advisable on the basis of short-term changes, since the changes may not be representative of longer-term trends.

Data was presented at four levels:
- Process cell summary of aggregated change over one year
- Management Unit overview of one year's beach changes
- Plotted time series of beach profiles
- Trend analysis of beach cross-section area

The Management Unit overview (see Figures 5 and 6) provides an at-a-glance summary of changes during the past year. Colour-coded lines highlight areas of maximum change with the arrows representing the average accretion, no change or erosion for each Management Unit.

Analysis was conducted for those sites where a minimum of four surveys were recorded. Where possible, changes are measured relative to the Mean Low Water Springs level, although this is not possible at many sites for a variety of reasons. Where possible, longer-term records from earlier programmes are also presented in the profile analysis, although historical data was often collected using significantly different survey techniques, specifications and even data.

With regards to the topographic survey data no significant change is shown for the majority of units in the north of the Isle of Wight. There is however notable accretion at Alum Bay and also between Cliff End and Sconce Point, whilst Totland Bay shows considerable erosion. The analysis indicated no net change in the units analysed in the south of the Isle of Wight.

The first baseline bathymetric survey of the Isle of Wight was completed in May 2003. No further analysis will be carried out until after the next baseline survey in 2006.

The Southern half of the Isle of Wight (sub-cell 5e) shows no notable change in beach cross sectional area. In the northern half of the Island (sub-cell 5d) most change is at the western point. TOT 2 and NEW 1 show substantial accretion, while TOT 3, which lies between these two bays, shows significant erosion. On the eastern side of the island there is little change apart from slight erosion in RYD10 and accretion in RYD6. The northern tip of the Island shows no net change.

A full time series of plotted beach profiles is shown, with the profiles superimposed and relative to a master profile for each profile location (see Figure 7 as an example). The master profile provides the basis for calculation of beach cross-section area changes. Where possible, identical depth boundaries have been used for all profiles within a Management Unit. However, even where this has not been possible, direct comparisons can be made for the beach cross sectional area at one profile over time, since the master profile is constant for each profile. The trend in cross sectional area is presented as a graph for each profile.

Condition of individual Management Units is also provided in the report detailing specific movement for each unit.

Conclusions

The South-East Strategic Regional Coastal Monitoring Programme offers a standard and repeatable approach to coastal monitoring which has been lacking in the past. Although the programme is still in its early stages there have already been significant advances made in data collection and management as a result of the programme. It is hoped that approval will be granted in the next 6 months for funding for the next five years of the project. General consensus is that this should be the case as the programme is already offering significant advantages over previous methods of monitoring and that a long-term programme is essential for the effective management of the coastal zone.

The survey programme includes measurement of a wide range of coastal process drivers and responses. Land Based Topographic Surveys will include the survey techniques: Levelling; Total station theodolite; Kinematic GPS. Other Land-based topographic surveys will include: Control network; Baseline beach surveys; Beach profiles; Post-storm beach surveys; and Beach management plan sites.

CASE-STUDY N°8 - Messina Component Two Recommendations for a Coastal Monitoring Programme in Sète, France.

The coastline of the Languedoc-Roussillon region is characterised by large sand dunes that are of great ecological importance, whilst also providing a natural barrier to the threat of coastal erosion. However, with the potentially increasing erosion rates as a result of sea level rise and the intensification of land-use along the coastal strip, the coastal features are becoming threatened and destroyed.

The Lido of Sète can be described as a narrow strip of land that separates the lagoon of Thau and the Mediterranean Sea (Figure 45). This 12 kilometre band of dunes and sand is located between Marseillan and Sète, in Southern France. Among about thirty costal lagoons in the Languedoc-Roussillon region, the lagoon of Thau is the largest (75 km2) and the deepest (Component 3 'Valuating the Shoreline', 2004).

The coastline from Sète to Marseillan suffers particularly from the effects of erosion with almost 45 hectares having disappeared between 1954 and 2000. The storm of 1982 caused significant damage to the coastline with a huge reduction in beach material and the destruction of coastal businesses and infrastructure, including the main coastal road (Figure 46).

Figure 45. The Coastline of Sète.

In 1953, three groynes were constructed along the southern end of the lido in order to protect a 400m stretch of the coastal road and the adjoining campsite. An additional groyne was constructed in 1954 to aid beach nourishment of the Lazaret beach on the south side of the strip.

Figure 46. Destruction caused by the 1982 storm.

Technical studies undertaken following the storm of 1982 suggested a need for the installation of hard engineering protection works along the whole coastline. The construction of a number of offshore breakwaters between 1987-1993 allowed for the creation of tombolos behind the structures and increased the beach size by 150m. However, the effectiveness of these coastal protection measures has been questioned because of their negative impacts downdrift of the last breakwater, showing a high erosive trend, especially intensive in the section where the coastal road is close to the beach (Component 3 'Valuating the Shoreline', 2004).

At the end of the nineties, local authorities started to search for a long-term solution to the management of the Sète coastline. Currently, this solution implies moving backward hard infrastructures (e.g. coastal road) and restoring the dunes to increase the system's resilience against erosion. People are aware that the ideal solution is to remove all the hard infrastructures from the lido (road, railway track, etc.), but this alternative is not accepted socially because of the high use of the road. Therefore, a long-term solution is required in order to avoid any further significant impacts on the environment.

A number of studies have been carried out, looking into potential solutions for managing the lido. The first study launched in 2001 aimed to identify the general problems of degradation of the site, putting forward an effective strategy on long-term soft engineering techniques and proposing solutions of a sustainable manner. A second study carried out in the summer of 2002 intended to determine the logistics and environmental impacts of moving the road whilst identifying new connections that would be required to join existing networks. The study stresses the importance of the littoral road, quoting usage figures of almost 12,000 vehicles per day with figures reaching 18,000 in high season. Between 1991 and 2003, the usage of the road increased by 30% with figures rising from 9,000 to 12,000 vehicles per day.

In 2003 a further study was carried out based on the findings from the previous two studies. The aim of this was to establish a detailed programme, following full consultation, illustrating the procedures and costs involved in such a scheme. The project was estimated to cost €48 million and involved eight local authorities. The programme design was based on the use of soft engineering techniques in order to protect the dunes and the relocation of sections of the main road.

The operational and pre-technical studies have been carried out between 2004 and 2006 and have involved the compilation of data from topographical surveys, geotechnical investigations, and hydro-geological and geological surveys. The geological, hydro-geological and geotechnical investigations were intended to determine the feasibility of the investments and to identify the constraints likely to affect construction, maintenance, and the conditions for implementation of the projected works. The topographical surveys include measurements taken from photogrammetric surveys as well as measurements taken on foot. In addition, bathymetric surveys were also carried out where necessary.

Aims of the study

The main aims of the study are as follows;

i. To restore normal functionality to the beach and to ensure long-lasting protection against erosion.

The strategic retreat process is the best-adapted solution for sustainable protection against erosion. This makes it possible to recreate the sedimentary balance that the construction of the road has broken.

ii. To ensure an effective and long-lasting protection of ecologically rich wetlands and salt marshes.

The project should contribute to the safeguarding and restoration of wetlands and salt marshes because of their significant ecological importance. Public access to such areas will be restricted to less fragile areas with areas of high ecological importance being strictly protected.

iii. To maintain the local function of the littoral road.

About half of the traffic using the littoral road uses the route between Sète-Balaruc-Frontignan and Agde-Marseillan: this local road of the southern part of the basin of Thau is therefore to be preserved.

iv. To preserve viable conditions for wine-producing activity.

The vineyards are one of the major characteristics of the landscape of the Lido de Sète, with more than 270 hectares being used for such purposes. It is therefore essential that a favourable environment be maintained for such activity.

v. To ensure the maintenance of the existing economic activities.

The two major economic activities located on the Lido must be preserved. The unit of Listel produces 42 million bottles of wine per year with 120 employees and over 7000 visitors per annum. In addition to this, the campsite of Castellas offers nearly 1000 pitches and creates almost one-sixth of all Sète's tourist trade.

vi. To support the maintenance of the traditional activities such as fishing and hunting.

vii. To allow the visitors to discover the richness and diversity of the lido environment and to gain a better understanding of the delicate balance between human intervention and the natural environment.

To ensure the protection of the most diverse and ecologically rich areas, visitors will be restricted to certain areas of the reserve. Information and interpretation exhibits will be on display to visitors interested in the site.

Recommendations for Monitoring the Region of Sète.

As part of Messina Component 2, a number of recommendations have been put forward with regards to the monitoring of the Sète coastline. However, it was felt that the following points needed to be taken into account when designing a coastal monitoring programme before any further recommendations could be made.

1. Priority must be given to monitoring techniques rather than modelling techniques. Evidence from the Netherlands National Monitoring Programme has suggested that available funding should be focused towards monitoring, as models are simply an innovative means of prediction rather than being useful for day-to-day interpretation or prediction of data patterns (see section 2.6.1).

2. The development of a comprehensive monitoring programme requires procedures that are standard and repeatable. It is essential that there is a fixed structure both in terms of timing and procedure, which all monitoring should adhere to. Monitoring should not be allowed to occur on an ad hoc basis.

3. It is essential to ensure the correct training is given to all staff. Choices have to be made by policy makers with the best of technological and scientific input and it is essential that these decisions be fed down to those carrying out the practical work. The data collected by staff can only be as good and as accurate as the training that they have been given.

4. Finally, where possible, securing funding for a long-term programme is best. There is little value in data collected over short time periods. Long-term data sets are essential to build up a picture of trends in data and allow for accurate predictions to be made. Benefits of coastal monitoring programmes are often developed over long periods of time, typically more than ten years. A clear vision is needed to plan for the development of strategic programmes over a period of 25 years or more; this can be achieved only when high quality data is available for decision-making (Bradbury, 2004). In order to secure funding, a good rapport between the local and national politicians and technicians is important. A good example of where this has occurred is in Ragusa, Sicily (see section 2.5.1.12).

At this stage, subject to further research and consultation, the Messina Component 2 would suggest the consideration of the following as a starting point for monitoring of the Sète coastline. These suggestions are based on experiences gained from the South-East Strategic Regional Coastal Monitoring Programme, UK.

1. The survey programme should be designed on a risk basis, developed from a conceptual model of data requirements. More data is generally required at those sites that are most vulnerable or heavily managed.

2. A robust position-control network within which the surveys can be conducted needs to be established using GPS. A single control network should be developed that will provide a framework for land surveys, aerial surveys, and hydrographic surveys.

3. The programme should include a combination of topographic and bathymetric surveys along with the collection of long-term wave and tidal measurements. Survey measurements should, where possible, be collected using RTK GPS due to its highly accurate nature. The speed of data capture using GPS is also high, thus allowing for a large amount of data to be collected in a short time frame.

   - A balanced topographic survey programme should include a combination of both land and aerial survey techniques (Bradbury, 2004). Profile spacing of approximately six profiles (perpendicular to the coastline) per kilometre is generally adequate for strategic overview planning at both regional and sub-cell levels (Bradbury, 2004). These profiles surveys should be carried out at a minimum of twice a year (spring and winter) with a baseline survey consisting of profile lines at every 50m being carried out once every five years. In addition to the baseline profile measurements, detailed spot heights and contours at 0.5-1m intervals parallel to the shoreline should be taken at 5 yearly intervals.
   - A high quality baseline bathymetric survey should be carried out for the area, ideally using swath bathymetry to maximise coverage. Intermediate bathymetric surveys should be conducted on a variable temporal basis, depending on exposure, tidal range and bed composition (Bradbury, 2004). With regards to the South-East

Strategic Regional Coastal Monitoring Programme in the UK, bathymetric surveys encompass the coastal zone between Mean Low Water (MLW) to a depth of approximately 10m below Mean Sea Level (MSL).

- The provision of post-storm profile surveys should be incorporated into the programme. These will typically be required once or twice per year, depending on exposure and the degree of storm action. Surveys should be conducted within 24 hours of the storm, ideally on the low tide following the storm (Bradbury, 2004)
- Where possible, a nearshore directional waverider buoy should be deployed to monitor wave conditions along with the collection of tidal data from a tide gauge. Wave and wind data should be used to inform development of numerical modelling and predictive techniques (Bradbury, 2004).

4. Data collection and analysis should be managed within a central database. A meta-data record should be recorded for each survey and each data set.

5. Data sets and analysis should be distributed to all relevant authorities and individuals. With regards to the South-East Strategic Regional Coastal Monitoring Programme in the UK, an Annual Report is produced to identify management problems or natural trends and to propose actions to rectify operational monitoring programme problems. In addition to this report, a website has been established (www.channelcoast.org) so that the general public and any other interested party have free access to the data collected.

These points have been suggested based on experiences from the UK and are by no means set guidelines for the region of Sète. However, it is hoped that these suggestions be taken on board when designing a monitoring programme, as in most cases they offer the most cost-effective and standardised method of coastal monitoring.

3 Modelling Techniques

Once the raw data has been acquired there are then numerous models available to further analyse and predict shoreline change. Modelling techniques can either be in the form of a mathematical/numerical model (for example the CERC Equation can be used to predict the volume of sediment transported alongshore as a function of the wave height, period and obliquity) or of a computational model. Computational models can be used to analyse and predict sediment transport (e.g. UNIBEST TC, UNIBEST CL+, MIKE 21 ST and MIKE 21 ST). Other packages are available to model coastal change and erosion (e.g. ESTMORF, GENESIS, SBEACH and UNIBEST-DE).

Computational hydrodynamic models are site-specific as oceanographic parameters vary around the UK. These range from lower resolution regional models to high-resolution local models. A hydrodynamic model could be run during extreme events to try to predict how sediments might move within a given area. The cells for the model can cover any extent providing there is sufficient data for the area. Models can be run to model the waves, wind, current and tidal effects on sediment transport. Examples of wave models wave include MIKE 21 NSW, MIKE 21 BW, MIKE 21 EMS, MIKE 21 PMS, SWAN and STWAVE.

3.1 Wave Models

For many years the Met Office has run second-generation global and regional wave models to provide forecasts of sea state, supporting a range of user applications. The sea state at any point may be thought of as the sum of many individual waves, each of a particular direction and frequency. This can be represented as the wave energy spectrum, where the wave energy in each frequency and each direction is known (Bidlot *et al*, 1999). The Met Office wave model divides the wave energy spectrum at each grid point into 13 frequency components and 16 direction components. The lowest model frequency is at 0.04 Hz (25 seconds period or 975 m deepwater wavelength), and the highest frequency resolved by the model is 0.324 Hz (three seconds period or 15 m deepwater wavelength). The effect of waves at higher frequencies is included in the calculation of source terms (Bradbury *et al*, 2004).

The wave models account for growth of waves due to wind input, dissipation of energy by breaking waves, and transfer of energy between spectral components by non-linear interactions. Wave energy is advected from one grid point to the next at the group velocity. The wave models are run using hourly surface winds from our global and mesoscale numerical weather prediction (NWP) models and there are three operational wave model configurations, with different areas and resolutions, currently in use (global, European and for UK waters). All the models include some shallow-water physics, namely bottom friction, refraction and shoaling (Bradbury *et al*, 2004).

Future developments to the Met Office wave model will include the assimilation of spectral wave data from the ERS-2 Synthetic Aperture Radar (SAR) and, later, the use of ENVISAT data. A project is also ongoing to implement the third generation WAM model within the Unified Model framework.

Wind Stress Formula

3.1.2.1 Basic Principles

Wind stress formula, developed by Wu (1980), quantifies the transfer of energy from the wind blowing over the ocean to the water surface (wind stress or wind shear), which results in an elevation of the sea level (wind set-up). Wind stress represents the actual force that causes water to move over the shelf and slope. The formula may be adapted to estimate the surge level. This interaction between wind and sea surface is not well understood and the formula undeniably stands for the best approximation known (Eurosion, 2004).

3.1.2.2 Limitations

The formula depends however on empirical coefficients (e.g. 'drag coefficient') which may not be adaptable to specific situations (Eurosion, 2004).

Wave Overtopping Model

3.1.2.3 Basic Principles

The Wave Overtopping Model, as devised by Owen, 1980, is used to predict the quantity of water passing over the crest of a sloping structure per unit of time. For sea defence structures, wave overtopping (usually given by the mean overtopping discharge) may be predicted by empirical or numerical models. The mean overtopping discharge varies with wall shape, crest level, water level and wave conditions. Generally design procedures are expected to calculate the crest freeboard (height of crest above water level) that would limit overtopping to below a chosen limit. Empirical models or formulae use relatively simple equations to describe wave-overtopping discharges in relation to defined wave and structure parameters (Pullen and Allsop, 2003).

The model was primarily developed for impermeable structures, with gradient ranging from 1:1 to 1:5. However, the model incorporates a roughness coefficient that is based upon the relative run-up performance of alternative construction materials. This roughness coefficient enables the method to be adapted for permeable sea defences such as shingle beaches, storm-induced dune profiles and rock armoured slopes. The model requires the empirical determination of coefficient related to the slope (Eurosion, 2004).

3.1.2.4 Limitations

Empirical equations and coefficients are limited to a relatively small number of simplified structure configurations. Their use out of range, or for other structure types such as vertical seawalls, may require extrapolation, or may indeed not be valid.

MIKE 21 NSW

3.1.2.5 Basic Principles

MIKE 21 Nearshore Wave (NSW) is a spectral wind-wave model, which describes the propagation, growth and decay of short-period waves (between 0.21s and 21s) in nearshore areas (Eurosion 2004). The model includes the effects of refraction and shoaling due to varying depth, wave generation due to wind and energy dissipation due to bottom friction and wave breaking. The effects of current on these phenomena are included. The model is derived from the approach proposed by Holthuijsen et al. (1989). The following basic input data are required in MIKE 21 NSW:

- Bathymetric data
- Stationary wind field (optional)
- Stationary current field (optional)
- Bed friction coefficient map (optional)
- Wave breaking parameters (optional)

- Offshore wave boundary conditions

It is adapted for coastal areas where diffraction and reflection are negligible, and for the simulation of short period waves (Eurosion, 2004).

MIKE 21 BW

3.1.2.6 Basic Principles

MIKE 21 Boussinesq Wave (BW) module is mainly used to study wave dynamics (significant wave height, wave disturbance coefficient, water surface elevation and the depth-averaged particle velocity) in ports and harbours and in small coastal areas. The model has been primarily designed for coastal harbours but can also be applied to small and complex coastal embayments (Eurosion, 2004).

The model is capable of reproducing the combined effects of most wave phenomena of interest in coastal and harbour engineering. These include shoaling, refraction, diffraction and partial reflection of irregular short-crested and long-crested finite-amplitude waves propagating over complex bathymetries. Phenomena such as wave grouping, generation of bound sub-harmonics and super-harmonics and near-resonant triad interactions, can also be modelled using MIKE 21 BW (DHI Software website, 2006).

MIKE 21 EMS

3.1.2.7 Basic Principles

The Elliptic Mild-Slope (EMS) Wave Module, MIKE 21 EMS, simulates the propagation of linear time harmonic water waves on a gently sloping bathymetry with arbitrary water depth (Eurosion 2004). MIKE 21 EMS is based on the numerical solution of the Elliptic Mild-Slope equation formulated by Berkhoff in 1972 and is capable of reproducing the combined effects of shoaling, refraction, diffraction and back-scattering. Energy dissipation, due to wave breaking and bed friction, is included as well as partial reflection and transmission through for instance pier structures and breakwaters. Sponge layers are applied where full absorption of wave energy is required. In addition, the model includes a general formulation of radiation stresses, based on Copeland (1985), which is valid in crossing wave trains and in areas of strong diffraction (DHI Software website, 2006). This model is restricted to coastal areas with a gently sloping bathymetry. It is not adapted to other cases (Eurosion, 2004).

MIKE 21 PMS

3.1.2.8 Basic Principles

MIKE 21 PMS is based on a parabolic approximation to the elliptic mild-slope equation governing the refraction, shoaling, diffraction and reflection of linear water waves propagating on gently sloping bathymetry (DHI Software website, 2006).

The parabolic approximation is obtained by assuming a principal wave direction (x-direction), neglecting diffraction along this direction and neglecting backscatter. In addition, improvements to the resulting equation, Kirby (1986), allow the use of the parabolic approximation for waves propagating at large angles to the assumed principal direction (DHI Software website, 2006). Furthermore, MIKE 21 PMS can produce the wave radiation stresses required for the simulation of wave-induced currents, which is very important in the computation of coastal sediment transport. Adapted to open coastal areas with a gently sloping bathymetry and where reflection and diffraction are negligible along the principle wave direction (x-direction), i.e. in the cases of small breakwaters and groyne fields, and navigation channels (Eurosion, 2004).

SWAN Model

3.1.2.9 Basic Principles

The SWAN (Simulating Waves Nearshore) model is a spectral wave model developed at the Delft University of Technology, The Netherlands. The SWAN model is a third-generation stand-alone (phase-averaged) wave model for the simulation of waves in waters of deep, intermediate and finite depth (Figure 39).

In the model, waves change height, shape and direction as a result of wind, white capping, wave breaking, energy transfer between waves, and variations in the ocean floor and currents. Initial wave conditions, including wave height, wave direction and wave period (time it takes for one wavelength to pass a fixed point), are entered into the model, and the model computes changes to the input parameters as the waves move toward shore. Model results are computed on a 500-m by 500-m grid for the area of research. Model output information (wave height, wave direction, and wave velocity) is produced for each cell in the model grid, and can be displayed in a map view to simplify visualization of changes in waves over the study area (Eurosion, 2004).

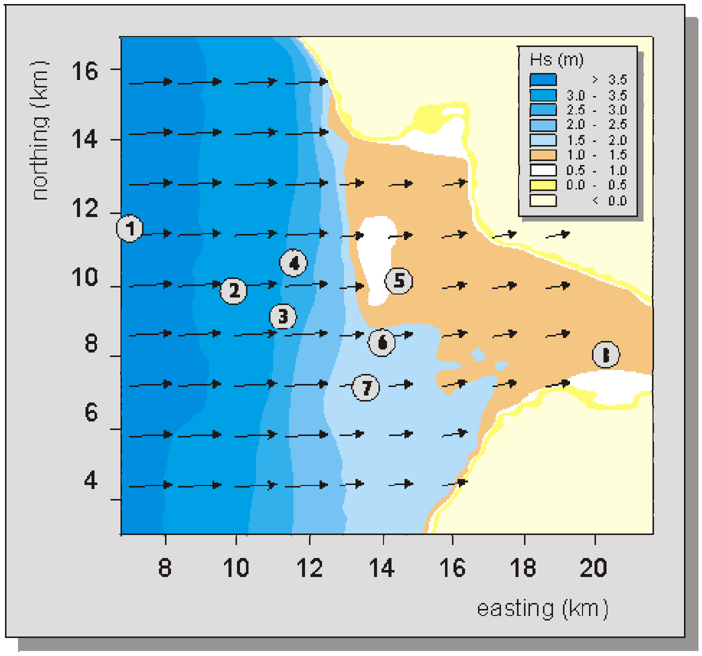


Figure 47. Example of the computed significant wave height pattern and mean direction of energy transport [denoted with vectors] (taken from WL Delft Hydraulics Website, 2006).

3.1.2.10 Limitations

SWAN is among the best model of wave transformation in the near-shore. But it has to be combined with other models to derive information on sediment transport or anticipate morphological changes (Eurosion, 2004).

STWAVE Model

3.1.2.11 Basic Principles

STWAVE (STeady State spectral WAVE) is a model developed by the US Army's Corps of Engineers for nearshore wind-wave growth and propagation (Eurosion 2004).

STWAVE is a steady-state, finite difference, spectral model based on the wave action balance equation. STWAVE simulates depth-induced wave refraction and shoaling, current-induced refraction and shoaling, depth- and steepness-induced wave breaking, diffraction, wave growth because of wind input, and wave-wave interaction and white capping that redistribute and dissipate energy in a growing wave field. The purpose of STWAVE is to provide an easy-to-apply, flexible, and robust model for nearshore wind-wave growth and propagation.

3.2 Sediment Transport Models

The Coast3D Project

The Coast3D project, as covered in section 2.4.3.1.2, was established as a means of improving understanding of the physics of coastal sand transport and morphodynamics. In addition to this, it aimed to aid the validation of both data, and current numerical modelling techniques, for predicting coastal sand transport and morphodynamics.

Tests carried out at Egmond in the Netherlands and Teignmouth in the UK, suggested that numerical models could be used to predict coastal process patterns. The application of a 1DX hydrodynamic and morphodynamic model and a 2DXZ hydrodynamic model to the Egmond field site yielded hydrodynamic and morphodynamic results that compared favourably with the field data. A quantitative comparison of computed and measured wave data suggests that the accuracy of the predicted values was approximately 20 percent (Coast3D, 2001). This relatively low accuracy has caused many scientists to use models for research purposes rather than for prediction purposes. Generally, models are only used to try and innovate rather than for day-to-day interpretation or prediction of data patterns. Experts in RIKZ often do not see models as being useful over a short time or even over longer time periods due to a lack of understanding of many of the modelling systems resulting in an inability to create accurate predictions.

Bijker Transport Formula

3.2.2.1 Basic Principles

The Bijker formula (1971) estimates sediment transport by modelling a 'bed load transport' (Sb) and a 'suspended load transport' (Ss). These are a function of the deep-water wave height, period and approach angle, current velocity, grain size and density, particle fall velocity, and bottom roughness (Eurosion, 2004). Bijker's (1971) model is used widely by practicing engineers due to its ready implementation and also because its predictions are broadly similar to those of more complicated, practical models. It also has the appeal of being based on classical concepts for the bed load and suspended load, rather than relying on empirical curve fitting to transport data. (Davies and Villaret, 2003).

3.2.2.2 Limitations

Bijker formula is suitable for a wider range of applications than the CERC formula, in particular in estuaries where currents become dominant. However, it requires more field measurements (Eurosion, 2004).

MIKE 21 ST

3.2.2.3 Basic Principles

MIKE 21 Sediment Transport (ST) is designed for the assessment of the sediment transport rates and related initial rates of bed level changes of non-cohesive sediment (sand) due to currents or combined wave-current flow (Eurosion, 2004). MIKE 21 ST calculates sediment transport rates on a rectangular grid covering the area of interest on the basis of the hydrodynamic data obtained from a simulation with MIKE 21 HD and (eventually) the wave data provided by MIKE 21 NSW/PMS/EMS together with information about the characteristics of the bed material (DHI Software website, 2006). The model provides and compares results coming from different transport theories including Engelund-Hansen, Engelund-Hansen, Zyserman-Fredsøe, Meyer-Peter and Müller, Ackers-White, and Bijker. It is only adapted for non-cohesive sediment (e.g. sand) for which it provides good results (Eurosion, 2004).

MIKE 21 MT

3.2.2.4 Basic Principles

MIKE 21 Mud Transport describes the erosion, transport and deposition of mud and sand/mud mixtures under the action of currents and waves (Figure 40) (Eurosion, 2004).

The model is essentially based on the principles in Mehta et al (1989) with the introduction of the bed shear stresses due to waves, a stochastic model for flow and sediment interaction first developed by

Krone (1962), and a non-cohesive sediment transport based on Van Rijn (1984). MIKE 21 MT can be applied to the study of engineering applications, for example: sediment transport studies for fine, cohesive materials or sand/mud mixtures in estuaries and coastal areas, in which environmental aspects are involved and degradation of water quality may occur; siltation in harbours, navigational fairways, canals, rivers, reservoirs; and dredging studies (Eurosion, 2004).

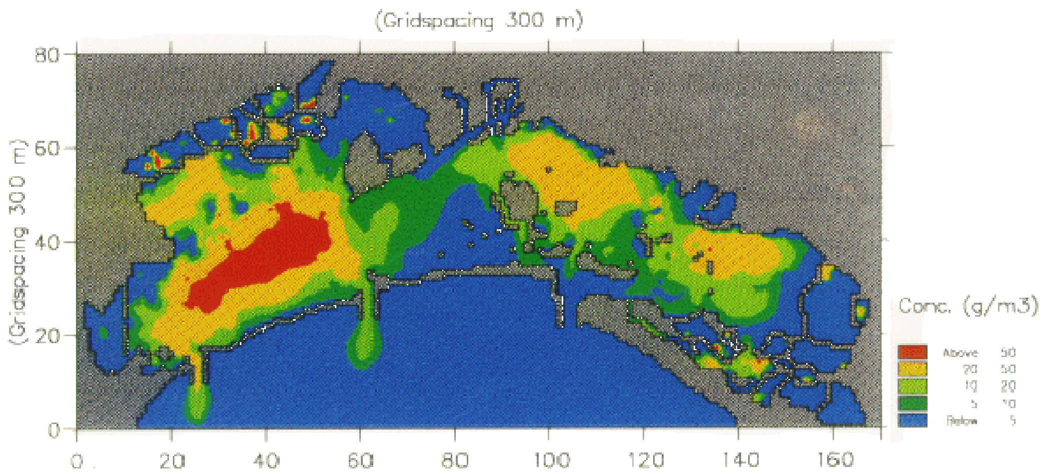


Figure 48. Example of the computed suspended sediment concentrations (taken from DHI Software website, 2006).

UNIBEST TC

3.2.2.5 Basic Principles

UNIBEST-TC is the cross-shore sediment transport module of the UNIBEST Coastal Software Package (Eurosion 2004). UNIBEST (UNIform Beach Sediment Transport) is a generic term for a software package that computes sediment transport along a uniform sandy coast and the coastal behaviour during human interference or storm. The software package UNIBEST consists of four separate modules; UNIBEST-LT, -CL, -TC, and -DE. UNIBEST-LT (littoral transport) can be used for the computation of net sand transport in longshore direction and its cross-shore distribution. UNIBEST-LT supplies the boundary conditions for UNIBEST-CL (coastline behaviour), which can be used to assess coastline changes due to human influence (e.g. breakwaters, groynes). UNIBEST-TC (transport cross-shore) can be used to assess coastal profile developments due to wave action. UNIBEST-DE can be used to compute dune erosion, and is quite similar to the TC module, but is especially intended to compute the effects of stormy episodes (NetCoast website, 2006).

UNIBEST-TC is designed to compute cross-shore sediment transports and the resulting profile changes along any coastal profile of arbitrary shape under the combined action of waves, longshore tidal currents and wind. The model allows for constant, periodic and time series of hydrodynamic boundary conditions to be prescribed. UNIBEST-TC takes the principal cross-shore processes such as wave asymmetry, undertow, gravity and mass-flux below wave troughs into account (Eurosion, 2004).

3.2.2.6 Limitations

The model requires a significant amount of input data and computational resources (Eurosion, 2004).

UNIBEST CL+

3.2.2.7 Basic Principles

UNIBEST-CL+ is a sediment balance model (part of the UNIBEST package of models) with which longshore transports computed at specific locations along the coast can be translated into shoreline migration (Eurosion 2004).

The typical application is the analysis of the large-scale morphology of coastal systems to provide insight into the causes of coastal erosion or to predict the impact of planned coastal infrastructure (such as a port) on the coast. But the model can also be used for considerations on a smaller scale, like the evaluation of the shoreline evolution around coastal protection works (groynes, revetments, river mouth training works and to some extent detached breakwaters). Sediment sources and sinks can be defined at any location to simulate river sediment supplies, the effect of land subsidence or sea level rise, offshore sediment loss, artificial sand bypass and beach mining. These features make it a suitable tool for the functional design of coastal defence schemes and the prediction of their impact on the coast, in the feasibility stage and in many cases also in the detailed design stage of projects. Technical features of the model, as stated by Eurosion (2004) include:

- Curvilinear grid (thus adaptable to different types of coast including straight coasts, deltas, bays.
- Computation of wave-propagation and wave-induced longshore current included.
- Longshore transport and its distribution along the coastal profile can be evaluated according to several total-load sediment transport formulae for sand (such as Bijker, van Rijn) or gravel (Van der Meer & Pilarczyk).
- Time-dependent response of the longshore transport on changes of the coast-orientation with time.
- Input of up to hundreds of combinations of wave- and tidal conditions.
- Different shapes of the coastal profiles can be defined along the coast and seasonal variations in the wave climate can be simulated.

3.3 Hydrodynamic Models

MIKE 21 HD

3.3.2.1 Basic Principles

MIKE 21 HD is the basic computational hydrodynamic module of the entire MIKE 21 system, providing the hydrodynamic basis for other MIKE 21 modules such as for Advection-Dispersion (AD), ECO Lab, Particle tracking (PA) and Sediment Transport (ST, MT) (DHI Software website, 2006).

MIKE 21 Hydrodynamic (HD) simulates the water level variations and flows in response to a variety of forcing functions in lakes, estuaries, bays and coastal areas. The water levels and flows are resolved on a rectangular grid covering the area of interest. Eurosion 2004 states that MIKE 21 HD includes formulations for the effects of;

- Convective and cross momentum.
- Bottom shear stress.
- Wind shear stress at the surface.
- Barometric pressure gradients.
- Coriolis forces.
- Momentum dispersion
- Wave-induced currents.
- Sources and sinks (mass and momentum).
- Evaporation.
- Flooding and drying.

MIKE 21 HD is applicable to a wide range of hydraulic and related phenomena. This includes modelling of tidal hydraulics, wind and wave generated currents, storm surges and flood waves. This model requires a wide range of input data and significant resources (Eurosion, 2004).

3.4 Beach Slope Profile Models

CERC Equation

3.4.2.1 Basic Principles

The CERC equation (1950) helps to predict the volume of sediment transported alongshore as a function of the wave height (in the break zone), period and obliquity. Improved versions of the CERC equation – Davies and Kamphuis (1985), Sayao, Nairn and Kamphuis (1985) – include grain size and beach slope in the model (Eurosion, 2004).

3.4.2.2 Limitations

Applicable only in those cases where sediment transport is principally induced by waves approaching at oblique angle and have the same properties at all points along the coast. Not applicable when other driving forces (e.g. tidal currents) become significant. Not applicable either to shoals, dumping grounds or near dredged channels (Eurosion, 2004).

DUROS Model

3.4.2.3 Basic Principles

To judge the safety of the Dutch dune coast a computation model is used that, for given design conditions, determines the amount of dune erosion. The core of this model is the so-called DUROS-model.

DUROS model (DUne eROSion 1986) helps predict the response of a dune profile to a severe storm surge. The 'storm profile' is a function of the significant wave height (deep water), the maximum surge level, the grain size, and the initial profile. DUROS model is suitable to provide a quick assessment of whether the existing dunes are 'safe' or not (Eurosion 2004).

3.4.2.4 Limitations

The DUROS model is not appropriate for analysis of complex coastal areas including semi-enclosed bays or complex shoreline geometry.

Bruun Rule

3.4.2.5 Basic Principles

The Bruun rule estimates the response of the shoreline profile to sea level rise. This simple model states that the beach profile is a parabolic function whose parameters are entirely determined by the mean water level and the sand grain size. Bakker (1968) and Swart (1976) have adapted the Bruun rule to predict cross-shore sediment transport (Eurosion 2004). The application of the Bruun Rule has also been used to develop Atkins Coastal Hazard Simulator. The simulator has been designed to illustrate coastal evolution by mapping a predicted retreat line based on past trends from orthorectified aerial photography. The simulator provides calculations of future coastal change based on the analysis of historical erosion rates through the digital photography whilst also taking into account allowances for sea-level rise.

3.4.2.6 Limitations

Only applicable for small scale local sites. Over long stretches of coast, the Bruun rule and associated cross-shore transport models become complex (Eurosion 2004).

SBEACH Model

3.4.2.7 Basic Principles

SBEACH (Storm-induced BEAch CHange Model), developed by the US Army's Corps of Engineers, is a numerical simulation model of cross-shore beach, berm, and dune erosion produced by storm waves and water levels. The model is applied in beach fill project design and evaluation and in other studies of beach profile change.

UNIBEST-DE

3.4.2.8 Basic Principles

UNIBEST-DE is the module of the UNIBEST Coastal Software Package used to compute the cross-shore profile developments during storm conditions of a coast consisting of loose material (Eurosion, 2004).

In addition to large wave attack, these conditions are characterised by a considerable rise of the mean water level (storm surge). The intense breaking of waves generates high turbulence levels causing large amounts of sediment to suspend. Accordingly the transport of this suspended sediment is the predominant transport mechanism under such conditions. The model is verified with large-scale data from physical models and field data. The model represents the cross-shore transports in a one-dimensional (cross-shore) grid with variable mesh size. The capabilities of the models are relevant for applications such as:

- Dune erosion and beach profile change under extreme conditions.
- Design of beach nourishments.
- Design of dune revetments.

The model requires pre-defined time series of waves and water levels and comes with options to automate a large number of simulations. Model results are in ASCII output files that can be inspected graphically as time histories or distributions along the bottom profile (Eurosion, 2004).

GENESIS Model

3.4.2.9 Basic Principles

GENESIS (GENEralized Model for SImulating Shoreline Change), a model developed by the US Army's Corps of Engineers is a system of models for calculating shoreline change caused primarily by wave action.

The system is based on the one-line theory, whereby it is assumed the beach profile remains unchanged permitting beach change to be described uniquely in terms of the shoreline position. The model can be applied to a diverse variety of situations involving almost arbitrary numbers, locations, and combinations of groynes, jetties, detached breakwaters, seawalls, and beach fills. Other features included in the system are wave shoaling, refraction, and diffraction; sand passing through and around groynes, and sources and sinks of sand (Eurosion, 2004).

ESTMORF

3.4.2.10 Basic Principles

ESTMORF is a one-dimensional model of estuarine morphology, which includes three-dimensional effects, developed by RIKZ. In nature, the main channel transports the water flow and the flats serve as storage areas (Eurosion, 2004).

The ESTMORF schematisation distinguishes three parts of a cross-section: main channel, low flat and high flat. In ESTMORF, sediment is transported through the estuary via the main channels, whereas sediment exchange occurs on the flats. The flats store sediment or supply sediment to the channel. ESTMORF computations are based on a combination of empirical and physical laws. The morphological equilibrium is determined from empirical laws. It is known from observations in many estuaries around the world, that there are relationships between the size of a channel and the volume of water it transports. Similarly, there are relationships between the size of the flats and the tidal range. Thus, the equilibrium geometry of the channels and the flats can be related to the tidal flow. The equilibrium concentration and the actual concentration field (due to natural development and/or human interference) are based on physical laws. The sediment concentration field is determined from a transport equation, which includes physical properties of the sediment and the residual flow field in the estuary. Sedimentation and erosion is determined from the deviation of the actual concentration and equilibrium concentration. This model was initially developed for the Western Scheldt estuary, but may be applied to other tidal basins. The model is not adapted for other types of coasts (Eurosion, 2004).

3.5 Modelling Techniques – Conclusions

Despite the numerous models available for the prediction of coastal processes and trends, coastal managers and scientists often see models as being useful in terms of providing an innovative means of prediction rather than being useful for day-to-day interpretation or prediction of data patterns. As new software is developed and modelling techniques become more refined, the value of modelling with regards to monitoring of coastlines is likely to increase substantially.

Table 14 Airborne/Space born Monitoring Applications

Satellite	LiDAR	CASI	SAR	GPS	Arial photography	Wind profiler radar
Land Use Slope profile Wind Waves Currents	Fronts Temperature Habitats Benthic habitats	Land Use Slope profile Wind Waves Currents Fronts Temperature Habitats Benthic habitats Water Quality (turbidity, chlorophyll)	Land Use Slope profile Wind Waves Currents Fronts Temperature Habitats Benthic habitats	Slope stability	Land Use Slope profile Habitats	Wind Waves Temperature

Table 15 Ship-born Monitoring Applications

Bathymetric survey	Sidescan and multibeam sonar	Sub-bottom profiling	ASCS	Buoys	LLS	Sediment Profile Imaging	Photography and videography	Grab and Sediment core sampling
Erosion of bedrock Sediment change Bottom profile	Geology Sediment type	Sediment type and layers	Bottom type Sediment type Benthic habitat	Waves	Benthic habitat and fish	Sediment type and layers, grain size Benthic habitat	Sediment type Benthic habitat	Sediment type and size

Table 16 Ground-based Monitoring Applications

Levelling, Transits, Theodolites, Triangulation and Trilateration	Total Pressure cells	Settlement cells and Soil Strainmeter	Data Loggers	Goodman Jack, Beam sensors and Tiltmeters	Hydrological Studies	Piezometers, Inclinometers, Borehole Extensometers	Video	Tracers
Beach change.	Warn of soil pressures in excess	Measure ground movement and change.	Provide an early warning system for ground instability	Beach change.	Predict Slope stability over time	Predict Slope stability	Beach change	Sediment transport

4 APPENDIX

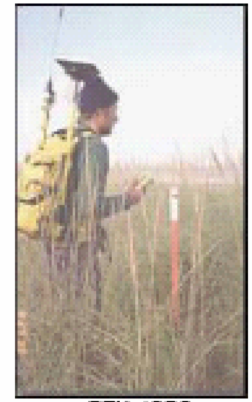
EUROSION 2004

OVERVIEW OF MONITORING TECHNIQUES COMMONLY USED IN EUROPE

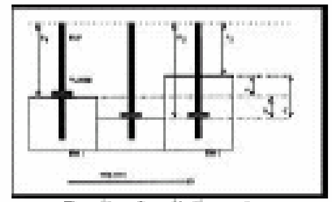
ANNEX 3 - OVERVIEW OF MONITORING TECHNIQUES COMMONLY USED IN EUROPE

	TYPE OF TECHNIQUE	NAME OF TECHNIQUE	
DIRECT OBSERVATIONS	TOPO-BATHYMETRICAL TECHNIQUES (to make beach profiles)	EMERGED BEACH	• RTK-dGPS (in-car, bag carried) http://www.ecy.wa.gov/programs/sea/swces/research/change/monitoring.htm • Total station + survey rod • Distance meter + survey rod
		SUBMERGED BEACH	• Total station + survey rod • Depth-of-activity rods • CRAB (-WESP) • SLED • Profiling Bar (BP) • Sounding lead • Hydrostatic profiler
	TRACERS (for measure sediment transport)		• Color paint • Fluorescent paint • Radiactive tracers • Natural tracers • Magnetic sands

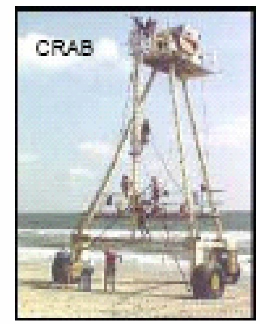
Total station / distance meter + survey rod

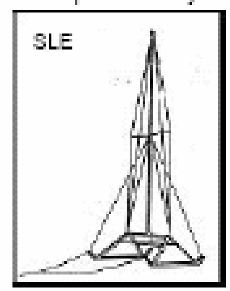


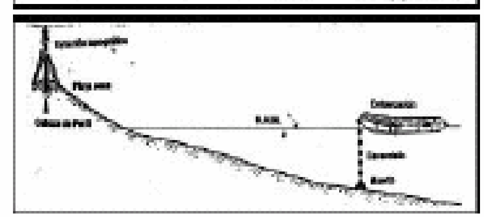
RTK-dGPS



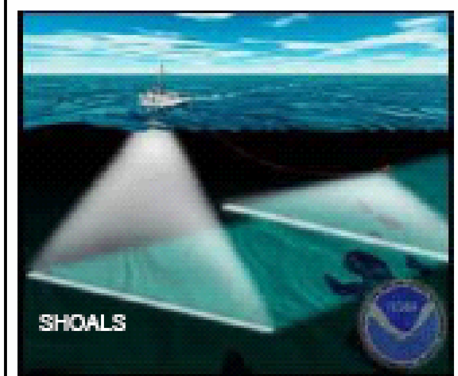
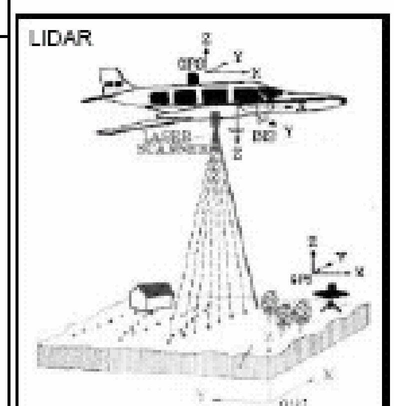
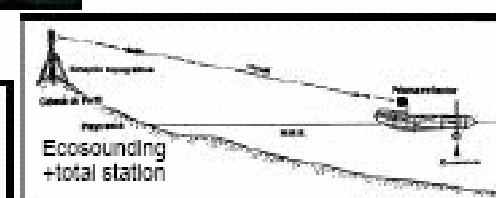
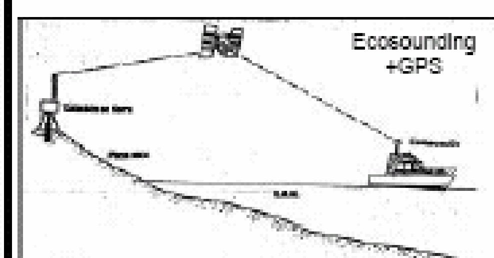
Depth-of-activity rods







Sounding lead

REMOTE OBSERVATIONS	FIXED		• ARGUS http://www.wldelft.nl/cons/work/argus/index.html • Horizontal photography • Historical maps and navigation charts	 
	MOBILE	AIRBORNE	• Aerial photography (Digital photogrammetry, Orthophotos) http://dcn.waterland.net/neonet/ • Satellite images (LANDSAT, SPOT, Ikonos...) • LIDAR (=laser altimetry; SHOALS...) http://duff.geology.washington.edu/data/raster/lidar/laser_altimetry_in_brief.pdf • WRELADS • SAR http://dcn.waterland.net/neonet/indexeng.html http://www.sandia.gov/radar/whatis.html	 
		SHIPBORNE	• Ecosounding+GPS (hovercraft, boat...) http://www.eurosense.com • Echosounding+survey rod+total station (zodiac) • SIDE SCAN SONAR http://www.kleinsonar.com/discript/sssonar.html • SBP (for ancient coastlines detection-seismic data)	  

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