Concepts and Science for Coastal Erosion Management

Specific Targeted Research Project

Thematic priority: Forecasting and developing innovative policies for sustainability in the medium and long term

Inventory of coastal monitoring methods and overview of predictive models for coastal evolution

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1 Introduction

In the last few years there has been a rapid change in the technology developed for monitoring in the coastal zone, with the emergence of remote sensing, in particular, radically altering the type and volume of data available for addressing coastal management problems. Many of these tools have been developed by scientists to answer questions about detailed coastal processes. Translating the measurements and models of detailed processes (often on small space and time scales) into tools for coastal erosion risk management is not easy or straightforward (Mulder et al., 2001, van Koningsveld et al., 2004 etc).

At the same time there has been an increase in the use of centralised data-stores with standardised procedures and formats for the storage of coastal monitoring at a regional scale. Examples of this include the development of the Channel Coast Observatory[1] in the UK and the Jarkus database in the Netherlands. Moreover there has been an increase in the development of large-scale numerical models of systems of defences for flood risk management (such as Risk Assessment for Strategic Planning in the UK and VNK in the Netherlands). However, the coastal erosion element in flood and coastal erosion risk management has been neglected up to now.

In light of the above, Task 5.1 of CONSCIENCE[2] has produced this inventory of innovative monitoring methods and has updated the overview of models developed in EUROSION[3].

Activities:
1) Review journals and conferences for technical details of monitoring techniques. This will include LIDAR, SAR, ARGUS, SHOALS, CHARTS, Fli-Map, ATLAS, CASI, ortho-rectified aerial photos, NDT, GPS tide gauges, wave buoy networks and other appropriate techniques.
2) Review present monitoring guidance and practice among coastal and marine management authorities. This will include guidance for Shoreline Management Plans (UK) and a review of the Channel Coast Observatory (UK).
3) Review and where necessary update the overview of models developed in EUROSION.

[1] www.channelcoast.org
[2] www.conscience-eu.net
[3] www.eurosion.org

2 Monitoring methods and other data sources

Monitoring of beaches provides important information about the state of the coastal system. The data from monitoring provides the input into the statistical descriptors and numerical models of beach behaviour. It also provides the information with which to judge the bias, accuracy or skill of any predictor (Sutherland et al., 2004). This section of the report describes much of the equipment available for monitoring beach levels and the other data sources, such as Ordnance Survey maps, that provide useful information on beach widths. It is a general review of beach monitoring techniques. Some of the equipment has not been used to monitor beach levels in front of coastal structures, as far as the authors are aware, but has been included if this is a potential future use. It is convenient to categorise monitoring methods by the length scale that they cover as each method can be used for different purposes at different timescales.

2.1 Small Scale

2.1.1 Linear arrays of point sensors

HR Wallingford has developed the "Tell Tail" scour monitoring system, which can be installed at new or existing structures and gives a clear indication of the depth of scour under all conditions (within its vertical range). The system records the onset of scour, the depth of scour reached, and in-filling of scour holes following storm events.

The system is based on a linear array of omni-directional motion sensors, buried in the sea bed adjacent to the structure. The sensors are mounted on flexible "tails" and are connected via cable through protective conduit to a solid state data recorder. The scour monitors typically operate for 2 to 3 weeks before the data needs to be downloaded and the batteries replaced. Under normal conditions, the sensors remain buried and do not move. When a scour hole begins to develop, the sensors are progressively exposed and each begins to oscillate in the flow. Each oscillation is logged on a solid state data recorder. Use of an eight level array of sensors provides a measurement of the depth of scour through a tide, thereby indicating if a scour hole has re-filled.

Tell-Tail scour monitors have been deployed in front of seawalls at Teignmouth (Whitehouse et al., 2000), at Southbourne (Sutherland and Pearce, 2005) as shown in Plate 1 and at Blackpool (HR Wallingford, 2005). In each case beach lowering and recovery during a tide has been detected that could not have been picked up by successive beach profiles measured at low tide. An example from Southbourne is shown in Figure 2, which shows the level of the lowest active sensor, the significant wave height measured by a buoy at -10.5m CD and the water level measured at Boscombe.

Plate 1 Tell-Tail scour monitors at Southbourne

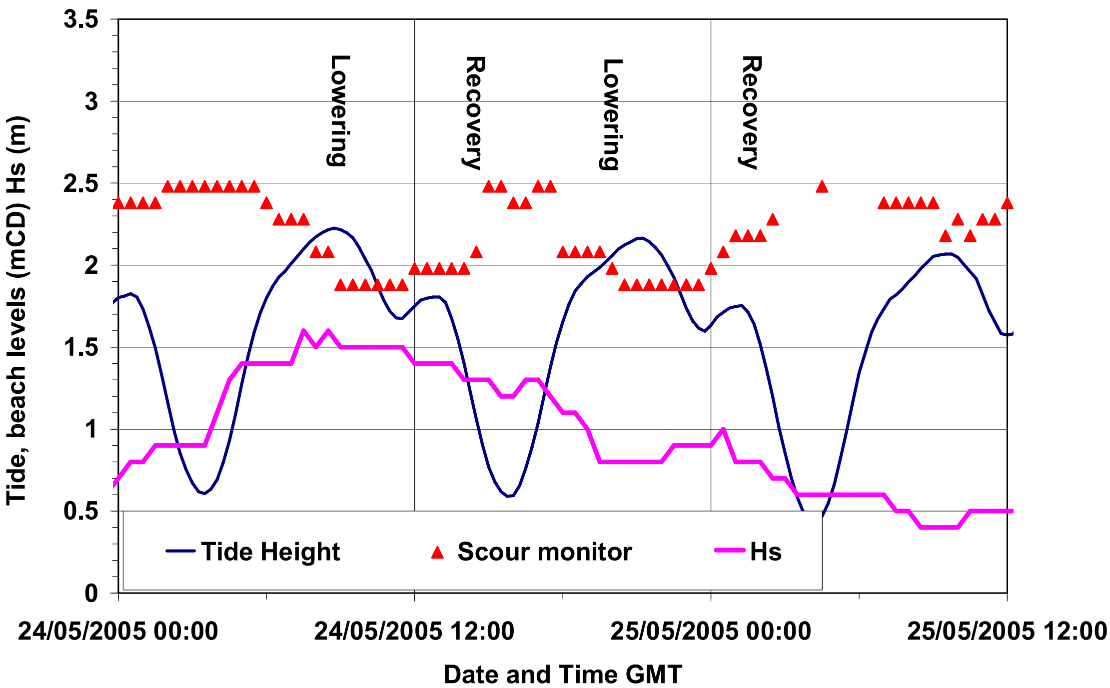

Figure 2 Plot of beach lowering and recovery during a tide at Southbourne

Cassen et al. (2005) have developed a scour monitor based on a linear array of electrical conductivity meters. The scour monitor relies on the fact that sea water has a high electrical conductivity while dry sediment has a low conductivity and saturated sediment has an intermediate conductivity. Arrays of 8 to 32 sensors can be deployed at 0.10m spacing on a supporting pole and logged by a data logger at the top of the pole. The instrument was used to measure erosion in the inter-tidal zone of a beach at Bicarrosse (France) and is still in development.

Cassen et al. (2005) also mention the following alternative devices for detecting bed level through a tide:

- Photo-Electric Erosion Pin of Lawler (1991) which detects daylight at an array of optical sensors and has been used in the swash zone by Robinson et al. (2005);
- Sedimeter of Erlingsson (1991) which used an array of infra-red transmitters and backscatter detectors; and
- Ridd's (1992) electrical conductivity measuring device.

2.1.2 Underwater acoustic measurements of the seabed

An acoustic backscatter device can be used to detect the level of the seabed and give information about sediment in suspension in situations where the seabed and instrument are fully submerged. As far as the authors are aware no such system has been used to measure scour in front of a seawall. However, these systems have been used in the surf zone and could be deployed at a seawall.

Gallagher et al. (1996) used a sonar altimeter to survey the seabed level in the surf zone, where a special filter had to be used to remove the signal from air bubbles. Hoekstra et al. (2004) describe the deployment of an Autonomous Sand Ripple Profiler (ASRP) in the intertidal zone at Teignmouth (UK) to measure the rapidly migrating ripple field close to the main channel at the mouth of the Teign Estuary. The ASRP uses a mechanically scanned 2MHz pencil beam acoustic transducer to measure the height of the sea bed along a 3.5 metre line parallel to the flow into and out of the estuary. There were gaps in the data near low water, when the instrument was out of the water, as it cannot operate across an air/water interface. Scans of the sea bed were made approximately once every minute and timestacks of profiles showed the evolution of the ripple profiles through the tidal cycle.

2.1.3 Measurements of emerged toe levels

There are a number of techniques that can be used to measure emerged coastal defence structure toe levels at a point every low tide. These include:

- Acoustic distance measurements in air. Such products are sometimes used to measure wave heights but could also be used to measure beach levels at a point;
- Photography/video of the seawall (possibly with marked elevations) from a camera mounted overhead of a sloping seawall or offshore from a vertical wall, perhaps on a pier; (see also Section 2.2.5 on Argus) and
- Counting the number of steps above the beach level at access points, or the number of planks visible on either side of a groyne.

The first two could be operated remotely, so could collect a large amount of data with little running cost, once the system is set up.

2.1.4 Measurements of mixing depth

The seabed mixing depth is the maximum depth below the seabed where sediment motion occurs. Immediately below this level the sediment is immobile. The mixing depth therefore determines the vertical limit of sediment transport. Ferriera et al. (2000) provide a summary of the available methods and a bibliography of case studies. These are:

- Plug holes filled with marked materials up to surface level. One example (not included in Ferreira et al., 2000) is the use of a stack of numbered aluminium disks of known height. The stack of disks is buried in the beach and the top level is surveyed. The disks are left in the beach for a period. On return the sand is removed until the uppermost undisturbed ring is exposed. The mixing depth can be determined from the elevation of the top of the stack, the height of each disk and the number of disks moved, which is known from the numbering system. Moved disks can often be retrieved using a metal detector.
- Graduated sticks or rods with or without washers. Beach levels at rods without washers must be observed, so this technique is generally confined to the swash zone. Rods with washers can be left in the beach. On return, the sand around the rod is removed until the washer is exposed. The depth of the washer gives the lowest mixing depth during the period of deployment. No information is obtained about when the deepest point is attained or about the recovery as the wave heights and / or water levels decrease (except when regular observations are possible). The washers may occasionally stick rather than sliding down the rod, thus giving an inaccurate reading.
- Analysis of the distribution of tracers, such as dyed sand, with depth. Native sand should be used wherever possible and fluorescent dye is particularly useful as it can be easily detected using UV light. In these tests perhaps 100kg of dyed sand is injected into the beach face. Sediment cores are then taken at the next low tide and the vertical distribution of grains within each core is measured. Taking a number of different cores at known locations allows a picture of the vertical and horizontal distribution of sand grains to be built up. The 80% cut-off rate proposed by Kraus et al. (1982) is often used to determine the significant mixing depth for each sample.

2.1.5 Relative merits of small scale monitoring devices

Any of the linear arrays of measuring devices should give a reasonable time series of beach levels over several tides before the data has to be downloaded and batteries replaced. Some of the devices, such as the Tell-Tail monitors, measure beach movements in discrete steps so small changes can be missed, but make up for that in reliability and in the length of time they operate between downloads. These devices also measure time series through a tide during storms, which manual methods cannot.

The underwater acoustic measurements have the potential to measure the changes in bed level through a tide and measure the sediment transport at the same time, thereby providing more information on the processes involved. They cannot measure through the air-water interface so require a certain depth of water to work in. They cannot therefore capture the full tidal evolution in intertidal zones. They have never been used to measure time series of beach levels in front of seawalls, where the interaction of incident and reflected waves can lead to severe pressures and forces, so their robustness for use there has not been proven.

Of the three methods, the analysis of the distribution of tracers gives the clearest picture of the lateral and horizontal extent of mixing, but requires by far the greatest amount of work. Either the filled plug holes or the graduated rods with washers should be able to measure the greatest depth of sediment transport in front of a seawall reasonably well and can be left for days or even weeks at a time. None of the mixing depth methods provides a time history through a tide. They can only be used to provide a time history of maximum mixing depth during each tide by recovering and resetting the method at each low tide, which would be a time-consuming and labour-intensive exercise.

Linear arrays of measuring devices therefore provide the best way of obtaining time series of beach lowering and recovery through a series of events.

2.2 Medium-scale

2.2.1 Cross-shore profile surveys and topographic surveys

A large amount of each survey data has been collected in the last few years. Large-scale data collection programmes have been set up such as the EA Anglian Region bi-annual measurement of beach profiles and the Channel Coast Observatory[4] mixture of beach profiles, topographic surveys and aerial photography. Beach profiles and topographic surveys are typically collected using the following methods.

2.2.2 Total station

The most frequently used data capture method, in historical monitoring programmes, is by total station theodolite (usually in conjunction with a data logger). The speed of data acquisition is faster than for levelling, since the instrument generally has to be set-up less frequently.

2.2.3 Kinematic GPS

Kinematic GPS provides the opportunity to capture data with a vertical accuracy of approximately ±2 to 3cm and horizontal positioning at approximately ±5cm. A minimum of two GPS receivers, linked by radio, is required. One receiver acts as a base station. The second is carried in a backpack or is mounted on a wheel or staff or an all-terrain vehicle, such as a quad bike.

2.2.4 Laser scanning systems

There are several laser scanning systems on the market that were originally designed for local civil engineering surveys. They scan a laser beam rapidly over a surface and detect the point where the laser beam strikes the surface, thereby quickly building up a cloud of points in three dimensions. These point clouds can be georeferenced by scanning targets at known points. The most common type of scanner measures the time of flight: where a laser pulse is emitted in a known direction towards a surface and the time taken for light scattered from the surface to return to the unit is measured. These devices can have maximum ranges of typically 100m to 1000m and sometimes larger, with the accuracy decreasing with distance. Typically thousands of points may be surveyed each second.

Laser scanning systems have been used to profile beaches where they can survey the beach topography over an entire groyne bay. They have also been used to survey cliffs and coastal defences, so that erosion and the deterioration of defences through time can be established. Research is under way to develop a fixed laser scanning device that will be able to provide a time-history of beach and water levels along a

[4] www.channelcoast.org

cross-section, thus opening up the possibility of simultaneous measurements of tides, waves and (emerged) beach levels (Dr M.R. Belmont, Exeter University, *pers. comm.*, 2006).

2.2.5 CRAB & WESP

CRAB and WESP are tall motorised instrument platforms on three long (typically 6m) legs with large tyres at their bases, which allow these devices to be driven into the sea to a water depth of up to about 5m. The platforms have surveying equipment so that their movements can be used to map out the bathymetry above and below the water level. They may also carry other instruments.

2.2.6 Repeated digital photography

The Argus system of video cameras for beach monitoring has been developed at the Coastal Imaging Laboratory of Oregon State University (Holman et al., 1993). An alternative system called Cam-era has subsequently been developed in New Zealand (Niwa Scientific, 2006). Each installation consists of one or more video cameras that take a snapshot photograph and a 10-minute long averaged exposure photograph of the coastal zone every daylight hour, every day of the year. Each camera is mounted on a tower, promontory or other suitably high feature to allow the photographs to be taken from as high a position as possible, so that the images cover a few hundred metres of the coast. The photographs can be orthorectified so that the location of features can be determined.

Plate 2 Example of Argus snapshot photograph from Teignmouth

Examples of the use of these digital photography systems include:

- The snapshots can be used to identify the shoreline. The cameras can be linked to a tide gauge so that the shoreline positions can be converted into contours, at least when wave activity is low and there is little setup;
- time-averaged photographs can be used to identify where waves break by picking up the foam from breaking waves. Water depth can be inferred, if wave height is known;
- monitoring the evolution of a sandbank at Teignmouth (Aird et al. 2004) and Cleveleys (Alegria Arzaburu et al., 2007);
- determining the intertidal momentary coastline position (MICL), which is used as a coastal state indicator in the Netherlands (Wijnberg et al., 2004). Temporal variation in the MICL can be used to determine when beach nourishment should be performed;
- identifying the location of rip currents; and
- monitoring beach usage by humans or birds.

Detailed examples of application of video images for coastal zone management related issues can be found in Davidson and Medina (2007).

Plate 3 Example of Argus timex (time exposure) photograph from Teignmouth

2.2.7 X-band radar

X-band radar is capable of tracking the movement of wave crests over an area of several square kilometres (Bell, 1999). It works during night times and under rainy and stormy conditions where camera systems offer poor or no resolution. X-band radar can monitor coastal processes during storms and may operate at a site for long periods of time. Time-averaged images can be used to detect the shoreline or the position of longshore bars (Lee et al., 2004, Takewaka, 2005, Esteves et al. 2007, Takewaka et al., 2007). Shoreline positions can be combined with local water level measurements to produce contour lines, from which the foreshore slope can be obtained. Movements in shorelines or bas positions can be assessed using successive time-averaged X-band radar images.

This procedure works if the wave set-up is low (i.e. calm conditions) or if the setup is measured or can be estimated using knowledge of wave height, period and direction. Under good conditions the method was compared to surveyed data and found to produce a mean error of -1.4m in shoreline position with a standard deviation of 11.1m. The X-band radar suffers from shadow zones behind structures so is unlikely to be able to measure beach levels at the toe of a seawall. However, in locations where an X-band radar has been deployed close to a tide gauge it could conceivably produce useful long-term records of beach levels and slopes.

2.3 Large-scale

2.3.1 Map Tidelines or shorelines

The position of the shoreline or tidelines (i.e. location of some representation of high water level and low water level) is commonly marked on maps. Different editions of the same map series, sometimes stretching back more than 100 years, can be used to determine long term changes to the position of the shoreline.

For example, Ordnance Survey rural 1:2500 scale maps (roughly 25” to the mile) include Mean High Water of Ordinary Tides and Mean Low Water of Ordinary Tides and were first commissioned in 1854. In 1880 the production of these maps was accelerated to cover the whole country. These maps are known as the County Series as each county was surveyed separately and often on its own grid system. The County Series were the first UK maps to have been surveyed with regard to a geographical reference system that was displayed on the map itself. The standard scales for detailed mapping became 1:2,500 in rural areas, 1:1250 in urban areas and 1:10,000 in upland areas. The advice in Defra (2003a) is to use 25” to the mile County Series maps (or 1:2500 maps) for the most detailed historical information as these maps provide typical accuracy of 2m to 3m, whereas 6” maps provide accuracy of over 5m. Problems associated with using OS maps to calculate long-term shoreline change have highlighted by Dornbusch et al (2006) and HR Wallingford (2006).

2.3.2 Orthorectified Aerial or Satellite Photos

Aerial photographs have been used in the past, for example by the OS and in some SMPs, to illustrate geomorphologic features and to derive datasets of, for example, the changes in shoreline position. Beach profiles can also be obtained from photogrammetry, as can a detailed topographic map.

They are not, however, maps and offsets may be apparent between overlapping images which can necessitate the use of automated software to correct the distortion (Leatherman, 2003, Moore, 2000). Geo-referenced orthorectified aerial photographs can be incorporated within a GIS to provide the basis for displaying features. Overlaying photographs from different periods allows the changes in identifiable features to be plotted. It is also possible to use satellite photographs for the same purpose, although the resolution is likely to be too poor for satellite photos to be useful in many cases.

Pre 1980 OS aerial photographs are available from the Royal Commission for Historical Monuments for England. OS aerial photographs after 1980 may be purchased from OS agents. Some coastal groups, such as the Channel Coast Observatory have their own photographs. Table 1 shows the relative performance of two different aerial survey programmes within CCO. However, CCO will replace photogrammetry with topographic LIDAR (see Section 2.3.3) in future years.

Table 1 Relative performance of ABMS and Arun DC aerial survey programmes (© 2006 CCO)

Survey variable	ABMS	Arun DC
Frequency	Annual	Quarterly
Shoreline covered	440km	27km
Profile spacing	Approx. 200m	Approx. 20m-50m
Survey Control	Limited ground control, plan position based on OS 2500 scale mapping	Fixed shoreline markers at 300m spacing, photo identifiable control on landward line
Photo scale	1:5000	1:3000
Photography conducted over low water periods	Yes	Yes
Repeatability of survey lines	Variable	Very good
Approx. cost /km/survey (1999 rates excluding control)	£230	£300
Lines perpendicular to shoreline	Variable	Yes
Supply of profiles to end user after survey	Approx. 18 months	Photographs 2 weeks Photogrammetry Approx. 1-2 months
Vertical accuracy (theoretical)	+/-150mm	+/-100mm

2.3.3 Topographic LIDAR

Light Detection and Ranging (LIDAR) is an airborne mapping technique that uses a laser to measure the distance between the aircraft and the ground. Standard LIDAR systems are mounted in aircraft, fly at a few hundred metres altitude and collect 1 to 2 elevation readings per square metre. LIDAR is being used to measure land topography and assess coastal erosion and geomorphological changes. Post-processing routines have been written to allow for the removal of surface features from the data sets including vegetation and buildings. LIDAR data can be used to generate colour-coded elevation models, height contour plots and three-dimensional perspective views allowing easy visualisation of surveyed areas.

LIDAR systems can be combined in a survey aircraft with other operational remote sensing instruments, including the Compact Airborne Spectral Imager (CASI), thermal imager, high quality sVHS video camera and a digital camera. The LIDAR aircraft is positioned and navigated using Global Positioning Satellite (GPS) corrected to known ground reference points. LIDAR surveys typically involve flying at a height of about 800 metres above ground level, which allows a swathe width of about 600 metres to be surveyed. Individual measurements are made on the ground at 2 metre intervals [with a vertical accuracy of ±0.10m to ±0.25m depending on system].

LIDAR and other remote-sensing systems create a point-cloud of positions and elevations that can be can be used to a digital elevation model (DEM or DTM). A datum-based shorelines can then be is created from the intersections between the model and High Water and Low Water contours. If the intention is to achieve historical consistency the Mean High Water / Mean Low Water levels should be set at the same values used in the production of historic maps. In practice the level of MHW/MLW varies along the coast (so is not really a contour at all) so to obtain the actual Mean MHW/MLW at a point it is necessary to perform measurements over a considerable period of time or use numerical modelling to obtain a reasonable approximation.

2.3.3.1 Low-level, low speed LIDAR

Fli-map and Airborne Topographic Lidar System (ATLAS) are air-borne LIDAR systems for surveying linear features and small areas. The systems are based on laser-scanner systems (i.e. LiDAR systems) linked to differential GPS and mounted in a helicopter which flies at an altitude of 60m and 170m (see Investigation of "Fli-map" System for Flood Defence Asset Monitoring, by Tim Burgess, R&D Technical Report W5A-059/TR/1 or ATLAS – High resolution Laser Terrain Mapping). They are similar to LIDAR surveys by aircraft, only operated at lower speed and altitude thereby offering a greater density of points and a better vertical resolution. Typically resolution is 12 – 16 points per metre squared and up to 28 points per metre squared for ATLAS at 150m elevation and 60kph, with a typical swath width of 60m. There was a quoted standard deviation of 80mm on vertical height for Fli-map compared to 170mm for LIDAR from a comparison at one site. ATLAS promises an absolute 3D accuracy of 5cm from 150m altitude. During Fli-map flights, vertical and forward-looking videos are recorded which allow for asset identification and condition monitoring.

2.3.4 Bathymetric LIDAR

Standard topographic laser systems cannot measure through the water surface so are limited to dry, or in the case of beaches, damp areas. The same technology has been adapted to bathymetric surveying and at least three systems have been used in the UK to date:

1. Admiralty Coastal Surveys, using the Hawk-Eye II system;
2. Tenix LADS with the Laser Airborne Depth Sounder, Mark II; and
3. Fugro with the Optech SHOALS-1000T (Scanning Hydrographic Operational Airborne Lidar Survey).

A system that combines bathymetric and topographic lidar with as CASI hyperspectral imager is the U.S. Army Corps of Engineers CHARTS system

(Wozencraft et al., 2007) although the author is not aware of such a system being used outside the USA. The combination of bathymetric and topographic LIDAR allows mapping to be conducted across the shoreline, while the addition of hyperspectral CASI data allows the calculation of coastal classifications such as bottom type and vegetation type.

The main differences between topographic and hydrographic LIDAR are in the wavelength, power and focus of the laser beam. A lower wavelength (typically green rather than infrared) is used to penetrate the water surface but a higher power must be used as the beam is attenuated on passing through water. The laser beam may shine directly at people, who are likely to look up at any aircraft flying at low altitude overhead, so it must be spread out to reduce its intensity and make it eye-safe. The bathymetric LIDAR therefore has a relatively large footprint and averages over an area of the seabed with a diameter roughly half the water depth. The systems are limited to depths of less than about 2 to 3 times the visible depth of water (as determined by the maximum depth a Secchi disk can be seen at).

The systems are normally aircraft mounted and survey over a SWATH in front of the aircraft. The advantages over traditional bathymetric data-gathering systems are the SWATH width and the speed of survey. The data density is not as good as a multi-beam sonar system and they cannot work through surf. More information can be obtained from company web sites or publications by, for example, Pope et al., (1997) or Wozencraft (2003). The systems are accurate to IHO Order 1 specifications, with quoted vertical accuracies of typically ±0.15m and horizontal accuracy ±3m with DGPS and ±1m with KGPS (for SHOALS).

2.3.5 Synthetic Aperture Radar

The application of the recently built MDSF (Modelling and Decision Support Framework) to the development of CFMP's and SMP's has triggered the need to acquire more appropriate flood plain/area topographic data than that produced by LIDAR. It has led to the Environment Agency co-funding (with Norwich Union) the collection of SAR (Synthetic Aperture Radar) data as a basis for developing a DEM (digital elevation model) of fluvial flood-plains and coastal flood prone areas. SAR is also known as Side-Looking Airborne Radar (SLAR) as it only works when the radar beam is mounted sideways. SAR imagery requires tremendous signal processing power, transmitter signals of extreme purity and a platform that moves precisely in a straight line (although deviations from a linear path can be processed out). SAR can look through clouds and rain and does not rely on daylight. Different ground features have different reflectance properties and signal processing can be used for land cover classification.

2.3.6 Bathymetric surveying

Historically bathymetric data was obtained using a lead line (a weighted line) deployed from a ship to measure the water depth. A correction has to be made for tidal elevation to obtain seabed level. This was combined with standard surveying to obtain a position.

More recently the use of single beam echo sounder allowed a line of points to be surveyed. This system allowed significant underwater features to be missed if the survey transect spacing was significant compared to the bathymetric feature. This limitation was overcome by the development of multi-beam (or swathe) bathymetry systems which survey over a width of seabed that is up to about eight times the water depth. Swathe systems need the use of a gyro-system as well as DGPS to allow the data to be transformed into a given coordinate system.

2.3.7 Advantages and disadvantages of medium and large scale survey techniques

The longest time series of shoreline positions can be obtained from OS maps. The best accuracy can be obtained from 1:1250 or 1:2500 OS maps from 1879 onwards (providing that MHWOT/MLWOT were mapped rather than MWHS/MLWS). Records of aerial photographs sometimes extend back over 50 years and have been the most common source of OS tide lines since the 1970s.

Airborne SAR and LIDAR can survey a large area faster than ground surveys. The use of DGPS on a backpack or quadbike is a faster method of ground survey than conventional triangulation. LIDAR systems can therefore survey large lengths of defence in a day and are particularly useful for remote defences or those with difficult access (because of, say, saltmarshes).

LIDAR systems record the first returned signal, which can be from the top of vegetation, so routines have been written to remove such surface features. The lower-level higher-resolution systems, such as Fli-Map, collect a much larger number of points per metre squared (have a higher point-cloud density) so they are more likely than conventional LIDAR to see through gaps in vegetation and record the ground level underneath tree cover. A ground survey can obtain more than just top surface level and position, so can contribute more to a condition survey than even high-resolution LIDAR.

A ground survey is still the most accurate form of survey. Conventional (higher level, faster speed) LIDAR is suitable for large area surveys (>10km^2) where detail is not too important, while lower level, higher resolution LIDAR is suitable for long lengths of structure (>2km) with video images being used to assist in condition surveys. Ground surveys are suitable for detailed descriptions of small areas or vegetated areas, particularly where further information is required.

One of the most important data needs is for the beach level at the toe of coastal defence structures. In order to be able to identify the beach levels with reasonable confidence, a high resolution is required. Conventional LIDAR can now provide elevations within ±0.15m, which is good enough for this purpose, but if the data is at 2m intervals, the LIDAR system may miss a seawall. High-resolution LIDAR can provide greater accuracy and reduced distance between surveyed points, so it and ground-survey would achieve the required resolution. All remote sensing systems need a good network of control points to be at their most effective.

3 Monitoring Guidance and Practice

Different regions and countries have different practices for data collection. Examples of regional data collection programmes include:

1. Jarkus coastal profiles collected annually along the Dutch coastline since 1964.
2. Anglian Region coastal profiles collected twice a year since 1991.
3. Channel Coastal Observatory, which includes waves, tidal levels, coastal profiles measured typically four times per year since 2001. See http://www.channelcoast.org/programme_design/ for information on survey programme design.

The key points for monitoring guidance include (in no particular order):

- Establish a reliable system of ground control points or permanent markers that are used by all surveying groups, whatever technique they are using;
- Explicitly state the datum system to be used;
- Establish a clear set of guidelines for the surveys, including tolerances and National or International Standards to be met (such as ISO or British Standards) and guidance on when to survey (with respect to the months, the spring-neap tidal cycle and the occurrence of storms);
- Establish what the data is to be used for. A wide range of data could be used in coastal management, including data on winds, waves, tides, beach sediment, offshore bathymetry, coastal profiles, geomorphologic features, coastal defences, beach nourishment or recycling. All will cost money to collect and that cost should be justified. A survey programme may, therefore, be based on a conceptual (or numerical) model of coastal hazards or risks. For example, exposed sites with a high risk or flooding or coastal erosion may be surveyed at a closer spacing and more often than a hard rock coastline with a strategy of no active intervention.

4 Models for coastal erosion risk management

4.1 Historical trend analysis

Historical trend analysis relies on the extrapolation of historic data to predict future coastal evolution. A statistical model can only predict behaviour under conditions that are similar to those in the historic record and cannot cope with changes in forcing conditions, beach management or geological controls. Statistical methods can use long-term data sets, such as OS maps, which are available for the entire coastline at a number of times. The use of long-term datasets may allow extrapolation further into the future than from using shorter datasets. Shorter-term, often more detailed datasets, can be used to try and confirm the long-term behaviour and can be used for analysis at shorter timeframes.

The majority of statistical modelling performed for coastal management appears to have been carried out using the simpler linear analysis methods detailed in Section 4.2. The more complicated linear analysis techniques (Section 4.3) and the non-linear analyses (Section 4.4) have only recently been applied to beaches. Their use generally requires larger quantities of high-quality data than have historically been collected.

Larson et al. (2003) noted that the choice of method for data analysis depends crucially on the quality and the quantity of data. The more sophisticated methods require more data of good quality and may pose additional constraints on the data, such as the need for data to be equally spaced in time and position. This will restrict their use to the limited regions where long term high quality datasets of coastal morphology exist. The shortage of locations with high quality data on morphology extending over years to decades is one major obstacle in the quest to understand and predict beach response over these scales. The shortage is being addressed through the development of regional monitoring programmes, such as the Environment Agency's Anglian Region beach monitoring programme that has been performing beach profile surveys twice a year since 1991 and the Channel Coast Observatory that has been operating since 2002. The use of the more advanced linear and non-linear techniques is likely to become more widespread in time as the quantity and quality of data collected increases, provided that the original examples of the methods prove to have been useful predictors.

Any analysis is likely to start with a review of bulk properties such as the mean and standard deviation of the beach level at each point or the cross-shore position of a contour line. The more advanced methods allow the morphological response at different scales to be identified, with the analysis and modelling at that scale being independent of processes at other scales. In some areas statistically-based models may show as much skill as physically-based models, but the application of a statistical model to a different beach to the one it was developed at is likely to require more data to recalibrate the model than a physics based model would require. 'Skill' is defined as a non-dimensional measure of the accuracy of a prediction compared to the accuracy of a baseline prediction (Sutherland et al., 2004).

4.1.1 Linear analysis of beach level data

Straight lines fitted to beach level time series give an indication of the rate of change of elevation and hence of erosion or accretion. The measured rates of change are often used to predict future beach levels by assuming that the best-fit rate from one period will be continued into the future. Alternatively, long-term shoreline change rates can be determined using linear regression on cross-shore position versus time data.

Douglas and Crowell (2000) have shown that simple regression is superior to end-point rate and complex statistical methods for calculating shoreline erosion rates. Genz et al. (2007) reviewed methods of fitting trend lines, including using end point rates, the average of rates, ordinary least squares (including variations such as jackknifing, re-weighted least squares, weighted least squares and weighted re-weighted least squares) and least absolute deviation (with and without weighting functions). Genz et al. recommended that weighted methods should be used if uncertainties are understood, but not otherwise. The ordinary least squares, re-weighted least squares, jackknifing and least absolute deviation methods were preferred (with weighting, if appropriate). If the uncertainties are unknown or not quantified then the least absolute deviation method should be preferred.

Confidence limits can be calculated to provide a measure of the reliability of the erosion or accretion rate. They provide a range for the calculated erosion or accretion rate and depend on the variance of the data, the number of samples and the desired level of confidence. They strictly apply only to the time period the data was collected in. The extrapolation of trends and confidence limits into predictions assumes that the future hydrodynamic climate will be statistically similar to the climate during the period the measurements are made.

That assumption is tested by calculating a prediction horizon, defined as the average length of time over which a trend produces a useful level of prediction of future beach levels. This method for establishing a prediction horizon is taken from meteorological modelling and was outlined by Murphy and Epstein (1989), adapted for cross-shore profile modelling by Brady and Sutherland (2001) and was adapted by HR Wallingford (2006) for the prediction of beach levels at the toe of a coastal structure.

The procedure uses the Brier Skill Score (Murphy and Epstein, 1989, Sutherland et al., 2004), which is a non-dimensional measure of the accuracy of the linear trend (fitted to M years of data) relative to the accuracy of a baseline prediction of future beach levels. In this case the baseline prediction of future elevations is that they will all remain at the average level of the M years of measured data. Murphy and Epstein found that their meteorological model had a skill score that decreased smoothly with time, on average. The prediction horizon was the maximum length of prediction that gave a useful level of predictive skill, determined from when the average skill score dropped below a threshold value. Here the useful threshold value of the Brier Skill Score is zero, as it is at this level that the baseline prediction is as good as the prediction obtained from extrapolating the trend.

Results from 30-year long time series of measurements in Lincolnshire (England) indicated that the linear extrapolation of the best-fit straight line fitted to 10 years of data had a prediction horizon of 1 to 15 years, depending on the profile. Part of the reason for having low prediction horizons may have been alterations in methods of coastal management during the period of the measurements, which may have caused relatively rapid responses in the beach levels. This violates one of the assumptions in the method.

4.1.2 Advanced linear analysis of beach level data

There are a number of linear data analysis and modelling techniques that are useful for the prediction of the long-term evolution of beaches. These have been summarised by Larson et al. (2003) whose paper this section is based on. Correlation may be used to assess the effect of, say, wave height on bar movement. Fourier analysis and Random Sine Function (RSF) analyses are useful in identifying features of different lengths, but are less useful in determining beach levels at a coastal defence structure. Fourier theory assumes that the signal has a constant average and is periodic in nature.

4.1.2.1 Wavelet analysis

Wavelet analysis uses a mother kernel (an oscillating signal) that is localised in time or space, so wavelets are well suited to looking at phenomena that vary in time or space. Each kernel has a zero mean and a squared norm of 1 and they all damp rapidly to zero. Li et al. (2005) used the adapted maximal overlap discrete wavelet transform (AMODWT) to analyse beach profiles at the USACE Field Research Facility at Duck (NC, USA). Their first analysis used spatial wavelets to look at the relative importance of variations at different lengthscales across the beach. Locations where the variance in elevation changes can be identified from a simple analysis, but wavelet analysis enables the length scale of the changes to be identified.

The second analysis used wavelets of different timescales, which showed that there were no dominant timescales of variation throughout the record. The balance between different time scales varied along the beach profile. The shortest timescale of 2 months showed a reasonably smooth change in variance with cross-shore position, with the highest wavelet variance occurring near the innermost position of the bar trough and decreasing gently over the bar. The longest timescales (32 and 64 months) showed two peaks in wavelet variance, associated with the base of the beach (inshore of the bar) and a typical bar position. This indicates a link between the development and cross-shore movement of the bar and the beach inshore from it. Further work is going on to look at the shoreline trend, which may provide a useful tool for investigating beach level changes at the toe of coastal structures.

4.1.2.2 Empirical Orthogonal Function (EOF) analysis

EOFs are shape functions extracted from morphological data. They correspond to a statistically optimal description of the data (Larson et al., 2003) with respect to how variance is concentrated in modes. The variance decreases as mode number increases so a finite (often small) number of modes explain most of the observed variance in the data. There is no reason for the EOFs to have a physical meaning, although EOFs often can be matched to physical processes. One disadvantage of EOF analysis is that it cannot resolve fixed shapes that propagate with time, although that can be addressed by extending the technique to Extended EOF (EEOF) analysis or Complex Principal Component Analysis (CPCA) (Larson et al., 2003, p765).

EOF was originally applied to coastal morphology in investigations of beach profiles where morphological characteristics were associated with lower EOF modes. EOF has become increasingly used in research studies where beach profile data extends over a few years (Winant et al., 1975, Aubrey, 1979, Wijnberg and Terwindt, 1995, Möller, 1997, Larson et al., 1999b).

4.1.2.3 Canonical Correlation Analysis (CCA)

Canonical Correlation Analysis (CCA) "may be used to investigate if there are any patterns that tend to occur simultaneously in two different data sets and what the correlation is between associated patterns" (Larson et al., 2003, p768, column 1). Larson et al. (1999a) used CCA to determine the covariability between waves and profile response at Duck, North Carolina, USA. The profile response was reasonably well correlated to the nearshore wave conditions, indicating that CCA could be used for the prediction of beach profiles from waves, particularly close to the shoreline where wave-breaking processes were dominant. CCA could therefore be used to provide a predictive tool for beach levels in front of coastal structures.

4.1.2.4 Principal Oscillation Pattern (POP)

In POP the data is analysed using patterns based on approximate forms of dynamical equations so may be used to identify changing patterns, such as standing waves and migrating waves (Larson et al, 2003). POP is a linearised form of the more general Principal Interaction Pattern (PIP) analysis. A POP analysis using the long-term Dutch JARKUS dataset of cross-shore beach profiles (Jansen, 1997) showed that POP systematically lost 4% to 8% more data than an EOF analysis. The prediction method was optimised using 8 POPs as adding more POPS included more of the noise. Różyński and Jansen (2002) applied POP analysis to 4 beach profiles at Lubiatowo (Poland) and recommended that en EOF analysis be carried out first.

4.1.3 Nonlinear analysis of beach level data

There are a number of non-linear data analysis and modelling techniques that are useful for the prediction of the long-term evolution of beaches. These have been summarised by Southgate et al. (2003) whose paper this section is based on. They note that the available time series of morphological data from in-situ measurements are usually too small for a full non-linear statistical analysis of the system dynamics. In these cases it may still be possible to test a hypothesis.

4.1.3.1 Singular Spectrum Analysis

Singular Spectrum Analysis seeks to identify the type of attractor state and the number of independent variables needed to describe the system. SSA is an application of EOF analysis that uses time-lagged variables. SSA could be employed for predictive purposes in the coastal zone if it was combined with an autoregressive model to form a linear forecasting algorithm. SSA has been used to extract long-term fluctuations in shoreline positions at Ogata, Japan and Duck, NC, USA (Southgate et al., 2003). The sum of the three lowest components from the SSA analysis was plotted with the raw data and gave the appearance of a smoothing filter. However, the method is capable of picking up long-term trends.

Różyński (2005) studied the long-term shoreline response at the Coastal Research Station at Lubiatowo (Poland) using multi-channel SSA (MSSA). Three longshore standing waves were detected with periods of several decades, 20-22 years and 7-8 years. The typical period of the North Atlantic Oscillation corresponds to that of the most frequently encountered 2nd standing wave component (7–8 years) indicating that the NAO may drive a component of the morphological evolution.

4.1.3.2 Fractal Analysis

A fractal shape is self-similar so it looks similar if seen at different scales. Every fractal process has a Hurst exponent, H, that represents the amount of persistence in the system. Fractal analysis requires less data than SSA and has been applied to beach profile data from Lincolnshire by Southgate and Beltran (1996) and Duck, NC, USA by Möller (1997) and Southgate and Möller (2000). The fractal analysis showed which timescales were dominated by self organised behaviour and which by forced behaviour.

4.1.3.3 Neural Networks

A neural network consists of a set of inputs and outputs connected by one or more layers of nodes. Each input and output is normally connected to all the nodes in the next layer. Most neural networks need to be trained using test data sets of input and output. The neural network should then have a forecasting capability when presented with new input data. Experience with neural networks is mixed. Southgate et al. (2003) reported the results of one forecasting competition where neural networks gave both the best and the worst results. Southgate et al. (2003) concluded that successful neural networks require some preliminary data analysis and expert knowledge. Kingston and Davidson (1999) provide a good example of the use of neural networks to predict sand bar evolution.

4.2 Process-based models

A considerable amount of research has been carried out over the least 20 years to develop predictive numerical models of coastal evolution covering periods of up to 20 years or more. These models are based on representations of physical processes and typically include forcing by waves and/or currents, a response in terms of sediment transport and a morphology-updating module. However, there are still major gaps in our understanding of long-term morphological behaviour (de Vriend et al., 1993, Southgate and Brampton, 2001, de Vriend, 2003, Hanson et al., 2003) which mean that modelling results are subject to a considerable degree of uncertainty. Their use requires a high level of specialised knowledge of science, engineering and management.

Southgate and Brampton (2001) provide a guide to model usage, which considers the engineering and management options and the strategies that can be adopted, while working within the limitations of a shortfall in our scientific knowledge and data. They also include a short description of the major classes of model and some of their descriptions are used in the following sections, which have been augmented by a few additional references and comments.

4.2.1 One Line models

In these models, the sand beach morphology is represented by a single contour, and such models are therefore often referred to as “one-line” models. Usually the x-axis is established approximately parallel to the coastline, and the y-axis directed offshore. The changes in the position of this contour, together with other parameters such as wave conditions, currents, and sediment transport rates, are functions of only longshore position (x) and time (t) and so the model is referred to as “one-dimensional”.

Predictions of changes in the beach and nearshore seabed plan-shape are produced. The beach profile is usually assumed to be constant, i.e. unchanging with time. A good starting point for those interested in the theory and application of beach plan-shape models is the paper by Bakker, Klein Breteler and Roos (1970). This not only discusses the simplest “one-line” approach to such modelling but also takes the first step in the development of a model that allows some variation in profile along the shoreline.

One-line numerical models originated from analytical solutions to the diffusion equation for the small amplitude departures from a rectilinear coastline (Pelnard-Considère, 1956, Falqués, 2003). There has been revived academic interest in the use of analytical solutions in recent years (Falqués, 2003, Murray and Ashton, 2003, Reeve, 2006) but most one-line modelling for coastal management is likely to be performed using numerical models (e.g. Hanson and Kraus, 1989, Ozasa and Brampton, 1980) due to their flexibility in modelling realistic, non-idealised coastlines. Numerical models can include seawalls and groynes.

Sometimes the one-line model is extended to model a number of different contours. These models are known as N-line models, but they are relatively uncommon compared to one-line models.

4.2.2 Coastal Profile Models

Coastal profile models simplify the coastal system to a 2D system (with elevation and cross-shore distance) which assumes longshore uniformity. These models commonly include wave shoaling, wave breaking due to depth and bottom friction, cross-shore undertow and sediment transport, but usually there is only a very limited representation of the effects of longshore transport. All such models predict beach profile changes, and the movement of sediment perpendicular to the contours (but not both together).

Van Rijn et al. (2003) compared the results from coastal profile models with hydrodynamic and morphodynamic data on the time scale of storms and seasons and the results from van Rijn et al (2003) are summarised below. Profile models were shown to predict the cross-shore variation in significant wave height to within 10% if properly calibrated. They were also shown to predict offshore and longshore current speeds in the laboratory and in the field within 40%. Profile models can also reasonable represent the movement of outer and inner sand bars on the time-scale of storms. They cannot simulate the beach recovery process on the post-storm scale, as the 3D processes involved are not sufficiently well understood to be parameterised. Profile models cannot be used to simulate the behaviour of sand bars or the beach on a seasonal scale unless they have been tuned using beach profile data.

4.2.3 Coastal Area Models

Process-based coastal area models have been used for years to study short term (generally depth-averaged) hydrodynamic and sediment transport problems, and given their ability to simulate fields that are both identifiable and (potentially) verifiable, there is appeal in the potential for applying such models to longer term problems. However, the issues associated with application of process based models are long-established (see for example, de Vriend et al., 1993), and include problems associated with the requirement to model large areas, with relatively fine meshes (in order to resolve the relevant processes) and the need to simulate relatively long timescales. There are also the associated problems of supplying the model with the correct set of input conditions (and sometimes the sequence of these conditions) that will determine the morphology.

In order to drive the model for long-term simulations it is necessary to perform simplifying or filtering techniques. These are of 2 main types:

- Input filtering involves selecting a number of representative cases, rather than running a full time series;
- Process filtering involves reducing the number of computations made by, for example reducing the number of calls to the flow model and using continuity, for example, to adjust flow speeds between full runs of the flow model.

One of the limitations of coastal area models for considering beach evolution in front of coastal structures are that surf-zone processes, such as undertow, are not represented in the model. Wave reflection and diffraction are only rarely included in coastal area models.

4.2.4 Systems model: SCAPE

Walkden and Hall (2005) have recently developed a long-term model of the effect of waves, tides and sea level rise on littoral transport and the erosion and profile development of soft cliffs and shore platforms, called Soft Cliff And Platform Erosion (SCAPE). This models the development of the shore platform, beach, talus and cliff at a series of representative cross-shore profiles, each of which is represented by a column of elements. The quasi-3D representation is achieved by allowing the profiles to interact, by exchanging beach material alongshore between profiles using a simple 1-line approach.

Each cross-shore profile can also be run independently (provided the beach volume is set by the user). SCAPE is effectively a longshore-linked set of relatively simple cross-shore profile models that includes a one-line module. As such it is more complicated and representative than an N-line model or a set of cross-shore profile models.

SCAPE models the interactions between different elements of the system and the emergence of system properties, particularly profile shape. The model is processed-based, so allows the effects of climate change and the construction of local defences to be included. The model may be run over the timescales of decades (Walkden & Hall, 2005) and centuries (Dickson et al, in press) and over tens of kilometres.

SCAPE has been used to model the soft cliff and platform erosion at the Naze, Essex (Walkden and Hall, 2005) and the between Weybourne and Happisburgh, Norfolk (Dickson et al., 2005). Koukoulas et al. (2005) describe the addition of a GIS front end to help presentation and interpretation of the results.

4.3 Vulnerability Mapping

Vulnerability mapping is carried out by associating mapped features with a risk of coastal erosion and combining a number of these factors to give an overall measure of the vulnerability of the stretch of coastline to coastal erosions. The features involved typically include:

- source hazards, such as wave climate, tidal range and relative sea level rise; and
- receptor strength; such as geomorphology, historic coastal erosion rates and coastal slope.

Examples of vulnerability mapping for coastal erosion are given in the subsections below. Vulnerability mapping for coastal flooding is more common.

4.3.1 Eurosion exposure to coastal erosion

The Eurosion project used a list of regional indicators and weighting functions to map out each region's exposure to coastal erosion, based on its sensitivity to erosion and the impact of erosion. Eurosion's maps can be used to assess the coastal typography, geology and coastal erosion trends of a region. The maps also include the location of engineering works (whether harbours, jetties groynes or breakwaters). There is an additional map for regional exposure to coastal erosion. The GIS layers are downloadable from the European Environment Agency.

4.3.2 Flood and Coastal Defence national overview of coastal erosion potential

The UK shoreline is eroding in response to a continuous rise in sea levels that has taken place since the last ice age. Predicted increases in the rate of sea level rise (accelerated sea level rise or ASLR) will increase the erosion potential at the coastline. The response of the coast to erosive forces depends on the geomorphology of the coastal zone. There is a degree of interdependence between adjacent stretches of the coastline, so no stretch should be considered in isolation. 67% of the coastline is under threat of erosion (Halcrow, 2002). Work for Defra (2001) determined that 1/3 of coastal defences could not be maintained in the future with present-day levels of expenditure.

The Office of Science and Technology's Flood and Coastal Defence Foresight project (Evans et al., 2004) has estimated potential unconstrained shoreline evolution under four UKCIP02 future climate change scenarios (National Enterprise, Local Stewardship, World Markets and Global Sustainability). Evans et al. (2004) used basic assumptions on relative sea level rise, surge activity, wave height, littoral drift and shoreline movement. Average erosion rates were predicted at a national level, reproduced in Table 12. The results are mapped in Figure 37 (reproduced from Evans et al., 2004). The calculations ignored coastal defences, however, so actual levels of erosion may be lower. The results indicate the importance of considering long-term coastal erosion as well as toe scour in considering the long-term stability of coastal defences.

Table 12 FCD estimates of average future erosion over 100 years for England and Wales (Evans et al., 2004, Table 6.1)

Present conditions (benchmark)	World Markets	National Enterprise	Local Stewardship	Global Sustainability
20-67m	141-175m	113-150m	99-138m	82-123m

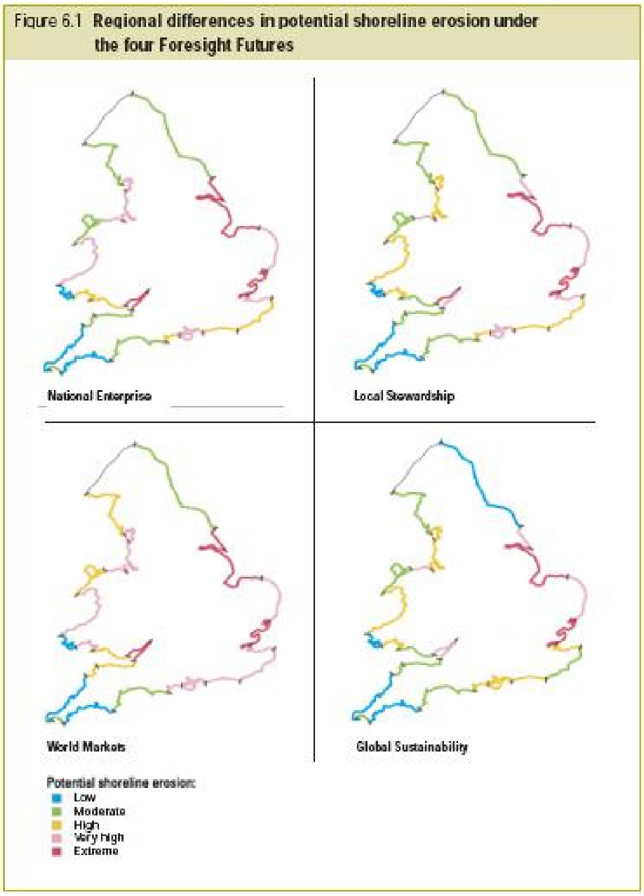

Figure 37 Regional differences in potential shoreline erosion over the next 100 years for different UKCUP02 climate change scenarios (Evans et al., 2004, Figure 6.1, © Crown Copyright, 2004)

4.3.3 USGS Coastal Vulnerability Index

The US Geological Survey (USGS) has devised a physically based coastal vulnerability index (CVI) to assess the vulnerability of the coastline to climate change (Hammer-Close and Thieler, 2001; Thieler and Hammer-Close, 1999, 200a, 2000b). The prediction of future coastline position is a difficult task, for which no standard predictive techniques have been developed. The National Research Council (1990) report listed the following approaches and outlined the limitations of each:

- extrapolation of historical data (e.g. coastal erosion rates);
- static inundation modelling;
- application of a simple geometric model (e.g. the Bruun Rule);

- application of a sediment dynamics/budget model; or
- Monte Carlo (probabilistic) simulation based on parameterized physical forcing variables.

In addition to the limitations of the approaches, the data needed to apply the approaches is almost certain to be of variable quality (if it exists at all). Furthermore human intervention at the coast will affect its development and the priorities of coastal management. The USGS team collected data on the following six physical variables (Hammer-Close and Thieler, 2001; Thieler and Hammer-Close, 1999, 200a, 2000b):

1. Geomorphology derived from state geology maps;
2. shoreline erosion and accretion rates (m/yr) from the Coastal Erosion Information System (May et al., 1982);
3. regional coastal slope (percent), from the subaerial coastal plain to the submerged continental shelf. This was calculated using data from up to 50km offshore, as coastal slope affects the risk of flooding and coastal erosion (Pilkey and Davis, 1987);
4. rate of relative sea-level rise (mm/yr) from tide gauges;
5. mean tidal range (m) from the National Ocean Service; and
6. mean wave height (m) from the USACE Wave Information Service.

The variables were mapped at the level of the coastal county. Each variable was allocated an integer ranking between 1 (very low risk) and 5 (very high risk) for each section of the coast. An example of the ranking of the elements of the CVI is shown in Figure 38 for the Atlantic coastline. Different ranges were used for the coastlines of the Gulf of Mexico and the Pacific. Large tidal ranges were assigned a low risk as high tidal levels and high storm surges will occur together for relatively short periods of time compared to situations with a low tidal range.

	Ranking of coastal vulnerability index				
	Very low	Low	Moderate	High	Very high
VARIABLE	1	2	3	4	5
Geomorphology	Rocky, cliffed coasts Fiords Fiards	Medium cliffs Indented coasts	Low cliffs Glacial drift Alluvial plains	Cobble beaches Estuary Lagoon	Barrier beaches Sand Beaches Salt marsh Mud flats Deltas Mangrove Coral reefs
Coastal Slope (%)	> .2	.2 – .07	.07 – .04	.04 – .025	< .025
Relative sea-level change (mm/yr)	< 1.8	1.8 – 2.5	2.5 – 2.95	2.95 – 3.16	> 3.16
Shoreline erosion/ accretion (m/yr)	>2.0 Accretion	1.0 – 2.0	-1.0 – +1.0 Stable	-1.1 – -2.0	< - 2.0 Erosion
Mean tide range (m)	> 6.0	4.1 – 6.0	2.0 – 4.0	1.0 – 1.9	< 1.0
Mean wave height (m)	<.55	.55 – .85	.85 – 1.05	1.05 – 1.25	>1.25

Figure 38 Ranking of the six variables in the CVI for the US eastern coastline (from Thieler and Hammer-Close, 1999)

The CVI for each section of coastline was calculated using Equation 4, where *a*, *b*, *c*, *d*, *e* and *f* are the integer rankings of the six variables in Figure 38.

$$CVI = \sqrt{(a \times b \times c \times d \times e \times f)/6} \qquad (4)$$

The CVI values were placed in rank order and the 25th, 50th and 75th percentiles were chosen as the boundaries between the ranges for low, moderate, high, and very high risk areas (Thieler and Hammer-Close, 1999). Different variables contributed the most to vulnerability in different sections of the coastlines mapped. Examining the results at a more detailed scale showed that erosion and accretion rates contributed the greatest variability to the CVI at short (~3 km) spatial scales (Thieler and Hammer-Close, 1999). The rates of shoreline change were believed to be the most poorly documented variable used, indicating that improvements to the methods of determining shoreline position and adopting a consistent approach along the whole of a section of coastline to be considered would lead to improvements in the vulnerability assessment.

Boruff et al. (2005) developed a coastal social vulnerability index (CoSVI) to determine the socioeconomic vulnerability of coastal counties to sea level rise. They also combined the CVI with the CoSVI to determine an overall place vulnerability index (PVI). Maps of CVI, CoSVI and PVI were produced for US Atlantic coastal counties, Gulf coastal counties and Pacific coastal counties.

4.3.4 Storm erosion potential index

Zhang et al. (2001) reviewed various measures of the erosion potential of storm and derived a Storm Erosion Potential Index (SEPI). They deduced that the severity of coastal erosion induced by storms is a function of total water level (tide + surge + set-up), wave energy, storm duration and beach characteristics. Dean (1991) used his equilibrium beach profile theory to argue that storm induced beach erosion depends on water level more than wave height. Steetzel (1991, 1993), for example, performed a set of laboratory tests and found that water level was the most important factor in causing beach erosion, with wave height a secondary effect. Balsillie (1986, 1999) deduced that water level contributes 75% of the storm-induced beach erosion along America's East and Gulf coasts and that storm duration is also important in allowing waves to erode the beach.

Water level has to include tidal level, storm surge, wave set-up and swash run-up. Kriebel and Dalrymple (1995) estimated that setup is about $H_0/8$, where H_0 is the incident significant wave height in deep water. Zhang et al. (2001) noted that dune erosion was small until the water level reached the toe of the dune, which is often around Mean Higher High Water (MHHW). They used MHHW as the threshold elevation for beach erosion and calculated the water level above MHHW, denoted S_{MHHW}. They also calculated a relationship between wave height and storm surge height so used the storm surge height above two standard deviations, S_{2SD}, to represent storm wave energy. The Storm Erosion Potential Index (SEPI) was then calculated using Equation 5:

$$SEPI = \sum_{t=0}^{t_d} S_{2SD}(t) S_{MHHW}(t) \Delta t \qquad (5)$$

where t_d is the duration of the storm and Δt is the time interval between data points. Tide gauge data was used to calculate S_{2SD} and S_{MHHW} without removing long-term trends in sea level. The model results were compared to three storms and to time series of shoreline position at some locations. Zhang et al. (2001) noted that the frequency of occurrence of water levels above present MHHW has increased due to increases in sea level. This has exacerbated erosion and flood damage and means that coastal structures will suffer greater levels of damage that may require mitigation.

Mendoza and Jiménez (2006, 2007) have developed a method to estimate coastal vulnerability to storm impacts at regional scale. It assesses the physical coastal vulnerability to storm impacts by separately estimating two components: flooding and erosion and it was applied to the Catalan coast.

4.4 Geomorphological analyses

Geomorphology is the study of the features that make up the earth's surface and their relationship to the underlying geology. A geomorphological study will provides a conceptual picture of coastal processes and the potential behaviour of the coastal system. This includes taking into account changes in the bedrock composition that could affect the potential rate of future coastal evolution. The results tend to be qualitative, rather than quantitative. This section starts with a description of how a sediment budget may be used to provide a view about future beach levels in front of a coastal structure. The section then describes the UK Futurecoast project that have has a significant geomorphological component. Many geomorphology studies use a range of tools, including predictive numerical models. As such many geomorphology studies are effectively a composite of the different modelling techniques, as advocated by, for example, Cooper and Pilkey (2004).

4.4.1 Sediment Budget

Sediment budgets are often constructed to assist with coastal management. A sediment budget allows an estimate to be made of the rate of accretion or erosion of sediment within a pre-defined area of the coastal zone (see Rosati, 2005, for a recent review). The main steps involved in constructing a sediment budget are:

- Set appropriate boundaries for the sediment budget and for internal boundaries that separate sub-cells within the overall area to be considered;
- Identify sources, pathways, stores and sinks of sediment within the budget area;
- Calculate the rate of erosion from sources and stores and accretion in stores and sinks. These estimates may come from numerical models but are more likely to be derived from data;
- Calculate the sediment transport rates at the boundaries of the subcells and estimate the uncertainty in each transport rate. The calculations of transport rate may come from data but are more likely to be derived from numerical models; and
- Integrate the gains and losses within each section to obtain an overall sediment budget.

A good sediment budget will provide a useful indication of whether a beach in front of a coastal structure is likely to be subjected to beach lowering due to loss of sediment from the entire beach. Even if this is not the case and beach volumes have been constant or increasing, a coastal structure may be subject to beach lowering due to local effects.

4.4.2 Futurecoast

Futurecoast (Halcrow, 2002, Burgess et al., 2002) was commissioned by Defra (2003b), to improve the understanding of coastal evolution for the open coast of England and Wales. Futurecoast is the obvious starting point for any assessment of future coastline behaviour over decadal timescales. It contains:

- Shoreline behaviour statements that give an improved understanding of coastal behaviour and qualitative predictions of future coastal evolution at both large and small scales;
- Assessment of future behaviour for an unconstrained scenario (with no defences or management) and a managed scenario (where present management practices continue indefinitely); and
- A 'toolbox' of supporting information and data including cliff behaviour statements, historical shoreline changes, wave modelling, an uncertainty assessment, morphological measurements including beach width, a coastal geomorphology reference manual and a thematic studies on onshore geology, offshore geology, coastal processes, climate change and estuaries.

Honeycutt and Krantz (2003) also illustrated how the local geology affected shoreline change rates along the Delaware coast, using data from high-resolution seismic-reflection profiles, cores and historic shoreline positions. They believe that it may be possible to quantify the effect of large-scale changes in geology on shoreline erosion, but not small-scale ones. Honeycutt and Krantz (2003) provide a different scientific basis for modifying calculations of past shoreline change rates to estimate future shoreline change rates.

4.5 Parametric equilibrium models

Parametric equilibrium models represent the shape of the coastline or its response to forcing through simple equations that have been derived through a mixture of curve-fitting and theoretical considerations. They are necessarily simplistic, but quick to apply.

4.5.1 Equilibrium Beach Profile

Bruun (1954) examined beach profiles in Denmark and California and concluded that the cross-shore profile in the vertical could be expressed in the form:

$$h = Ay^{2/3} \qquad (6)$$

where h = water depth, A is a sediment scale parameter and y is the cross-shore distance from the shoreline. In 1977 Dean examined the forms of equilibrium beach profiles that would results from different dominant forcing mechanisms and concluded that equilibrium beach profiles would take the form shown above if the dominant destructive force was wave energy dissipation per unit volume (Dean, et al., 2002). The sediment scale parameter can be related to sediment size or fall speed (Dean, ibid) so Equation 6 can be used to make predictions about beach profiles.

Alternative forms of the equilibrium beach profile have been developed by other authors, but these have more free parameters and so are less suited to making predictions as calibrations tend to be site-specific (Dean et al., 2002). The main problems with the equilibrium beach profile are that the slope is infinite at the water line and the profile does not allow for bars.

4.5.2 Bruun rule for coastal retreat

Bruun (1962) proposed Equation 7 for the equilibrium shoreline retreat, R that will occur as a result of sea level rise, S.

$$R = S\frac{L}{h + B} \qquad (7)$$

Here L is the cross-shore width of the active profile (i.e. cross-shore distance from closure depth to furthest landward point of sediment transport), h is the closure depth (maximum depth of sediment transport) and B is the elevation of the beach or dune crest (maximum height of sediment transport). The equation balances sediment yield R(h+B) from the horizontal retreat of the profile with sediment demand, SL, from a vertical rise in the profile (Dean et al., 2002). The Bruun rule does not depend on a particular coastal profile. The magnitudes of h and B are difficult to determine, however and the actual seabed will need time to respond to a change in sea level. The Bruun rule has been extensively modified and developed (see Dean et al., 2002 for a summary).

4.5.3 Bayed coastlines

Sand beaches are often limited by headlands or other fixed points. These beaches form bays of specific shapes, particularly when there is a dominant wave direction. In time, such a bay may reach a form of static equilibrium and cease to erode further (providing conditions do not change and no sediment is lost by processes other than longshore drift). The plan shape of a static equilibrium bay is predictable, for a given wave obliquity with its form being predicted by using different kind of mathematical expressions to describe curves (see review in Silvester and Hsu, 1997). Among the different existing bay models, the most widely used is the parabolic beach, which provides equilibrium bays shapes described by a two grade polynomial based on the position of control points (where dominant waves diffract) and predominant wave direction.

4.6 Stochastic modelling

A single run of a process-based numerical model gives a single deterministic prediction of the future shoreline. It is common practice among numerical modellers to also perform a series of sensitivity tests of a model, where input variables are systematically altered by some estimate of their uncertainty to see how much the output changes. This gives an indication of sensitive the output is to the likely error in the inputs.

Stochastic modelling is related to, but different from sensitivity testing. The emergence of stochastic modelling signals a shift from making a single deterministic prediction to making a statistical forecast by generating a probability distribution of outcomes and thereby acknowledging the uncertainty in any prediction.

A statistical distribution is obtained for each of the major sources of uncertainty in stochastic modelling, which may be forcing variables or variables in the parameterisation of a process. The model is then run many times using a different random selection of variables each time and a statistical forecast is made of the output variables of interest. Examples of stochastic modelling include Dong and Chen (1999), Spivak and Reeve (2002), Reeve (2004, 2006) and Cowell et al. (2006).

Reeve (2004) highlighted the fact that stochastic modelling is relatively less well developed than deterministic modelling. Moreover there are relatively few people trained in the running of such models and the advantages of stochastic models are relatively poorly understood. Measures of central tendency from a stochastic model are analogous to the result from a single deterministic 'best estimate' model run (Cowell et al., 2006). Stochastic models also provide an indication of the variability about the central tendency and can be used to establish confidence limits and determine the statistical significance of differences caused by varying effects.

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