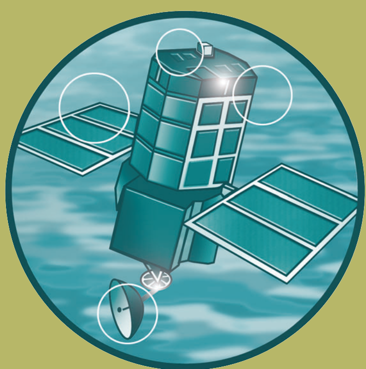
Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Understanding the lowering of beaches in front of coastal defence structures, Stage 2 Technical Note 3

R&D Project Record FD1927/PR3



Environment Agency

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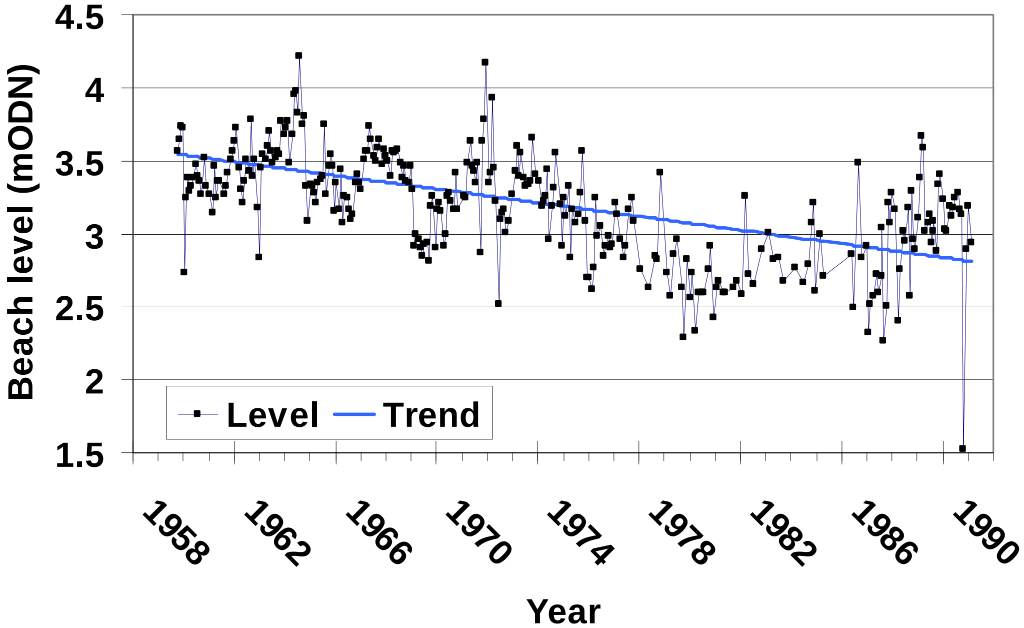
Department for Environment Food and Rural Affairs

Understanding the Lowering of Beaches in Front of Coastal Defence Structures, Phase 2

Assessment of beach lowering and toe scour



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1. Introduction

The purpose of this document is to place the phenomenon of toe scour at coastal defences in a broader context. The work has been carried out as part of the Defra R&D project FD1927 “Understanding the lowering of beaches in front of coastal defence structures, Stage 2”. The role of general beach lowering on sediment levels at the toe of a structure and on the fronting beach was recognised in the Stage 1 scoping study Sutherland et al. (2003). Research in FD1927 concentrates on small length scales (a few metres cross-shore) and small time scales (typically a few hours). The overall performance of a structure depends on morphological changes over a much broader range of length scales, detailed below and illustrated in Figure 1.

- Toe scour - often occurring and recovering completely during the course of a single tide (if in the intertidal zone, at least). Occurs over a cross-shore lengthscale of a few metres but may extend considerably further in the longshore direction;
- Storm response - lasting for a few tides and causing toe scour, beach lowering and recovery over cross-shore scales of up to a few hundred metres and rather longer distances in the longshore direction;
- Recovery between storms - the beach will respond to the changing forcing conditions and variations in beach level can be observed. Recovery from a storm can take 10s of tides and will affect a similar area to the storm;
- Seasonal variation – it is commonly observed that beach levels draw-down more in winter and build up during summer;
- Inter-annual variability in climate – this will have a net effect on the coastline by generating erosion or accretion and there are considerable variations between years. The annual wave climate affects the whole coastline so its effects are felt over the scale of the sediment cell, say 10s of km alongshore by of the order of 1 or 2 km cross-shore; and
- Coastal evolution and sea level rise – changes are driven by sea level rise and dominated by longshore transport. Occurs over longer timescales and even larger spatial scales than beach changes due to variations in annual conditions.

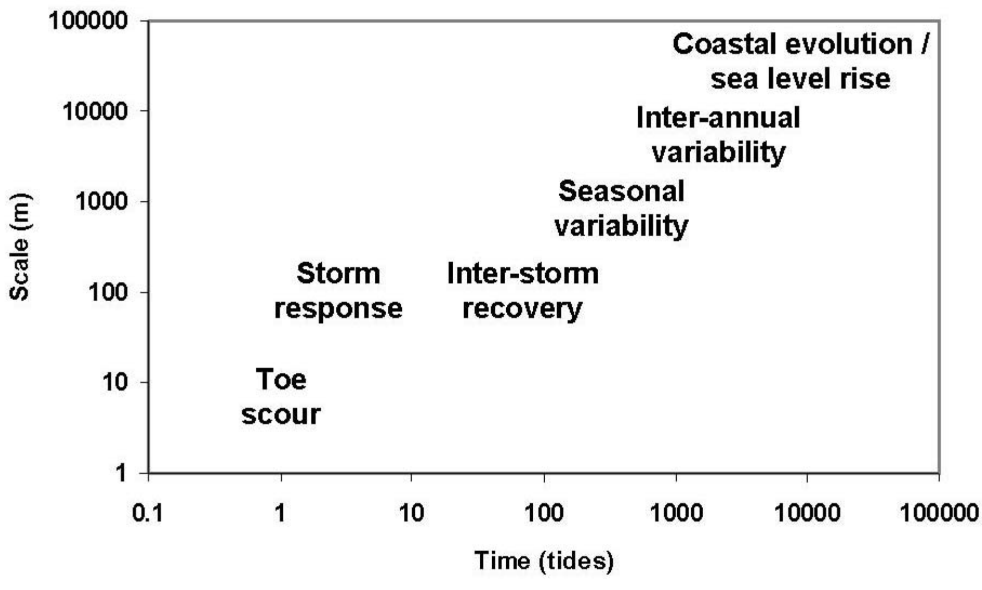


Figure 1 Length-scale versus timescale plot showing different processes

In general, the spatial scale increases with the timescale and longshore sediment transport processes increase in importance compared to cross-shore transport processes as the timescale increases. Data on beach levels are therefore needed at a range of spatial scales and time scales in order to assess the changes to a beach in front of a coastal defence structure. The first part of this report (Section 2) summarises the available technology for monitoring beaches in front of structures. This ranges from small-scale devices that record time series of beach levels at a point through the tidal cycle to the use of airborne LIDAR to survey 10's of kilometres of beach in a single flight. The review includes a number of instruments that have been developed recently and have never or only rarely been used to monitor beach levels in front of structures, although all have the potential to do so.

The first part of the report also describes the range of historical Ordnance Survey maps that can be used to see how tidelines have changed over potentially more than 100 years. The representation of tidelines is discussed as are the problems associated with the use of tidelines to assess coastal evolution.

Different tools are needed to predict the response of the coastline at different scales. These tools come with different levels of reliability, accuracy, skill and required expertise. These tools may be allocated to one of four basic types:

1. Statistical analysis (Chapter 3);
2. Process-based numerical modelling (Chapter 4);
3. Geomorphological analysis (Chapter 5); and
4. Parametric equilibrium models (Chapter 6).

It is possible to combine the different types of modelling to obtain a balanced outcome.

This report contains a section describing each of these types of tools. It is not the purpose of this report to describe these in detail, rather an overview of each is provided, except where new methods have been developed and demonstrated. This is intended to be complementary to the descriptions and analysis provided in Defra's revised Shoreline Management Plan (SMP) Procedural Guidance, Appendix D (Defra 2003a), which is intended to apply to relatively long timescales (10 to 100 years). Appendix D summarises the available techniques for predicting long-term shoreline evolution and provides a more detailed framework for the prediction of shoreline interactions and response in second round SMPs. This framework encourages the use of the results from the Futurecoast project (Halcrow, 2002, Burgess et al., 2002, Defra, 2003b) in determining future coastal behaviour as it gives a 100-year view of coastal behaviour and evolutionary tendency at a high level.

A variety of sources and techniques must be used to develop an understanding of shorter-term and smaller-scale behaviour up to a period of years. This report concentrates more on the techniques that can be used for shorter-term determination of beach levels. This may have been expressed in terms of a change in the plan shape of beaches, rather than changes in beach level at a structure, but changes in plan shape can be converted into changes in elevation using some knowledge of the beach slope. The options available for predicting bed levels at different timescales are discussed in Section 7.

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 pays particular attention to the equipment's ability to measure levels at the toe of coastal structures, but also acts as 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. Data analysis methods are described in Section 3.

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

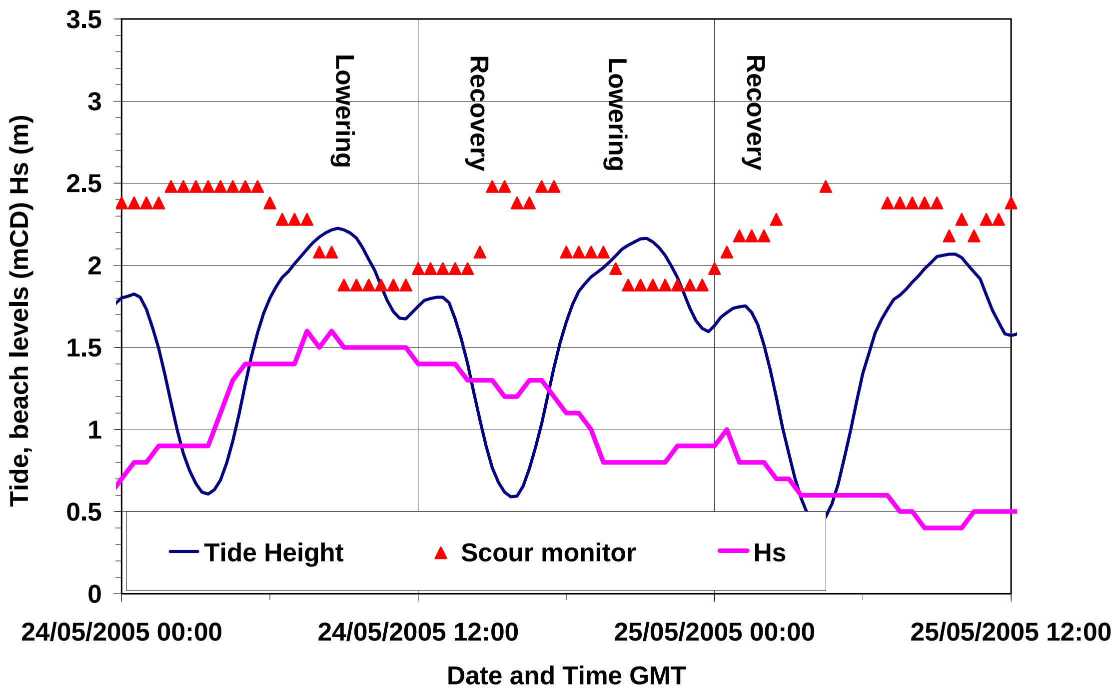


Figure 2 Plot of beach lowering and recovery during a tide at Southbourne

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 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 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 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);
- 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.

In May 2005 Wyre Borough Council installed two Argus systems at Cleveleys just north of Blackpool, which should collect data for at least 3 years. The cameras were installed North and South from an area where a new seawall will shortly be built so that changes in the beach in front of the seawall can be monitored. The images and beach survey data collected by the Council will be analysed at Lancaster University. If the resolution is good enough it may be possible to determine the beach level against the seawall or another known object, such as a pole or the end of a groyne. If this can be done regularly at low tide using Argus (or any other video or still camera system) then a long-term record of the variability of the beach level at the seawall could be built up. This requires the seawall to be in or above the intertidal zone.

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

2.2.6 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. Lee et al (2004) used X-band radar at two sites in Japan and used time-averaged images to detect the shoreline. This information was combined with a local water level measurement to produce contour lines, from which the foreshore slope was obtained. Measurements made in August 2002 and January 2003 showed how the foreshore slope had decreased following a succession of winter storms.

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 location 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 Ordnance Survey Maps

Historical Maps

Ordnance Survey maps of England and Wales have shown tidelines (High Water Line and Low Water Line) since the introduction of the first series of OS 1" to the mile (1:63360) maps in 1801. The series took 70 years to complete. OS maps therefore provide the longest time series of shoreline position, giving a maximum length of time of 200 years for determining historic trends in the positions of high water level and low water level. Better accuracy can be obtained by using larger scale maps, however.

In September 1841 surveying began on the first map at 6" to the mile (1:10,560) scale, in Lancashire. Rural 1:2500 scale maps (roughly 25" to the mile) were commissioned in 1854 and 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 maps to have been surveyed with regard to a geographical reference system that was displayed on the map itself. All maps were transferred to the National Grid in 1944-1945. 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 following list gives a summary of the main detailed historical map series available. There is considerable overlap between the series, particularly the National Grid overhaul which began in 1945 and continued until the 1980s.

1. the first County Series survey; published 1843 to 1893, scales 1:2,500 and 1:10,560.
2. the first County Series revision; published 1891 to 1912, scales 1:2,500 and 1:10,560.
3. the second County Series survey; published 1904 to 1939, scales 1:2,500 and 1:10,560.
4. the third County Series survey; published 1919 to 1939, scales 1:2,500 and 1:10,560.
5. the first survey/overhaul to the National Grid; published dates from 1945, scales 1:1,250 (urban areas), 1:2,500 (rural areas), 1:10,560/1:10,00 (moorland and highland areas).
6. the first National Grid revision.
7. the second National Grid revision.
8. the third National Grid revision.
9. the fourth National Grid revision.

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. A joint venture between the Ordnance Survey and Landmark Information Group has created copies in digital format, suitable for use in a GIS (Ordnance Survey, 2006a). An academic license is also available through Edina (2006).

The absolute accuracy is a measure of the error in determining the position of a feature relative to the National Grid. Relative accuracy is a measure of the error in determining the position of a feature relative to close-by features. Relative errors are always less than absolute errors.

Ordnance Survey digital maps

The maps listed above were created from ground or photogrammetric surveys. A programme to digitise these maps was started in 1971 and was accelerated in the 1980s when the demand for digital data increased (Ordnance Survey, 2006c, p151). These maps have been revised digitally since their capture and are marketed as the Land-Line® product. Converting the unstructured tile-based data into an object-based, seamless dataset took from April 200 to October 2001 and resulted in the Mastermap® product. A consultation exercise has already taken place into the effects of withdrawing Land-Line® at some stage.

Representation of tidelines on OS Maps

Surveyors in the 19th and 20th centuries were given detailed instructions on when and how to survey these lines, which were of legal importance (Johnston, 1905, Winterbotham, 1934, Oliver, 1995, 2005). Early OS maps portray tide lines from ordinary spring tides on maps of England and Wales. The tide lines mapped on the County Series maps since 1868 (Dornbusch et al 2006) or 1879 (Winterbotham, 1934, as cited in Ryan, 1999) are Low Water Mark of Ordinary Tides (LWMOT) and High Water Mark of Ordinary Tides (HWMOT) which are "those of high and low water of ordinary tides (i.e. tides half way between neaps and springs) which define the limit of the foreshore" (OS, 1882:4).

Ryan (1999) reviewed the procedures used to obtain tidelines. He noted that the Ordnance Survey (1882) instructed surveyors to use tide tables to ascertain the high and low tides that most closely correspond to HWMOT and LWMOT. If tide tables were not available then OS (1882:4) instructions state that, "As the next best approximation…the fourth tide before new and full moon and before first and third quarters" should be utilised for the LWMOT/HWMOT. OS's instructions to field examiners (Johnston, 1905) contained similar advice: surveys of Mean High Water and Mean Low Water were taken from "tides half way between a spring and a neap, and should generally be taken at the fourth tide before new and full moon" (Johnston, 1905). Maps of Scotland show high and low water marks for ordinary spring tides, which "generally occur the third of fourth tide after new or full moon" (Johnston, 1905).

Surveys were to be made during calm weather (OS, 1882), which limited the opportunities to survey but at least meant that changes in water level due to storm surge and wave setup were minimised. Note, however that calm weather is associated with high pressures, which could have led to systematically low water levels (Dornbusch et al, 2006). As a rule of thumb, an increase in atmospheric pressure of 1milleBar will lower the water level by around 10mm.

Tide lines on County Series maps usually came from measured line surveys with offsets (Ryan, 1999). High tide lines were captured by 1 of two methods:

1. Objects (e.g. sticks) were placed on the beach at the time of high water. The positions of the objects were surveyed and the surveyed points were joined to form the MHW or MLW mark. The sketching between points is expected to have added a greater error than that at surveyed points.
2. A proxy tideline was surveyed. Winterbotham (1934) noted that high tide "generally leaves a clear mark … there is not much difficulty in surveying this line." A proxy-based shoreline is derived when a physical feature is taken to represent the shoreline. This can be the strand line (representing high water) or (for maps other than OS maps) the crest of a beach ridge, the foot of a dune or the point where the sand changed colour.

Low tide lines were captured in similar ways, with low water surveys undertaken half an hour either side of low water (Ryan, 1999).

Ryan (1999) reported that the OS instructions of 1932 and 1963 contained the same information, although the 1963 definitions were expanded to include procedures for conducting air surveys. Tide lines on early Original National Grid Plans were collected using the traditional methods outlined above. Since about the 1970s the Ordnance Survey has mainly provided tide line data from aerial surveys using either standard pan or colour film, and preferably black & white infrared film as this shows the water/foreshore interface more clearly. The older methods were still used in some cases, however. For these maps the Mean High Water (MHW) and Mean

Low Water (MLW) were determined for a particular length of coast using current Admiralty tide tables, making any corrections from the nearest standard harbour tide tables (Ball, 2006).

The name changes from MHWOT to MHW and MLWOT to MLW are not significant as the definitions remained the same. Note, however, that MHW & MLW are not given in Admiralty Tide Tables: MHWS, MHWN, MLWN and MLWS are. This is not a problem provided consistent calculations of MHW & MLW are performed.

Once MHW and MLW had been calculated, the tide tables were examined to find suitable high and low tides which were within ± 0.3metres of MHW and MLW. The aerial photographs were taken at the time of low tide and provided an instantaneous snapshot of the tide line position. Note, however, that MHW and MLW on the same map could have been surveyed in different years.

At the present time the OS uses photogrammetry to create contours at the appropriate elevation using a Digital Photogrammetric Workstation (Ryan, 2006). In this digital age, major coastal and non-coastal defences designed to reduce the risk of flooding are in the OS Category A, which means they will be captured as part of a continuous revision process within 6 months of completion. Note, however, that no historical records are maintained about the date of survey for continuous revision (Edwards, 2001). Mean high and low water when affected by changes to other features (such as coastal defences or jetties) and significant changes to tidelines (when evident from aerial photography conducted as part of the national sweep or when notified by a customer) are classified as Category B and will be captured as part of a national sweep programme, which occurs every few years.

The Ordnance Survey, British Geological Survey and UK Hydrographic Office have completed a project that produced test areas of an Integrated Coastal Zone Map (ICZMap) that aimed to joint the maps and charts from the OS, BGS and UKHO seamlessly through the coastal zone (Ordnance Survey, 2003). There were problems in matching the OS topographic representation of MHW line and MLW line and the UKMO depth area polygon bounded by MHW and MLW lines as often these were quite different (Ordnance Survey, 2003, p17). The common coastline used in this instance was a generalised version of the OS MasterMap coastline. This work was completed for the trial areas in March 2005. Mastermap *does not have a clean and coherent MLW line* (Ordnance Survey, 2003, p27).

The procedure for establishing tidelines on OS maps are summarised below:

- OS maps from 1879 to the present day nominally surveyed tide lines at MHW and MLW;
- The elevation of MHW and MLW have consistently been determined from Admiralty Tide Tables, so are subject to periodic change;
- Tide tables have been used to select tides with a high water or low water level close to the desired elevation when tide tables have been available (although it is not clear when they were not). It is not clear how close to the target MHW/MLW level the predicted tide had to be originally, although for aerial surveys the predicted tide had to be within ±0.3m of the target level.
- Tide lines surveyed may not have been at the correct level because (i) predictions were not always accurate, (ii) atmospheric pressure, storm surge and setup changed the water level (with instructions to survey in normal conditions minimising these effects) and (iii) surveys took a finite length of time to undertake, during which time water levels changed. Low water surveys should have been performed within half an hour either side of low tide. The marking of high water is assumed to have taken place within a similar timeframe about high water.

- Relatively long stretches of coast were surveyed using predictions from a single standard port (in Admiralty Tide Tables). At some point between standard ports the prediction switched from one port to the next. This resulted in adjacent stretches of coast being surveyed at different levels, so discontinuities in the position of MHW/MLW can be expected where adjacent surveys meet. Indeed, the Ordnance Survey (2003, p27) admit that their most recent and accurate MasterMap® product does not have a clean or coherent MLW and this may be partly responsible.
- If more standard ports were added to the Admiralty's list, the level of MHW/MLW would probably be different from the adjacent ports. As a consequence any new mapping near the added port would be using a different definition of MHW/MLW from before.
- Tolerances are expressed in terms of vertical differences from the target value. The horizontal difference that this corresponds to depends on the beach slope. As beach slopes are generally lower at low water than at high water, the positional accuracy of low water will be less than of high water.

Problems with OS tidelines

Oliver (2005) reported that some of the pre-1868 spring tide lines were simply copied onto maps produced after this date (i.e. first series County Maps) and were renamed but not resurveyed. Admiralty Surveys use Mean Low Water Springs and this data was also sometimes used on OS maps of England and Wales and a note provided to explain this. (If this note was in the marginalia, it may not be included in digital copies produced by the OS, so the information would be lost.) Maps of Scotland show high and low water marks for ordinary spring tides (i.e. MHWS and MLWS).

There would be a systematic and in some cases significant difference between the positions of tidelines mapped at Mean High/Low Water Springs and Mean High/Low Water. Low water tidelines produced from spring tides will be offshore from those produced by mean tides, while high water tidelines produced from spring tides will be onshore from those produced by mean tides. Dornbusch et al (2006) report that MLWS is about 0.8m below mean low water in the southeast England. On a 1:100 beach slope this corresponds to a horizontal difference in position of up to 80m.

Dornbusch et al (2006) highlighted the uncertainties introduced by relying on surveys taken at the fourth tide before new and full moon by calculating the mean low water elevation for these tides for the tide gauge at Newhaven in 2004. The elevations varied between 0.35m above mean low water and 0.6m below mean low water. The average level of these tides was 0.12m below the mean low water elevation. Different surveys, carried out using the same criteria during the same yea,r could therefore have been conducted at elevations up to 0.95m apart. On a 1:100 beach slope this corresponds to a horizontal potential difference in position of up to 95m. These tides were only used if suitable tide tables were not available, but it is not clear on which parts of which maps these tides were used.

Johnston (1905) noted that "on long flat foreshores the lines of high and low water mark are generally surveyed and plotted" but "if the foreshore has sandbanks or difficulties which would make the survey expensive, or if it is steep and rocky with only small sandy bays the low water mark will often be supplied by the Examiner" and were presumably not actually surveyed. There would appear to be no way of knowing whether the MLW line was made up or surveyed.

Dornbusch et al (2006) noted that the LWL on some of first series sheets from the 1870s had a more jagged appearance than on any subsequent sheets of the same stretch of coastline. Possible explanations are that there was no sand cover on the beach at the time (and the survey was of a jagged rock platform) the surveys were less accurate, the surveys had fewer points or that the LWL was an artistic impression, based on the fact that the coast is rocky (although LWL is and has been for many years covered in sand). If the first explanation is correct, the substantial shift shorewards in LWL between first and second series maps would most likely have been caused by substantial erosion of the shore platform (at an unprecedented rate) for which there is no physical explanation. This explanation therefore seems unlikely.

The tidelines on the first series county maps should be treated with caution and ideally analysis of tidelines would start with the second series maps. When asked about the accuracy of cliff-top position, a Senior Surveyor at the Ordnance Survey (Edwards, 2001) noted "it is unlikely that taking measurements either from current or historical Ordnance Survey data will provide you with any consistently reliable results for this type of detail." He went on to recommend that the original aerial photos be acquired and re-analysed.

Height differences of ± 0.3metres can lead to significant changes in position. For example, if the beach has a slope of 1:200 around low water, a vertical error of ± 0.3metres corresponds to a horizontal error of ±60m.

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.

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	£230	£300

control)		
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 in the UK 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.

The EA has a LIDAR system which it has installed in a survey aircraft along with its other operational remote sensing instruments, including the Compact Airborne Spectral Imager (CASI), a thermal imager, high quality sVHS video camera and a digital camera. The aircraft is positioned and navigated using Global Positioning Satellite (GPS) corrected to known ground reference points. Environment Agency LIDAR surveys 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]. A large and extensive archive of EA LIDAR data files is available and is searchable using a downloadable database.

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 MHW and MLW ‘contours’. If the intention is to achieve historical consistency the MHW/MLW levels should be set at the values from the nearest standard port. 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.

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 by the 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).

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 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. Statistical analysis of beach level data

Statistical models rely 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.

Statistical models are derived from data using an analysis method. The available monitoring methods for collecting data are summarised in Section 2, while the available analysis methods are summarised here. The large majority of statistical modelling performed for SMPs has been carried out using the simpler linear analysis methods detailed in Section 3.1. The more complicated linear analysis techniques (Section 3.2) and the non-linear analyses (Section 3.3) 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).

3.1 LINEAR ANALYSIS OF BEACH LEVEL DATA

3.1.1 Introduction

The linear analysis of beach level data is demonstrated here using a set of beach profile measurements carried out along the Lincolnshire by the National Rivers Authority (now the Environment Agency) and its predecessors. Data were collected from 18 standard stations between 1959 and 1991. The 18 stations are located from just north of Mablethorpe to just south of Skegness. These data have been entered into HR Wallingford's Beach Data Analysis

System (BDAS). BDAS can store and statistically analyse large amounts of beach profile data, as well as present it graphically.

About 300 surveys were measured at each station over 32 years. Most of the time there are ten or twelve surveys per year but there were fewer than six per year between 1978 and 1987. Sometimes two surveys were taken the same month, or only one for a period of six months. Despite the irregularities in sampling, this dataset represents the most detailed database of its kind in the UK due to the frequency of the surveys, the duration of the surveys and the number of profile lines. This Lincolnshire dataset therefore ranks alongside the Duck (USA), JARKUS (NL) and Lubiatowo (Poland) datasets for frequency and length.

Since 1991 the Environment Agency has continued measuring beach profiles in Lincolnshire, but only twice a year. This data was not included in the analysis as it was measured less frequently and included a major beach nourishment project in 1994. Elsewhere in the UK some other local authorities have been collecting beach profiles for a similar length of time. For example, Bournemouth Borough Council has measured beach profiles twice a year for almost 30 years, with recent measurements included in the Channel Coastal Observatory.

Importantly for looking at the behaviour of beaches in front of coastal structures, many of the Lincolnshire beach profiles were backed by a seawall. Three Ordnance Survey maps at 1:25,000 were used to identify the positions of the stations on the coast. The maps were TF48 & part of TF58 Mablethorpe (1953), TF57 Chapel St. Leonards (1960) and TF 56 Skegness (1960). Locations where the MHW was close to a seawall were identified. A set of beach stations were selected for further analysis based on maps, average beach profiles and time series of beach levels in front of the seawall or high up the beach.

Average beach profiles were derived for each of the 18 stations by interpolating the surveys to set chainages (distances from the profile origin) and calculating the average elevation at each of the set chainages. Examples of average beach profiles are given in Figure 3 to Figure 10, which were output from BDAS.

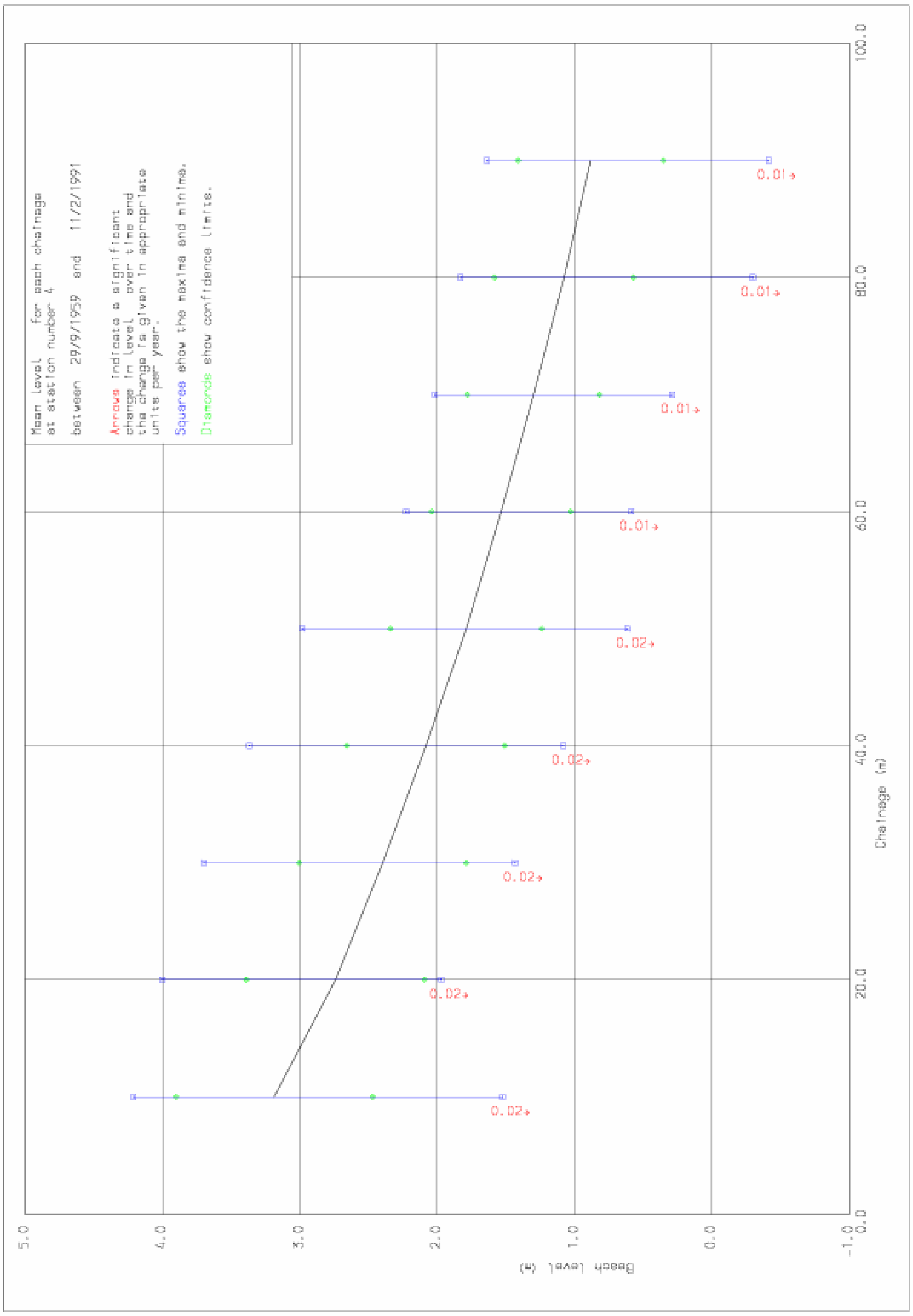


Figure 3 Average beach profile at Mablethorpe Convalescent Home

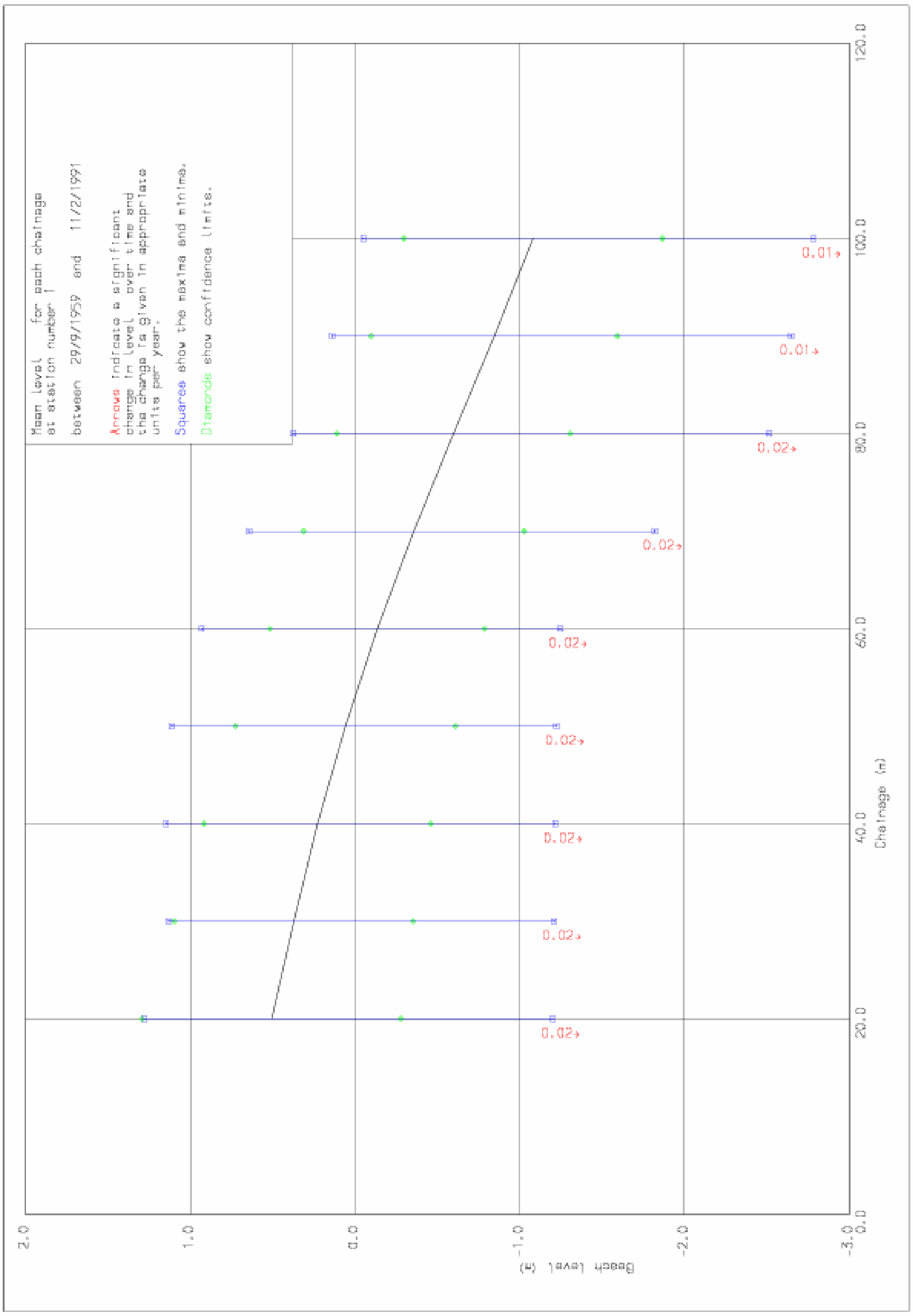


Figure 4 Average beach profile at Trusthorpe Outfall

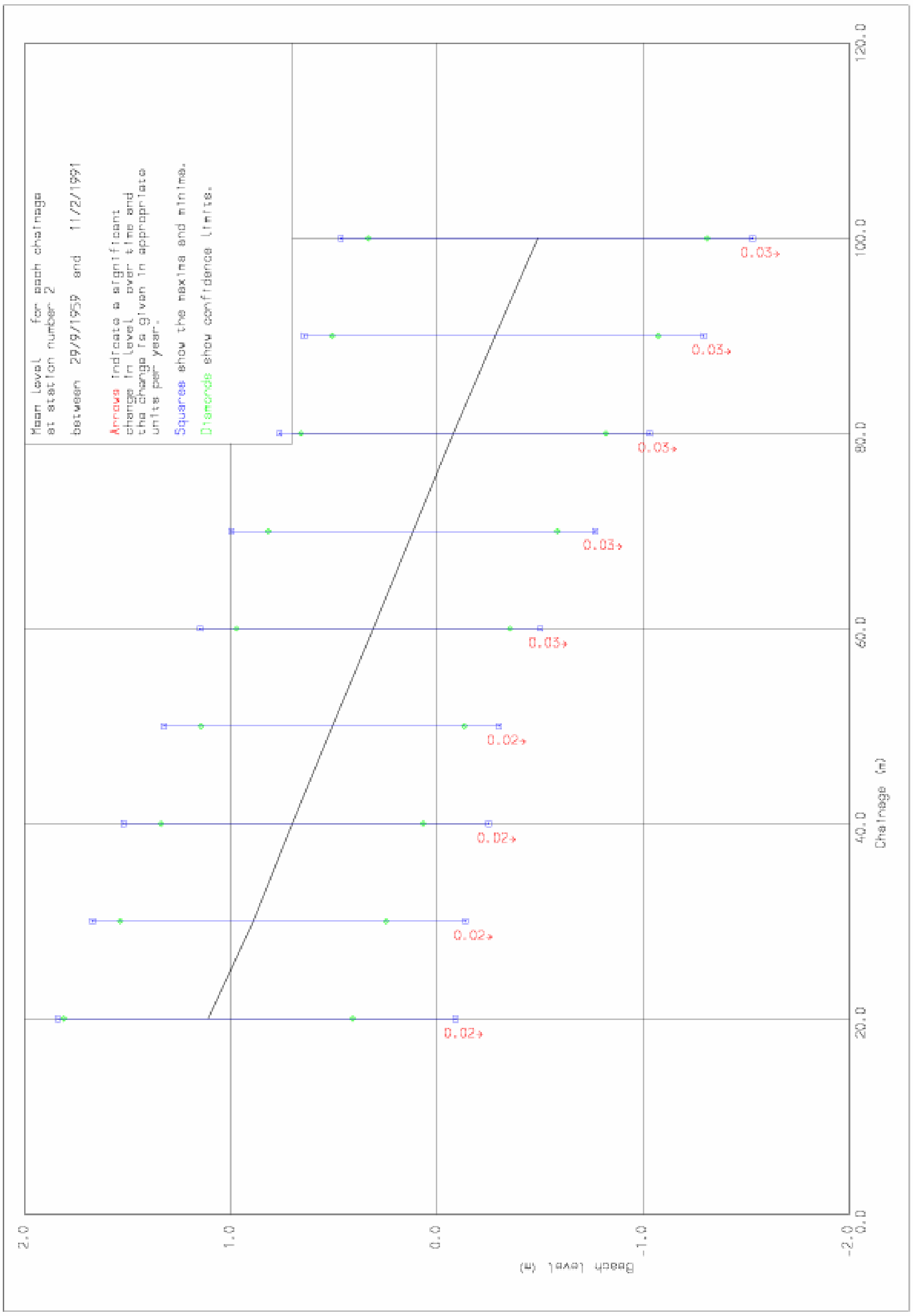


Figure 5 Average beach profile at Bohemia Point

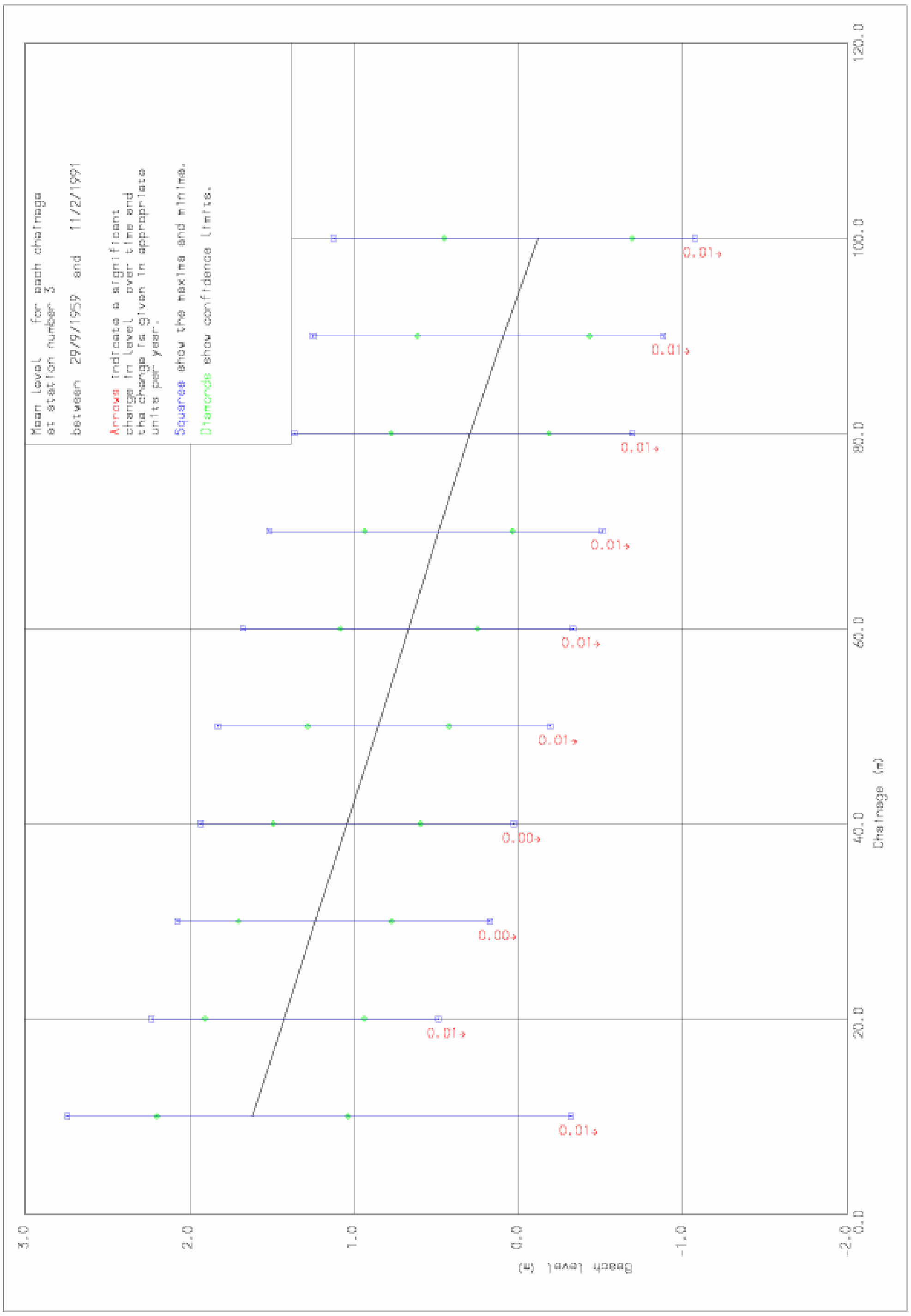


Figure 6 Average beach profile at Sutton Pullover

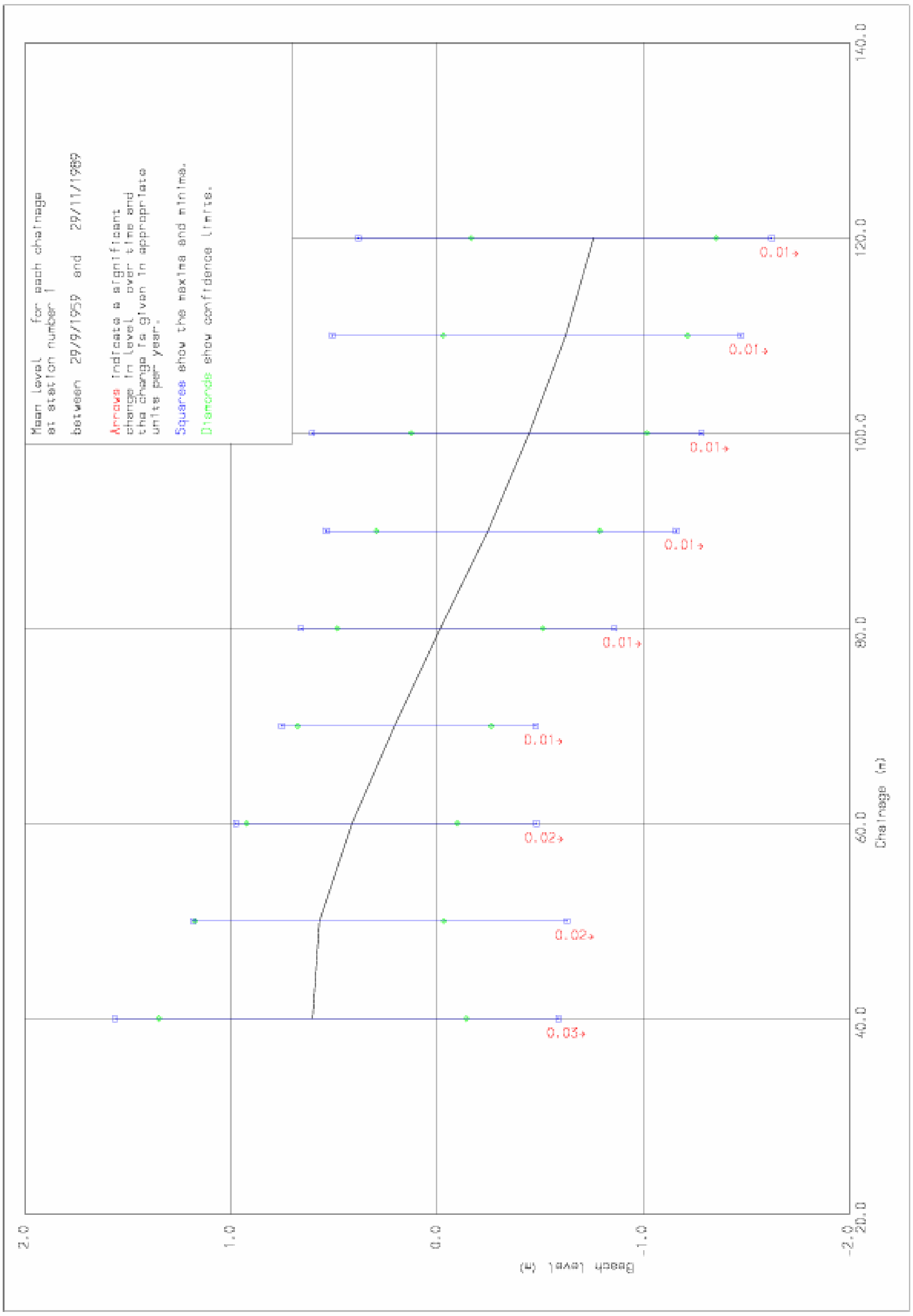


Figure 7 Average beach profile at Boygrift Outfall

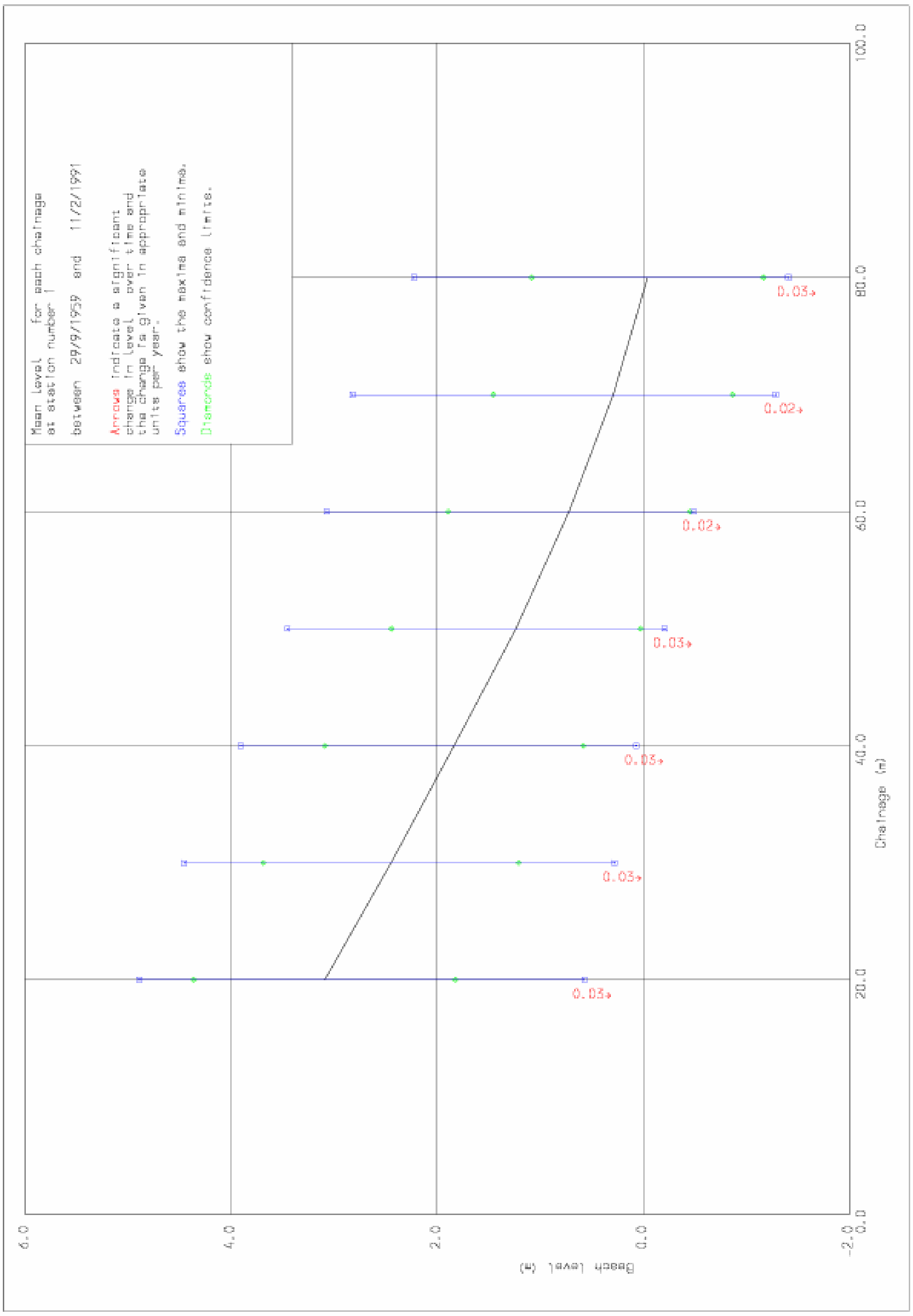


Figure 8 Average beach profile at Chapel Point

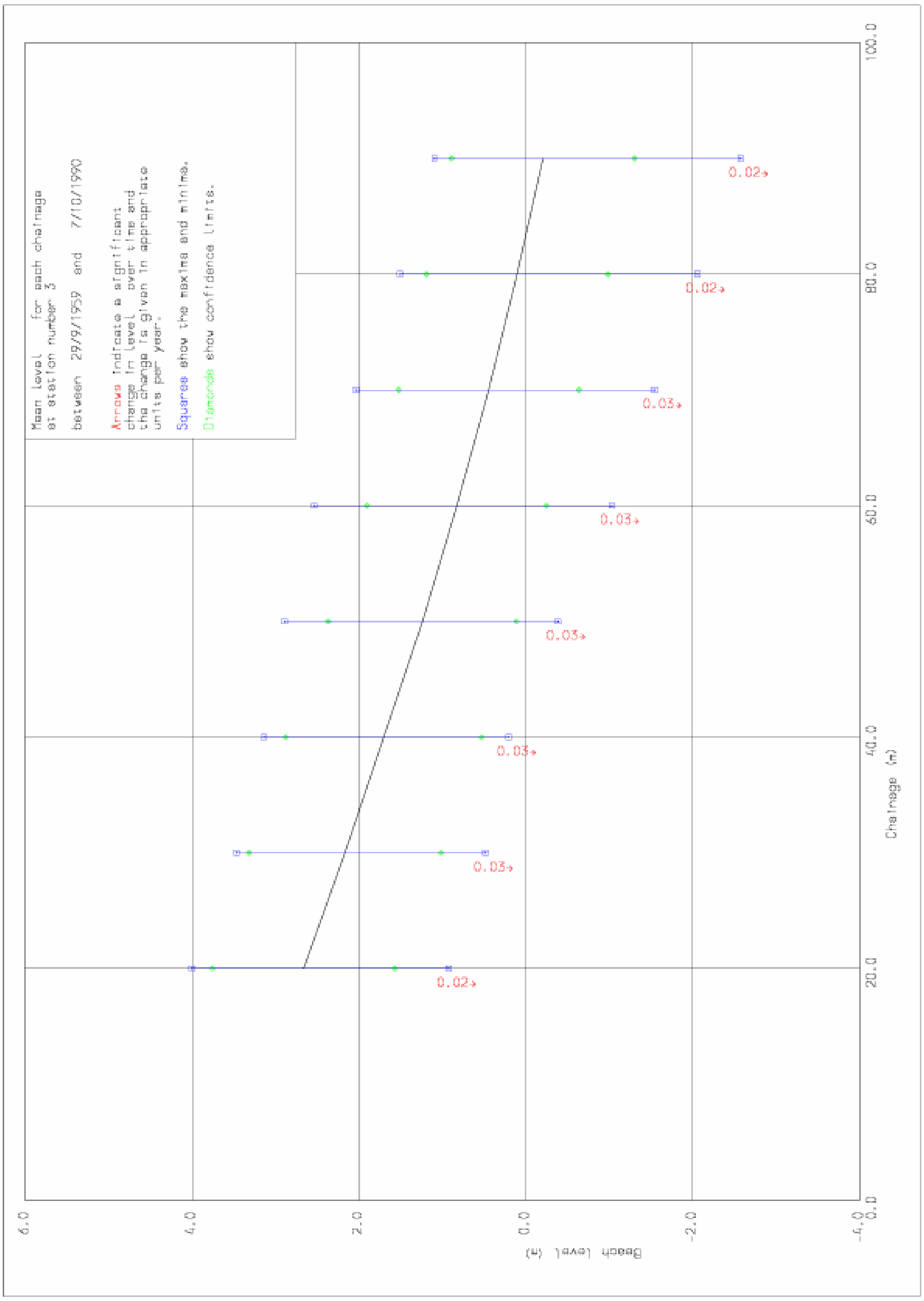


Figure 9 Average beach profile at Trunch Lane

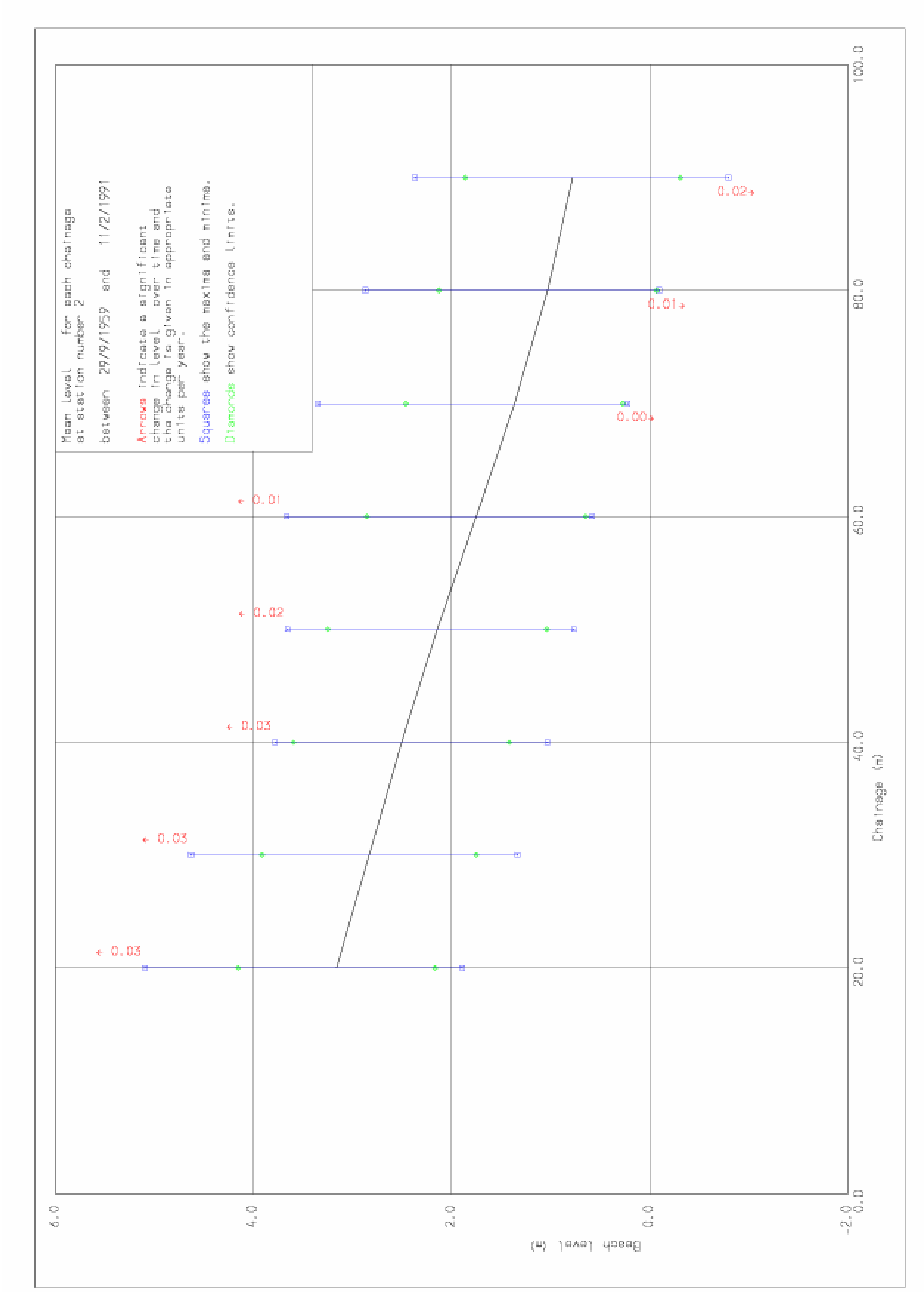


Figure 10 Average beach profile at Jacksons Corner

A position near the top of the beach profile was identified for each station. Positions close to the toe of the seawall were chosen (where the seawall position was obvious from the profile). Time series of elevations were plotted and a best-fit straight line calculated. Examples of elevation time series are given in Figure 11 to Figure 18.

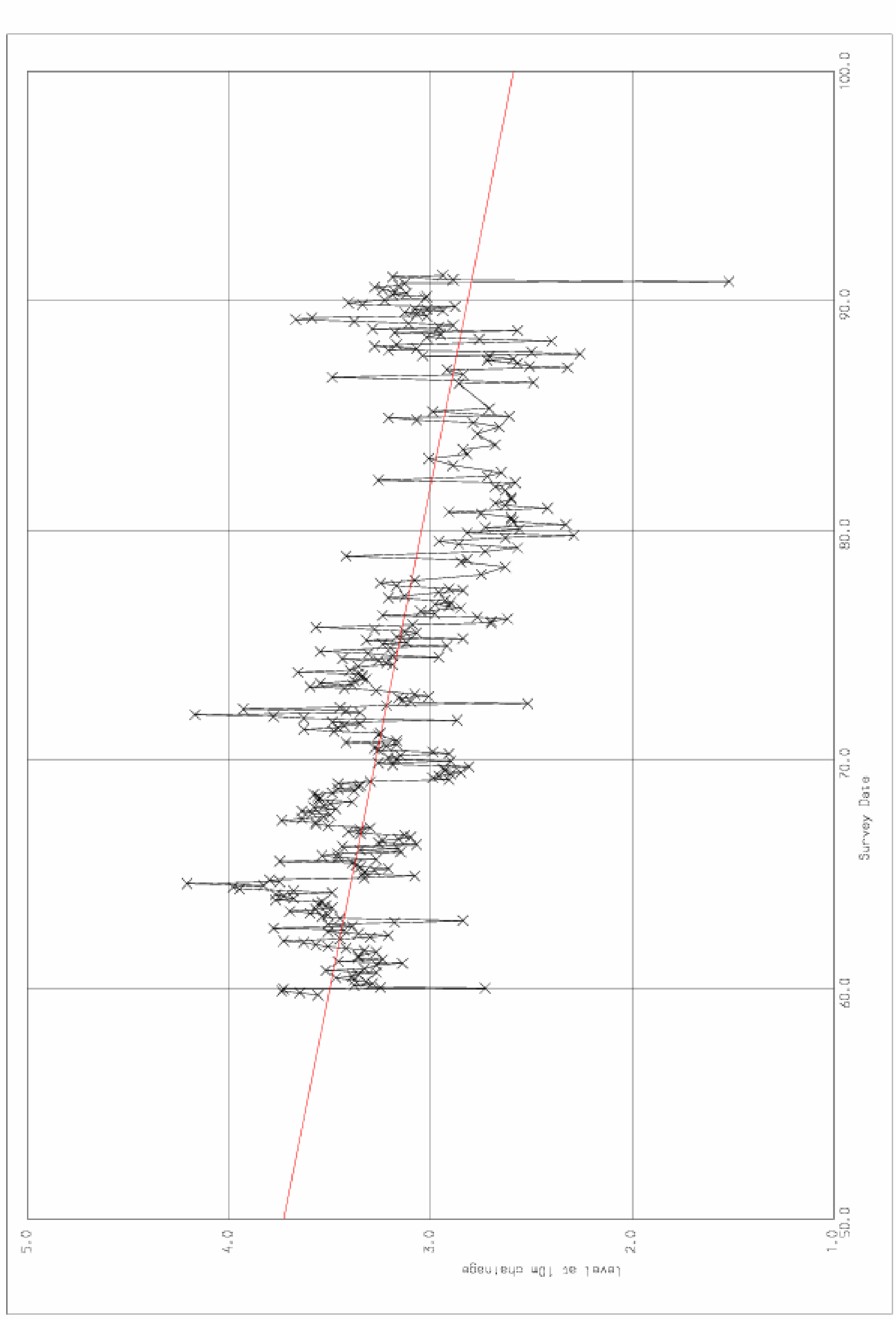


Figure 11 Time series of beach level at 10m chainage at Mablethorpe Convalescent Home. Survey date is years since 1900, so 50 = 1950, etc.

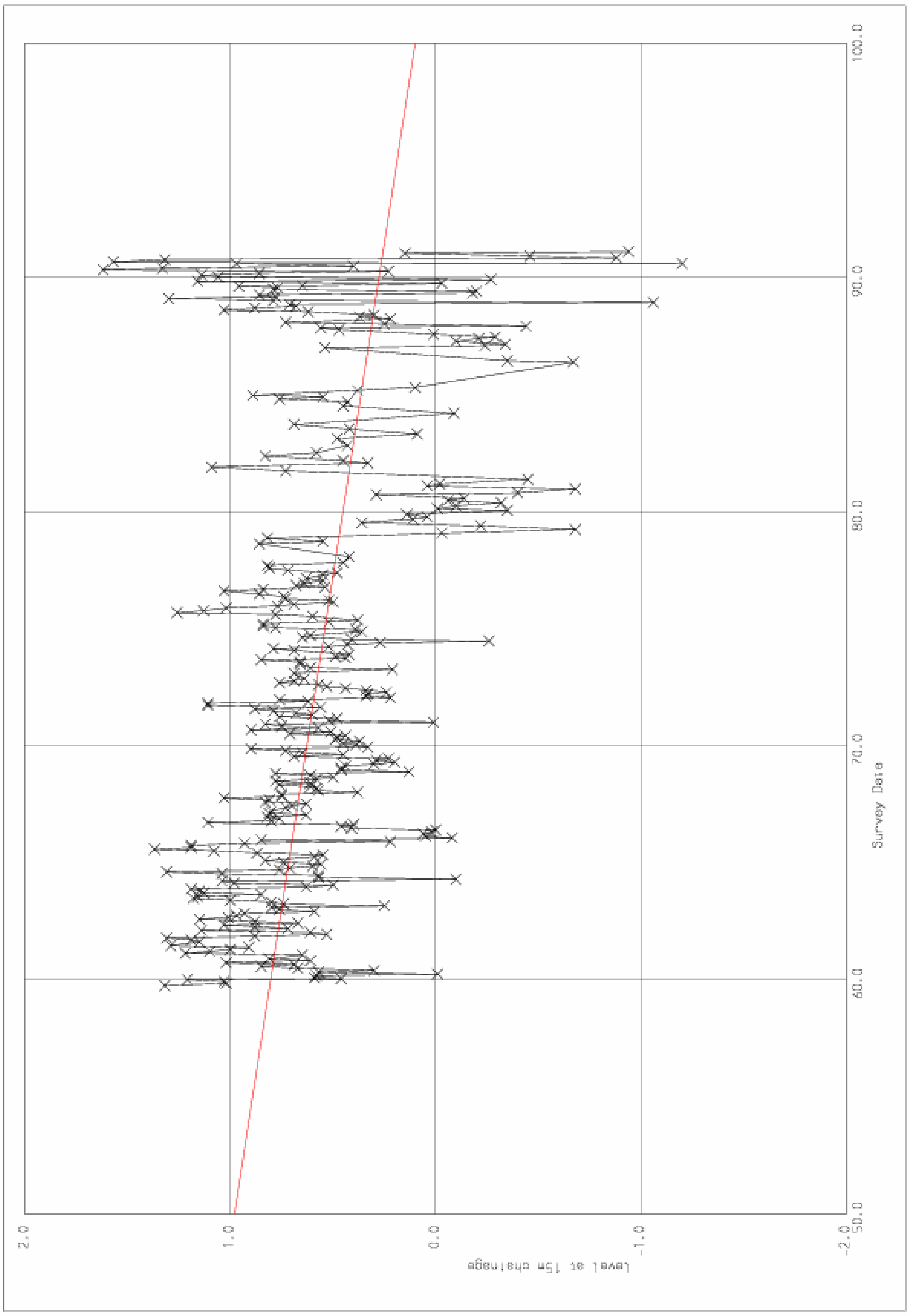


Figure 12 Time series of beach level at 15m chainage at Trusthorpe Outfall

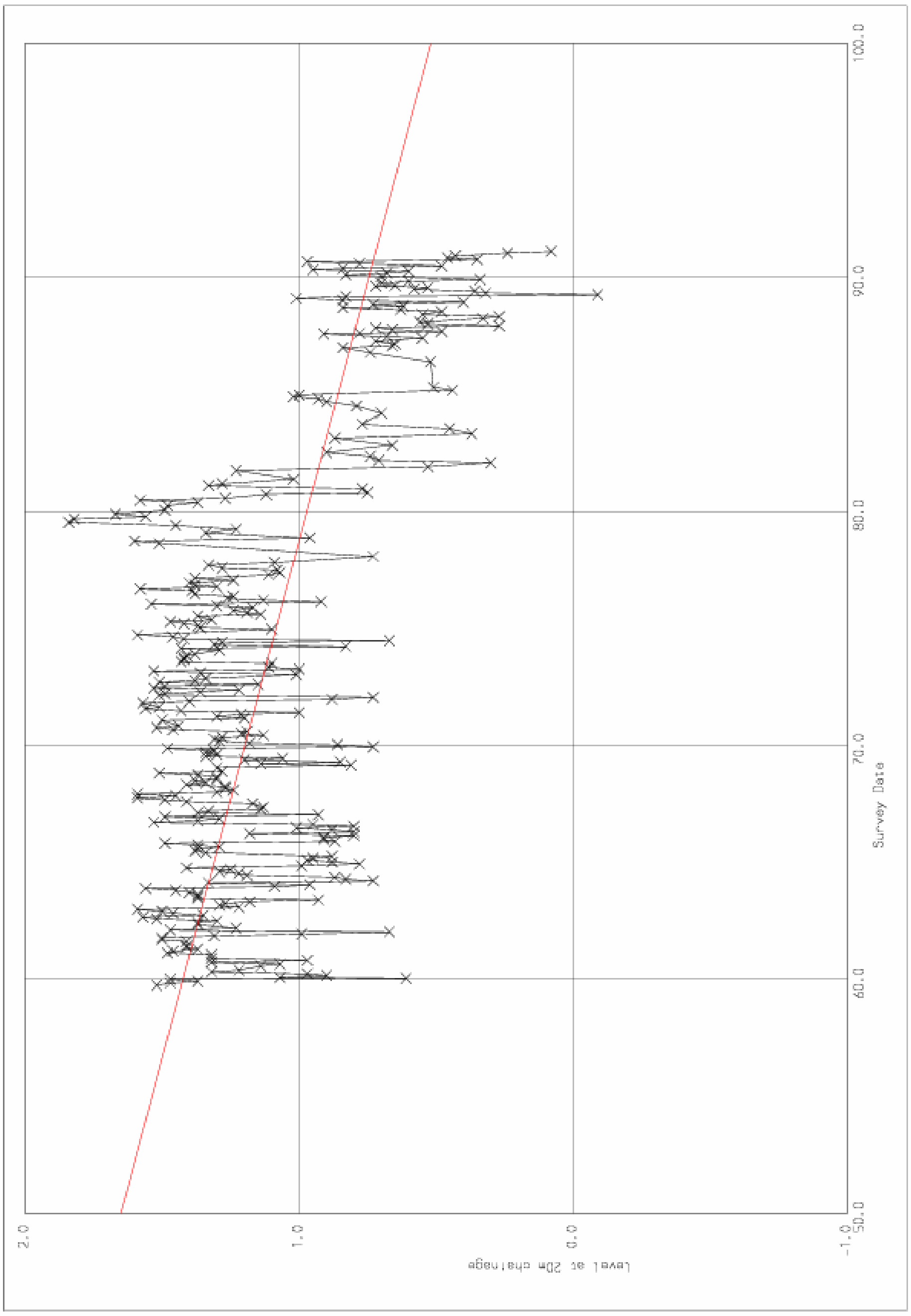


Figure 13 Time series of beach level at 20m chainage at Bohemia Point

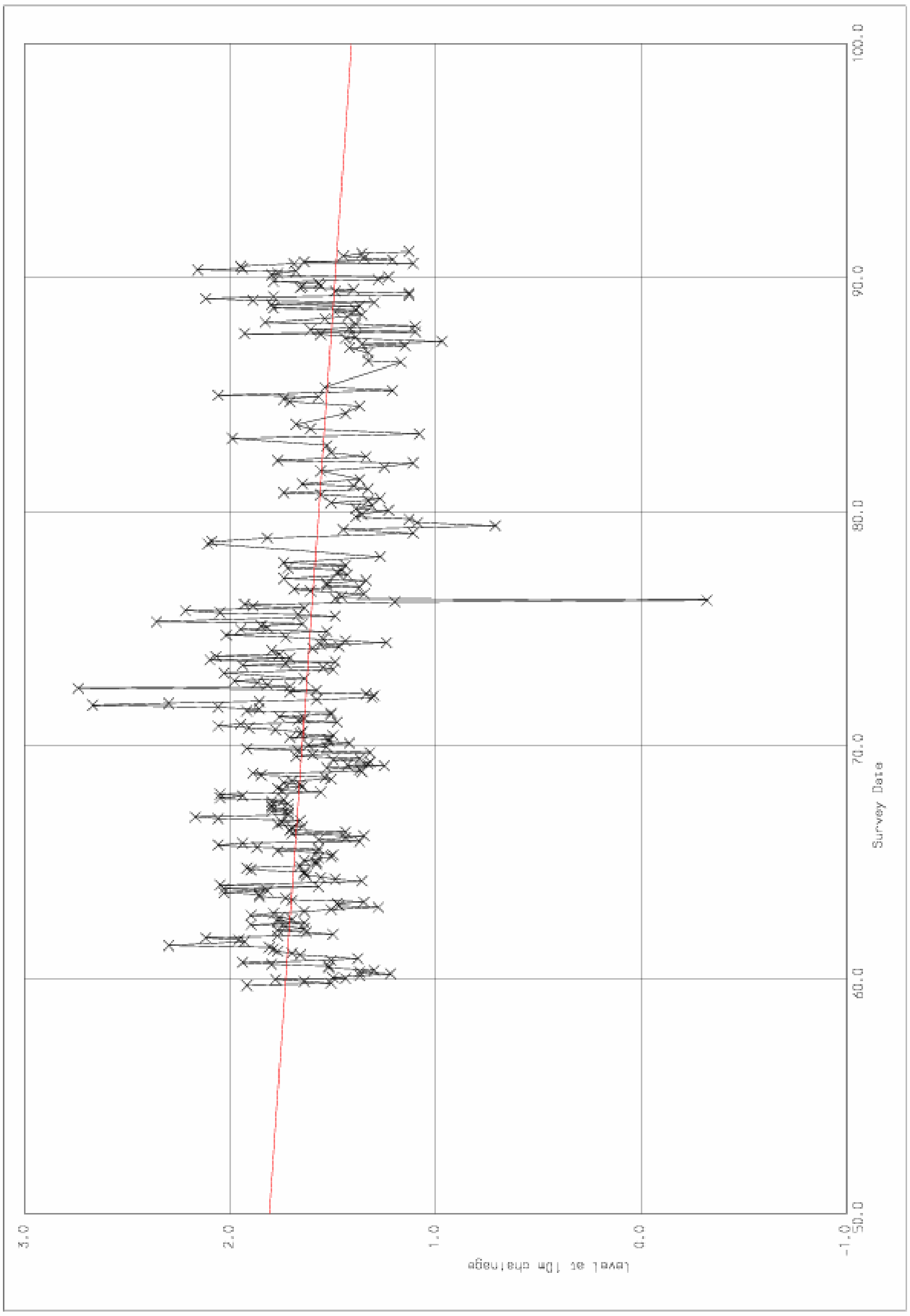


Figure 14 Time series of beach level at 10m chainage at Sutton Pullover

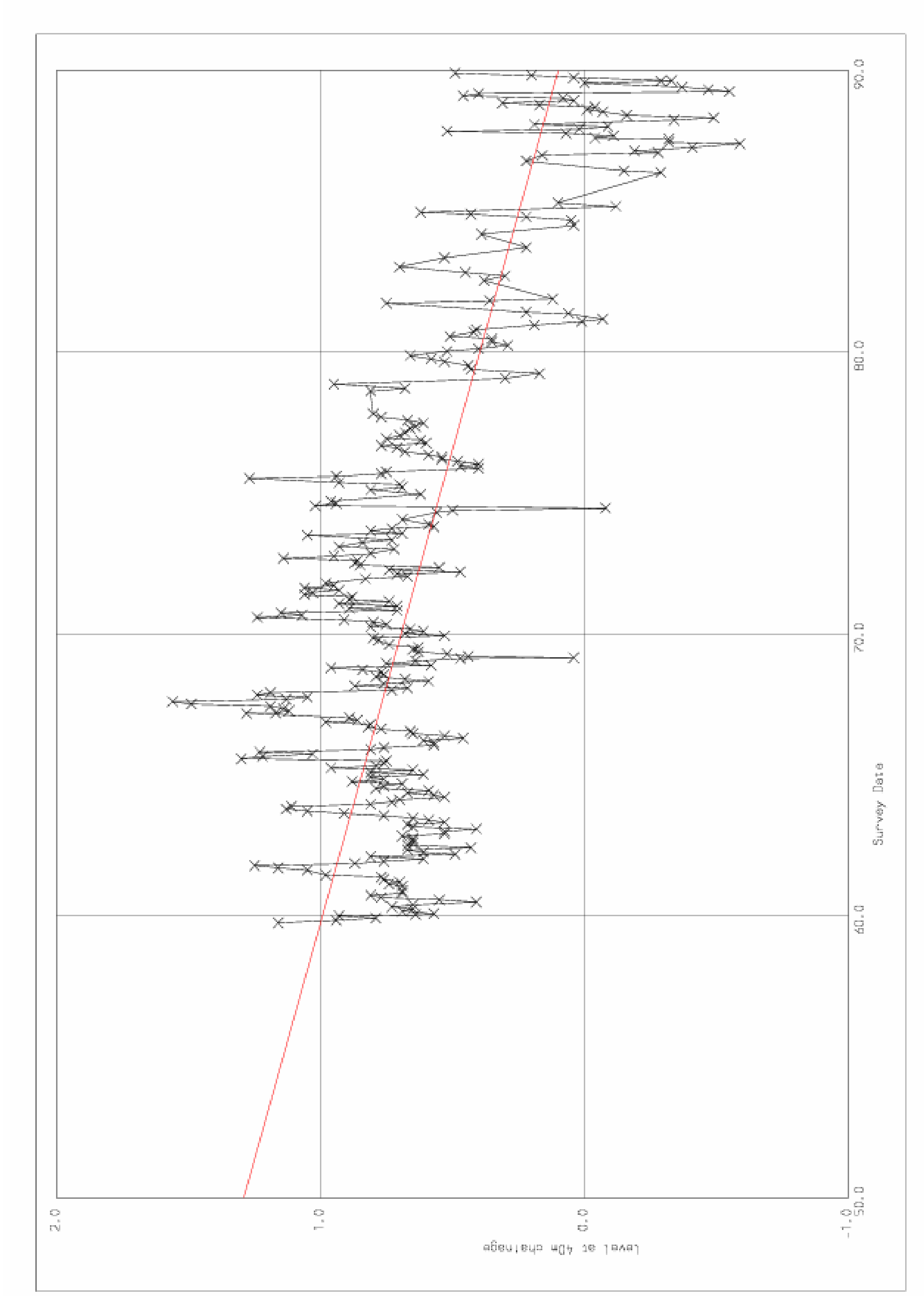


Figure 15   Time series of beach level at 40m chainage at Boygrift Outfall

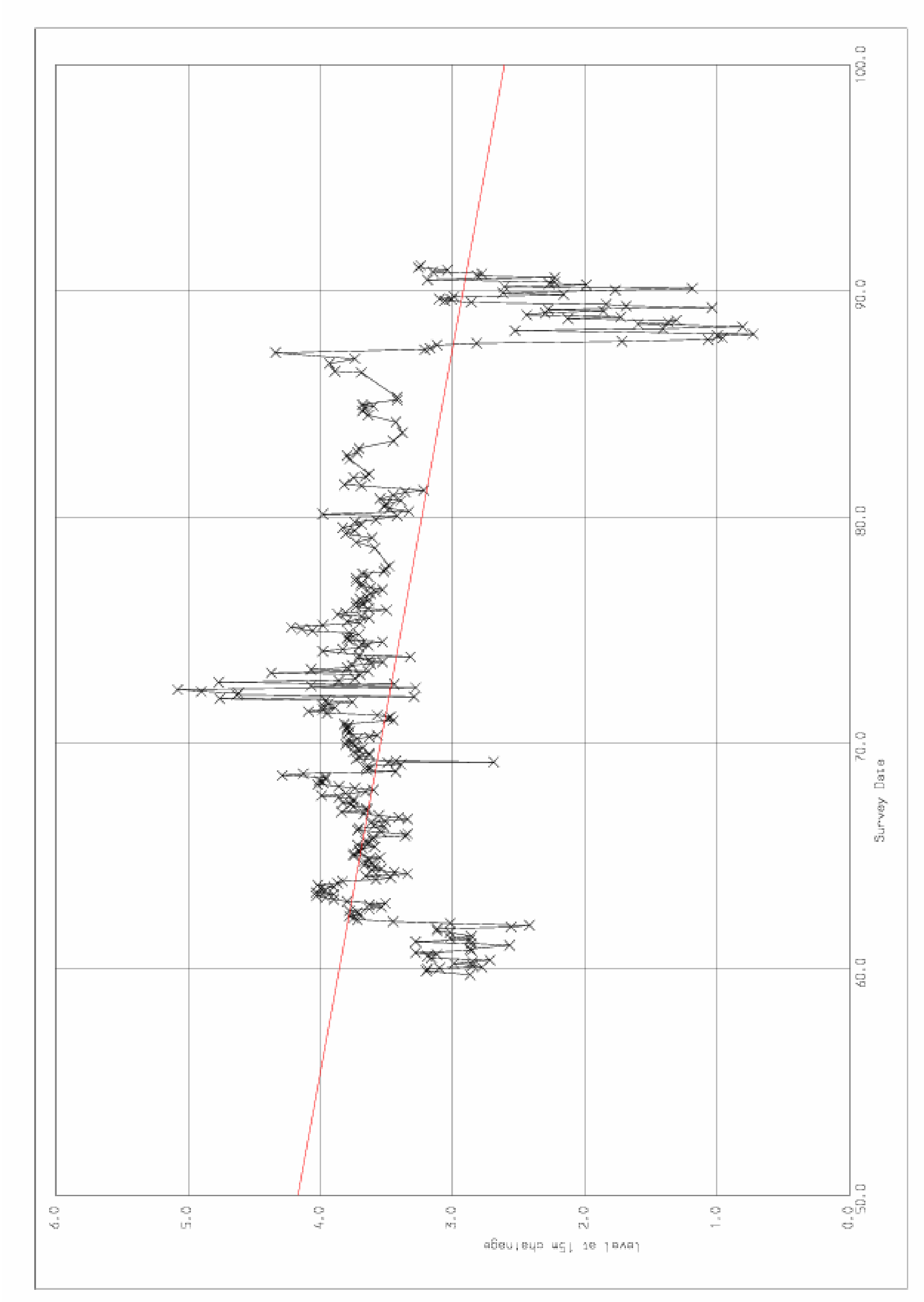


Figure 16   Time series of beach level at 15m chainage at Chapel Point

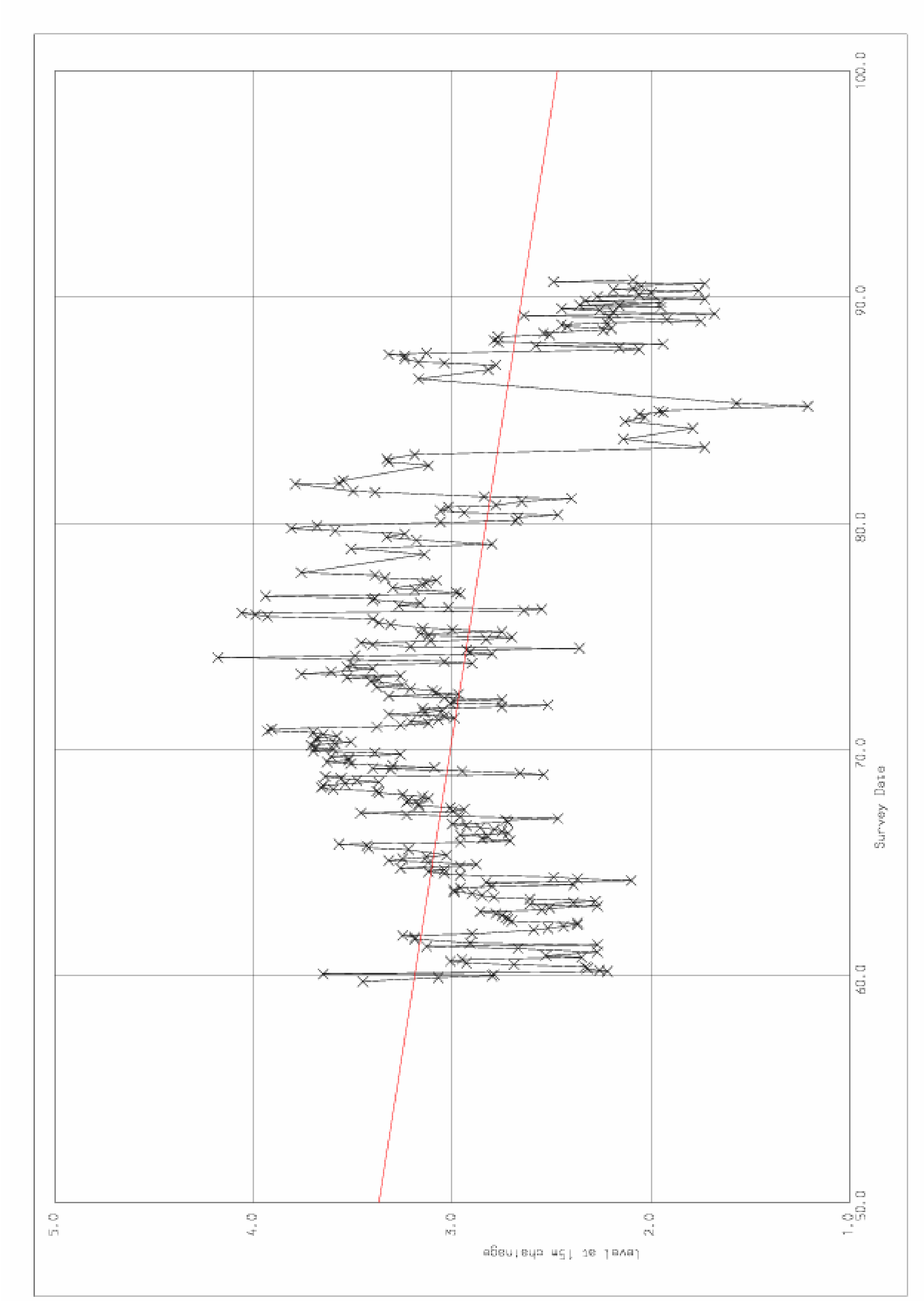


Figure 17 Time series of beach level at 15m chainage at Trunch Lane

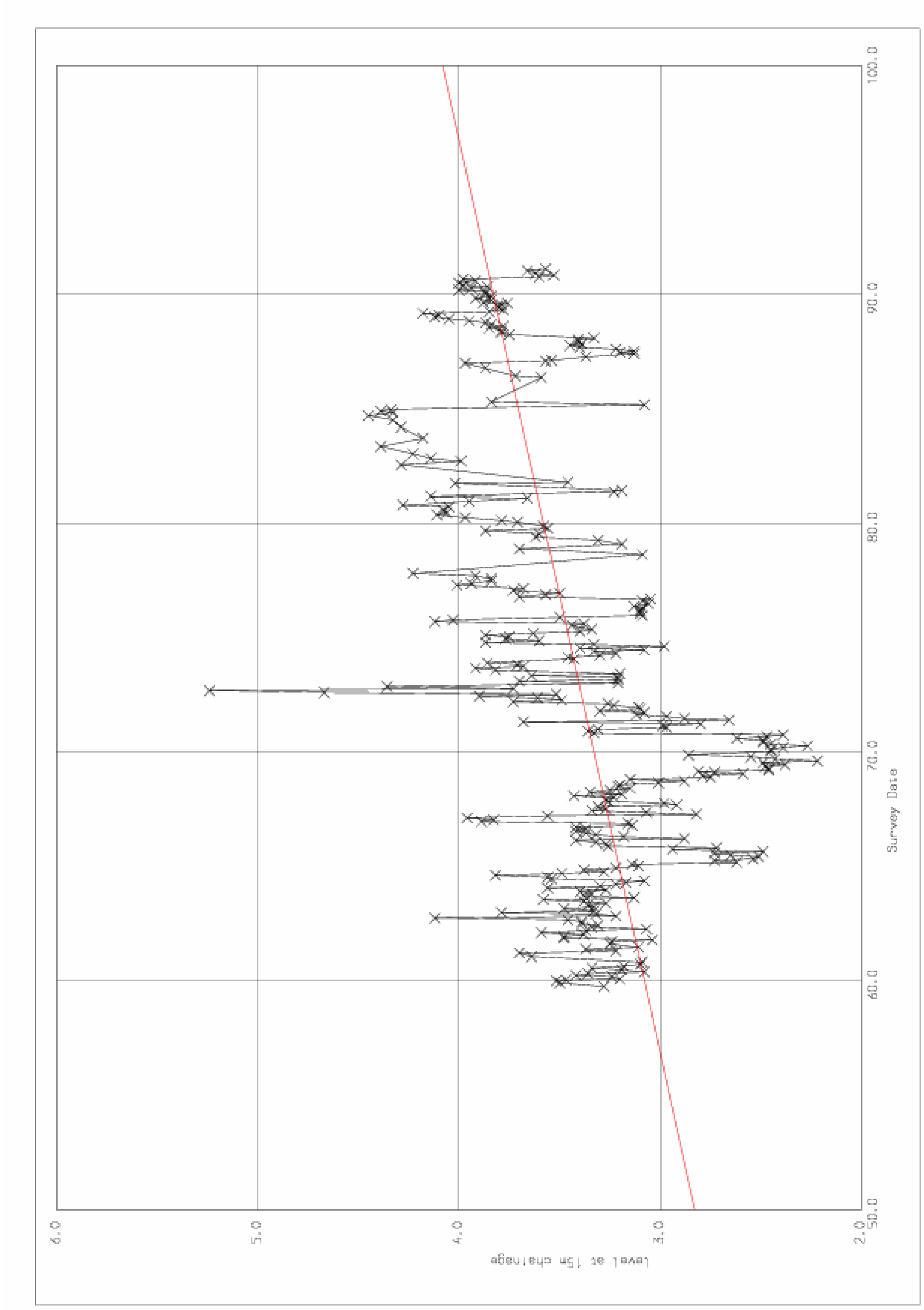


Figure 18 Time series of beach level at 15m chainage at Jacksons Corner

Eight stations were chosen for more detailed analysis using the information from maps, average profiles and time series. Details of the cross-sections are given in Table 2, which includes both NRA and HR Wallingford station numbers, a place name, National Grid coordinates (mE, mN) of the top of the profile, the bearing of the profiles (degrees clockwise from grid North) and the chainage of the chosen point near the base of the seawall.

Table 2 Details of chosen stations for more detailed analysis.

Station number		Place Name	National grid coordinates (mE mN)	Bearing grid N (°)	Chainage at wall (m)
HR	NRA				
A4	12	Mablethorpe Convalescent Home	551278 384400	54 17 15	10
B1	13	Trusthorpe Outfall	551504 384115	83 31 55	15
B2	14	Bohemia Point	551815 383288	90 31 59	20
B3	15	Sutton Pullover	552251 382143	85 06 51	10
C1	17	Boygrift Outfall	553401 379919	86 18 40	40
D1	21	Chapel Point	556240 373285	71 54 55	15
D3	23	Trunch Lane	556620 371068	86 16 01	15
E2	26	Jacksons Corner	557320 366403	108 57 00	15

Average profiles of the chosen stations are shown in Figure 3 to Figure 10. The procedure for calculating average beach profiles in BDAS also calculated the standard deviation in the level at each of the chosen chainages and plotted the confidence limits (average ± 2 standard deviations) the maximum and minimum value and the linear least-squared best-fit trend in the data, expressed as change in elevation per year (with positive being an increasing level and negative being a decreasing beach level). The confidence limits were calculated as the average ± 2 standard deviations on the assumption that beach levels have a normal, Gaussian distribution about the mean value. If this is the case then about 95% of all results should be within the confidence limits. Note, however, that the confidence limits do not take into account any long-term trend in the data. The annual change in elevation at each chainage is also shown in the average profiles (as the red arrows).

Time series of beach elevations at the toe of the structure are shown in Figure 11 to Figure 18. The time series all show a considerable variability about their trends. The Convalescent Home time series (Figure 11) shows that there is variability in the data about the mean, including some variations from the mean with durations of a few years. Figure 11 also shows one outlier (after 1990) that is noticeably further away from the mean than any other point. Most of the other time series (Figure 12 to Figure 18) show similar variations.

The Chapel Point profile shows the most extreme variations from the long-term trend. The time series can effectively be split into three sections: 1959-1961, 1962-1987 and 1987-1991. The beach level jumped approximately 0.8m towards the end of 1961. It remained at a similar level, with relatively small variations until the middle of 1987. The beach level then rapidly dropped 2m before increasing back to the long-term trend line. The most obvious explanation for the sudden changes in beach profiles is that a change in coastal management took place. The Chapel Point profile is about 50m north of the coastal engineering works that maintain Chapel Point. We understand from conversations with local authority personnel that changes to the point and / or to the associated breakwater took place about the time of the rapid changes in beach level. However, detailed maintenance records have not been kept by the local council so it is impossible to verify the exact timing of engineering works.

The Trunch Lane time series also shows considerable changes from the best-fit linear trend. Here the beach levels increase from 1960 to 1970 then fall, at first slowly, then more rapidly until 1991. There is also a sudden fall of about 1m near the beginning of 1983 and a similar increase at the end of 1985.

The Chapel Point time series acts as a warning to anyone who wants to use historical records to form a statistical model that can be used to make predictions of future behaviour. Statistical models rely on the assumption that the behaviour of the past will continue at the same rate into the future. Changes in beach management, whether it is the construction of new defences or beach nourishment (which occurred over this entire stretch of coast starting in 1994) may lead to changes in the coastal state or coastal processes which will invalidate the use of any statistical model.

The profiles and time series reveal that the chosen stations are at a range of different beach levels and are changing at different rates. Table 3 gives the elevation of the beach near the structure toe in 1959, derived from the best-fit lines, plus the annual change in elevation. Admiralty Tide Table from 1991 were used to give the following water levels at Skegness (the only standard port within the survey area): MLWS = -2.85mODN, MLWN = -1.25mODN, MSL = 0.36mODN, MHWN = 1.55mODN and MHWS = 3.15m ODN. This shows that in 1959 three stations (Convalescent Home, Chapel Point and Trunch Lane) had best-fit beach levels above MHWS so the seawall would only occasionally get wet. A fourth station at Jackson's Corner had a beach level just below MHWS. These four stations may be considered together.

The stations at Sutton Pullover and Bohemia Point had beach levels close to MHWN so waves would reach the seawall near high water for some (Sutton Pullover) or all (Bohemia Point) tides. The other two stations at Trusthorpe Outfall and Boygrift Outfall had best-fit beach levels just over 0.8m so were submerged by over 0.7m of water at MHWN.

There is no clear link between the best-fit beach level in 1959 and the rate of change in level at that point. All bar the most southern station at Jackson's Corner showed falling beach levels with rates between 0.08 mm/year and 3.1 mm/year. Beach levels increased at Jackson's Corner so that by 1991 the beach level had reached 3.88m, 0.73m above MHWS.

Table 3 Elevation of beach in front of seawall in 1959 and annual change in elevation

station number		Place name	Elevation at 1959 (mODN)	Change in level (cm/year)
HR	NRA			
A4	12	Mablethorpe Convalescent Home	3.511	-2.3
B1	13	Trusthorpe Outfall	0.824	-1.8
B2	14	Bohemia Point	1.43	-2.3
B3	15	Sutton Pullover	1.757	-0.8
C1	17	Boygrift Outfall	0.837	-2.8
D1	21	Chapel Point	3.838	-3.1
D3	23	Trunch Lane	3.252	-1.8
E2	26	Jacksons Corner	3.077	+2.6

3.1.2 Usefulness of best-fit linear trend as predictor

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. 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.

The following question then arises: how useful is a best-fit linear trend as a predictor of future beach levels? In order to examine this, the thirty years of Lincolnshire data have been divided into sections: from 1960 to 1970, from 1970 to 1980, from 1980 to 1990 and from 1960 to 1990, for most of the stations. In each case a least-squares best-fit straight line has been fitted to the data and the rates of change in elevation from the different periods are shown in Table 4.

Table 4 Rates of change in elevation in front of seawalls for different periods

Period	Convalescent Home rate of change (m/year)	Bohemia Point rate of change (m/year)	Boygrift Outfall Rate of change (m/year)	Chapel Point Rate of change (m/year)
1959-1991	-0.023	-0.023	-0.030	-0.031
1960-1990	-0.025	-0.021	-0.030	-0.028
1960-1970	-0.017	-0.001	0.010	0.069
1970-1980	-0.063	0.010	-0.035	-0.028
1980-1990	0.047	-0.061	-0.051	-0.186

The data above indicates that 10-year averages provide little predictive capability for estimating the change in elevation for the next 10-years, let alone for the planning horizon that might need to be considered for a coastal engineering scheme. Few of the 10-year averages are close to the 30-year average.

However, the above analysis does not reveal how far ahead a best-fit straight line can be extrapolated to give a useful prediction of future beach levels, compared to, for example, using the average measured beach level. This can be expressed as, what is the average prediction horizon from extrapolating a best-fit linear trend fitted to a M year long beach profile record? The prediction horizon is defined as the average length of time over which a trend produces a better level of prediction of future beach levels than a simple baseline prediction. A procedure has been developed to determine the average prediction horizon from a time series of beach levels at the toe of a structure. The procedure is outlined below and demonstrated using the Lincolnshire dataset.

Procedure to establish average prediction horizon

The following procedure can be used to establish the average prediction horizon, defined as the average length of time over which a trend produces a useful level of prediction of future beach levels. The proposed 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 is adapted here for the prediction of beach levels at the toe of an 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 be 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 from extrapolating the trend.

The procedure for determining the average prediction horizon given by a trend line fitted to *M* years of a time series of beach levels at a point is as follows:

1. Let *X* be a set of *N* measurements of beach level at a point with x_n the *n*th value of the set ($n = 1, \ldots, N$) measured at a time t_n. Starting at the first point, x_1, identify all, points ($x_1 \ldots$, x_p, say) that are within *M* years of x_1. The dataset must, of course, be longer than *M* years.
2. Calculate the best-fit trend to this set of points ($x_1 \ldots, x_p$). The most common trend line fitted is a simple linear, straight line, trend.
3. Calculate the average of all points within the *M* year data set. This is the baseline prediction for all future points: $B = \langle (x_1, \ldots, x_p) \rangle$ where <> denotes an average.
4. Extrapolate the best-fit trend line to the end of the record to give $y_{p+1}, \ldots y_N$ where y_m is the extrapolated value at time t_m corresponding to measured value x_m with $m = p+1, \ldots, N$.
5. For each extrapolated point, calculate the duration of prediction (i.e. time from end of *M* year record), $d_m = t_m - t_p$, the square difference between the measured end extrapolated elevations, $(x_m - y_m)^2$ and the square difference between the measurement and baseline prediction, $(x_m - B)^2$.
6. Repeat steps 1 to 5 starting at the second point in the record. Add points to d_m, $(x_m - y_m)^2$ and $(x_m - B)^2$ vectors.
7. Continuing repeating steps 1 to 5, starting from one point forward each time, until *M* years from the end of the record (at which time there are no points left to extrapolate to);
8. Sort d_m, $(x_m - y_m)^2$ and $(x_m - B)^2$ vectors by d_m into *I* bins of, for example, 1 year ($i = 1, \ldots, I$).
9. Calculate mean square difference between the measured and predicted elevations for each bin, $\langle (x-y)^2 \rangle$, and the mean square difference between the measured elevation and the baseline prediction for each bin, $\langle (x-B)^2 \rangle$;
10. Calculate the Brier Skill Score for each bin, *i*, using Equation 1.

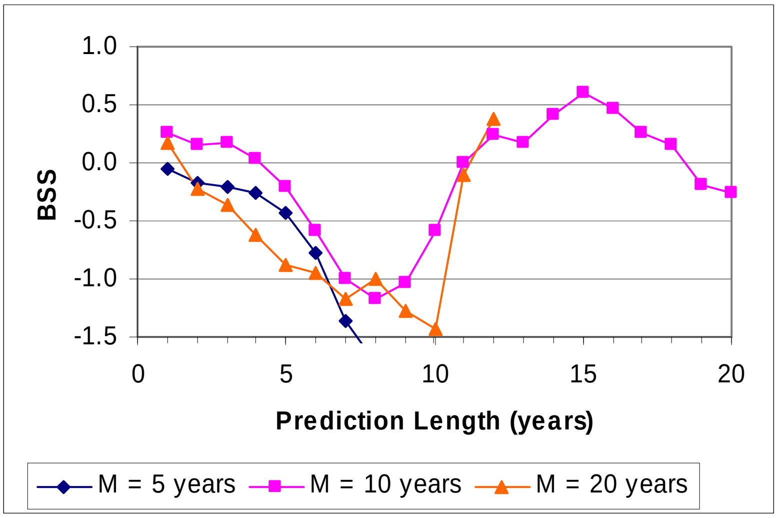
$$\mathrm{BSS}(i) = 1 - \frac{\left\langle (x-y)^2 \right\rangle}{\left\langle (x-B)^2 \right\rangle} \tag{1}$$

Plotting the Brier Skill Score as a function of duration of a prediction shows how much more accurate it is to use a trend line rather than the average of the measured points to predict future beach levels. This skill score compares the square difference between the extrapolated trend and observation with the square difference between baseline prediction and observation. Perfect agreement gives a Brier score of 1 whereas modelling the baseline condition gives a score of 0. If the model prediction is further away from the final measured condition than the baseline prediction, on average, the skill score is negative. This skill score is reduced by errors in the prediction of amplitude, phase and mean. It provides an objective measure of model performance (Sutherland et al., 2004).

The extrapolation of the best-fit trend in historic beach profile time series will act as a better predictor of future beach levels than the average beach level for time differences where the average skill score remains above zero.

The above method has been used to calculate the prediction horizon for some of the long-term Lincolnshire datasets. The results from the Mablethorpe Convalescent Home and Bohemia Point are shown in Figure 19 for the least-squares best-fit straight lines fitted to $M = 5$, 10 and 20 years. The results show that the best-fit straight line has a *negative* level of predictive skill for all durations of forecast for $M = 5$ years. In other words the use of a straight-line trend from 5 years' data is on average worse than the use of the average beach level as a predictor of future beach levels. This occurs as the relatively short timespan leads to a wide range of gradients from the fitted lines. These can lead to relatively large errors when extrapolated beyond the period of the measurements used.

Only for the cases of $M = 10$ years and $M = 20$ years does the best-fit straight line provide a better prediction of future beach levels than the average beach level for the first few years of prediction. The prediction horizons at Mablethorpe Convalescent Home and Bohemia Point are 4 years and 7 years from fitting to a 10-year record length. The prediction horizons for 20-year record length are actually shorter, which may be because there are fewer examples to average over.



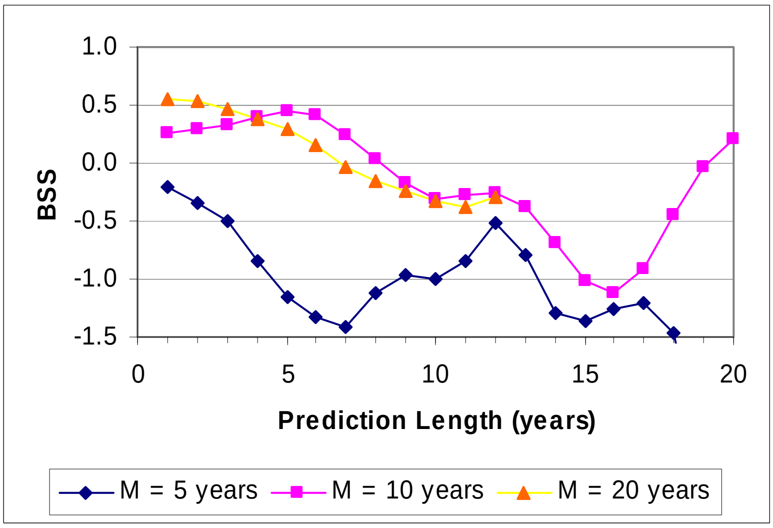


Figure 19 Brier Skill Score versus duration of prediction for linear trends fitted to 5, 10 and 20 years' data for Convalescent Home (top) and Bohemia Point (below).

Figure 20 shows the Brier Skill Score versus time for all the calculated profiles in Lincolnshire, based on fitting to 10 year's data. The linear trend is a better predictor than the average beach level for prediction durations between zero years (Jackson's Corner) and 14 years (Boygrift Outfall). The average Brier Skill Score from the 8 profiles is also shown. This has a positive value for both 1 and 2 year lengths of prediction, but a negative value thereafter.

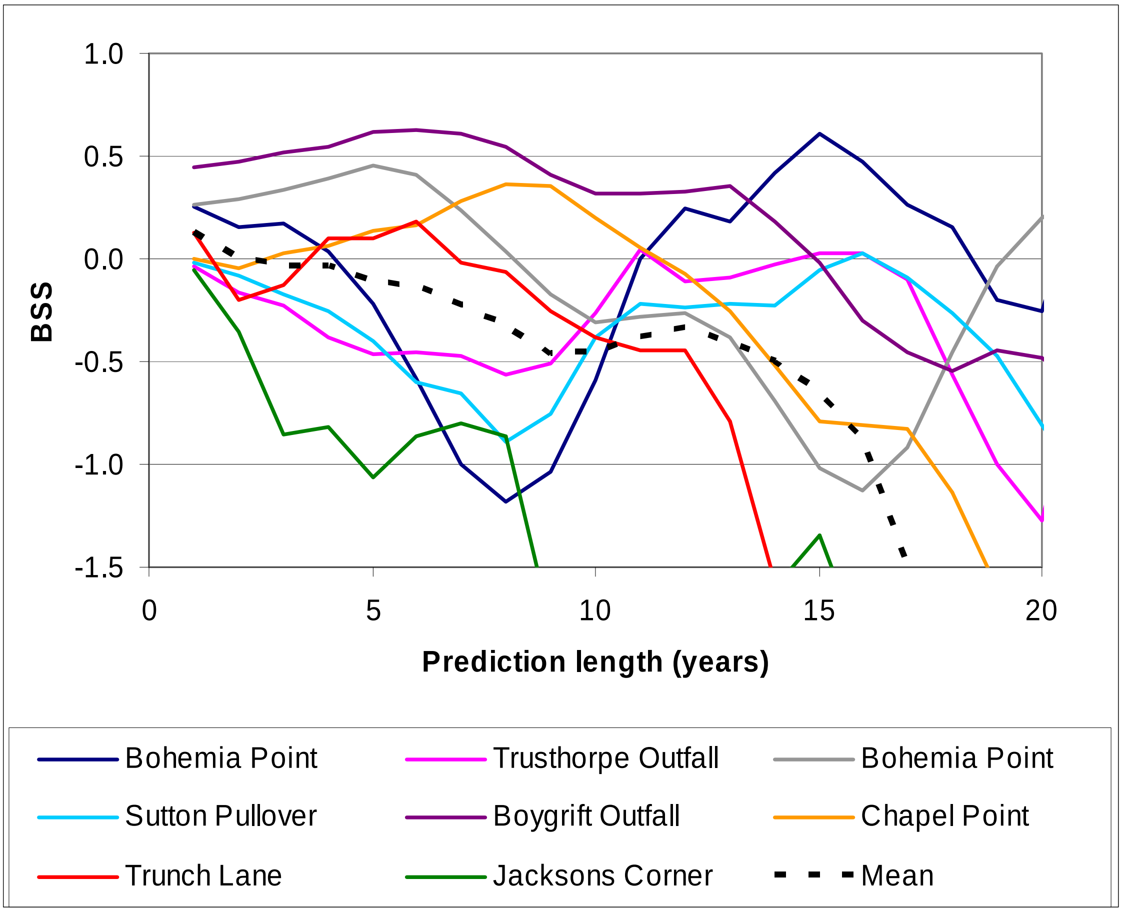


Figure 20 Brier Skill Scores versus time for Lincolnshire profiles based on linear trends fitted to 10 years' data

The above procedure has been applied to sandy beaches only. Zuzek et al. (2003) considered shoreline change rates in cohesive shores. They recommended that the length of the data record be at least as long as the planning horizon if past erosion rates are to be used to predict future shoreline positions in cohesive shores. Zuzek et al. (2003) also noted that when the erosion rate is averaged over a number of cross-shore transects, "the population mean provides a poor indication of the future erosion hazards because approximately half the transects will erode at a rate greater than the mean."

Implications for coastal management

Section 3.1.3 outlines a procedure that can be used to determine the length of time (or prediction horizon) over which the extrapolated best-fit straight line will provide a better predictor of future beach levels than the average of the measured beach levels. The results from an the analysis of 8 profiles in Lincolnshire indicate that it is better to use an average beach level than a linear trend if only 5 years' data is available. If 10 year's data is available then a linear trend can provide a better predictor of future beach levels than the average value for prediction lengths between 0 and 14 years, with an average value of 2 years.

These results apply only to Lincolnshire and a similar regional analysis should ideally be carried out for other coastal regions when sufficient data is available. The results illustrate that the predictive ability of a straight line fit to data is limited to a few years beyond the end of the dataset. This duration is shorter than the timeframes normally considered for coastal management, which may be 10 to 20 years.

A regional approach can be taken to provide guidance on possible changes in beach level at a structure toe over 10 to 20 years. Table 4 shows the change in beach level per year at the toe of the structure for eight profile locations. The values range from -31mm per annum to +26mm per annum. An indicative allowance of, say, 30mm per annum for Lincolnshire would provide a guide to potential beach lowering rates that could be used for the design and maintenance of coastal defences. The indicative allowances for beach lowering would be applied in the same way as indicative allowances for sea level rise.

3.1.3 Gaussian distribution of elevations

It is sometimes assumed that elevations at a point will follow a Gaussian or normal distribution. This assumption has been tested using the Lincolnshire data. First, the time series were de-trended by subtracting the best-fit straight line from the time series to give residual elevations. The range of elevations was split into bins of 0.2m range and the number of elevations within each bin was used to form a probability distribution. A Gaussian distribution was calculated with the measured average and standard deviation and was plotted on the same graph as the measured distribution. Figure 21 to Figure 28 show the measured and Gaussian distributions.

There were occasional problems with the calculated best-fit lines in BDAS due to rounding errors emanating from the limited resolution of the given slope, particularly at Bohemia Point. These resulted in non-zero mean residual levels, which skewed the distributions. Otherwise the distributions of residual levels were close to Gaussian provided that the straight line de-trending represented the long-term trend well. One case where this is not so is Chapel Point (See Figure 16). Here the linear-de-trending does not represent the sudden jumps in level that occurred twice during the sampling period. The resulting distribution of residual levels (Figure 26) is clearly different from the Gaussian distribution shown, which has the same mean and standard deviation.

This work has confirmed the correctness of the assumption that the residual beach levels (after removal of the long-term trend) have a Gaussian (or normal) distribution, provided that the long-term trend in beach level has been satisfactorily removed.

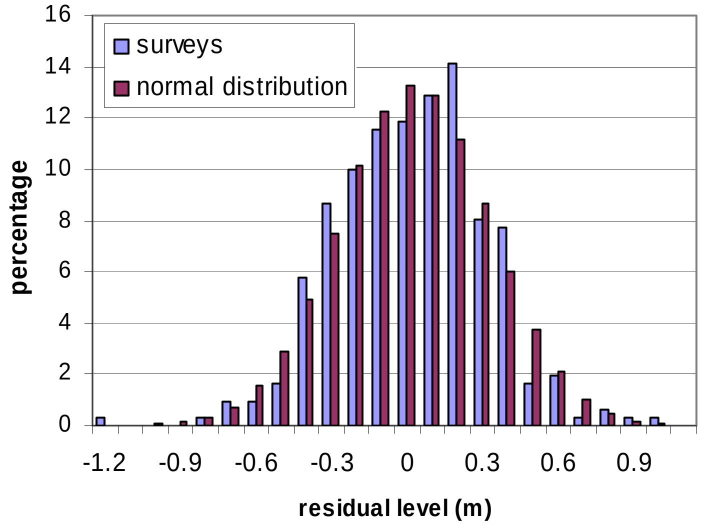


Figure 21 Measured and Gaussian distribution of residual beach levels at Mablethorpe Convalescent Home

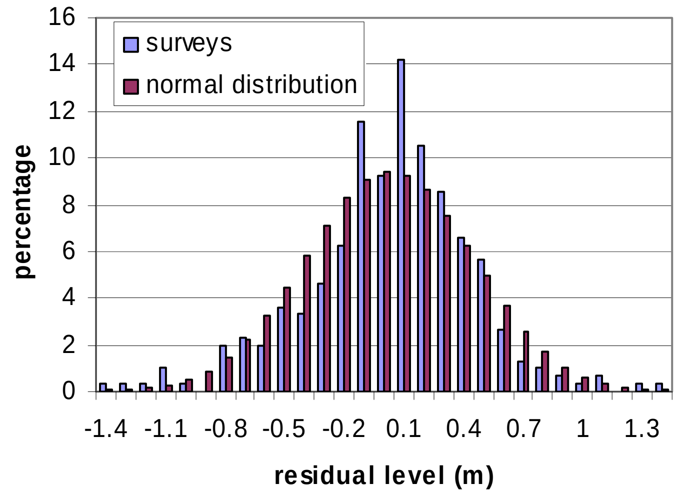


Figure 22 Measured and Gaussian distribution of residual beach levels at Trusthorpe Outfall

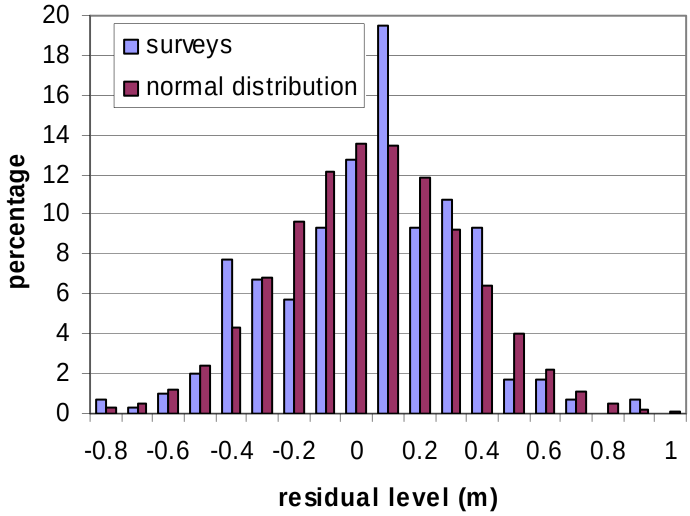


Figure 23   Measured and Gaussian distribution of residual beach levels at Bohemia Point

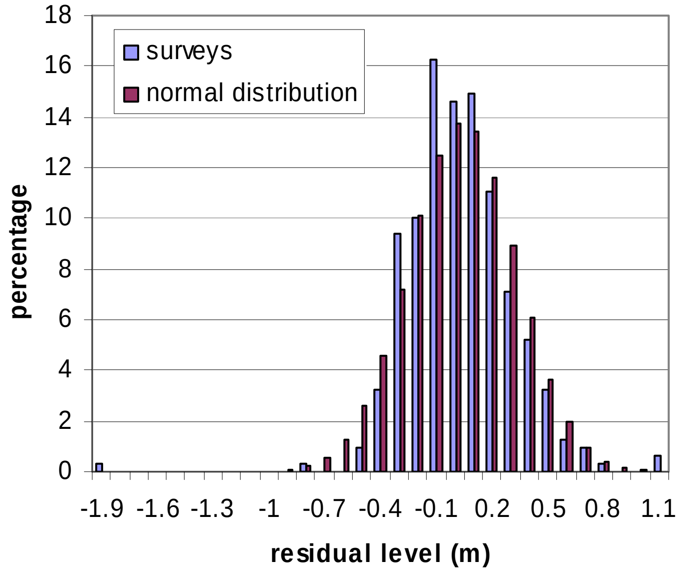


Figure 24   Measured and Gaussian distribution of residual beach levels at Sutton Pullover

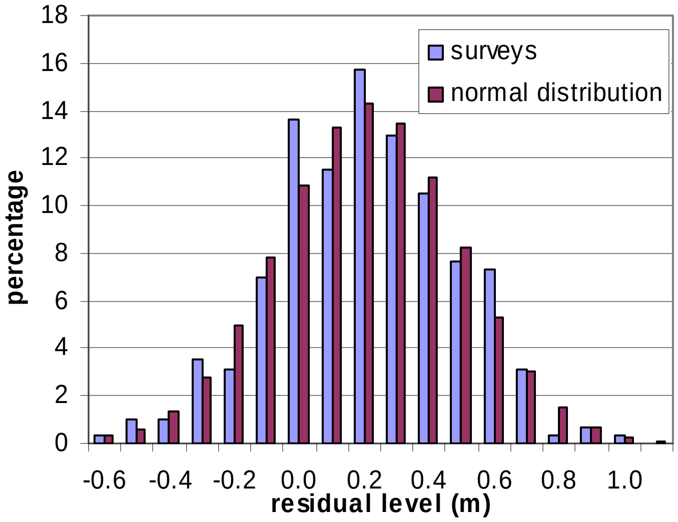


Figure 25   Measured and Gaussian distribution of residual beach levels at Boygrift Outfall

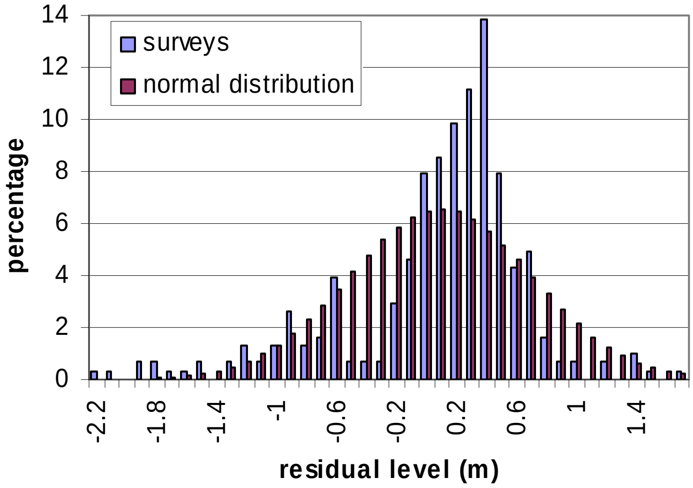


Figure 26   Measured and Gaussian distribution of residual beach levels at Chapel Point

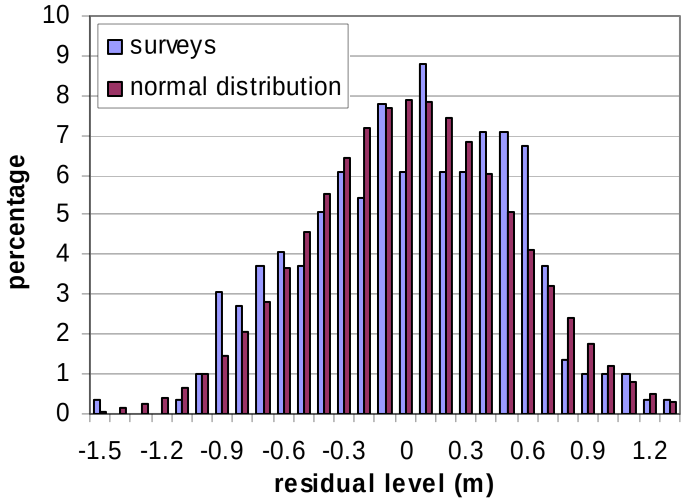


Figure 27   Measured and Gaussian distribution of residual beach levels at Trunch Lane

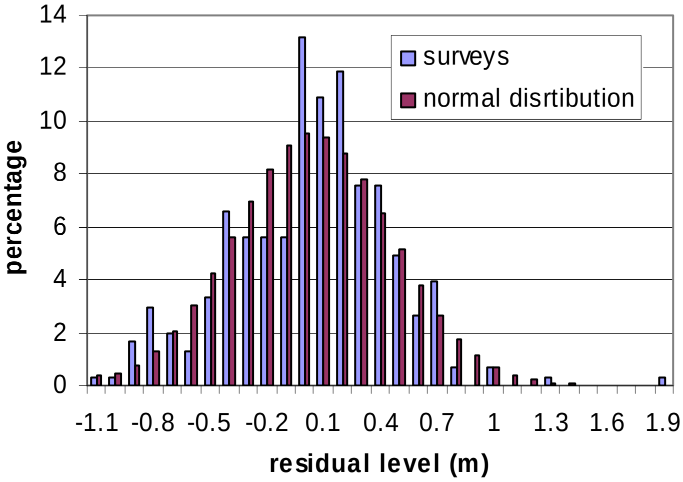


Figure 28 Measured and Gaussian distribution of residual beach levels at Jackson's Corner

3.1.4 Number of surveys in each year

Individual stations had between about 2 and 12 surveys in each year, with an average of about 9.5 surveys per station per year. This section investigates the effect of having 2, 3 or 5 surveys per year on the resulting statistics for beach level and standard deviation in beach level. The values obtained using all the surveys were treated as the baseline case. The beach profiles at the Mablethorpe Convalescent Home were used to illustrate the changes.

Figure 29 shows the changes in the average beach level for all the selected chainages. Changes were calculated by subtracting the average elevation from all surveys from the average elevation from 2, 3 or 5 surveys per year. The changes in average level were lowest for 5 surveys per year, with an average difference of -11mm compared to the value from using all surveys. The results from using 3 surveys per year showed a slightly greater difference from the baseline case, with an average change of -31mm, while the results from using only 2 surveys per year showed an average change of -63mm. Figure 29 illustrates that surveying only a few profiles per year may result in a systematic bias in the beach levels. This bias decreases as the number of surveys increases. Results from the Convalescent Home indicate that the bias introduced by sampling only 2 times per year could be over 60mm compared to an average from 9 to 10 profiles per year.

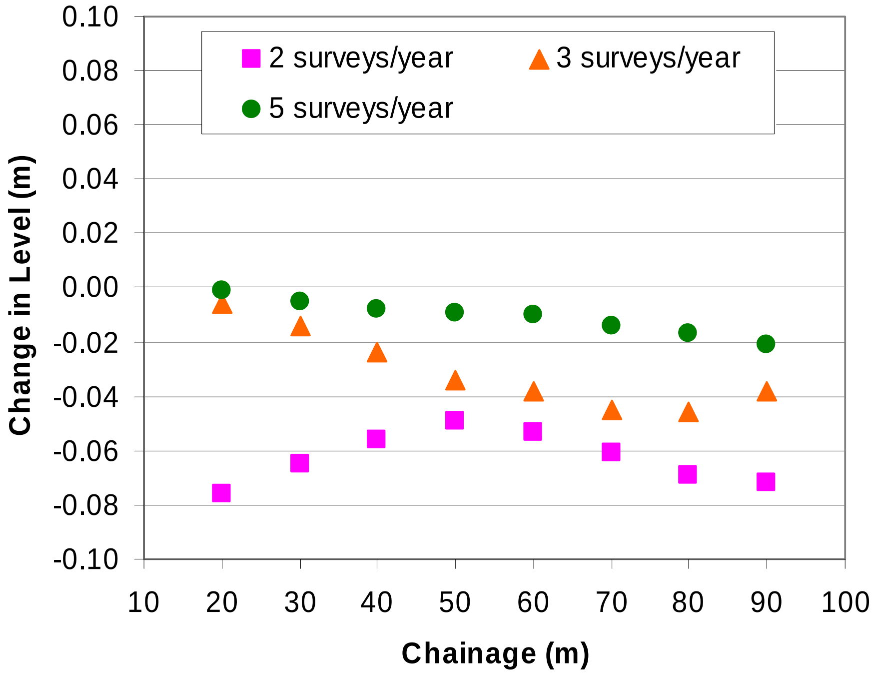


Figure 29 Changes in average beach level from 2, 3 and 5 surveys per year (compared to all surveys)

Figure 30 shows the percentage changes in the standard deviation in beach levels for all the selected chainages. Changes were calculated as the percentage difference from the standard deviation obtained from all surveys at that chainage. The standard deviations all had their minima at 50 m or 60 m chainage, while the changes in standard deviation and the percentage changes in standard deviation all had minima around 40 m or 50 m chainage. The lowest absolute percentage changes in the standard deviation (3%) came from having 5 surveys per year, but the mean absolute percentage changes from 2 and 3 surveys per year were both 6%.

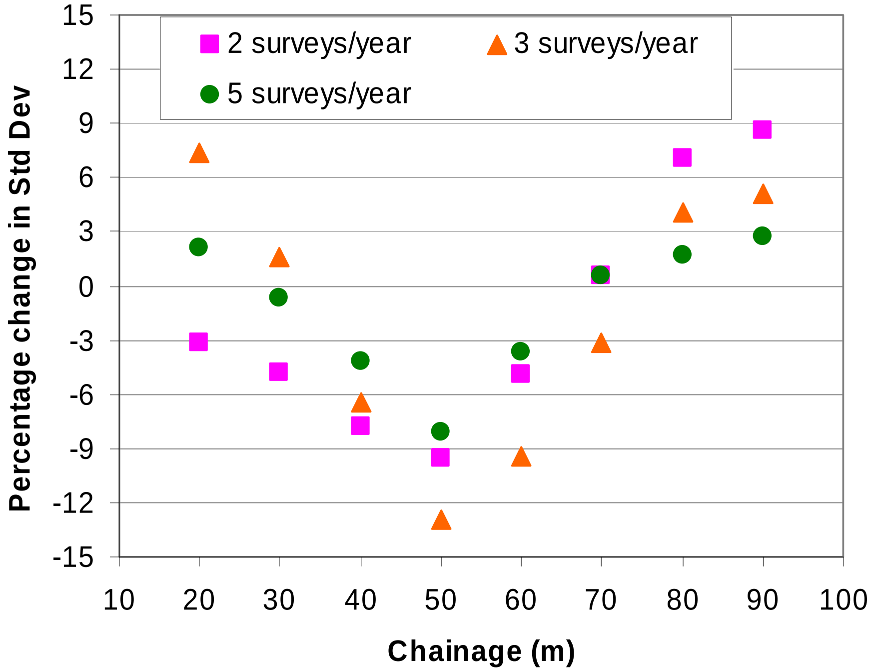


Figure 30 Percentage changes in the standard deviation in beach level from 2, 3 and 5 surveys per year

Figure 31 shows the calculated trend in level (m/year increase or decrease in level) from 2, 3 and 5 surveys per year plotted against the calculated trend in level from all surveys. Figure 31 shows that the results from 5 surveys per year were again the closest to those from all surveys, being on average 3% different. The trends from 3 surveys per year were on average 6% different from the trend from all surveys, while the trends from using 2 surveys per year were on average 11% different.

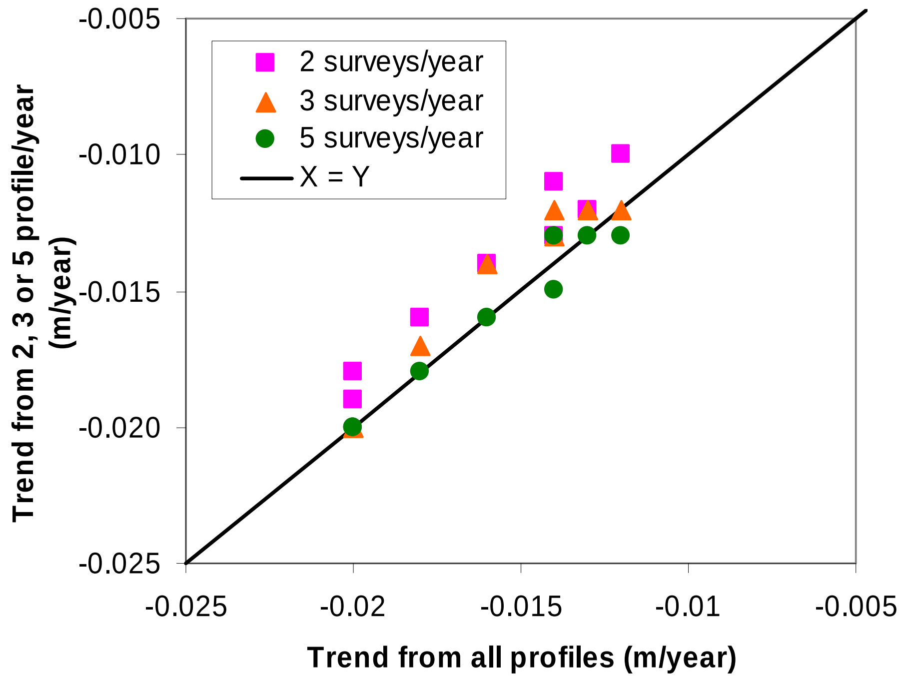


Figure 31 Trend in level (m change per year) for 2, 3 & 5 surveys per year plotted against trend from all surveys

The effect of collecting different numbers of surveys per year has been illustrated using the results from Mablethorpe Convalescent Home by first analysing the results from all surveys then by re-sampling 2, 3 or 5 times per year. The results indicated that the differences from using all the profiles increased as the number of surveys per year decreased. The standard deviation of beach level was on average 6% different from 2 surveys per year compared to all the surveys, while the percentage change in trend was on average 11% different. The differences in mean level and trend could be approximately halved by increasing the number of surveys from 2 to 3 per year.

3.1.5 Seasonal variations in beach levels at the toe of a structure

It is common to find beach levels lower in winter than in summer, due to the increased occurrence and severity of storms during winter. It also follows that beach levels may show a greater variation about their seasonal mean during winter. This will affect the optimum number timing of beach surveys, although these will vary depending on the purpose of the surveys. If the purpose is to establish the best long-term trend in beach level, this can best be achieved by surveying when the variability in beach levels is a minimum. If, on the other hand, the purpose is to establish the lowest level that a beach can fall to then it is best to survey when average beach levels are low and when the variability in beach levels is a maximum (if these 2 coincide).

In order to investigate this, the best-fit line of the form given in Equation 2 was fitted to 7 out of the 8 Lincolnshire stations analysed here. Chapel Point was not included as the linear trend did not represent the long-term behaviour of beach levels well.

$$Z(T) = a - bT + c\sin(2\pi/T) + d\cos(2\pi/T) \qquad (2)$$

where Z(T) is the best-fit beach level at the toe of the structure, T = time (in years) since 1900 and a, b, c and d are the fitted variables. The latter two terms can be combined to give the amplitude and phase of the best-fit seasonal trend, represented as a sine function. Figure 32 shows the best-fit seasonal trend for the 7 stations calculated. Six out of 7 stations had seasonal trends between 0.1 m and 0.2 m in amplitude which had their highest values in August or September. The other profile, from the Convalescent Home has a much lower amplitude (22mm) and peaked in October. The average profile had an amplitude of 110 mm and peaked in September, with its lowest value coming in March.

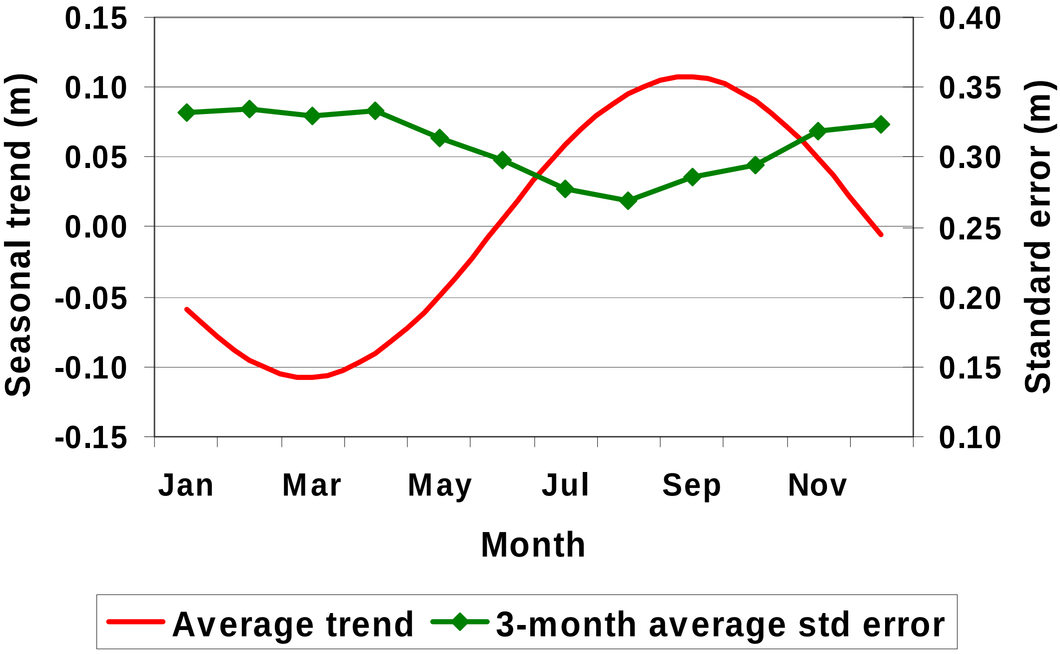


Figure 32 Best-fit seasonal trend from Lincolnshire stations

The residual level was calculated by subtracting Z(T) from the measured values. For four of the stations the mean residual level was calculated for each month (noting that the annual average residual level is zero). The standard error (standard deviation of the residual) was calculated for all stations.

Use of seasonal trend in planning surveys

The presence of a seasonal trend in both the mean and standard deviation of the beach level in front of a coastal structure will affect the beach monitoring programme. If the intention is to determine the best long-term trend in beach levels, the measurements should be taken when the standard deviation in the residual beach levels is at its lowest as this is when the signal-to-noise ratio will be at its highest. In other words the beach should be monitored in or around August (at least in Lincolnshire) when the variability in the beach level is at its lowest. At that time, however, the beach level will be close to its highest, so it is unlikely that any particularly low beach levels will be recorded.

Therefore, if the intention is to get an idea of how low a beach level can fall, the beach should be monitored when the average beach level is low and the standard deviation in the beach level is high. In Lincolnshire this occurs in and around March.

Note, however, that the relative timing of the seasonal trend will vary from place to place. For example, Zhang et al. (2002) analysed a detailed dataset of 588 high water line positions collected at Duck, North Carolina, USA between January 1996 and December 1999. They showed that the standard deviation of the high water line position was a minimum in June and July. They concluded that beach surveys that are to be used to predict long-term trends in shoreline position should be performed in June and July between spring and neap tides and should not be performed immediately after a storm.

3.2 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.

3.2.1 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.

3.2.2 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).

3.2.3 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.

3.2.4 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.

3.3 NON-LINEAR ANALYSES 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.

3.3.1 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.

3.3.2 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.

3.3.3 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.

3.4 SHORELINE OR BEACH VOLUME?

The Environment Agency (2003) has analysed beach profile data collected in north Lincolnshire, between Grimsby and Mablethorpe, from 1991 to 2000. Summer beach profile data from 1991 through to 1999 was analysed for mean annual shoreline retreat/advance (m/yr) at mean sea level (MSL) and mean annual volumetric rate of change (m^3/yr) using the volume of the compartment 500m to either side of each beach profile. The mean annual volumetric rate of change is the mean annual rate of change of the area under the profile multiplied by a typical distance between profiles.

Seven out of the 26 profiles between Grimsby and Saltfleet showed advancing MSL and 19 retreating, including 7 around Donna Nook. On the analysis of volumes 18 out of the 26 beach profiles showed increases in volume including 6 of the profiles at Donna Nook that exhibited MSL retreat. This indicates that the retreat/advance of a contour line on the beach may not be a good indicator of changes in volume of the beach.

An alternative method of exploring the link between beach volume and position of high water was developed for the beach profiles further south, between Mablethorpe and Skegness. Here, the chainage of Mean High Water Neaps (MHWN) was plotted against the area under the profile for four of the Lincolnshire datasets: Convalescent Home, Sutton Pullover, Chapel Point and Jacksons Corner. MHWN was chosen as there were more data points on the beach for the neap tide level than for the spring tide level (where the seawall was encountered more often). Moreover, MHWN was chosen over MWL as the longest records of shoreline position are from maps, which show MHW and MLW but not MWL. The area under the measured profile was calculated between set chainages with the inshore chainage set at the wall and above a stratum level, which is arbitrary but sufficiently low that the beach never drops to that level.

Figures 33, 34, 35 and 36 show the cross-sectional area plotted against the chainage of MHWN at Mablethorpe Convalescent Home, Sutton Pullover, Chapel Point and Jacksons Corner respectively. In each case the relationship between cross-sectional area and the chainage of MHWN is approximately linear so the position of MHWN can be used as a surrogate for beach volume.

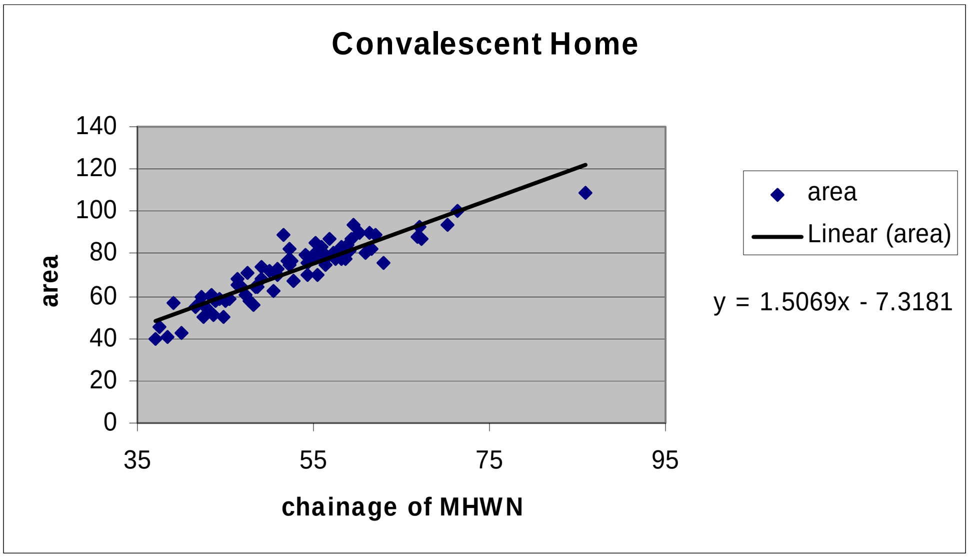


Figure 33 Cross-sectional area against chainage of MHWN for Mablethorpe Convalescent Home

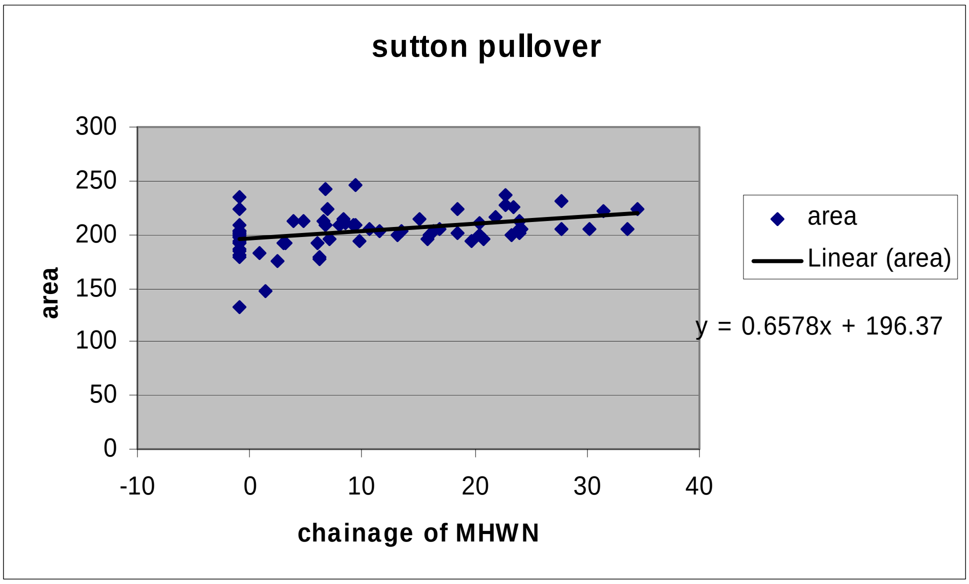


Figure 34 Cross-sectional area against chainage of MHWN for Sutton Pullover

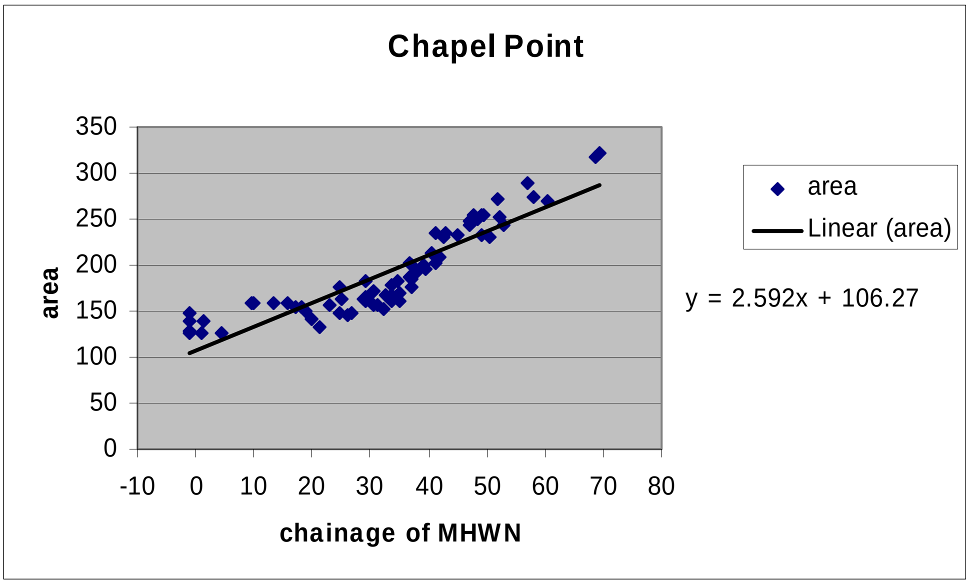


Figure 35 Cross-sectional area against chainage of MHWN for Chapel Point

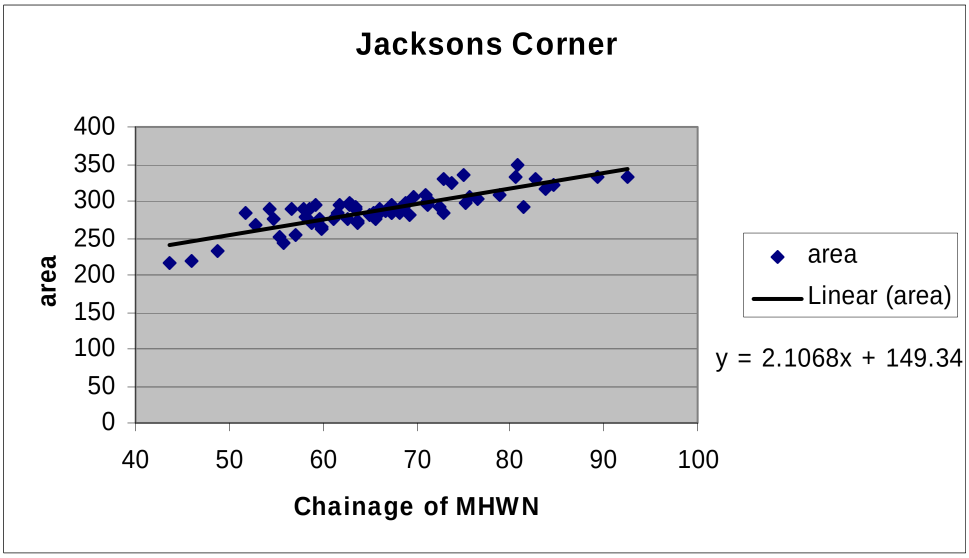


Figure 36 Cross-sectional area against chainage of MHWN for Jacksons Corner

3.5 ESTIMATING SHORELINE CHANGE FROM MAPS AND AERIAL PHOTOGRAPHS

Shoreline positions may be converted into shoreline changes by defining a baseline, generating orthogonal transects at set intervals, locating the position of MHW and MLW (or MHWS and MLWS) on the transects and calculating the change in positions. Rates of change are then determined by dividing the change in position by the time interval between the dates of collection of the datasets. The significance of the calculated rates of change depends on the signal to noise ratio. This can be improved by increasing the length of the series or by carefully selecting the data to be analysed. The former is limited by the length of the historic record. The latter can be improved by judicious choice of survey timing, as discussed in Section 3.2.

It is, however, extremely difficult to survey a true MHW mark as this should represent the land-water interface at the time when the water level is at MHW, given that the time of high water varies along the coast as does the elevation. Moreover the height of each tide varies through the month, the year and the 18.6 year lunar nodal cycle (Parker, 2003) and the position of the land/water interface varies with surge and wave conditions (including the effects of set-up). This illustrates the difficulty in using an instantaneous snapshot to define the shoreline position. Therefore true MHW (and MLW) marks are not plotted on maps. The OS has consistently used the same definitions of MHW and MLW from 1879 onwards (with some early exceptions) as far as changes in technology would reasonably allow, which should allow useful information to be obtained from successive releases of the same map.

Historic maps have been increasingly used in coastal management, without much discussion of the errors involved. Estimates of the total uncertainty in shoreline position are a combination of source uncertainty, interpretation uncertainty and natural short-term variability (Ruggiero et al., 2003).

Source uncertainty reflects the errors involved in the measurement of any point and includes errors in triangulation, the resolution of and type of corrections applied to aerial photos and GPS errors. Interpretation uncertainty represents the error in turning the data into a shoreline. This includes the difficulty of determining the shoreline from an aerial photo and the error in determining the mean high water position from a single visit. Natural variability reflects the dynamic changes in be shape of the beach that occurs in response to changes waves and water levels. Galgano, Douglas and Leatherman (1998) and Douglas and Crowell (2000) have shown that storms can cause beaches to erode substantially, thereby changing the shoreline position by a relatively large distance, which contaminates estimates of long-term erosion / accretion rates.

Ruggiero et al. (2003) have estimated the root-mean-square (rms) values of these errors for common American data sources. Examples of these are provided in Table 5. T-sheets are derived from detailed shoreline surveys used in navigation charts issued by the National Ocean Service. The variability errors due to natural variability in shoreline position were derived from a beach morphology monitoring programme carried out in the Columbia River littoral cell (in Oregon, USA) and are only applicable to this region. As the errors are statistically independent the total uncertainty was calculated as the square root of the sum of the squares of the Rms source, interpretation and variability errors.

Table 5 Total Rms uncertainty of shoreline estimates from Columbia River littoral cell, USA (Ruggiero et al., 2003)

Shoreline source	Rms source error (m)	Rms Interpretation errors (m)	Rms variability errors (m)	Total uncertainty (m)
1920 – 1950 T-sheets	±6	±8	±50-150	±51-150
Aerial photography	±4	±8	±50-150	±51-150
Beach profile survey	±2	0	±10-15	±10-15
Lidar survey	±3	0	±10-15	±10-15

The total error can be used to distinguish signal from noise in the determination of erosion or accretion from shoreline measurements.

There have been only a few systematic studies on the estimation of mapping errors in the UK to rival those in the United States, notably those by Carr (1962, 1980) and Ryan (1999). There have also been a number of studies that provide additional relevant information. These are summarised below. In cases where no study has been performed in the UK surveys in the USA and the UK may also be taken to have the same potential size of error, as a first approximation.

3.5.1 Errors in OS County series maps

Rms source error

Dornbusch (2005) scanned 1st Edition OS 6" scale (1:10,560) maps at 300dpi using an A3 scanner. The maps were georeferenced to the National Grid using the graticule printed on the maps. Georeferencing was performed using a first order transformation with RMS errors generally less than 0.6m. The georeferenced maps were overlain with OS Land-Line data and the position of features found on both maps were compared. In Kent individual features were offset by more than 20m in some cases. This gives an indication of the absolute error with respect to the National Grid. Sims et al (1995) noted edge mismatches across sheet edges of between 2m and 200m in historic OS 1:10000 scale maps. The large absolute errors measured indicate that tidelines should be measured relative to fixed local features, if sufficient immobile features exist close to the water's edge. Any comparison of the position of tidelines between successive maps should also include some measurement of fixed points, to check the relative and absolute errors that can occur.

Dornbusch (2005) then georeferenced the 6" maps again using common features that were on both maps, which produced positional errors less than 5m (a relative error). However, in some cases cliff lines were found to have advanced by up to about 10m, which is not realistic. Dornbusch (2005) concluded that a reasonable mean positional error for historic cliff lines was ±5m. This figure has been taken as a useful estimate of the Rms relative source error for 1:10,560 scale maps.

Ryan (1999) compared the positions of fixed points on 1:2500 County Series maps and National Grid maps to the results from a detailed GPS/total station survey around Porlock to obtain the rms error statistics given in Table 6. Here RMSTE is the Root-Mean-Square Total Error, RMSSE is the Root-Mean-Square Systematic Error and RMSRE is the Root-Mean-Square Random Error.

Table 6 RMS Source Errors from Ryan (1999)

Statistic	1888 County Series	1902 County Series	1928 County Series	Average County Series	1972 National Grid
RMSTE	2.96	3.47	3.37	3.27	2.62
RMSSE	1.59	1.88	2.38	1.95	1.24
RMSRE	2.50	2.90	2.37	2.59	2.31

The OS has been testing its National Grid maps for accuracy (OS, 1997a:5 and OS, 1997b:D10, cited from Ryan, 1999). Moreover the OS has recently completed a Positional Accuracy Improvement (PAI) programme, which has increased the absolute accuracy of data at 1:2500 scale (Ordnance Survey, 2006b, 2006c, p157). This has improved the absolute accuracy relative to OS National Grid. The PAI programme has delivered all rural 1:2500 scale areas to an overall root-mean-square-error of ±1.1m, with urban areas accurate to ±0.3m RMSE. The PAI programme has been applied to Land Line® and Mastermap® data. Table 7 summarises the size of the RMS Error (63.2% confidence limit) and the 99% confidence limit accuracy for National Grid and Mastermap mapping. Post-PAI Landline maps will have the same accuracy as Mastermap.

Table 7 Accuracy of OS 1:2500 National Grid Overhaul Mapping and Mastermap (& Landline)

Map Series	Type of error	RMSE = 63.2% confidence accuracy[m]	99% confidence accuracy [m]
National Grid 1:2500	Absolute	< ± 2.8m	< ± 5.8m
National Grid 1:2500	Relative	< ± 1.8m	< ± 4.7m
Mastermap 1:1250	Absolute	< ± 0.3m	< ± 1.0m
Mastermap 1:2500	Absolute	< ± 1.1m	< ± 2.4m

Tables 6 and 7 shows that the measured RMS absolute error for the National Grid maps (2.6m) was slightly lower than the OS PAI values (2.8m). Some studies will use absolute position and some will use relative position, but to provide a single indicative RMS source error for each type of map, a RMSE of 3.3m will be taken for the County Series (1:2500) and 2.8m will be used for the National Grid. In map tiles that are part land and part sea cover, the sea cover areas have not been altered by PAI, although the relativity of tidelines and landform have been maintained. Tidelines cannot therefore claim the post-PAI accuracies quoted above, but should be treated as having pre-PAI accuracy. Mastermap 1:2500 mapping will therefore be treated as having a RMS source error of 2.8m

Defra (2003a) claims that 25" to the mile County Series maps (or 1:2500 maps) provide typical accuracy of 2m to 3m, whereas 6" maps provide accuracy of over 5m, which is consistent with the values presented above.

Rms interpretation error

The estimation of rms interpretation error is made on the assumption that the LWL was surveyed and not added later by the Examiner. The decision about whether this has been done or not has to be made on a case by case basis and can be aided by having maps from successive county series and comparing the positions from all of them. The representation of tidelines on OS maps was described in Section 2.3.1.4. Interpretation errors come from:

- Uncertainty in the elevation of low or high water with respect to the target value;
- Uncertainty in deciding the instantaneous position of the moving shoreline which is subject to some irregular wave action.

The interpretation errors will be different for the two main methods of surveying: land-based (roughly pre-1970) and based on aerial photographs (post-1970). The errors from land-based surveying are considered first.

Uncertainty in the elevation of low or high water includes the variability in the predicted elevation of low water, the variation of the water level from the prediction and the variation in elevation during the course of the survey (assumed to last up to 1 hour for a survey conducted using a plane table and staff.). The following errors have been identified:

1. Levels in tide tables are set to the nearest 0.1m so have a maximum error of 0.05m, implying a Rms error of about 0.025m.
2. Water levels at the predicted time of high tide may not be at the MHW/MLW level. Surveys were to be taken when the predicted water level was close to the MHW/MLW level. The limits on accuracy of elevation are unclear, but on the switch to aerial photography a limit of ±0.3m was set. Ryan (1999) interpreted this to be an absolute maximum and inferred a standard deviation of 0.1m from this. Dornbusch et al (2006)

however showed a bias of just over 0.1m and a standard deviation of about 0.25m in the levels of low water from the fourth tide prior to new and full moon. Here Admiralty Tide Tables have been used to identify tides at standard ports that were predicted to fall within the MHW±0.3m limit during the summer (May to September) of 1996. Tides during the summer were chosen to avoid the worst storms and provide a data set close to normal conditions. 1996 was an arbitrary choice of year. The dates and times of these tides were noted and the measured water level at the port's tide gauge was recorded for the predicted time of high water. Time series of measured water levels from 8 tide gauges were supplied by the British Oceanographic Data Centre as part of the function of the National Tidal & Sea Level facility, hosted by the Proudman Oceanographic Laboratory and funded by the Environment Agency and the Natural Environment Research Council. The residual level was calculated as the measured – tide table MHW level. The mean and standard deviation of the residual levels are given in Table 8. These strictly apply only at the standard port and only for summer 1996. However, it is considered that they give a reasonable indication of the standard deviation in the residual for other years at the standard port and probably for other locations close to the standard port.

3. The variation in the water level within half an hour of high or low water can be estimated for primary ports from Admiralty Tide Tables mean spring and neap curves. The maximum changes in elevation at a number of primary ports are given in Table 8, based on the 1991 Admiralty Tide Tables. The elevation changes near low water are larger than the elevation changes near high water. Apart from Avonmouth (which has an unusually high tidal range) the maximum changes were 0.1m at high tide and 0.15m at low tide. The relationship between the elevation change 0.5 hours from high or low water and the Rms elevation change from a survey during this period depends on the shape of the tide curve near high or low water. As a reasonable estimate a Rms error of half the maximum has been taken. This can be calculated from the nearest primary port or, as a first approximation the following values can be used: Rms error for high water = 0.05m and Rms error for low water = 0.1m.
4. The error in determining the instantaneous position of the tideline. Given that it should be measured during calm conditions, during good weather a vertical Rms error of 0.05m is proposed for surveying with a plane table and a staff.

Table 8 Maximum elevation change within 0.5 hours of high and low water from Admiralty mean spring and neap curves, plus mean and standard deviation of residual water level (measured – MHW)

Port	Elevation change 0.5 hours from MHW (m)	Elevation change 0.5 hours from MLW (m)	1996 mean residual (m)	1996 standard deviation in residual (m)
Liverpool	0.1	0.15	-0.16	0.21
Swansea	0.05	0.1		
Avonmouth	0.2	0.5		
Devonport	0.05	0.15	0.10	0.21
Southampton	0.05	0.15		
Dover	0.1	0.15	-0.01	0.22
Lowestoft	0.05	0.1		
Immingham	0.1	0.2		
River Tyne	0.05	0.15	-0.01	0.18

The four errors are assumed to be independent, so are combined by calculating the square root of the sum of the squares of the standard deviations. This gives typical values of Rms error in level of 0.23m for high tide and 0.29m for low tide. This combination of errors ignores the measured mean errors (Table 9) which will bias the results. The method is therefore only valid if the mean errors are essentially invariant with time. This has not been investigated.

The horizontal error then depends upon the beach gradient, which will be greater for HWL than for LWL. This should be determined for each site from local beach profiles. As an indication of the difference, a number of cross-shore Rms interpretation errors are given in Table 9 for a range of potential beach slopes. These range between 4.6m and almost 57.5m.

Table 9 Potential Rms interpretation errors in cross-shore position for a range of beach slopes

Slope	High water RMSE (m)	Low water RMSE (m)
1:20	4.6	5.8
1:30	6.9	8.6
1:50	11.5	14.4
1:75	17.2	21.6
1:100	22.9	28.8
1:200	45.9	57.5

Interpretation errors from aerial photographs are discussed in section 3.1.2.2.

Rms variability errors

The Rms variability error is a measure of the horizontal variability in the cross-shore position of a given contour, due to natural changes in the waves, currents and water levels. Values for this figure should be obtained for each site by analysing beach profiles. Each profile should be interpolated to give the cross-shore position of MHW and MLW for each survey. Analysing a number of surveys will provide a time series of each. This time series should be de-trended (a straight line fit should be sufficient) and the Rms value obtained. This is the Rms variability error.

An example of this is provided by beach profile data collected in Lincolnshire between 1959 and 1991. The HWL was estimated to be the average of MHWS and MHWN at Skegness, while LWL was estimated as the average of MLWS and MLWN at Skegness (from the 1991 Admiralty Tide Tables). The resulting Rms variability errors are given in Table 10 for a number of cross-shore profiles, which also includes values for MHWN, MWL and MLWN. In some cases there were insufficient surveys at MLWN and/or MLW to provide a reasonable estimate. These cells have been left blank. The number of years of data used in the analysis is given in column 2. In cases where 10 years' data was used, the time span was 1981 to 1991.

Table 10 Rms variability errors for Lincolnshire profiles

Location	No. years	MHW	MHWN	MWL	MLWN	MLW
Convalescent Home	32	7.45	9.14	10	11.08	
Convalescent Home	10	6.07	8.62	10.36	11.08	
Trusthorpe Outfall	10	0	3.85	9.33	7.79	10.82
Sutton Pullover	10	2.01	9.26	14.34	10.73	22.25
Boygrift Outfall	10	6.31	4.84	13.65	14.88	15.57
Jacksons Corner	32	14.5	15.69	14.52		

Table 10 shows that the Rms variability error increases on going down the beach profile, as the beach profile flattens. The Rms variability error is zero at MHW at Trusthorpe Outfall as the beach level was so low, only the position of the seawall was recorded. The range of Rms variability errors at MHW was from 0 m to 14.5 m. The Rms variability error at MLW was not obtained for half the profiles where there were insufficient results at that level. The range of measured errors at MLW was from 10.8 m to 22.2 m.

3.5.2 Errors in aerial surveys

Rms source error

An example of the use of aerial photographs to determine shoreline evolution was provided by Halcrow (2004). In this two sets of aerial photographs of Studland Bay from 1951 and 2001 were digitised and each was merged into a single photo-mosaic. The high tide mark was chosen as the feature to be mapped, although it was acknowledged that this position would depend on preceding wave activity. The high tide mark has served as a useful proxy for the HWL in a number of studies as it is often visible from aerial photographs. The vegetated seaward edge of the dunes was not chosen as the photographs were taken at different times of year and a seasonal change in the edge of vegetation was anticipated. The still water line was not chosen, as the time of exposure was not known so the water level could not be determined.

The study frontage in Studland Bay was divided into sections and the digitised high tide lines were bounded onto polygons. The average distance of shoreline movement was estimated as the area of the polygon divided by the sector length. A rate of change followed by dividing the average distance by the time interval between photographs. The accuracy of measurements was determined by measuring the positions of 34 fixed points. The difference between the measurements was taken to represent the error in position. The average point error was 2.75m, with individual points ranging between 0.0m and 9.0m. The error values were interpolated to form an error surface, from which the average error for each section was estimated. In 6 out of 8 sections the total shoreline change was significantly greater than the mean error, while in the two sections with low total changes the mean error was higher than the total shoreline change. The ratios indicate how much confidence can be placed in the results.

Further along the coast between Rockley Point and Ham Common in Poole Harbour shoreline change rates were lower and the total changes were about the same as the mean error. In these sections the aerial photographs were close together in time and the mean error were lower. The average of the mean errors for all sections was 3.7m with a standard deviation of 2.6m. This is taken as a measure of the Rms source error, as it was based on fixed points, such as the corner of a building, rather than on the subjective selection of a tide line.

Rms interpretation and variability errors

It is assumed that the interpretation error that arises from picking out a particular line on the photograph will be the same as in the USA so a value of 8m has been taken. However, these errors will depend on the proxy shoreline used. There is also an interpretation error caused by errors in the level of water at the time of the photograph.

Water levels at the predicted time of high tide may not be at the MHW/MLW level. This interpretation error is the same as for historic maps as aerial photos are to be taken within ±0.3m of MHW or MLW. The standard deviations in elevation from Table 11 therefore apply here as well.

Interpretation errors due to picking out the tideline and in the elevation of that tideline are assumed to be independent so are combined by taking the square root of the sum of the squares of the errors. Combined interpretation errors for aerial photographs are given in Table 11 for different beach slopes.

Table 11 Rms Interpretation errors for aerial photographs

Slope (1:N)	Rms interpretation error	
	From (m)	to (m)
1:20	8.8	9.1
1:30	9.7	10.4
1:50	12.0	13.6
1:75	15.7	18.3
1:100	19.7	23.4
1:200	36.9	44.7

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3.5.3 Rms Uncertainty of shoreline estimates in the UK

Section 3.1 has given an estimate of the various error terms that may be expected from OS County Series Maps when the tidelines were surveyed by plane table (i.e. up to about 1970). After about 1970, MLW was determined from aerial photographs. The Ordnance Survey (Edwards, 2001) suggests that it would be better to use the original aerial photographs than the OS MLW in these cases. Estimates of the error terms that may be expected from aerial photograph have also been presented. The estimates of the possible errors are crude in some cases and rely on expert judgement and what little related work has been done in the UK by Dornbusch (2005), Dornbusch et al. (2006), Ryan (1999) and the new work here.

It has been easier to estimate the Rms vertical variations in some cases. These can easily be translated into typical horizontal distances if the local beach slope is known. The natural variation in the position of MHW and MLW can be derived from beach profiles and this should be done on a case-by-case basis. The sources of error are summarised below:

1. RMS Source error (RMSS) for 1:2500 scale mapping decreases from 3.3m for County Series maps to 2.8m for National grid maps. Mastermap mapping is taken to have the same error as National Grid mapping.
2. The RMS Interpretation error (RMSI) is given approximately by 0.23/tan(α) m for MHW and 0.29/tan(α) m for MLW where α is the beach slope at MHW/MLW. Similar values apply for County Series, National Grid and Mastermap. Regional differences are probably larger than differences between map series.
3. RMS Variability error (RMSV) can be determined from beach profiles. As an example, in Lincolnshire between 1959 and 1991, the RMSV at MHW varied between 0m and 8m, while that at MLW varied between 10m and 23m. Beach profiles were relatively steep, being around 1:30 at MLW. Larger errors may be anticipated on flatter beaches.

These values are not necessarily applicable outside the areas they were derived for and local values should be estimated in all cases. If the different errors are independent and have normal distributions, as we assume, then the total RMS error, RMST, is given by Equation 3.

$$\mathrm{RMST} = \sqrt{\mathrm{RMSS}^2 + \mathrm{RMSI}^2 + \mathrm{RMSV}^2} \qquad (3)$$

The range of expected values will then be about 4 times the Rms total error (at 95% confidence level).

A number of examples from Lincolnshire are set out below:

- MHW on a National Grid map with a 1:25 slope would have a RMS total error of 6 m to 10 m.

- MLW on a National Grid map with a 1:30 slope would have a RMS total error of 14m to 24 m.
- MLW on a National Grid map with a 1:100 slope would have a RMS total error of 31 m to 37 m.

So, for example, two surveys of MLW (if on a 1:100 slope) could be up to 150m apart, with the differences being caused by the survey methods used and the natural variations in the beach morphology. No net erosion or accretion need have taken place. The above examples are not the worst-case scenarios as there are obvious problems in determining LWL in cases where there are sandbanks (if the inshore channel level is about MLW) and ridge and runnel beaches. In the former case the channel bed may be above MLW and MLW will run at the seaward side of the sandbank or it may be below MLW and the MLW will run along the beach side of the channel. In the latter case the position of low water will depend on the configuration of ridges and runnels.

4. Process-based models

4.1 INTRODUCTION

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 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. Hansen 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.

4.3 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.

4.4 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.

4.5 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). SCAPEt 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.

4.6 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 6.1 Regional differences in potential shoreline erosion under the four Foresight Futures

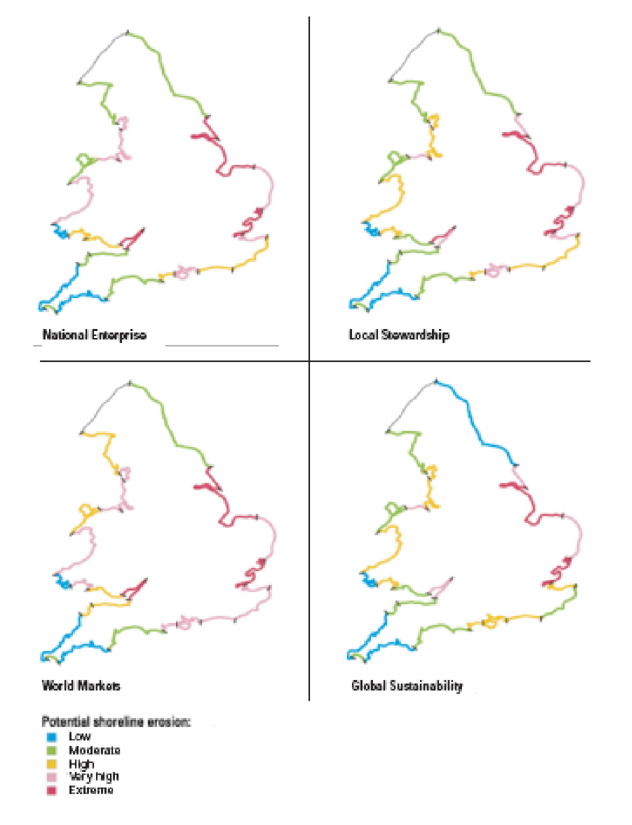

Figure 37 Regional differences in potential shoreline erosion over the next 100 years for different UKCUP02 climate change scenarios (Evans et al., 2004, Figure 6.1, © Crown Copyright, 2004)

4.7 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.

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

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.

4.8 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.

4.9 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.

5. 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 moves onto describe useful projects that have has a significant geomorphological component, namely Futurecoast and Eurosion. 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).

5.1 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.

5.2 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.

5.3 EUROSION

Eurosion (European Commission, 2004) was a European study into coastal erosion at a European scale. Its outputs were:

- A map-based assessment of European coasts exposure to coastal erosion;
- A review of existing practices and experience of coastal erosion management;
- Guidelines to incorporate coastal erosion into environmental assessment, spatial planning and hazard prevention; and
- Policy recommendations to improve coastal erosion management.

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.

Eurosion concluded that a more strategic and proactive approach to coastal erosion is needed for the sustained development of vulnerable coastal zones. It developed the concept of coastal resilience: the inherent ability of the coast to accommodate changes induced by sea level rise, extreme events and occasional human impacts, whilst maintaining the functions fulfilled by the coastal system in the longer term. To promote coastal resilience, Eurosion introduced the concept of favourable sediment status: the situation where the availability of coastal sediments support the objective of promoting coastal resilience in general and of preserving dynamic coastlines in particular. This should be achieved for each coastal sediment cell by designating strategic sediment reservoirs: supplies of sediment of appropriate characteristics that are available for replenishment of the coastal zone, either temporarily (to compensate for losses due to extreme storms) or in the long term (at least 100 years). They can be identified offshore, in the coastal zone (both above and below low water) and in the hinterland.

A coastal sediment cell is a coastal compartment that contains a complete cycle of sedimentation including sources, transport paths, and sinks. The cell boundaries delineate the geographical area within which the budget of sediment is determined, providing the framework for the quantitative analysis of coastal erosion and accretion. Eurosion considered that coastal sediment cells constitute the most appropriate units for achieving the objective of favourable sediment status and hence coastal resilience (European Commission, 2004).

6. 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.

6.1 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.

6.2 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 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 does not depend on a particular coastal profile, but does assume that no sediment is lost from the coastal system (which is likely to happen if there are fines in the area eroded). It assumes a coast of unconsolidated sediment, mainly sand, with (originally) a coastal dune and makes no allowances for gradients in the longshore or cross-shore transport of sand. However, the Bruun rule has been extensively modified, developed and used (see Dean et al., 2002 for a summary).

In the coastal regions where the Bruun rule can be said to apply, the rate of shoreline retreat (dR/dt) is directly proportional to the rate of sea level rise (dS/dt). It follows that the ratio of future shoreline retreat rate to present day shoreline retreat rate (the shoreline retreat rate multiplier) will be the same as the ratio of future sea level rise rate to present day sea level rise rate.

The shoreline retreat rate multiplier can be calculated using present day rates of sea level rise (IPCC, 2007) and regional sea level allowances from Defra (2006). IPCC (2007) states that the average rate of sea level rise (eustatic change) from 1961 to 2003 was 1.8 mm/yr. This was combined with the regional rates of vertical land movement (the isostatic change from Defra, 2006, derived from Shennan and Horton, 2002) to give regional rates of net relative sea level rise from 1961 to 2003, as shown in Table 3.5.

Table 13 Net rate of sea level rise from Defra (2006) and IPCC (2007).

		Net rate of sea level rise (mm/yr)				
Region	Land movement (mm/yr)	From 1961 to 2003	From 1990 to 2025	From 2025 to 2055	From 2055 to 2085	From 2095 to 2115
E & SE England (South of Flamborough Head)	-0.8	2.6	4.0	8.5	12.0	15.0
SW England & Wales	-0.5	2.3	3.5	8.0	11.5	14.5
NW & NE England, Scotland	0.8	1.0	2.5	7.0	10.0	13.0

The shoreline retreat rate multiplier was then taken as the net rate of sea level rise from future periods divided by the net rate of sea level rise from 1961 to 2003. The results are shown in Table 3.6 and show that shoreline retreat rates in regions where the Bruun rule applies could increase significantly – in some cases by a factor of 13 - during the 21st century. The shoreline retreat rate multipliers are highest for the Northwest and Northeast of England and Scotland as this region has the lowest present day rate of sea level rise, due to isostatic rebound following the last ice age, which may also imply lower rates of present day shoreline retreat.

Table 14 Shoreline retreat rate multipliers for different time spans

	Shoreline retreat rate multiplier				
Region	1961 to 2003	1990 to 2025	2025 to 2055	2055 to 2085	2095 to 2115
E & SE England (South of Flamborough Head)	1.0	1.5	3.3	4.6	5.8
SW England & Wales	1.0	1.5	3.5	5.0	6.3
NW & NE England, Scotland	1.0	2.5	7.0	10.0	13.0

These results should be treated with some caution, however, as the Bruun rule is a very simplistic analysis tool and difficult to validate. Bray and Hooke (1997) adapted it to look at the erosion of soft cliffs by adding sediment exchange and considered it particularly suitable for assessing the sensitivity of eroding soft cliffs to future climate change. On the other hand both Cooper and Pilkey (2004) and Stive (2004) cautioned against its use due to its simplicity and restrictions.

Dickson et al. (2007) compared the predictions of recession from the modified Bruun rule and the systems model SCAPE (Walkden and Hall, 2005) for 50km of the soft rock shoreline of northeast Norfolk. They found that the systems model SCAPE predicted a rather more complex response, with lower overall vulnerability to sea level rise, than the Bruun rule. Where beaches overlie shore platforms both SCAPE and the Bruun rule gave accelerated recession rates in response to sea level rise. However, in some areas with large beaches and gradients in the longshore transport rates the Bruun rule predicted recession where SCAPE predicted accretion due to sediment transport from eroding up-drift stretches of the coastline. This indicated the inadequacy of the Bruun rule in regions where there is a significant variability in the longshore transport rates.

Therefore the magnitudes of the shoreline retreat rate multipliers in Table 3.6 should be treated with some caution as they may well be too high. However, it appears probable that the shoreline recession rate will increase in many places if the rate of sea level rise increases.

7. Predicting bed levels at different timescales

Various options for predicting beach levels at different scales are given in Table 13. Monitoring features at all scales, but requires a number of different techniques of monitoring and analysis to turn a recorded level into a prediction. The subsequent sections outline the options for predicting the range of likely bed levels at different timescales.

Table 15 Options for predicting beach level changes at different scales

Tide / Storm	Weeks	Seasons	Years
Monitoring trigger level	Cross-shore profile modelling	Extrapolation of seasonal trend	Linear extrapolation of data
Coastal profile modelling (cross-shore)	Gaussian distribution in levels	1-line or N-line modelling	1-line or N-line modelling
Empirical scour predictors		Coastal area modelling	Geomorphological models
			Equilibrium profile

7.1 PREDICTING BED LEVELS AT A SCALE OF TIDES AND STORMS

7.1.1 Monitoring

Field work (Sutherland and Pearce, 2005 and HR Wallingford, 2005) has shown how bed levels can fall and recover during a tide. Measuring the variations during a number of tides can allow the distribution of local scour depths to be determined. This data can be used to determine the likely range of scour depths that can be achieved at a location. Alternatively the results can be analysed to give an empirical predictor of the short-term scour depth. The field data collected for this project (Sutherland and Pearce, 2005 and HR Wallingford, 2005) is being used to derive a scour predictor. The data itself could be used in real time to trigger a warning system, should beach levels drop too low.

7.1.2 Process-based modelling

Process-based numerical models of cross-shore beach evolution have been used for a number of years to predict the (generally) short-term cross-shore response of beaches to storms (van Rijn et al., 2003, Southgate and Nairn, 1993, Nairn and Southgate, 1993). Cross-shore profile models assume longshore uniformity and model the cross-shore hydrodynamics, sediment transport and bed level changes. These models have often been used to model the short-term cross-shore beach profile response to storms, but are generally less capable of modelling the recovery of beaches after a storm. They could be combined with a wave forecasting system (driven by a weather forecast) to predict changes in bed level over periods of up to about 5 days.

7.1.3 Empirical Scour Predictors

A variety of empirical scour predictors have been developed for predicting the short-term response of beaches to waves and water levels. These are dealt with elsewhere in the project (Sutherland et al., 2003, HR Wallingford, 2006).

7.2 PREDICTING BED LEVELS AT THE SCALE OF WEEKS AND SEASONS

7.2.1 Coastal profile modelling

As noted in Section 7.1.2, coastal profile models could be used over a timescale of weeks and in some calibrated cases potentially months to predict bed levels.

7.2.2 Extrapolation of measured beach levels

Measured beach levels can be used to identify a linear trend, a seasonal trend and a Gaussian distribution of beach levels about that trend.

7.3 PREDICTING BED LEVELS AT THE SCALE OF YEARS

Bed levels at the toe of structures are not generally calculated at a timescale of years and decades. It is more common to try and predict the behaviour of the shoreline and methods for doing this are discussed in Defra (2003a) Appendix D. Changes in shoreline position can be related to beach level at the toe of a structure through knowledge of the beach slope. Appendix D includes a comparison of the following methods for analyse shoreline interactions and responses:

- Geomorphic extrapolation;
- Numerical modelling;
- Extrapolation of historical data;
- Parametric equilibrium models.

These methods could also be used over shorter timescales of a few years. In particular bed levels at the toe of a coastal structure can be predicted in some locations using the extrapolation of a linear trend obtained from at least 10 years' data, as discussed in Section 3.1.2. Different locations along the Lincolnshire coastline were found to have different prediction horizons (i.e. different lengths of prediction before the predicted beach levels from the extrapolation of the linear trend became on average worse than the use of the average beach level). Further work should be undertaken to establishing typical prediction horizons from other stretches of coastline where sufficient data is available.

Intrinsic limits to knowledge mean that predictions of future shoreline position over a timescale of years to decades will never be definitive, particularly when considering the effects of climate change. Therefore it is useful to take an approach based on a range of available methods and data to arrive at the most likely position.

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