INVESTIGATION OF BEACH CHANGE AT HAYLE, CORNWALL

by

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MSc Hydrography

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Copyright Statement

Abstract

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The morphology of the Hayle Estuary mouth is highly dynamic stretch of coastline in both seasonal and decadal time scales. Recent accounts of beach erosion and subsequent accretion within the estuary, justified an assessment of these changes and their links to local dredging operations. Historical shoreline data was derived from archived aerial photographs spanning from 1946 to 1996. In addition, combined Real Time Kinetic Global Positioning System (RTK GPS) / bathymetric survey data from July 2004 was also compared to Light Ranging and Detection (LIDAR) survey data flown in March 2003.

Gradual retreat of the Towans dune system occurred between 1946 and 1988 with further dune erosion, closer to the channel entrance, continuing up until 2004. Since the end of the sluicing operations at Hayle, in 1971, rapid sand accumulation within the estuary mouth has occurred. Recent RTK GPS and LIDAR survey data comparisons reveal persistence of sand accretion despite ongoing dredging activities.

The study provided an insight into the accuracy and precision issues relating to inter-comparisons of multiple survey data sets. Accuracies of the LIDAR and RTK GPS survey techniques and data smoothing during digital elevation model (DEM) preparation resulted in the presence of substantial errors during volumetric analyses. Further detailed accuracy analyses of multiple survey data sets is recommended prior to using survey data in beach change assessment.

Table of Contents

List of Figures

Acknowledgements

I would like to thank my supervisor, Dr Victor Abbott, for his ideas and encouragement, Janet Burroughs and Steve Bennet for their valuable advice and instruction in operating the survey equipment and helping me to overcome some equipment shortcomings. A special thanks to my fellow MSc colleagues, Paul Hunt and Helen Smith, for their invaluable assistance during the extensive amount of fieldwork that was undertaken and for driving me and the equipment down to Hayle several times.

Cheers to Simon Mansell (Penwith District Council) for funding the vessel and skipper hire, Mark Williams (boat skipper) for his cooperation and flexibility during the boat survey, and to John Browne (Hayle Harbour Master) for his useful information. Thanks also to Phillipa Hoskin and colleagues (Cornwall County Council) for providing the archived aerial photographs of the study site and to Paul Nelson (Environment Agency) for providing the LIDAR data used in the study. Allan Jones, Lecturer in Geographical Sciences at University of Plymouth, deserves my thanks during the late stages of my project for his ArcGIS knowledge.

This wasn't the easiest project to undertake, as I knew conducting a full beach survey would prove logistically difficult. However, a great deal was gained, from learning to conduct a full scale beach survey through to teaching myself the finer points of ArcMap Geographical Information System (GIS) software.

Michael Golowyn

September 2004

Declaration

I declare that this work is the product of my own research and work.

Michael Golowyn

16 September 2004

Chapter 1

1 Introduction

1.1 Study Background

Beach erosion and shoreline change is a complex process involving oceanographic and coastal processes including waves, tides, currents and sediment transport. In order to measure and gain an understanding of these processes, a variety of techniques can be used including the use of mathematical models, aerial photography and topographic surveys can be employed.

Hayle Beach and Estuary mouth in St Ives Bay, Cornwall, United Kingdom (UK) is a dynamic stretch of coastline which has a long history of shoreline change. Local observations over recent years have noted a reduction in beach levels, a retreating dune system and subsequent accretion of sand within the Hayle Estuary mouth (Penwith District Council 2002).

Recent dredging operations within the estuary mouth have been a subject of keen public interest with many locals believing the problems observed at Hayle Beach are a direct result of the dredging. Considering marine aggregate extraction is known to impact on the hydrodynamic regime and to cause a disruption in coastline sediment supply (Posford Duvivier Environment & Hill 2001), the concerns of Hayle residents and visitors are valid.

In order to assess the estuarine and coastal processes observed at Hayle, Babtie Group Ltd was commissioned by the Penwith District Council (2002) to conduct a mathematical modelling study. It was discovered that reduction in beach levels were largely due to wave action and sediment transport processes in the intertidal zone. The accumulation of sand within Hayle Estuary mouth is a result of the dominance of the flood tide over Hayle beach transporting sand towards the estuary mouth.

Use of conventional land and bathymetric surveying techniques, such Real-Time Kinetic (RTK) Global Positioning System (GPS), Light Detection and Ranging (LIDAR) and hydrographic (bathymetric) surveys, are becoming more prevalent in the use of measuring beach and shoreline change. However, direct comparisons of different survey data sets for beach change analysis can result in errors, which include the sum of the inaccuracies, from conducting the actual survey through to interpolation and data processing errors.

1.2 Study Aims and Objectives

The aims of this study are to investigate the long term (~50 years) and short term scale (~1 year) erosion and accretion events that have occurred at Hayle Estuary mouth. A secondary consideration is to determine if recent dredging operations at Hayle Beach have resulted in the observed beach changes. This is will be achieved through the following study objectives:

1. To analyse a series of aerial photographs dating from 1946 to 1996, and to assess the extent of shoreline change over that period.
2. To undertake a full topographic and bathymetric survey at Hayle Estuary mouth, incorporating a geodetic, RTK GPS and a bathymetric survey, to provide a recent survey data set.
3. To directly compare the recent survey data with that of LIDAR survey data flown 16 months previous to evaluate areas of erosion and accretion.
4. To analyse and discuss the random and systematic errors in collecting, processing and presenting of survey data.

1.3 Project Structure

The background section in Chapter 2 begins with a description of the study area and proceeds with a comprehensive literature review on coastal processes that lead to changes in beach and shoreline morphology. Chapter 3 covers background information regarding various beach surveying techniques including their principles of operation and sources of error. Chapter 4 describes the equipment and methods used in conducting the Geodetic Global Positioning

System (GPS), Real Time Kinetic (RTK) GPS, and bathymetric surveys undertaken at Hayle Beach including the data processing that took place. Chapter 4 also explains the collection and processing of archived aerial photographs and LIDAR survey data with Chapter 5 describing the data analyses that took place.

The results of the analyses are presented in Chapter 6. Interpretation of results, including their significance with regards to recent dredging operations, is provided as the discussion section in Chapter 7. The dissertation ends with a summary of the main conclusions in Chapter 8.

Chapter 2

2 Background

2.1 Local Area Description - Hayle Estuary and Beach

Hayle Estuary is located on the north coast of Cornwall within the coastal cell of St Ives Bay, which extends from Clodgy Point to Godrevey Point (see Figure 2.1). The bay is approximately 3.5km wide with the headlands being approximately 8km apart. At the center of the bay is Hayle Estuary which lies at the mouth of the Rivers Hayle and Angarrack (Penwith District Council 2002). Extensive dune systems occur on both sides of the estuary mouth (Halcrow Maritime 1999).

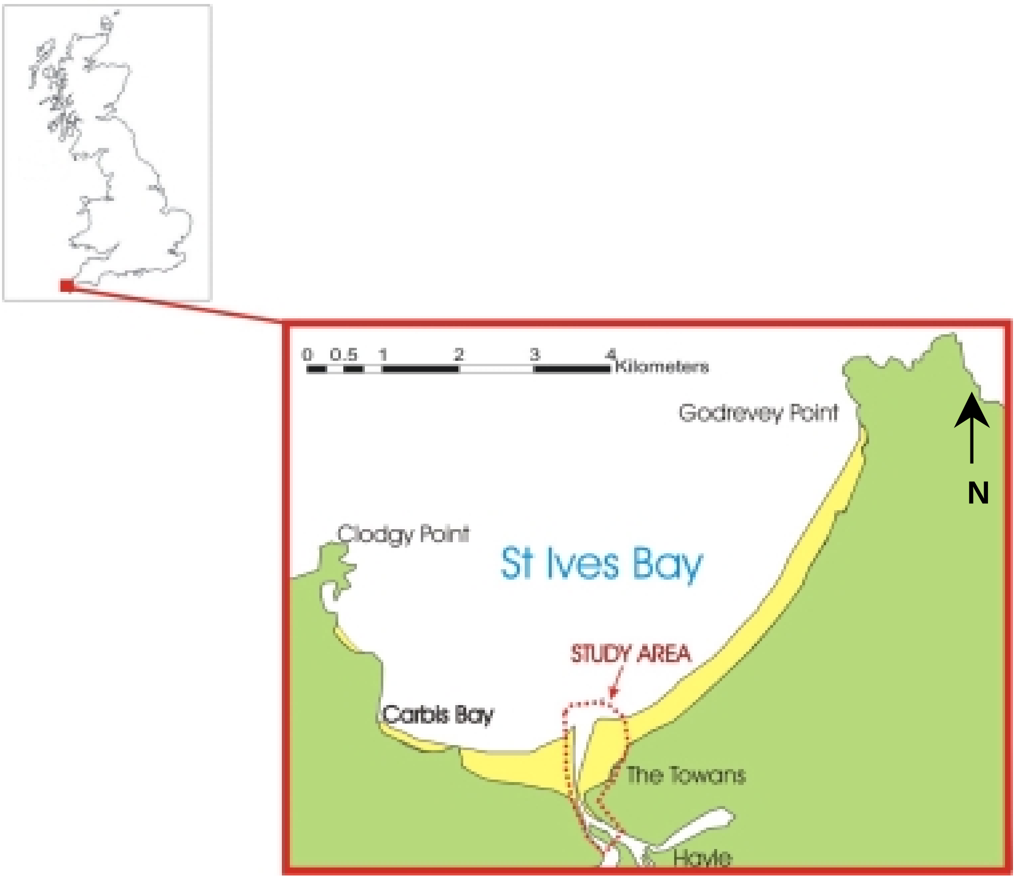


Figure 2.1: Map of St Ives Bay indicating the study area focus.

Hayle Beach is considered as a sub cell within St Ives Bay coastal cell. The sediment budget of Hayle Beach is dependent upon the source material feeding into Hayle beach and natural processes transporting material from the beach (see Figure 2.3) (Penwith District Council 2002).

It has been observed by residents and regular uses of the Hayle Estuary, in recent years, that a substantial amount of erosion has taken place on the beach and fore dunes to the east of the estuary mouth. Where sandy beaches and full sand dunes used to prevail, underlying rocks, mining waste, exposed landfill waste and a receding of the dunes now exist (see Figure 2.2). These are similar indications of beach erosion given by Bird (1996) such as cliffed backshore dunes and exposure of beach rock.

Figure 2.2: Photo of the Hayle Beach dunes showing evidence of dune retreat and rock exposure (Source: SOS Hayle 2003).

Correspondingly, a substantial amount of accretion of sand has taken place just inside the estuary mouth, at the harbour entrance, which is acting to squeeze the present deepwater navigation channel.

Up until 1971, when shipping in the area ceased, the large sluicing ponds of Carnsew Reservoir and Copperhouse Pool were used to flush sand out of the harbour entrance. From this period onwards, there has been a long history of sand extraction from the estuary, primarily to maintain a navigable channel for the local fishing fleet (Penwith District Council 2002).

2.2 Origin of Beach Sediments

Beach sediments have a variety of origins including fluvial sources, eroding cliffs and foreshores, sediment from the sea floor, wind blown sand sources and by inputs from human activity (Bird 1996). Sources that feed material to Hayle Beach include offshore areas, the estuary and from adjacent coastlines (Penwith District Council 2002). Sediment gains and losses at Hayle Beach can be summarized by Figure 2.3.

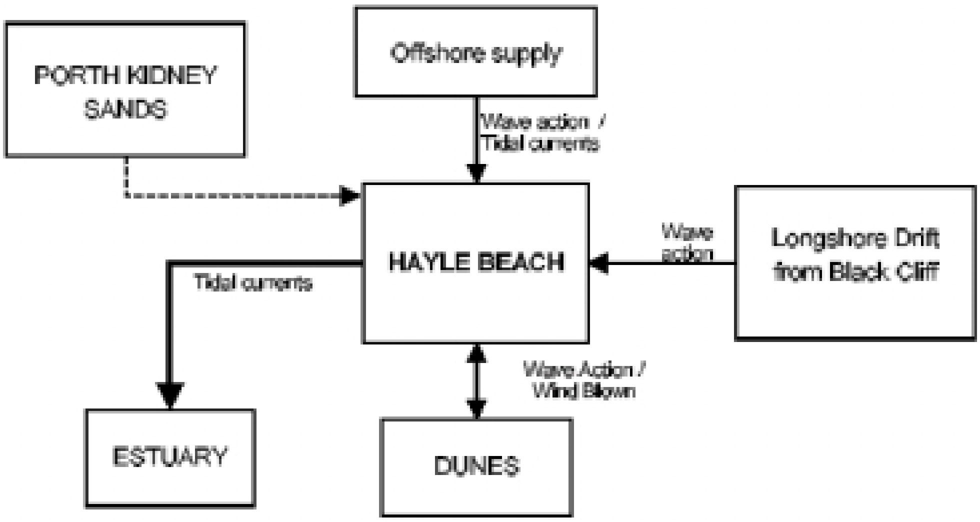


Figure 2.3: Summary of beach sediment input and loss processes at Hayle Beach (Source: Penwith District Council (2002)).

Fluvial beach sediments occur after sediment is washed down the mouth of a river (Bird 1996). Sand may then accumulate on the shores of a symmetrically growing delta, or be distributed alongshore by waves and currents to form beaches that can extend several kilometers along the coast. Since the flushing characteristics of Hayle Estuary are considered to be low, it is uncertain whether fluvial sediment sources, such as those from the Rivers Hayle and Angarrack, are eventually transported into St Ives Bay (Penwith District Council 2002).

Sediment sources from the sea floor include sand or gravel eroded from submerged geological outcrops or collected from unconsolidated bottom deposits (Bird 1996). Halcrow Maritime (1999) reports dune and beach material at Hayle Estuary mouth has a high carbonate content and concluded that the main source of sediment is derived from offshore sources.

Beaches can also contain small proportions of sand and gravel formed from fragments of glass, concrete, brick and other man made materials (Bird 1996). This can be observed at Hayle Estuary mouth where tipping of man made material during the late 1940s and early 1950s, together with windblown sand, have assisted in the dune development (Penwith District Council 2002).

2.3 Coastal Processes

Waves, tides and currents provide energy input which shapes and modifies beaches by eroding, transporting and depositing beach sediments (Bird 1996). Each process acts on the coastline in different ways. However, at Hayle Estuary mouth, waves tend to be the primary mechanism of coastline change, with tides being a secondary consideration.

2.3.1 Waves

A relationship exists between the patterns of refracted waves approaching the shore and the morphology and sediment characteristics of beaches (Bird 1996). Divergence on low wave energy sectors (orthoganols) tend to form beaches with gentler gradients, finer less well sorted sediment, decreased erosion and perhaps converging longshore currents causing accretion of beach sediment. Similarly, analyses conducted by Hobbs (2002) of existing wave conditions on the Mid-Atlantic coast of the United States demonstrated that modern shoreline stability is related to areas of concentration and dispersion of wave energy near the wave breaking zone.

2.3.1.1 Offshore Wave Climate (North Cornwall) [1]

The wave climate for the North Cornish coast is highly seasonal as seen in the respective Summer and Winter significant wave height (Hs) and significant wave period (Ts) distributions (see Figure 2.4). Meteorology Office offshore wave model data from April 1996 to March 2001 was analysed and included significant wave heights Hs (m), significant wave periods, Ts (s), and wave directions. The wave model Hs and Ts data values were divided into summer (June – August) and winter (December-February) months and then plotted together.

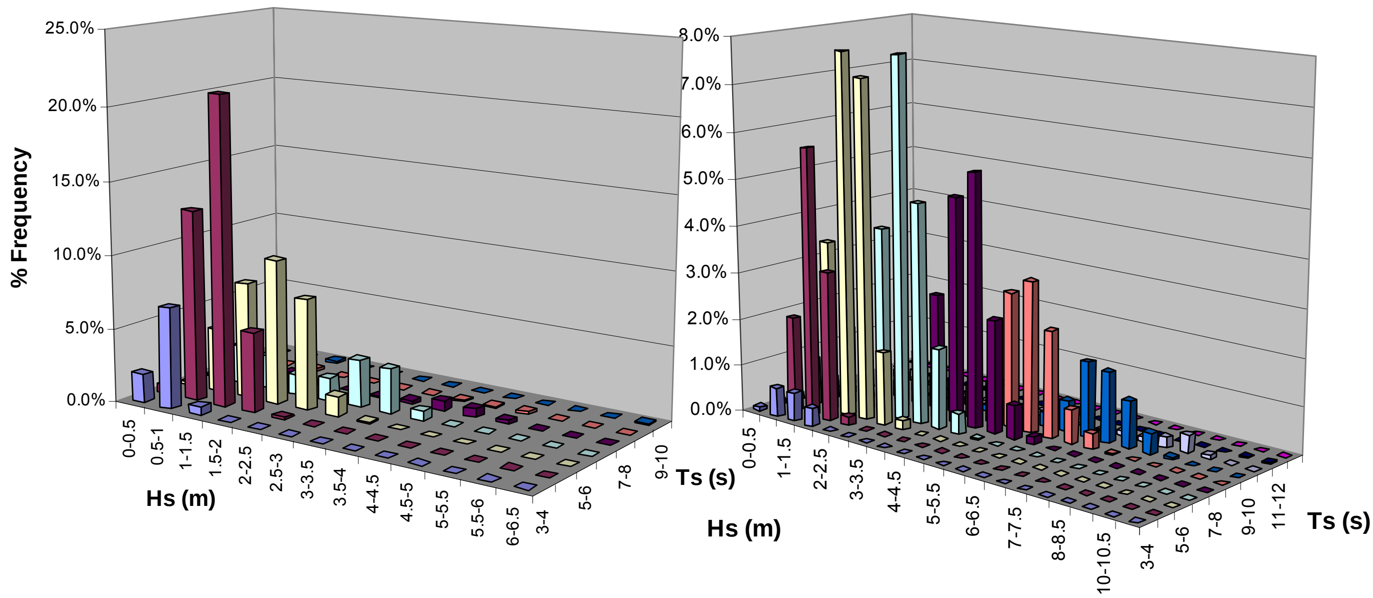


Figure 2.4: Hs and Ts histograms for summer (left) and winter (right).

During the summer months, waves of 1-1.5m in height with periods of 4-5s were the most frequent (20.9%). During the winter months, the most frequent (22.6%) wave heights were between 1.5-3.0m with 5-7s periods. This indicates that larger wave heights and periods occur during the winter months.

From equation (1) it can be seen that an increase in wave energy is proportional to the square of the wave height at a particular location.

[1] The offshore wave climate analysis was conducted as part of a separate study, however its relevance to this project warrants its inclusion here.

$$E = \frac{1}{8} pgH^2 \qquad (1)$$

Where E = wave energy (Nm^{-2})

p = density of water (kgm^{-3})

g = acceleration due to gravity (ms^{-2})

H = wave height (m)

Additionally, the total amount of energy associated with a long-period wave is greater than that of a short-period wave because the long-period wave has a larger wave length (Masselink and Hughes 2003).

2.3.1.2 Nearshore wave climate (St Ives Bay)

A study was conducted by Halcrow Maritime (1999), on the wave climate of the nearshore region in St Ives Bay. Using Halcrow Maritimes's refraction and shoaling model REFPRO and Shoreline and Nearshore Data System (SANDS), the inshore wave conditions were analysed using data from July 1992 to June 1997. Using offshore wave data inputs, REFPRO allows for changes in wave height and direction due to refraction over the nearshore bathymetry as waves travel from offshore to inshore.

Wave data consisted of 3 hourly data intervals incorporating significant wave height (Hs), significant wave period (Ts), and wave direction (degrees). Frequency analyses and extreme wave condition analyses were conducted for Hs, Ts and wave direction.

2.3.1.2.1 Wave height / Wave period analysis

Figure 2.5 shows wave heights between 0.5-1m with 4-5s periods are the most frequent in St Ives Bay occurring 20.1% of the time.

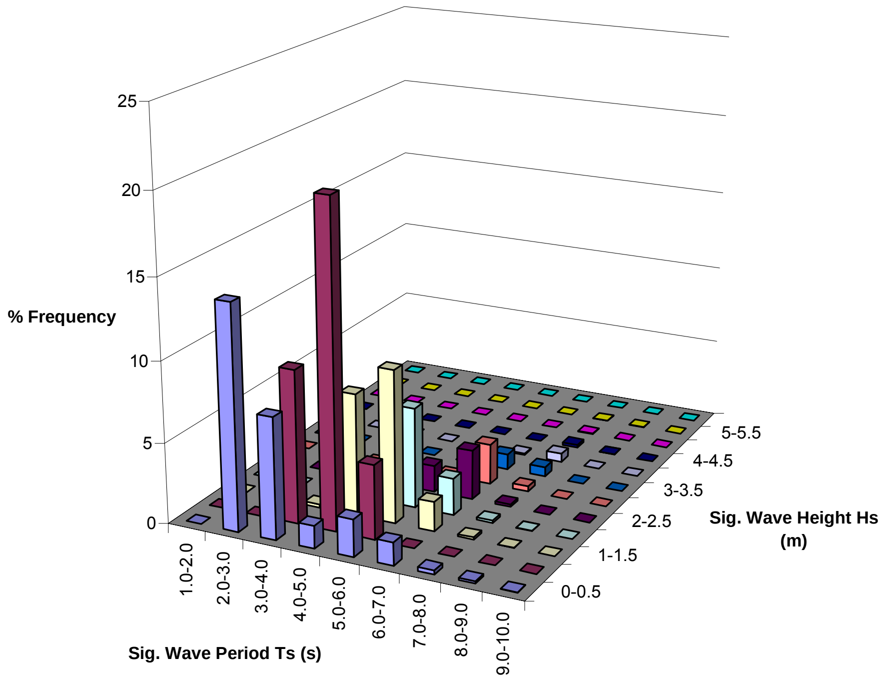


Figure 2.5: Nearshore significant wave height (Hs) / significant wave period Ts percentage frequency histogram.

Waves have significant impact on the coastline at the mouth of the Hayle Estuary where the predominant means of erosion is wave action (Penwith District Council 2002). Low swell wave conditions occur the majority of the time (refer Figure 2.5) and the wave energy is usually dissipated easily by the beach's natural defence mechanisms. During storm periods, wave energy is increased and if the beach is unable to respond by dissipating wave energy, portions of the beach can be eroded.

2.3.1.2.2 Wave height / Wave direction analysis

Figure 2.6 shows the occurrence of wave heights and directions within St Ives Bay after they have been refracted from offshore. Wave heights between 0.5-1m from 285-315º occur the most frequently (17.3%) indicating a predominant wave approach, within St Ives Bay, from the northwesterly direction.

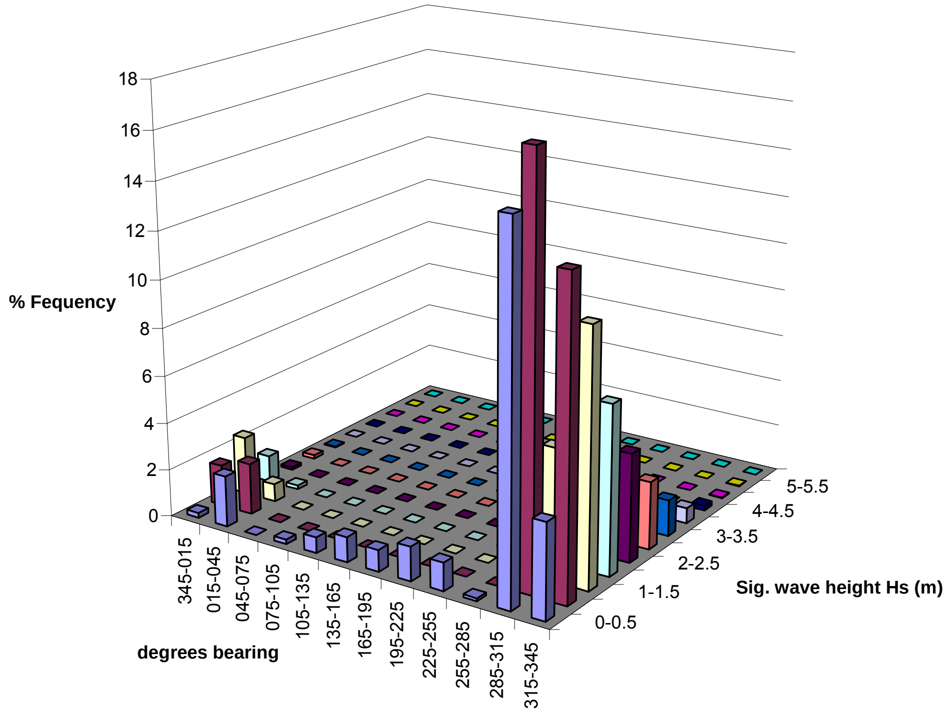


Figure 2.6: Significant wave height and wave direction frequency histogram in St Ives Bay.

2.3.2 Longshore Drifting

Longshore drifting of sediment along a coast occurs when sand is edged along the shore by waves arriving at an angle to the shore and producing a transverse swash, running diagonally up the beach followed by backwash retreating directly into the sea (see Figure 2.7).

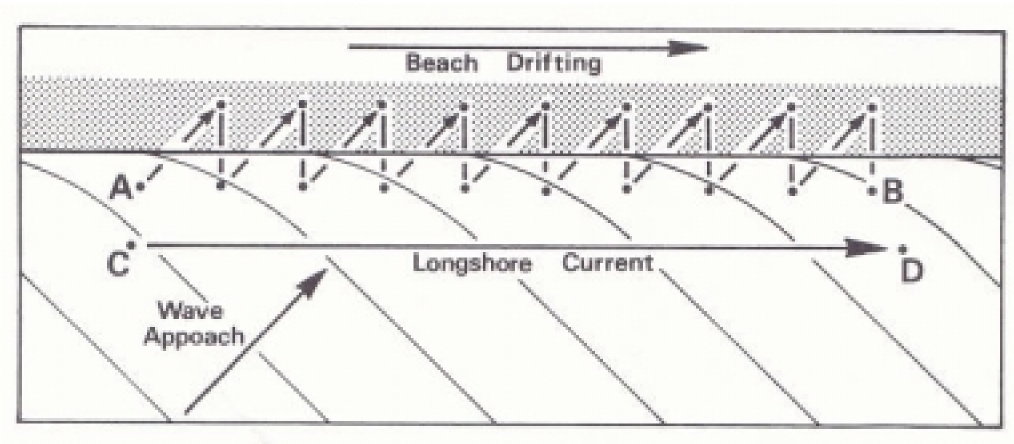


Figure 2.7: Diagram showing processes involved in long shore movement of sediment (Source: Bird (1996)).

Waves arriving more frequently from one direction result in a long term drift of sediment along the shore which may result in the growth of spits from deflection created by river mouths (Bird 1996). The net movement of sediment within St Ives Bay by littoral drift is predominantly from west to east, with evidence of this given by the formation of the spit extending from Porth Kidney Sands to the east across the Hayle Estuary mouth (Penwith District Council 2002).

2.3.3 Sediment Transport

In order to determine the sediment flux within a system, wave parameters such as wave height, wave angle and wave velocity need to be considered to give:

$$Q = \left(H_s C_g\right)\left(\overbrace{a_1 \sin 2\alpha}^{1^{st}\text{ term}} - \overbrace{a_2 \cos\alpha}^{2^{nd}\text{ term}} \frac{\Delta H_s}{\Delta x}\right)_b \qquad (2)$$

Where Hs = Significant wave height (m)
α = wave angle (degrees about baseline)
C_g = wave group velocity (ms^{-1})
b = at wave break point
a_1 and a_2 = non-dimensional coefficients (Kraus and Harikai 1983).

The 1st term in equation 2 corresponds to the CERC equation for long-shore sediment transport due to oblique wave approach, while the 2nd term corresponds to sediment transport due to long-shore variations in wave height (Young *et al* 1995). The coefficients, a_1 and a_2, are directly proportional to model calibration coefficients K_1 and K_2, and inversely proportional to the sediment grain size and beach slope.

Given this equation it is clear that wave height and direction play a significant role in determining the magnitude of longshore sediment transport that occurs on a particular stretch of beach. The beach slope has an effect on the duration of the flood tide and hence the time allowed for waves to suspend sediment.

Grain size is the sediment property most widely measured since it is of primary importance in a wide range of processes (Masselink and Hughes 2003). In general, coarser sediment is more permeable, reduces the effectiveness of backwash, and results in relatively steep gradients. Therefore a beach consisting of coarse and fine sediment will be sorted by the swash and backwash processes until the beach profile comprises of a coarser upper beach and a finer lower beach (Bird 1996).

2.4 Beach and shoreline change

It had long been known that sea level rise is the underlying driver of shorelines over geological time scales as evidenced by the large-scale transgressions and regressions of the sea in response to the Pleistocene ice ages (Leatherman 2003). However, for coastal planners, short term changes are the primary concern. Beach erosion and accretion involves short term changes up to a year to a few years, and longer term changes over decades or centuries (Bird 1996).

The main short term mechanisms are due to tidal phenomena and seasonal changes in wave climates. With a sequence of increasingly high tides from neap to spring tides, marine transgression occurs which can result in erosion. From the period from spring to neap tides, beach accretion would occur as a result of marine regression. Figure 2.8 illustrates the typical seasonal changes in beach profiles between summer and winter.

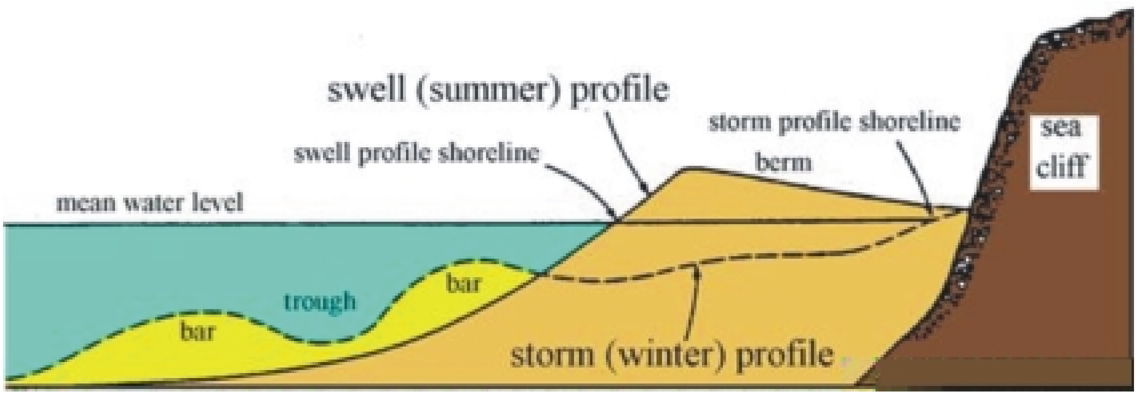


Figure 2.8: Typical seasonal changes in beach profiles (Source: Jenkin 2004).

Studies by Dail *et al* (2000) at Waimea Beach, Hawaii, found, that during winter swell events, significant erosion occurred across the entire beach except at the mouth of the Waimea River which filled in during the swell events. During the summer, or accretion phase, it was found the reverse situation occurred – re-establishment of berm coinciding with loss of sand at the river mouth.

2.4.1 Hayle Estuary and Beach

With use of mathematical modelling, Penwith District Council (2002) has assessed the combined effects of waves and tidal flows on sediment transport processes that are attributing to the general reduction of Hayle Beach forshore levels and the erosion of the Hayle Towans dunes.

A large tidal range, such as at Hayle Beach, implies a broad inter-tidal zone. Wave energy is expended in traversing such a broad shore zone and waves that reach the beach at high tide have been reduced by friction (Bird 1996). Penwith District Council (2002) reports that the dominance of the flood tide over Hayle Beach results in the transport of material towards the mouth of the estuary during a spring tide, which leads to a narrowing of the navigation channel.

Modelling conducted by Penwith District Council (2002) revealed that the high water mark is currently very close to the toe of the dune system. A reduction in beach levels has possibly exacerbated the erosion problem at Hayle Beach and Towans, since larger waves are able to penetrate further up the beach profile and increase the frequency of dune erosion. Therefore a predicted increase in wave height at Hayle Beach, due to the lowered profile, is likely to result in an increased volume of beach material to be transported by littoral drift mechanisms.

Correspondingly, coastal processes at Hayle Beach have transported sediment towards the mouth of the estuary. This has resulted in the loss of foreshore sand and consequent reduced beach levels (see Figure 2.11). Tidal flows with the estuary, particularly just inside the estuary mouth, were found to be ebb dominated in the middle of the deepwater channel, and flood dominated on either side of the channel. It was found that the area east of the channel is accumulating sand, transported by tidal and wave action from Hayle Beach (see Figure 2.9).

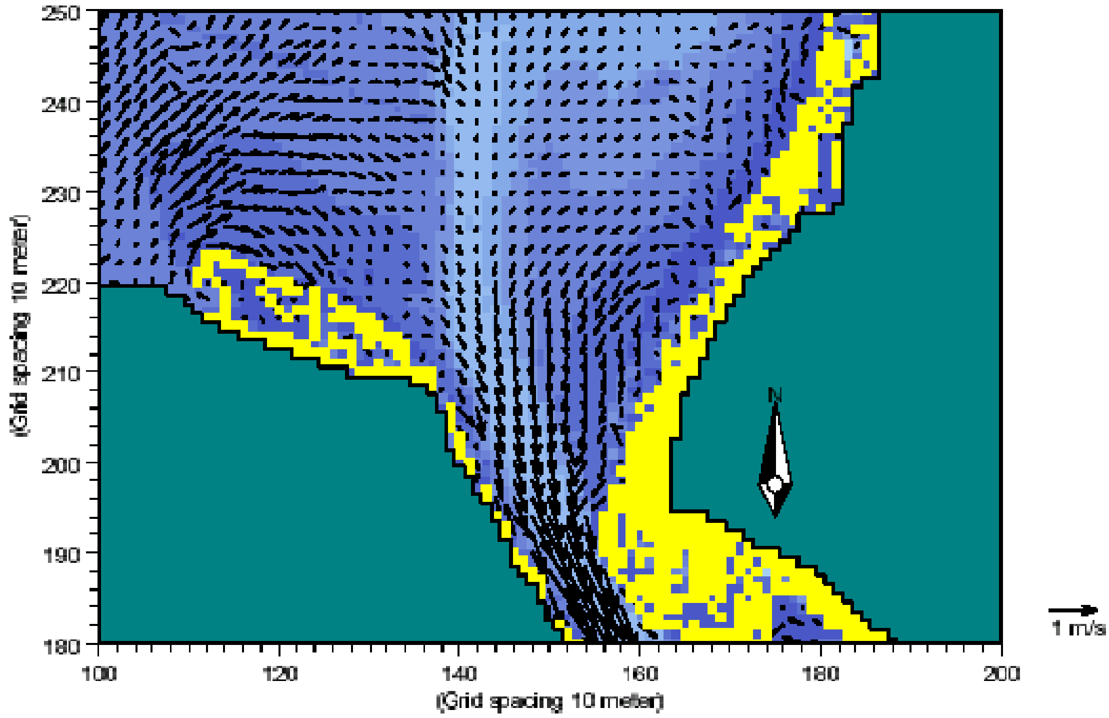


Figure 2.9: Tidal flows mid-flood at Hayle Estuary mouth (Source: Penwith District Council 2002).

The loss of sand from Hayle beach is reported to result in the early inundation of the foreshore during the tidal cycle which prolongs the effects of the flood tide, and increasing the net volume of sediment movement. Therefore the net predicted result of continued loss of sand from Hayle Beach is a progressive increase of the flood tide influence at the estuary mouth (Penwith District Council 2002). This pattern is consistent with Allan *et al* (2003), where it was revealed beach sand on a particular stretch of the Oregon Coast, USA, is also being lost as it is carried by tidal currents into estuaries.

2.4.2 Effects of marine aggregate extraction

A major impact of marine aggregate dredging activities in the nearshore area could cause the acceleration of coastal erosion resulting from changes of the hydrodynamic regime (Bray et al 1997). Maintenance dredging on a regular basis could deprive downstream coastal areas of sediment required to maintain coastal stability, by removal of sediment from the longshore transport system.

Aggregate extraction has the potential to impact indirectly on the wider marine and coastal hydrodynamic environment. Such impacts, relating to hydrodynamics and sediment transport include the following:

- damage to beaches caused by draw-down of sediment into a dredged area;
- changes to wave properties at the coast caused by changes to flow behaviour (for example, refraction, shoaling, breaking) over dredged areas;
- changes in tidal currents, particularly if such changes extend close to a coastline;
- disruption in sediment supply to the coast, either locally or at a distance from the dredged area (Posford Duvivier Environment & Hill 2001).

For example, at Hallsands, Devon the removal of an offshore shoal in the early 1900s is thought to have led to increased wave activity, onshore erosion and the destruction of the village. This example serves to highlight the potential impacts of alterations in coastal processes (Posford Duvivier Environment & Hill 2001).

2.4.2.1 Dredging in Hayle Estuary

The backhoe style dredging operation at Hayle is a human response to a natural process, in order to maintain a working harbour (Penwith District Council 2002) (see Figure 2.10). The sand around St Ives, and in particular at Hayle Beach, has a high carbonate content which has wide use in agriculture due to its basic properties. Therefore, a two-fold demand exists for dredging contractors, where a maintenance dredging regime can be carried out as well as supplying the local agricultural industry with a viable fertiliser and soil conditioner. It is a seasonal operation (January to May) and therefore coincides with the more energetic winter wave climate.

Figure 2.10: Photograph of dredging operation Hayle Estuary (Source: SOS Hayle).

Annual tonnage of dredged material in the Hayle Estuary mouth is estimated as approximately 25,000 to 30,000 tonnes, and more recently (Oct 2001 to Feb 2002), dredging of the harbour removed approximately 18,000 tonnes. It is believed that past and present sand extraction operations from the channel (see Figure 2.11) are not the sole cause of the coastal processes observed at Hayle Beach, and subsequent accretion at the harbour entrance, however it is considered to be a contributory factor (Penwith District Council 2002).

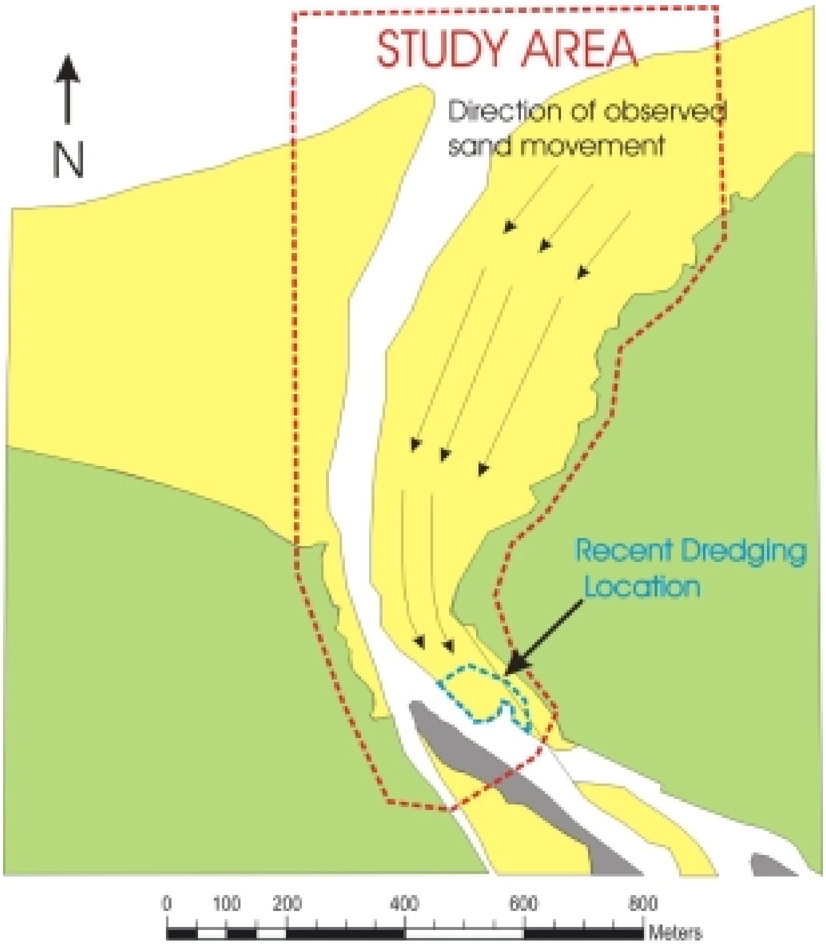


Figure 2.11: Map of Hayle Estuary mouth showing observed sand movements and approximate location of recent dredging operations.

Chapter 3

3 Measuring Beach Erosion and Shoreline Change

A variety of methods are employed in the assessment of the nature and magnitude of an erosion event, whether it be short or long term. Changes in the beach plan and profile are usually measured by repeated surveys along and across them such as with levels, theodolites or GPS technology. Beaches are traditionally surveyed at right angles to the contours, from datum points backshore down to the low water mark and into shallow water (Bird 1996). Surveys may be supplemented by a series of dated aerial photographs.

The main techniques used in this study to determine the extent of erosion and shoreline change at Hayle Beach are the use of aerial photographs, Light Detection and Ranging (LIDAR) surveys, Real-Time Kinetic GPS surveys and bathymetric surveys (see Figure 3.1). These three techniques are outlined below and discussed with regards to their principles, applications, accuracies, and sources of error.

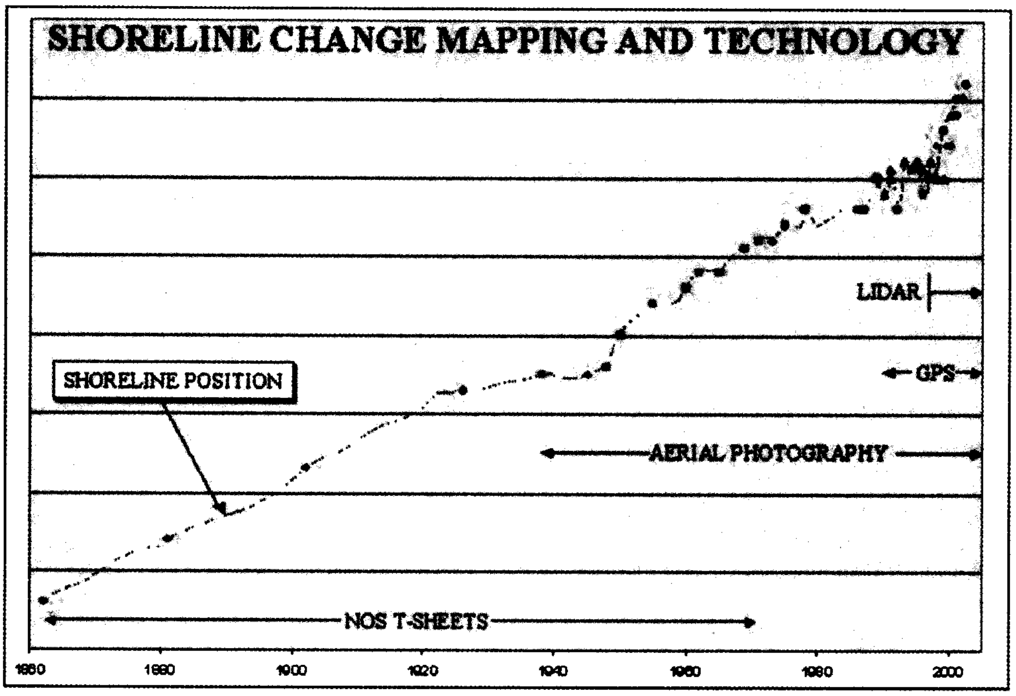


Figure 3.1: The progression of shoreline mapping technology and accuracy of shoreline position (Source: Leatherman 2003).

3.1 Aerial Photography

When an area is covered by vertical aerial photography, the photographs are taken along a series of parallel passes or flight strips. Normal flying height is 1500m, which provides 1:10,000 scale photography, and the photographs are normally exposed in such a way that each successive photograph overlaps part of the coverage of the previous photo (MacPhee et al 1981). This overlap, or *end lap,* is typically between 55 and 65%. Adjacent flight strips are photographed also to give a side lap (lateral overlapping) of approximately 30% (Wolf 1974).

Aerial mosaics are an assemblage of two or more individual overlapping photographs to form a single continuous picture of an area (Wolf 1974). Mosaics can be controlled, semi-controlled and uncontrolled. Controlled mosaics are the most accurate as they are rectified and ratioed by visible control points on the ground. Uncontrolled mosaics use no ground control and each mosaic is constructed by simply matching the image details of the adjacent photos. They are more easily and quickly prepared than controlled mosaics and are considered satisfactory for most qualitative uses.

3.1.1 Applications in Shoreline Mapping

Aerial photographs can be significant tools in identifying periods and areas of shoreline change provided photographs exist for the same area over a period of years or decades. Visual inspection of a time series of photographs may be satisfactory to get an idea of change, however a consistently defined shoreline is critical to many coastal management applications (Parker 2003).

A number of possible shoreline proxies exist such as the beach scarp, high water line (HWL), berm crest, vegetation line, dune toe, dune crest and the bluff edge (Leatherman 2003). The HWL is the most commonly used indictor since it is visible in the field and can be interpreted on aerial photographs by the gray scale or colour tone (see Figure 3.2).

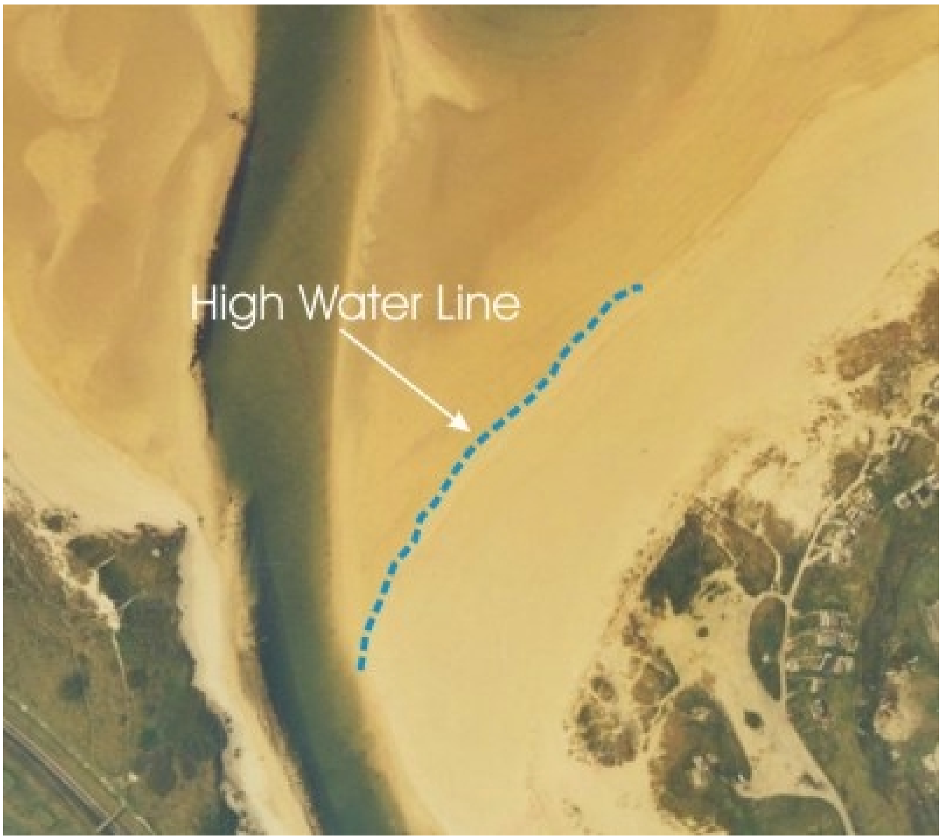


Figure 3.2: Aerial photograph showing the HWL as a shoreline indicator.

However use of the HWL as a shoreline indicator does have its discrepancies since it is sensitive to short-term fluctuations in wave and tide conditions (Leatherman 2003). Further, differing stages in the lunar phases (between spring and neap tides) compound inconsistencies in using this technique for mapping shorelines. However for comparison with historical aerial photographs, before the advent of LIDAR and GPS technology, the HWL shorelines must be utilized to take advantage of this historical information.

3.1.2 Sources of Error

Vertical aerial photographs are not maps and large offset errors occur for overlapping images (Leatherman 2003)(see Figure 3.3). The image directly below the aircraft becomes progressively distorted as one moves out from the center to give a form of oblique tilting towards the edge of the photograph. Therefore preparing uncontrolled mosaics becomes difficult around areas away from the centre of the photograph.

Figure 3.3: Mismatching of adjacent aerial photographs during preparation of an uncontrolled mosaic.

3.2 LIDAR Surveys

Light Detection and Ranging (LIDAR) is an airborne mapping technique which uses a laser to measure the distance between the aircraft and the ground (Environment Agency 2004). The aircraft flies at a height of about 700-800m above ground level and a scanning mirror allows a swathe width of about 30º (~600m) to be surveyed during a flight (see Figure 3.4). Individual measurements are made on the ground at 2m intervals allowing a highly resolved model of the terrain to be generated.

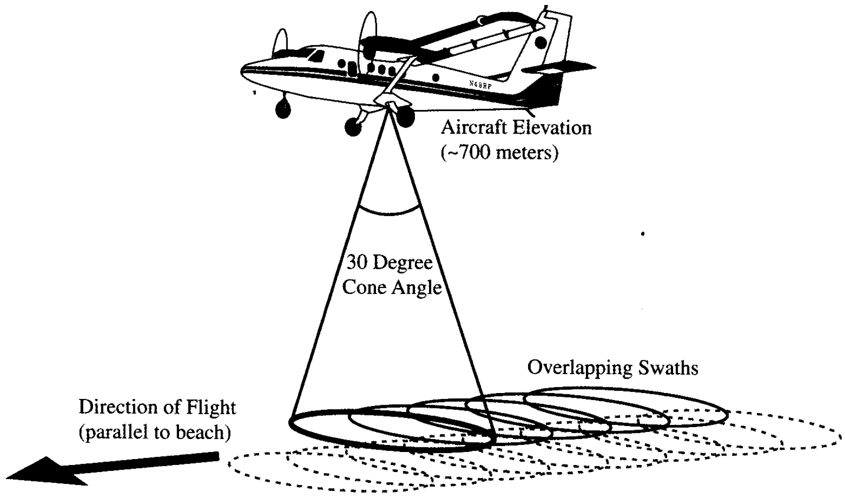


Figure 3.4: Diagram of conducting a beach LIDAR survey (Source: Sallenger *et al* 2003).

Airborne LIDAR offers a great potential to provide spatially dense data from local (10^1 to 10^2m) to regional (10^3 to 10^5m) scales (Sallenger *et al* 2003), and its use in mapping beach and shoreline change is becoming increasingly accepted as it is capable of providing high resolution topographic information in near-instantaneous time (Brasington *et al* 2003).

In general, two types of LIDAR systems are in use; bathymetric LIDARs and topographic LIDARs. Bathymetric LIDARs penetrate the water and provide measures of water depth incorporating the use of red and green lasers, while topographic LIDARs measure sub-aerial topography only.

3.2.1 Applications in beach change assessment

Volumetric analyses can be conducted between 2 or more surveys which have been flown over the same area but at a time span of months or years. Sediment budgets can effectively be derived through pair wise comparison of digital elevation models (DEMs), producing maps of difference to visualise and quantify the pattern of shoreline change (Brasington *et al* 2003).

3.2.2 Sources of Error

The reliability of the volumetric analysis results will rely largely on the accuracy of the position and elevation measurements. Various vertical (elevation) accuracies for LIDAR are quoted and typically range from 5 to 10cm (Parker 2003; Allan *et al* 2003) to 15cm (Sallenger et al 2003; Sallenger *et al* 2002; Buonaiuto and Kraus 2003). Horizontal positioning is normally carried out with differential Global Positioning System (DGPS) with typical accuracies of 2 – 5m (Ingham and Abbott 1991).

A study by Sallenger *et al* (2003) conducted a series of inter comparisons between RTK GPS ground survey measurements of a beach and LIDAR measurements found vertical differences ranging from 13 to 19cm. It was deemed that the largest source of error was due to drift in the DGPS system used onboard the LIDAR aircraft. These results still regarded the use of LIDAR as adequate to resolve beach-change signals typical of the impact of storms.

Other inaccuracies arise from data digitisation due to the interpolation method and grid cell size used. DEM validation based on independent check point observations is partially confounded by differences between the DEM grid size and the (typically smaller) foot print of the check point data, especially where surface roughness is high relative to the DEM grid spacing (Brasington *et al* 2003).

3.3 Real Time Kinetic (RTK) GPS surveys

Early in 1994 the first automatic, centimetre level RTK GPS system was introduced and recently has become the preferred surveying technique for a wide variety of applications (Edwards et al 1999). The system employs a method of carrier phase differential GPS positioning whereby users can obtain centimetre level position accuracies in real time (Langley 1998).

For high-accuracy position determination, carrier-phase measurements made by one receiver are typically combined with those made simultaneously by another receiver to form double differences in which the effects of satellite and receiver clock errors are essentially eliminated. The double differences are then processed, using a least squares filter, to estimate the relative coordinates of one receiver’s antenna with respect to another. If the coordinates of one of the receivers (base station) is well known from a previous geodetic survey, then the coordinates of the second receiver (roving receiver) can be determined (Langley 1998) (see Figure 3.5).

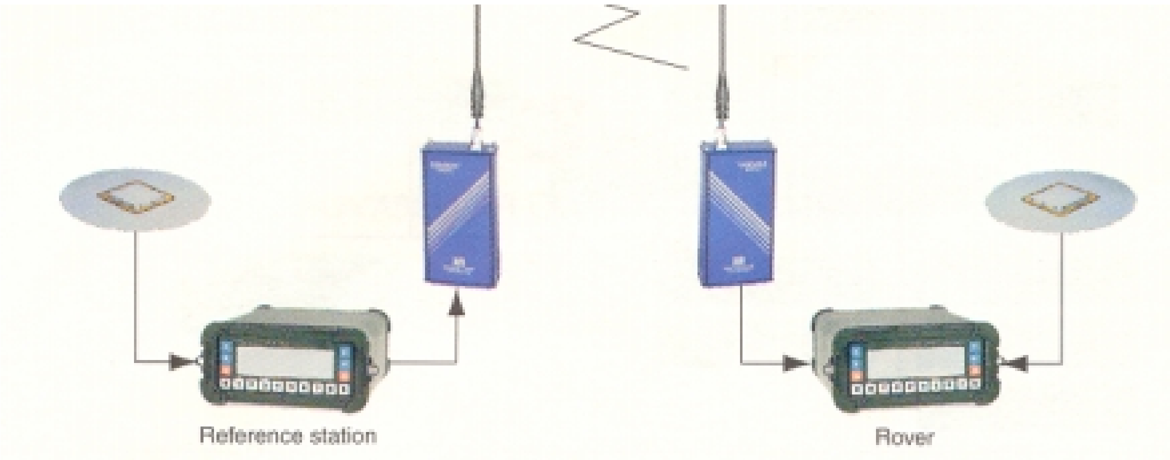


Figure 3.5: Basic RTK GPS system components.

While restricted in their spatial extent RTK GPS surveys can be conducted at very high densities with very high accuracy and therefore is a highly effective tool for beach surveying (Brasington et al 2003). Vertical and horizontal accuracies are typically found to the order of ±2-3cm and ±1-2cm respectively (Dail *et al* 2000). More recent studies by Abbott (2004) have found these quoted accuracies to be slightly ambitious with actual vertical errors measured under controlled conditions to the order of ±3.3cm.

3.3.1 Applications in Assessing Beach Change

While restricted in their spatial extent, these surveys are conducted at very high point densities and with high-precision measurement standards so that the resulting Digital Elevation Models (DEMs) provide a robust basis for quantifying beach change (Brasington *et al* 2003). RTK GPS surveying can be conducted on steep beaches by foot (Dail *et al* 2000) or can be mounted on an All Terrain Vehicle (ATV) (Sallenger *et al* 2003) for surveys of long and broad beaches.

3.4 Bathymetric Surveys

Bathymetric surveys normally involve depth measurement soundings from an echo sounder mounted on a vessel which travels over a series of previously planned survey lines. Vessels are normally positioned by Differential GPS (DGPS) with a horizontal positional accuracy of between 3 and 5m. Single beam echo sounders onboard measure depths to the order of ±0.1m. They are useful in providing information on the near-shore bathymetry of an adjacent beach which has been surveyed by conventional land survey methods.

3.4.1 Sources of Error

Errors in sounding position can arise from various sources including the depth resolution or transducer beam width, bottom slope, vessel heave, pitch and roll, the DGPS offset, calibration error and accuracy of tidal measurements.

The potential depth and positional error due to beam width limit the echo sounder's ability to resolve depth. Given that a conical echo beam from a circular transducer has a footprint, the position of the recorded depth will be plotted as being vertically below the transducer when in fact it will measure the shortest distance which can occur anywhere within that footprint (Thomas 1987). A similar situation occurs when sounding over a slope of steady gradient as illustrated in Figure 3.6.

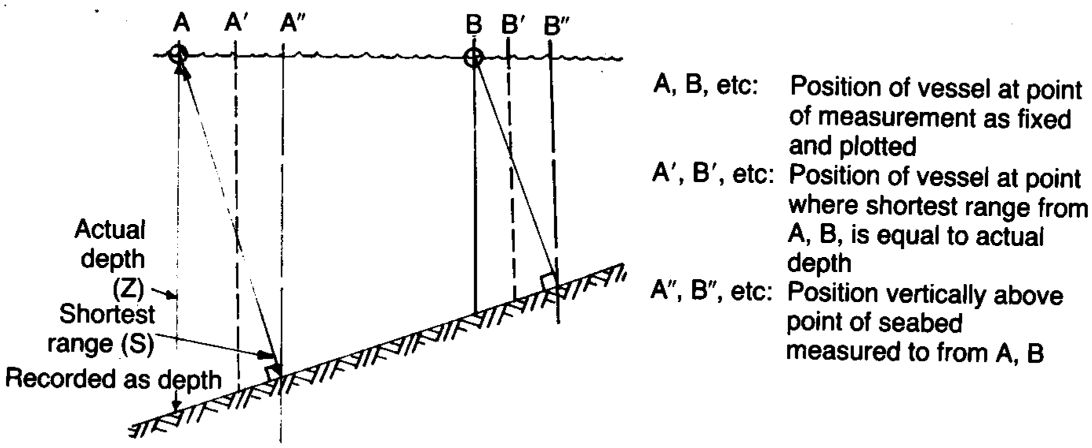


Figure 3.6: Error induced by measuring depth over a steady slope (Source: Ingham and Abbott 1992).

Errors due to the heave, pitch and roll of a vessel can be compensated with the use of heave compensators and gyros integrated with the echo sounding system. In the absence of these, surveys should only be conducted during very calm conditions. Figure 3.7 illustrates the deviation from the true depth for varying depths during vessel pitch and roll.

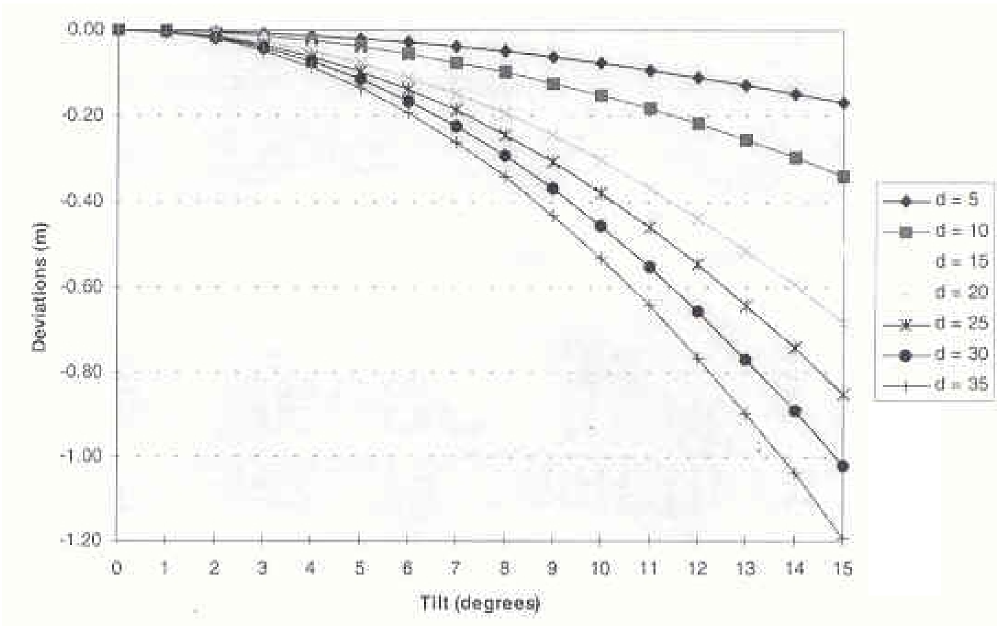


Figure 3.7: Deviation in horizontal position of measured depth during pitch and roll of a vessel (Source: Wiele 2000).

Along with the accuracy of the coordinates defined by the positioning system, errors can arise through measuring the positional difference or offset between the GPS antennae and the transducer (Wiele 2000). Inaccurate offset measurement or neglect in accounting for this offset would create considerable errors in the position of the sounded depth during episodes of pitch and roll.

Depth precision errors can be due to calibration errors during bar checks. During a bar check the echo sounder is calibrated for the velocity of sound through water and for the depth of the transducer below the surface. This is a crucial step since any discrepancies or errors introduced at this stage will be cumulative, and would continue throughout the rest of the survey.

Chapter 4

4 Methods – Data Collection

4.1 Land Survey

4.1.1 Geodetic GPS Survey (RTK Base Station Positioning)

4.1.1.1 Equipment

- 2 x York Survey tripods
- 2 x tribrachs
- 2 x Trimble 4000SE Single Frequency mobile receivers
- 1 x Trimble Dual Frequency Ground plate GPS antenna
- 1 x Trimble Dual Frequency Compact GPS antenna
- 2 x 12V batteries
- 1 x tape measure (height of antenna)

4.1.1.2 Data Collection

The Geodetic GPS survey involved two GPS receivers recording the phases of the carrier waves emitted by four or more satellites. The baseline vectors between these stations are derived from the differences between the phase histories observed at each station. Several hours of GPS observations are analysed in order to produce a position solution with accuracy within ±1cm (Dail *et al* 2000).

First, a geodetic control point of known latitude, longitude and height had to be identified close enough to the survey site. From the Ordnance Survey (OS) GPS website (OS 2003), this was determined to be the OS passive GPS station at Hudder Down (see Figure 4.1), which had the following ETRS89 Geodetic coordinates:

Latitude:	50 14’ 7.7829” N
Longitude:	5 22’ 1.7158” W
Ellipsoid height:	126.458m

A control point location had to be identified close to the survey site within line of sight for most of the beach to be surveyed. This was located on the dunes on the west side of the Hayle Estuary and overlooked the whole survey area (see Figure 4.1) and will be used as an RTK (Real-Time Kinetic) GPS base station.

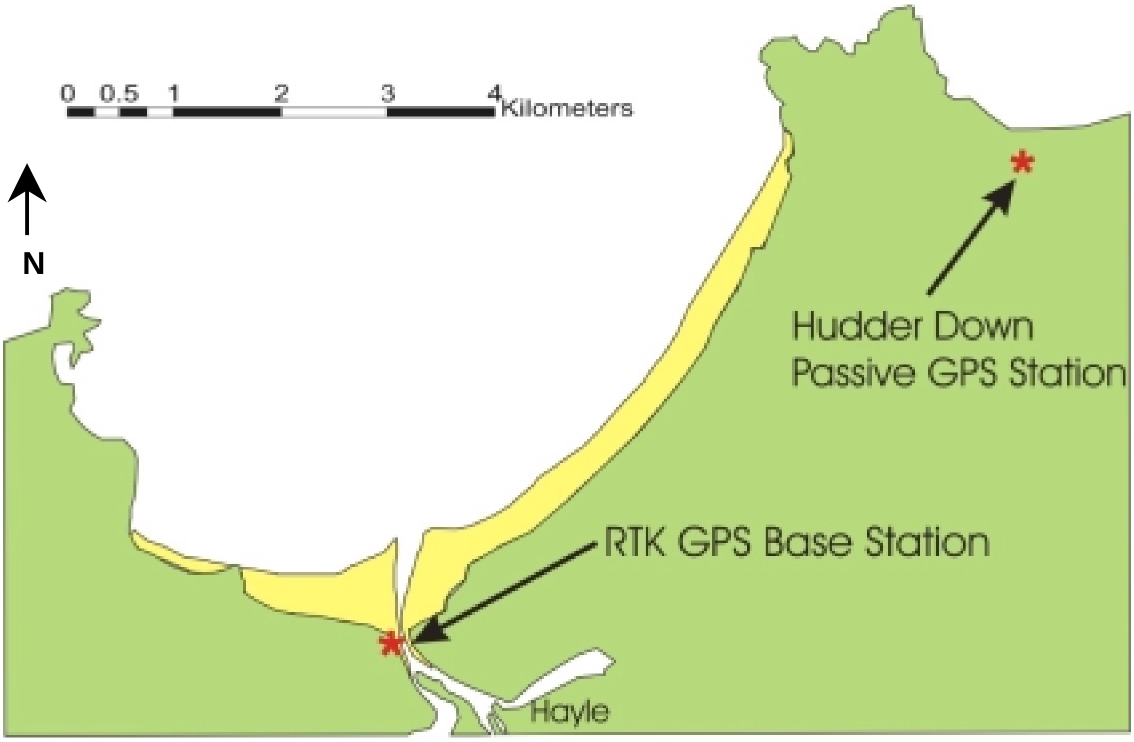


Figure 4.1: Map showing the two locations for the geodetic survey.

Once a suitable control point was identified for the RTK GPS base station, a GPS antenna mounted on a tribrach and tripod was mounted over each of the points and the receivers were set to log latitude, longitude and ellipsoidal height for a minimum 1 hour period. According to the Trimble 4000SE receiver, PDOPs (Positional Dilution of Precision) during GPS data logging ranged from 2.2 to 4.1 indicating satisfactory satellite geometry, which is consistent with PDOPs produced from Trimble Survey Planning Software (see Figure 4.2).

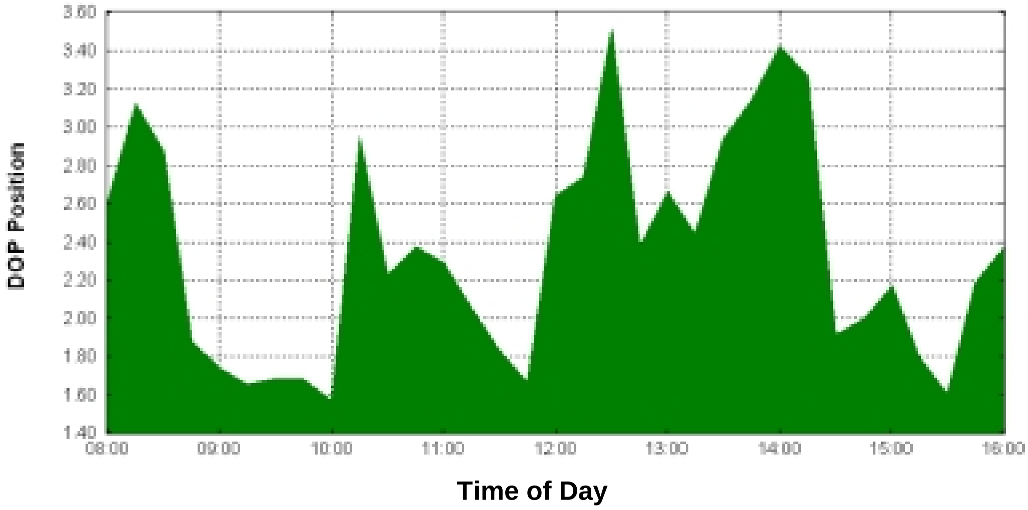


Figure 4.2: PDOP values during the geodetic survey on 16th July 2004.

Upon completion of data logging the height of the antenna above the ground was measured by tape measure and entered into the Trimble 4000SE receiver.

4.1.1.3 Data Post Processing

Data from both receivers was downloaded onto a personal computer (PC) and GP Survey software was used to post-process the data using the baseline method. GP Survey uses a series of iteration processes to calculate an accurate position based on the data logged at both a known (Hudder Down) and unknown (proposed RTK base station) location. The final post processed location for the RTK base station was calculated to be:

Latitude:	50 11’ 28.50582” N
Longitude:	5 26’ 9.47757” W
Ellipsoid height:	77.9997m

This position is regarded as being accurate to ±1cm (Dail *et al* 2000).

4.1.2 RTK Beach Surveying

4.1.2.1 Equipment

- 1 x tripod
- 1 x tribrach
- 2 x 12V batteries
- 1 x Trimble Dual Frequency Ground plate GPS antenna
- 1 x Trimble 4000SE Single Frequency mobile receiver
- 1 x Del Norte Technology UHF Data Link Module 96XLS
- 1 x Backpack with
  - Trimble 7400MSi GPS receiver
  - 2 x 12V battery
  - Satel Satelline 3AS Radio receiver
  - Trimble TSC1 Survey Controller
  - Antenna Pole
  - Trimble Dual Frequency Compact GPS antenna

4.1.2.2 Data Collection

A Trimble ground-plate antenna was set up over the RTK base station location using a tripod, and was connected to a Trimble 4000SE GPS receiver. The post processed derived coordinates (refer Section 4.1.1.3) were entered into the receiver which was then set to transmit corrections via a Del Norte Technology UHF Data Link Module 96XLS.

Corrections were received by a Satel Satelline 3AS Radio receiver connected to a Trimble 7400MSi GPS receiver which was contained within a portable backpack. A Trimble Dual Frequency Compact GPS antenna, connected to the Trimble 7400MSi GPS receiver mounted on a pole was set to a height of 2m and each point on the ground was measured for a period of 5s using the Trimble TSC1 Survey Controller. Horizontal and vertical positional accuracies ranged from 2-10cm and 4-20cm respectively, depending on satellite availability and masking effects due to measurements taken at the base of steep cliffs and dunes.

Each successive point position was measured at every 10-15m and more frequent surveying focused on elevations of change until an area of approximately 0.72km^2 and a total of 376 points were recorded (see Figure 4.3). The survey was conducted during the low water spring tide when most of the inter-tidal areas are exposed.

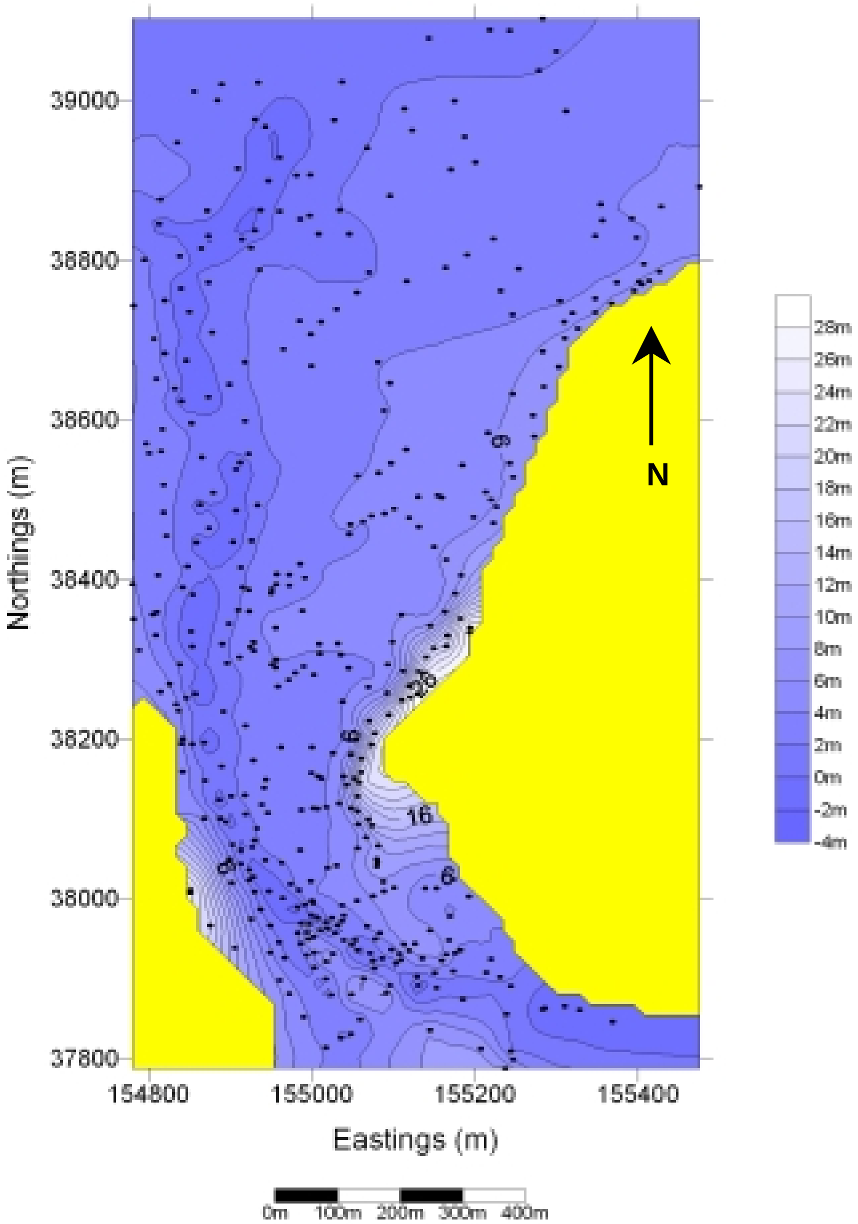


Figure 4.3: Surfer 7 contour plots for the RTK GPS survey showing points surveyed with elevations referenced to OD Newlyn. Yellow blanked out regions represent areas not surveyed.

At locations vulnerable to masking effects, such as at the base of the cliffs or dunes facing the north, fixing and tracking of satellites became close to impossible and movement into clearer ground was required in order to obtain a fix on a sufficient number of satellites by the roving receiver. PDOP values during the survey in Figure 4.4 are shown to be less than 4 and therefore satisfactory satellite constellations were constantly available.

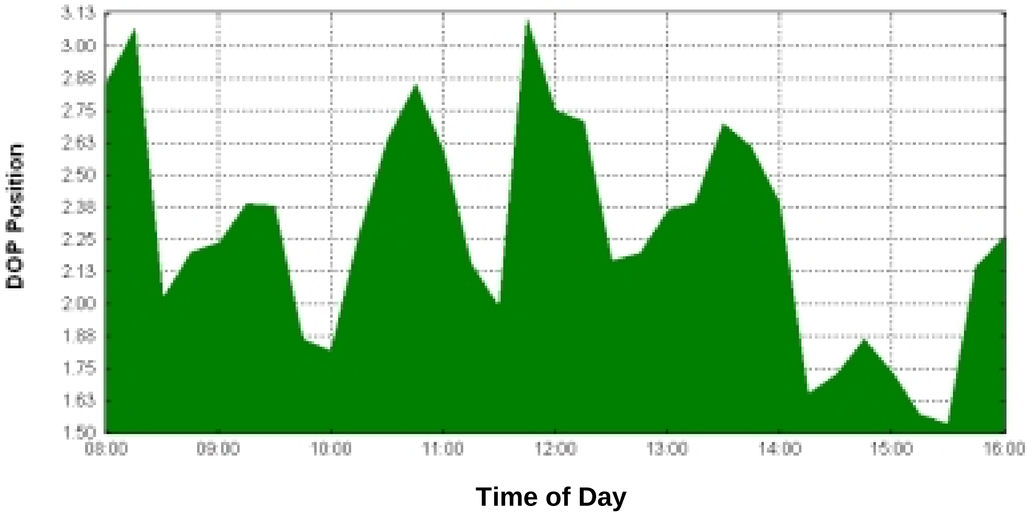


Figure 4.4: PDOP values during the RTK GPS survey on 19th July 2004.

4.1.2.3 RTK GPS Data Processing

All 376 recorded points were downloaded from the Trimble TSC1 Survey Controller onto a PC and were then converted from ETRS89 Geodetic coordinates and WGS84 ellipsoid heights into National Grid OSGB36 coordinates and Ordnance Datum (OD) Newlyn heights using Grid Inquest software. *Xyz* files were created for use with Surfer 7 and ArcGIS visualisation software.

The data was then imported into Surfer 7 software to produce grid format files, from which contour plots and Digital Terrain Models (DTMs) for the surveyed area were produced (see Figures 4.3 and 4.5 respectively).

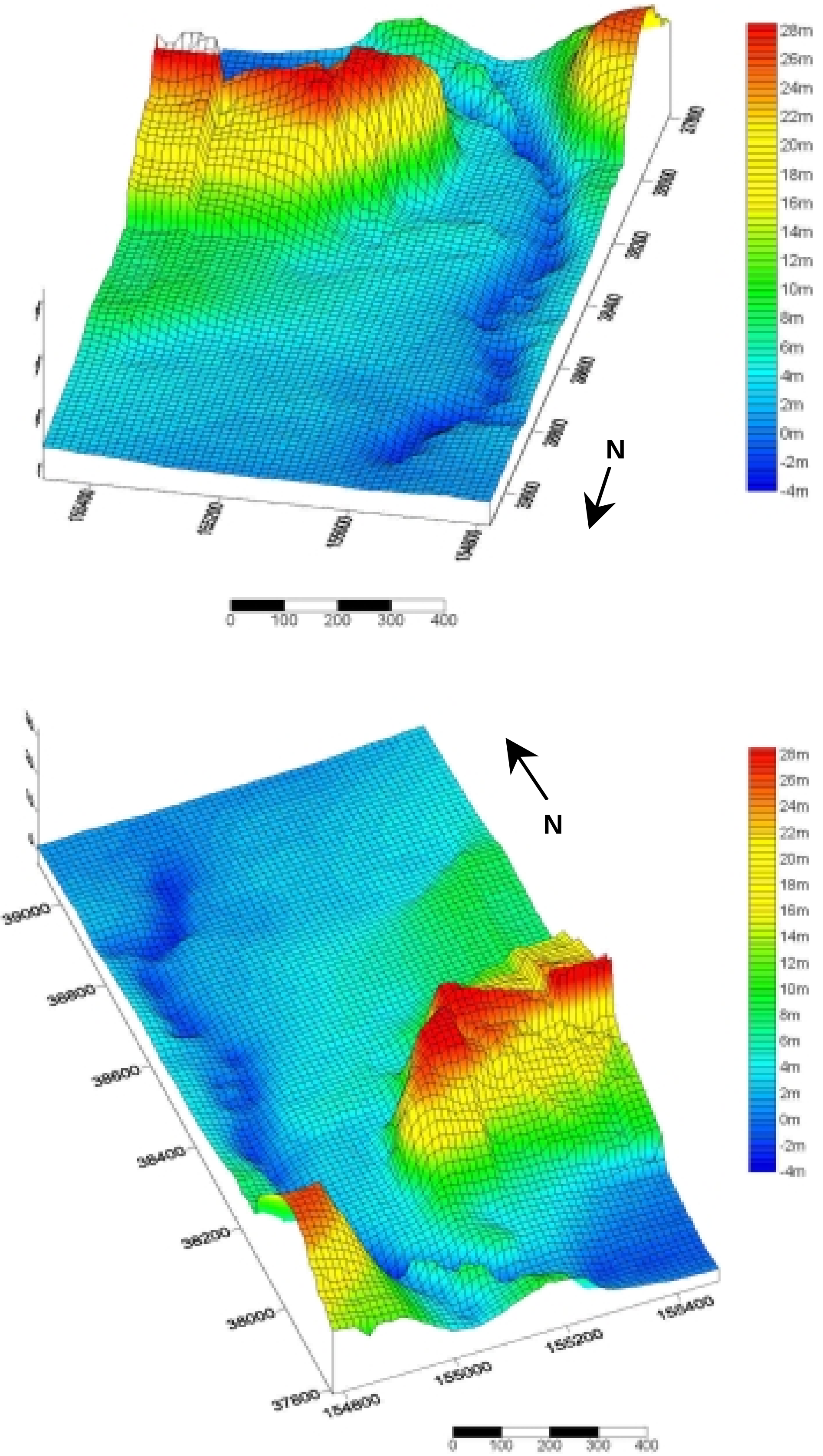


Figure 4.5: Two views of Surfer wire-frame plot for the RTK GPS survey (including bathymetric survey data) showing points surveyed.

4.2 Bathymetric Survey

4.2.1 Equipment

- 3 x 12V batteries
- 1 x Level Mark level
- 1 x levelling staff
- Toshiba laptop with HYDROpro Navigation Software
- Odom Hydrotrach echo sounder
- Garman GPS 48 Personal Navigator
- Trimble DGPS Probeacon receiver
- Trimble GPS antenna and radio receiver antenna
- 12V – 230V Inverter

Before the survey, panorama *.dxf* files supplied from DIGIMAP website was loaded into the HYDROpro Navigation software. Using geo-referenced 1996 aerial photographs (see Section 4.4.2.2), survey line coordinates were derived and plotted into the plan view of HYDROpro Navigation (see Figure 4.6). Survey lines, of 25m spacing, were named in three groups - Channel (1-3 lines), Mouth (1-3 lines) and Near (1-21 lines).

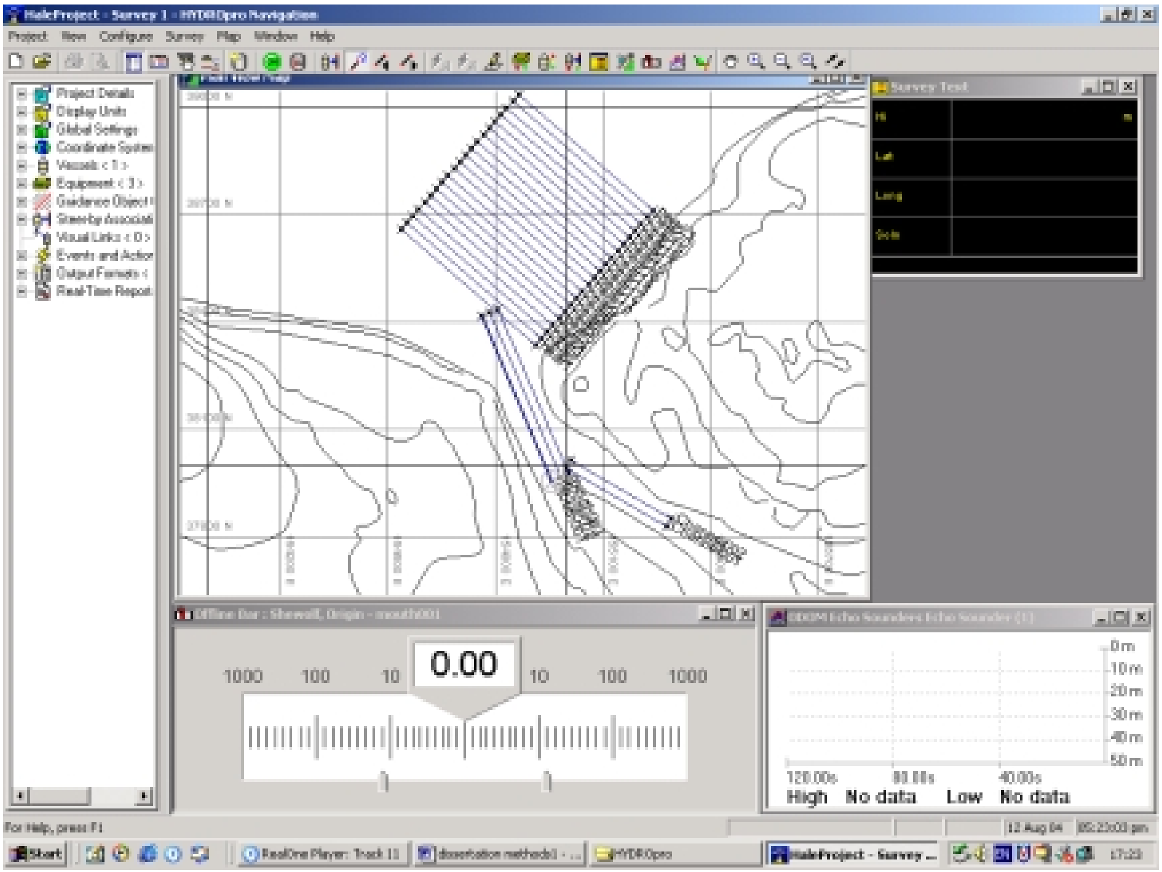


Figure 4.6: HYDROpro Navigation software with survey line locations in relation to .dxf contour file for the Hayle Estuary mouth survey area.

A 7m Cheetah Marine catamaran commercial fishing vessel with twin (90 and 50hp outboard engines) with a draught of 9 inches was hired for the survey with funding provided by the Penwith District Council. The echo sounder transducer pole was side mounted onto the vessel and connected to the Odom Hydrotrach echo sounder. A Trimble GPS antenna was mounted onto the roof of the wheelhouse and connected to Garman GPS 48 Personal Navigator and Trimble DGPS Probeacon receiver. The offset of the DGPS antenna to the echo sounder transducer was measured by tape measure and entered into HYDROpro Navigation. The offset value enabled differentially corrected GPS positions directly over the transducer. PDOP values on the day of the bathymetric survey indicated DGPS positions were measured within tolerance (see Figure 4.7).

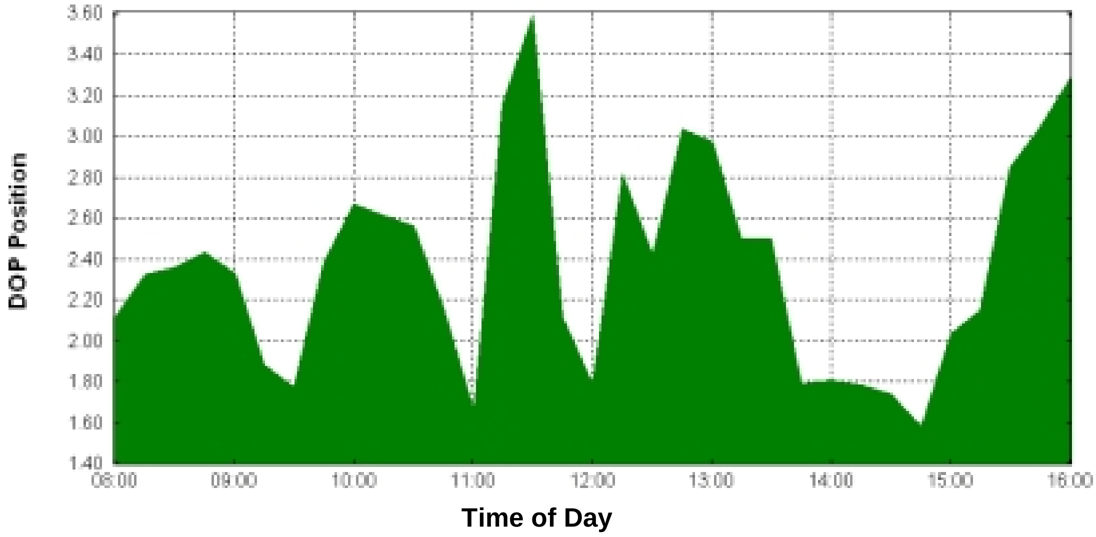


Figure 4.7: PDOP values during the bathymetric survey on 28th July 2004.

Both the echo sounder and DGPS receiver were connected to a laptop via RS232 parallel ports comms 13 and 14 respectively. Through HYDROpro Navigation software the vessel's Differential GPS (DGPS) position (latitude and longitude), differential solution status and the echo sounder depth (metres) measurement were then able to be integrated to provide real-time information during the survey.

4.2.2 Calibration of echo sounder

Calibration is normally carried with a bar-check involving lowering a horizontal beam below the transducer, however for portability, a secchi disc was used instead. Echo sounder calibration involved lowering a secchi disc to a depth of 1m account for the depth of the transducer below the waters surface. This effectively calibrated the echo sounder for the transducer depth below the surface.

4.2.3 Tide Gauge

Tide measurements were made by lowering a weighted tape measure from a location adjacent to the 'Channel' survey line group from a concrete wall located at the Hayle Harbour entrance. Measurements were recorded every 5 minutes from 11:56 to 13:51 hrs which covered the duration of the bathymetric survey.

4.2.3.1 Levelling

The tide gauge was levelled to a nearby bench mark BM 9.85mOD on the wall by the old power station (see Figure 4.8). Using a level and makeshift graduated staff (scrap pole with tape measure attached had to be used due to lack of proper equipment), back-sights and fore-sights were taken from the BM, to the tide gauge location and back again to the BM, to get a closure difference of 0.007m (see Appendix 1).

Figure 4.8: Photo of Hayle Harbour and Estuary showing location of Tide Gauge and BM 9.85m OD.

The tide gauge height was found to be 5.57m above OD Newlyn, and since Chart Datum (CD) is 3.14m below OD Newlyn, this offset was applied to all tidal height values to give tidal heights relative to CD (see Figure 4.9)

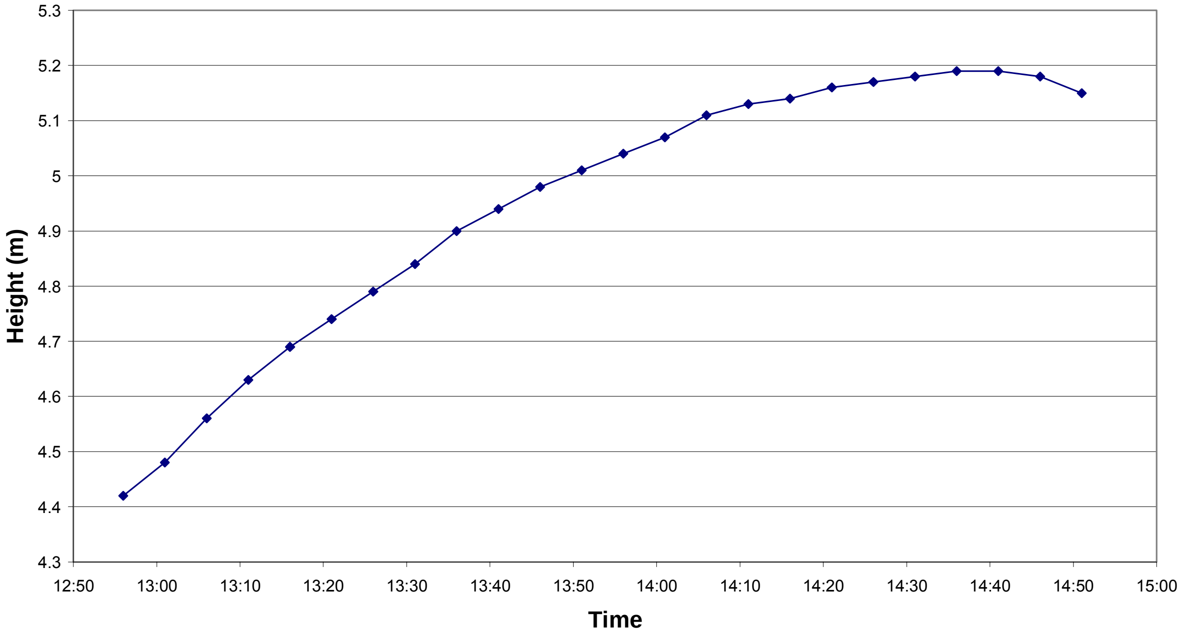


Figure 4.9: Tide curve for the period of the bathymetric survey on 28th July 2004 with heights referenced to Chart Datum.

4.2.4 Bathymetric Survey / Data Collection

The survey was conducted on a calm day with very low swell conditions as to minimise the effects of heave, pitch and roll. Once all the equipment was powered and found to be measuring (and displaying) depth and positional data, each of the survey lines were approached, as draft of the vessel would allow, and survey lines were run as per Figure 4.6. As each survey line was approached HYDROpro Navigation software was set to 'logging', which recorded all data into a project database.

Only one run was conducted for each of the Channel and Mouth survey lines since the channel was determined too narrow to conduct more parallel lines. Therefore it was decided to survey the line of the deepest part of the 'Channel' and 'Mouth' survey lines.

Survey lines 'near4' to 'near21' were then surveyed in turn where the vessel would finish on one end of a line and then turn around to start on the next successive line. Logging of data ceased during the turning between the lines. Lines 'near1' to 'near3' were determined to be unnecessary due to sufficient coverage of the Mouth3 survey line. Figure 4.10 displays the resultant recorded data events and survey area coverage.

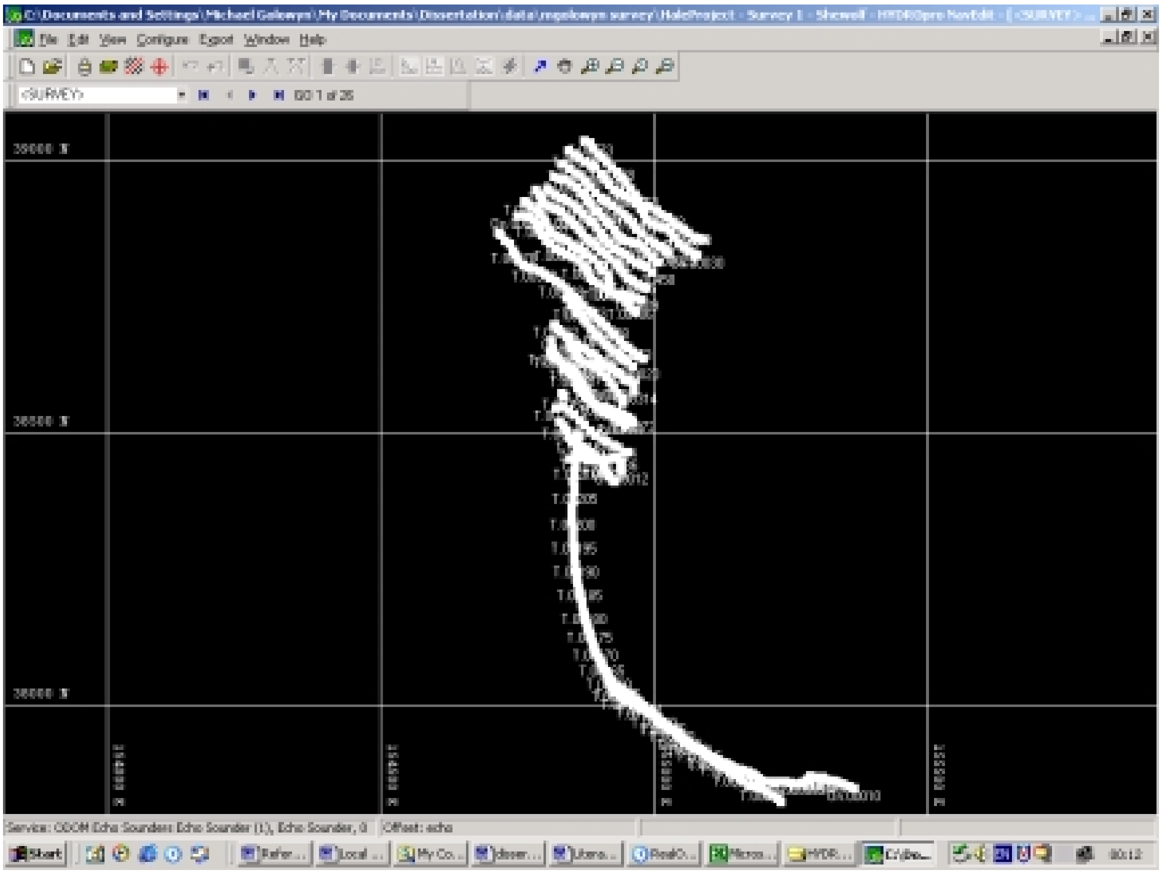


Figure 4.10: Data event point survey lines logged as part of the Hayle bathymetric survey.

All the survey data was stored into a project database and was ready for editing upon completion of the survey.

4.2.5 Bathymetric Data Processing

The project database created in HYDROpro Navigation software was then opened into HYDROpro NavEdit software. Each survey line was opened and edited in turn as to exclude (flag) outlying data points which would not be included in the reduction process. A tide file was created using the tidal heights relative to CD within NavEdit and the recorded depths were subsequently reduced to produce the view in Figure 4.11. Horizontal positional coordinates were in Ordnance Survey Great Britain 1936 (OSGB36) easting and northings

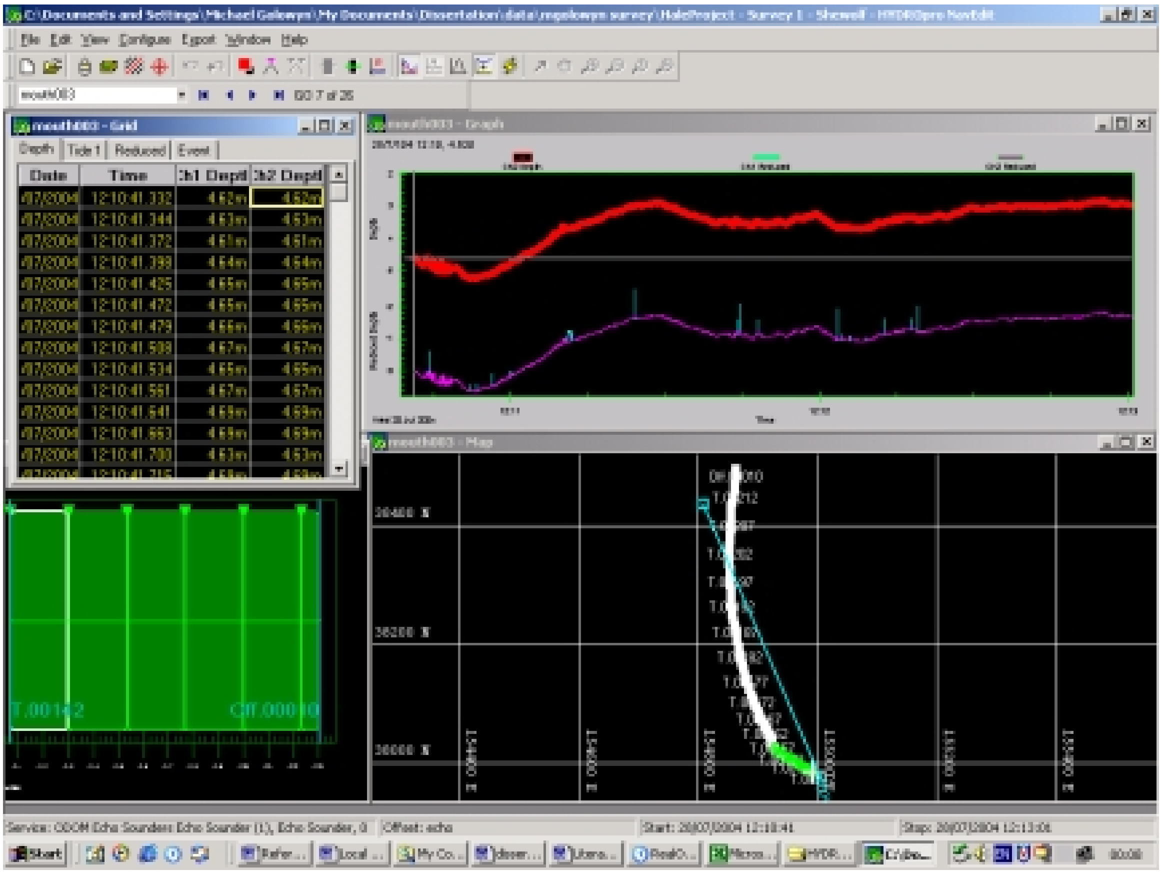


Figure 4.11: Hayle Estuary mouth bathymetric data viewed and edited in HYDROpro NavEdit software showing digitised echo sounder trace with measured (red) and reduced (purple) depths.

4.3 Merging RTK GPS and Bathymetric Data

Due to unforeseen problems with regard to the operation of HYDROpro edit software, the bathymetric data could not be exported to useable format. Manual extraction of key depths (mainly depths which were missed by the RTK GPS survey such the deepest parts of the channel), eastings, northings, tide heights and times were conducted and entered into an Excel spreadsheet (see Appendix 2).

Manual reduction of the data was made and depth values were adjusted from Chart Datum into OD Newlyn by subtracting 3.14m (refer Appendix 2) (Admiralty Publication 2004) for consistency with RTK and LIDAR elevation data analysis. The data (45 points) was then appended to the existing RTK GPS survey *xyz* file.

4.3.1.1 Data Processing

The merged xyz text file was imported into ArcView 3.3 software and converted into a grid file with grid cell sizes of 2m. The grid file was then converted into a TIN file with elevation value tolerances of 0.2m. The TIN file was then imported into ArcMap ready for profile and volumetric analysis.

4.4 Aerial Photographs

4.4.1 Data Collection

A series of aerial photographs for the Hayle Estuary mouth area, provided by the Cornwall County Council, were obtained for the years 1946, 1979, 1988 and 1996. The dates and times of each set of photographs were noted as the following:

- 1946 – 15/5/1946, time unknown
- 1979 – 29/10/1979, time unknown
- 1988 – 10/5/1988, 5.45pm
- 1996 – 13/6/1996, 3.55pm

Aerial photographs which covered the area of interest were selected and scanned at maximum resolution to maximize the accuracy of the photo analysis. All sets were photographed vertically with varying scales. 1998 and 1996 files were photographs at a scale of 1:10,000 with 1946 and 1979 scales left unknown.

4.4.2 Data Processing

4.4.2.1 Uncontrolled Mosaic Preparation

Uncontrolled mosaics were prepared for each set of aerial photographs for each year. For each year, from 1946 to 1996, all the photographs were imported in to Corel Draw 9 software, and then grouped together to form uncontrolled aerial mosaics. This was achieved by individually overlapping each photograph onto one another until the difference in overlap was at a minimum (approximately 60% overlap)(see Figure 4.12).

Figure 4.12: Raw 1988 aerial photographic mosaic showing Hayle Estuary mouth and the town.

Error due to oblique tilting around the edges of each photograph was minimised by primarily concentrating matching image details around the Hayle Estuary mouth area, and secondarily, the surrounding hinterland areas. Each mosaic image was then exported as a JPEG format image file.

4.4.2.2 Aerial Photograph Geo-referencing

Using ESRI ArcGIS ArcMap software, Ordnance Survey (OS) survey data in the form of OS line tiles that were obtained from the Digimap website, were imported. These tiles contained information such as Low water springs (LWS) lines, cliff and property boundaries all with predefined coordinates.

Each photo mosaic file was then imported in to ArcMap as a JPEG image file, and using the Geo-referencing tool, all permanent features including large rocks, cliffs, property boundaries and buildings were digitally referenced from the photo mosaics to the corresponding point on the OS lines tile. Once several points were geo-referenced with a satisfactory spacing over the mosaic, the image was transformed until most of the permanent features on the mosaic were within 2m of the OS line coordinates. The images were then rectified to be saved as images along with coordinate data.

4.5 LIDAR Data

4.5.1.1 Data Collection

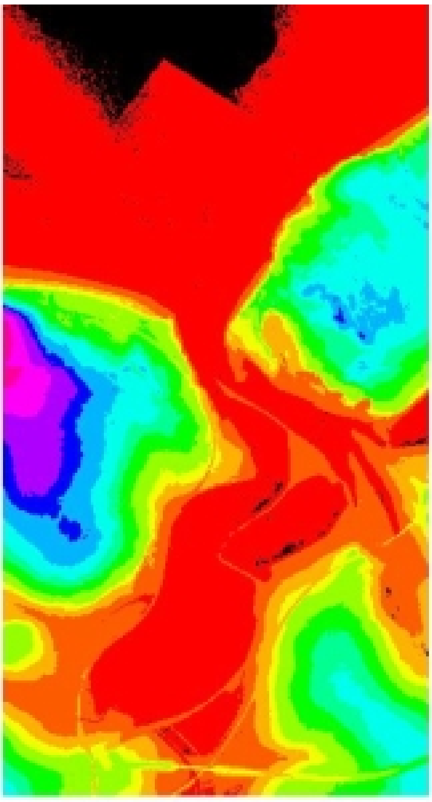
Two tiles of LIDAR elevation data were provided by the Environment Agency which covered an area of 4 km^2 each. The data was flown on the 31st March 2003, covered 99.7 and 78.8% of the tile areas respectively and the data was provided on CD Rom in ArcView ASCII Grid Format. Elevation measurements were provided in millimetres above OD Newlyn. The ASCII raster file format is a simple format that can be used to transfer raster data between various applications and basically contains a few lines of header data followed by lists of cell values.

Three types of data files were provided:

1. DEMs in ArcView grid format containing heights of objects such as buildings and vegetation as well as open ground.
2. DEMs in ArcView grid format data, of grid cell size of 2m, that has been passed through a classification and filtering routine that attempts to strip out vegetation and building from the LIDAR derived surface model to provide 'bare earth' elevation models.
3. Files in ArcView grid format data which represents the "filter mask" used in the filtering process to remove vegetation and building objects.

4.5.1.2 Data Processing

The 2nd filtered grid data type was selected as Brasington (2003) found that removal of sparse vegetation cover from DEMs is unlikely to have a major impact on surface quality. The grid data files were imported into ArcGIS ArcView 3.3 and the elevation units were converted into metres. The filtered DEM points were then re-interpolated by Delaunay triangulation to produce continuous Triangular Irregular Network (TIN) models with elevation value tolerances of 0.2m (see Figure 4.13).



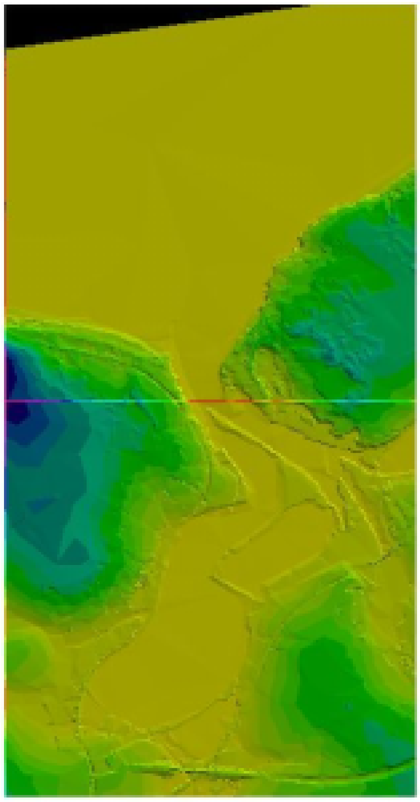


Figure 4.13: Filtered LIDAR data for Hayle Estuary mouth converted from grid DEM files (left) into TIN DEM files (right).

To assess the validity of the LIDAR elevation data for analysis with the RTK GPS / Bathymetry survey data, the elevations of a permanent feature in the survey area (artificial channel training wall at the entrance to Hayle Harbour) were compared. It was found that the LIDAR elevation values were of a mean value, 2.84m, below that of the RTK GPS survey values for the same permanent topographical feature. This indicates the presence of systematic error during data collection and processing, and will be discussed in Chapter 7.

Since the accuracy of the RTK GPS survey heights are regarded to be greater than that for LIDAR elevations by a factor of 5 (±15cm / ±3cm), it was decided to adjust the LIDAR elevation values by 2.84m for consistency during the analysis. The resulting TIN files were then imported into ArcGIS ArcMap software for analysis.

4.6 1998 Profile N11 in Halcrow Maritime's (1999) Shoreline Management Plan

An inspection report was conducted at Hayle Beach on the 23rd September 1998 which was compiled by Halcrow Maritime (1999) as part of a Shoreline Management Plan for the Cornish coastline. A beach profile, N11, was conducted using a theodolite and reflective prism from the top of the dune and extended out across the beach as illustrated in Figure 4.14. The location of the profile is only a rough approximation. This profile is used for analysis in Section 6.2.1.

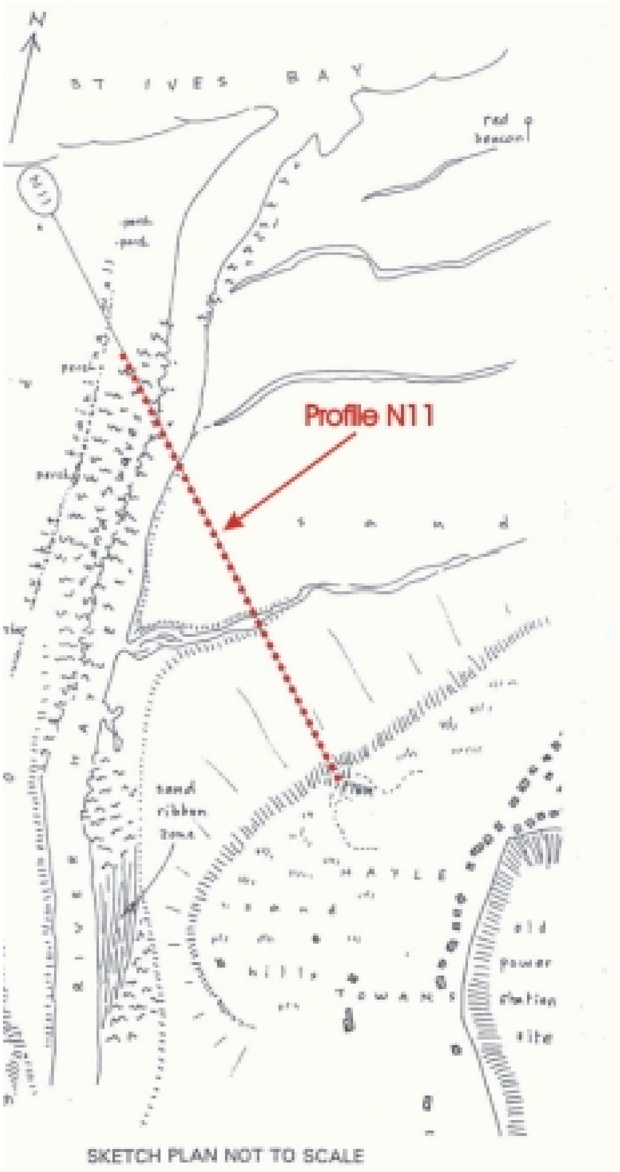


Figure 4.14: Sketch of approximate location of the 1998 profile conducted at Hayle beach by Halcrow Maritime (1999).

Chapter 5

5 Methods - Data Analysis

5.1 Aerial Photographs

The dates and times (where available) for each aerial photo mosaic (1946-1996) were recorded (refer Section 4.4.1). Tides and Currents software was used to access the predicted tide heights and times for each aerial photograph mosaic for the years 1946, 1979, 1988 and 1996 and entered into Table 5.1

Table 5.1: Times and heights of predicted tides at St Ives for the day each set of aerial photographs were taken.

Year	Stage of tide	Time of tide	Tide Height relative to CD (m)
1946 (springs)	HW LW HW Photo	5.44am 10.54am 6.02pm -	6.45 1.18 6.48 -
1979 (Neaps)	LW HW LW Photo	5.02am 11.05am 5.37pm -	2.08 4.97 1.96 -
1988 (Neaps)	LW HW LW Photo	5.58am 12.08pm 6.44pm 5.45pm	1.92 4.85 1.94 2.12
1996 (Springs)	HW LW HW Photo	2.53am 9.28am 3.20pm 3.55pm	5.71 1.41 5.77 5.61

Using ArcMap software, four profiles, A, B, C and D, were drawn across each photo mosaic to cover the Hayle Estuary Mouth and Beach (see Figure 5.1).

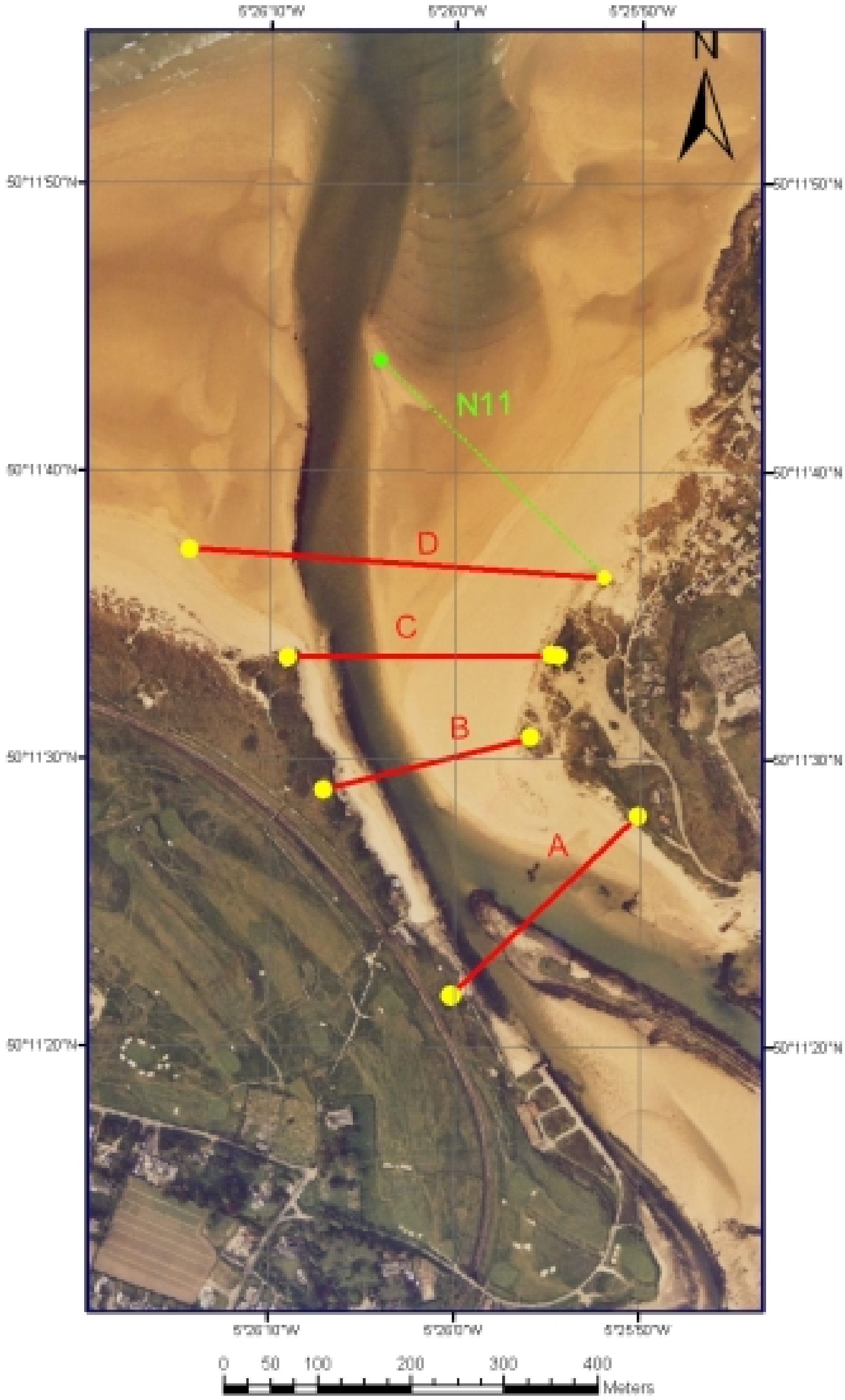


Figure 5.1: Aerial photo mosaic for 1988 showing profiles A, B, C and D lines drawn.

The HWL was first identified on each aerial mosaic. Using the data entered in Table 5.1 and the digital ruler tool in ArcMap, the distance from the profile origin (east end) to the HWL, the water level and each subsequent change in terrain, was measured and inputted into Appendix 3. From this data, cross sections along each profile were plotted and the horizontal distance between the HWL for each year were compared. The photograph analysis for the years 1946, 1979, and 1996 were conducted on the templates shown in Figure 6.1.

5.2 RTK GPS / Bathymetric Data (July 2004) Profiles

Using ArcMap, profiles A, B, C, D and N11 were superimposed onto the RTK GPS / Bathymetry data TIN file as shown in Figure 5.2.

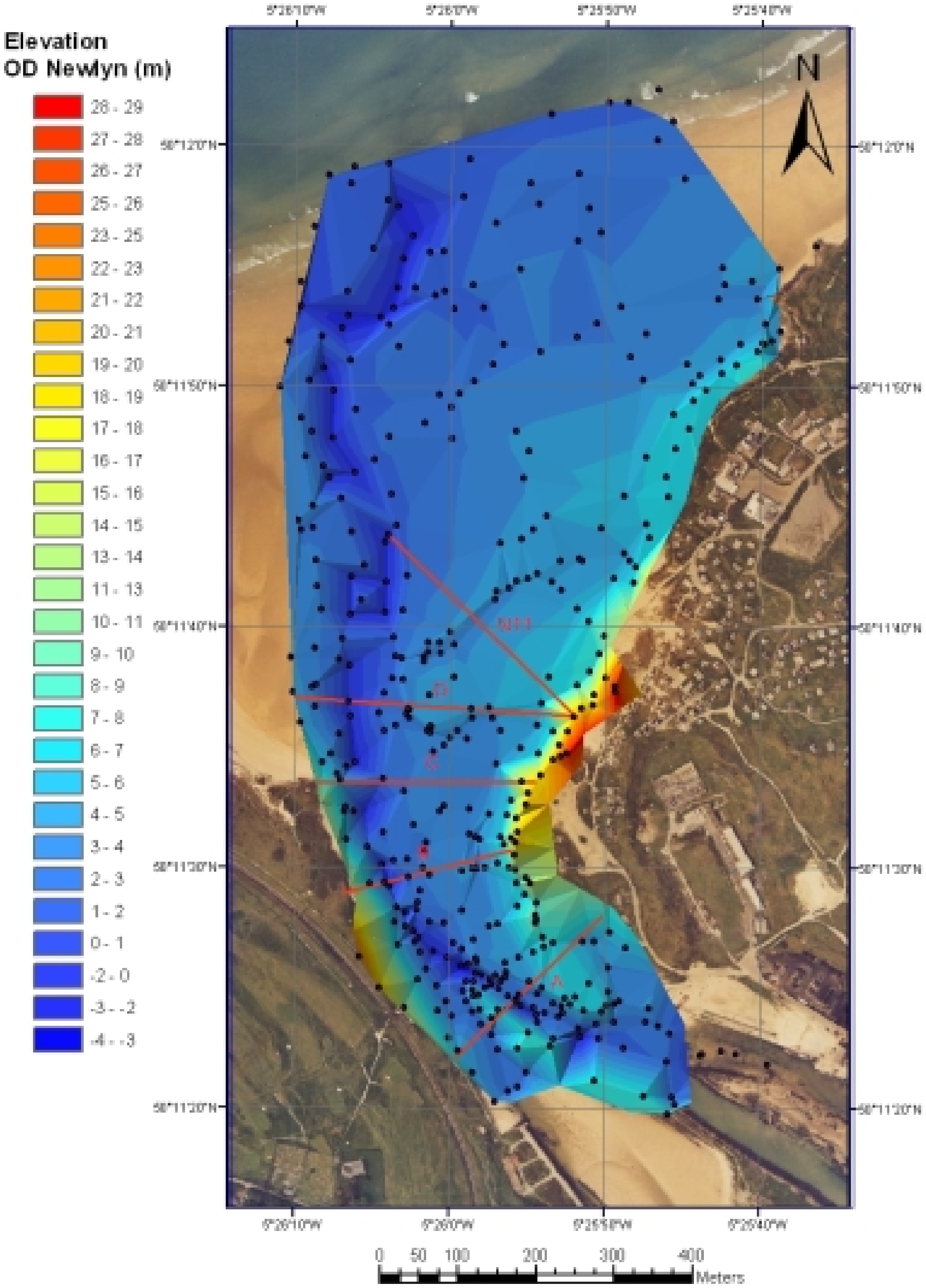


Figure 5.2: TIN DEM of RTK GPS and Bathymetry data with survey data points.

Using the Editor function in ArcMap, profile lines A, B, C, D and N11 were digitised and saved to a shapefile. Arcplot (ArcInfo Workstation) software was used to compute database files containing elevation values with distance along each profile. The database information was then imported into Microsoft Excel and cross-section profile plots were derived (see Figures 6.6 to 6.10). The eastern end of each profile was chosen as the profile origin.

5.3 LIDAR Profiles

A similar process as above was applied to the LIDAR data concerning the Hayle Estuary mouth area (see Figure 5.3). LIDAR data cross-section profiles A, B, C, D and N11 were plotted on the same axes as the RTK GPS/bathymetry profiles to enable direct comparison during analysis.

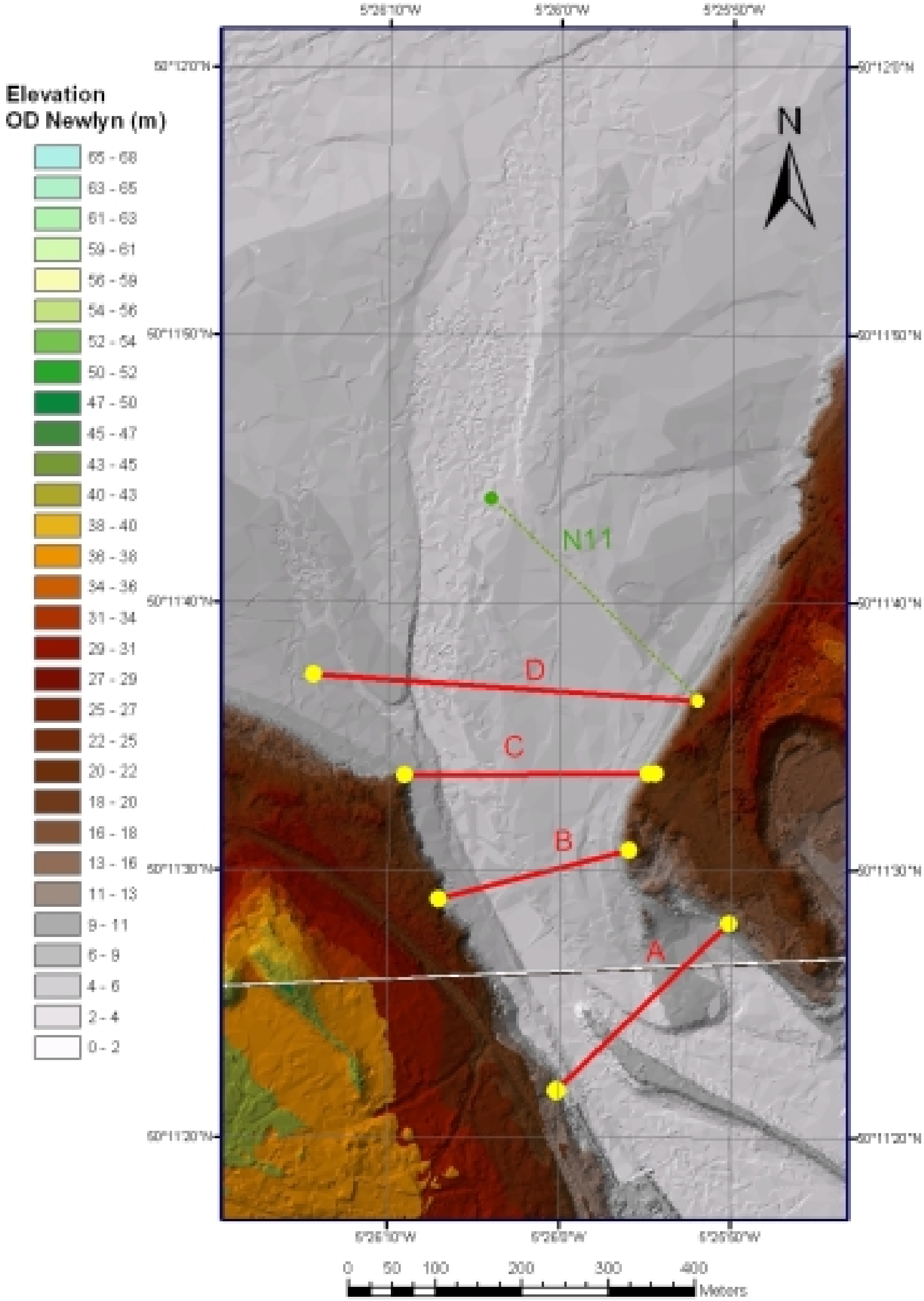


Figure 5.3: Zoomed image of LIDAR TIN files with profile lines superimposed.

5.4 RTK GPS / Bathymetry Data and LIDAR Data Volumetric Analysis

To make an assessment in the beach change from March 2003 to July 2004 the LIDAR data and RTK GPS / bathymetry data were analysed together. This was achieved by using the cut/fill option in ArcMap. Both TIN files for LIDAR and

RTK GPS / Bathymetry were selected, the LIDAR TIN file was chosen as the before data and a net gain (accretion) / net loss (erosion) diagram was constructed which showed the areas of erosion and areas of accretion (see Figure 6.11).

To conduct an elevation difference analysis, the raster calculator function was used with grid files of the LIDAR (2003) and RTK GPS / bathymetry (2004) data. The 2004 data was subtracted from the 2003 data to produce a contour plot elevation difference (see Figure 6.12).

Chapter 6

6 Results

6.1 Aerial Photograph HWL and Foredune Analysis

Due to the limited amount of information provided on the aerial photographs, the HWL shoreline indicator was used for this analysis. Ideally, Mean High Water (MHW) would have been used, however there was not a sufficient amount of information to be able to determine this level. Therefore due to the use of HWL, this indicator would change based on whether the photos were taken during a neap or spring tide cycle. For the purposes of this analysis, the stage of the tide cycle was noted but not incorporated in the shoreline measurements.

The position of the western estuary mouth shoreline appears to be relatively stable from observing Figures 6.1 to 6.5. Since Hayle Beach (east end of each profile) is the primary study focus, results will be mainly discussed with regard to this area.

On first inspection of Figure 6.1 it is immediately clear that the shoreline at Hayle Estuary mouth has undergone a high level of transition since 1946. it is worth noting that between 1946 and 1979 a large deposition of sand occurred between profiles A and B. It is not clear when this deposition occurred however it may be a result of the sluicing process ending.

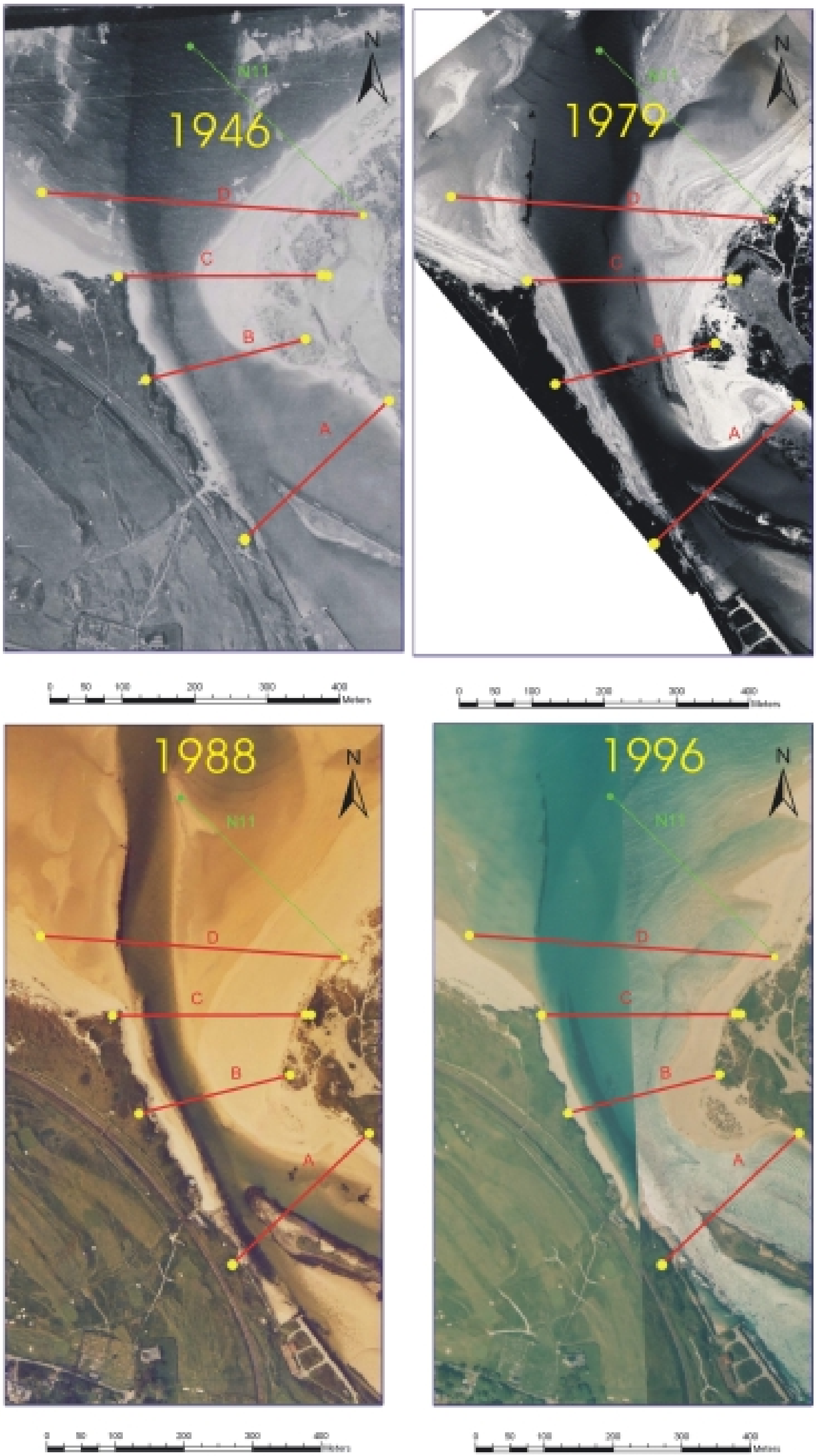


Figure 6.1: Zoomed in aerial photographs photos for all years collected. Note the change in shorelines in relation to the fixed profiles.

6.1.1 Profile A

Profile A (see Figure 6.2) shows the least change in the HWL position out of all the profiles.

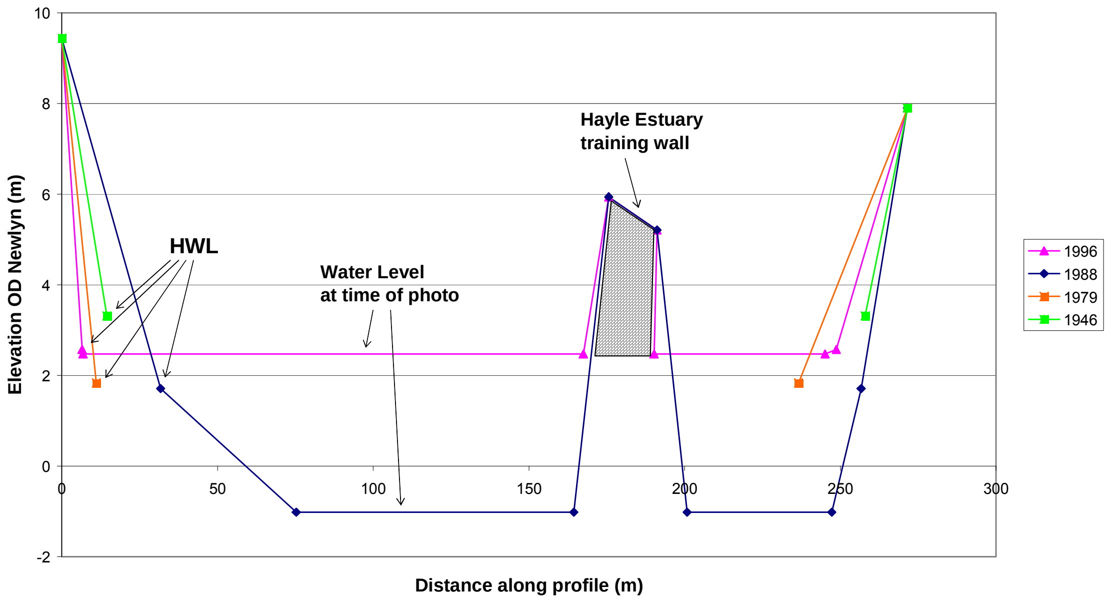


Figure 6.2: Plot of foredune and HWL positions along profile A.

This would be mainly due to its location well inside the estuary mouth near the harbour entrance. Between 1946 and 1979 little change in HWL position is apparent with the shoreline receding by 3.4m. From 1979 to 1988 shoreline progression occurs into the Hayle River by 20.6m before returning to its 1996 position (6.48m from the profile origin). The far end (west) of profile A exhibits a similar pattern of periodic retreat and advance of the HWL towards the river mouth.

6.1.2 Profile B

Figure 6.3 shows the foredune position to retreat inland progressively from 1946 to 1996.

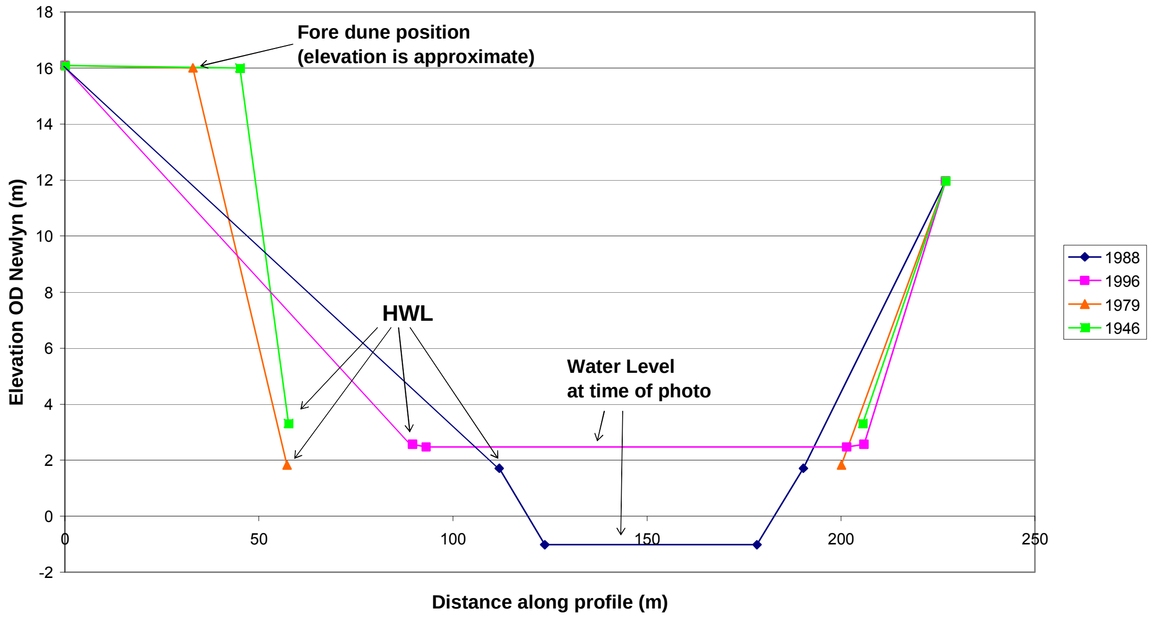


Figure 6.3: Plot of foredune and HWL positions along profile B.

From 1946 to 1979 inland dune retreat of 12.1m is observed. From 1979 to 1988 further regression of 33m is observed with little change between 1988 and 1996.

The HWL position does not exhibit the same linear transgression of the foredune positions. During 1946 and 1979, HWL is closest to the profile origin with values of 57.6m and 57.2m respectively. HWL positions for 1988 and 1996 are 111.9m and 89.6m respectively from the profile origin.

These results indicate that, in general, sand in being lost from the foredunes but accretion has occurred on the beach to result in the HWL moving away from the dunes.

6.1.3 Profile C

Foredune retreat along profile C is more marked between 1946 and 1979 (55.4m) (see Figure 6.4), with the horizontal position of the HWL shoreline retreating inland a similar distance of 56.0m.

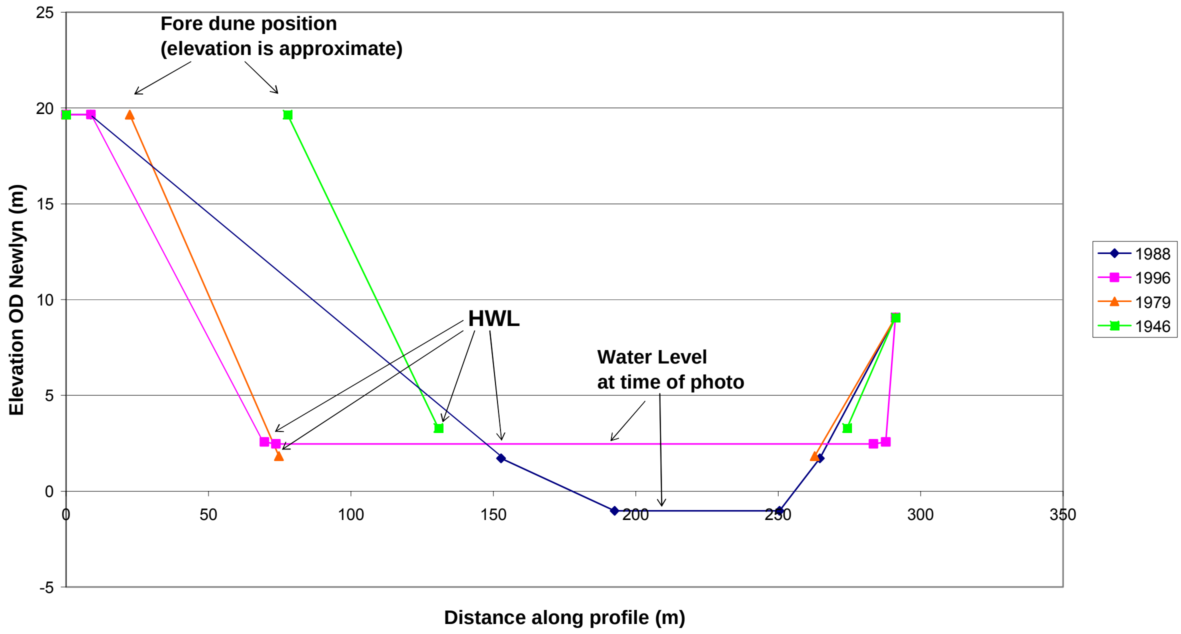


Figure 6.4: Plot of foredune and HWL positions along profile C.

An interesting shift in HWL position occurred between 1979 and 1988 with the shoreline protruding seaward 78.0m. Between 1988 and 1996 the foredune position has not shifted noticeably with HWL shoreline position progressing significantly inland by 83.0m, indicating a reduction in beach levels along profile C.

6.1.4 Profile D

Figure 6.5 shows that along profile D, foredune retreat of 43.1m is observed between 1946 and 1979 with further regression of 22.5m occurring up until 1988. Between 1988 and 1996 very little change in foredune position is observed.

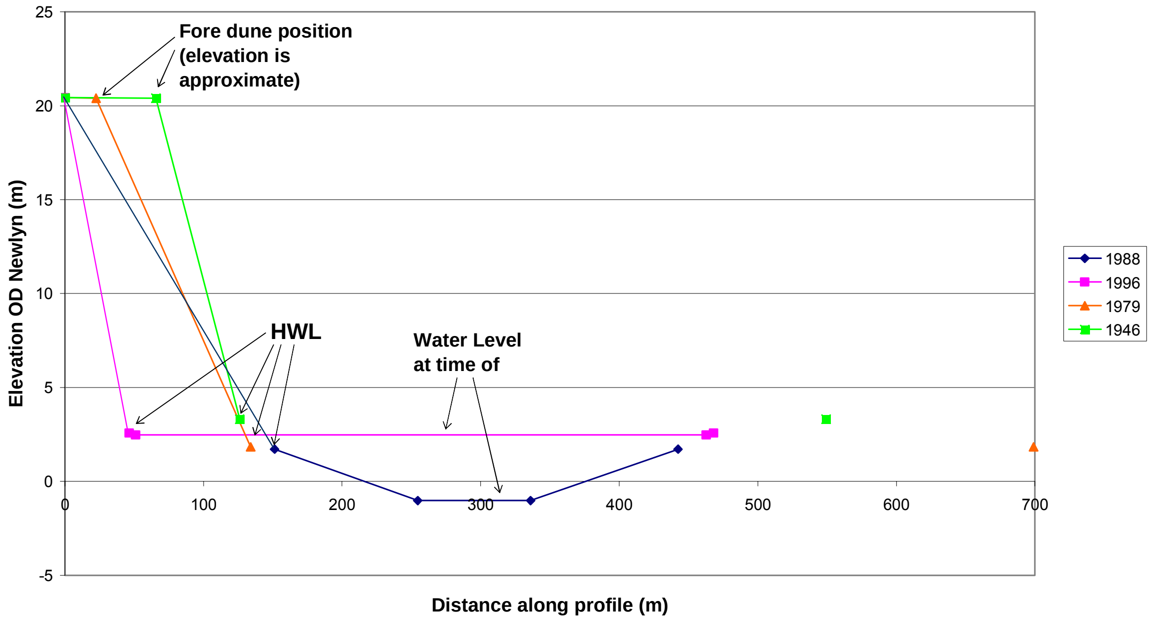


Figure 6.5: Plot of foredune and HWL positions along profile D.

The HWL shoreline has varied its position several times between 1946 and 1996. From 1946 to 1979 and from 1979 to 1988, HWL has shifted seaward by 8.0m and 17.2m respectively. From 1988 to 1996 the HWL shoreline has retreated inland by 104.8m, indicating a substantial reduction in beach levels during this period along profile D.

6.2 RTK GPS / Bathymetric Survey Data and LIDAR Data

The following profiles were derived from the data provided in Figures 5.2 and 5.3.

6.2.1 Profile N11

The position of the 1998 profile N11 (Halcrow Maritime 1999) is not consistent with the LIDAR or RTK GPS/bathymetry profiles, and appears to be offset below the others by a consistent value (see Figure 6.6). This would be more than likely due to the approximate derivation of the 1998 profile position from the sketch in Figure 4.15. Elevations of the 1998 profile are offset from the LIDAR profile elevations by a mean value of -1.66m.

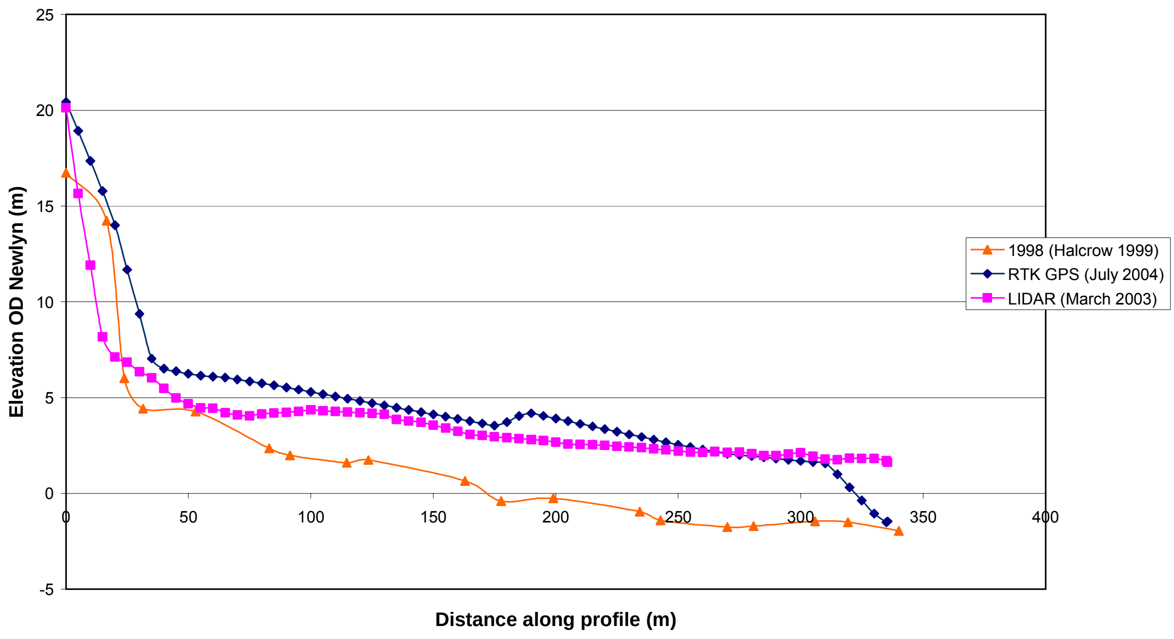


Figure 6.6: Theodolite, LIDAR and RTK GPS/Bathymetry survey profiles along profile N11.

The toe of the foredune shows evidence of accretion between 1998 and 2003 with the dune face appearing to have eroded. This is consistent with dunes experiencing blow-outs and Figure 6.1 shows the profile N11 origin located in this type of area. Between March 2003 and July 2004 accretion has occurred on the dune face to increase beach levels at the berm and dune location.

On the lower part of the beach profile, an increase in beach levels occurred along profile N11 between 1998 and 2003, with further accretion between March 2003 and July 2004.

At about the 190m mark sand wave or gutter feature is observed to have formed from the 2004 survey data. Towards the end of the profiles, July 2004 shows marked decline in elevation as the profiles intersects the Hayle Estuary mouth channel.

6.2.2 Profile A

A large discrepancy of 5.9m exists between the elevation at the profile origin between the LIDAR and RTK GPS/bathymetry data (see Figure 6.7). This indicates an error in the survey data processing (survey point interpolation) during DEM construction.

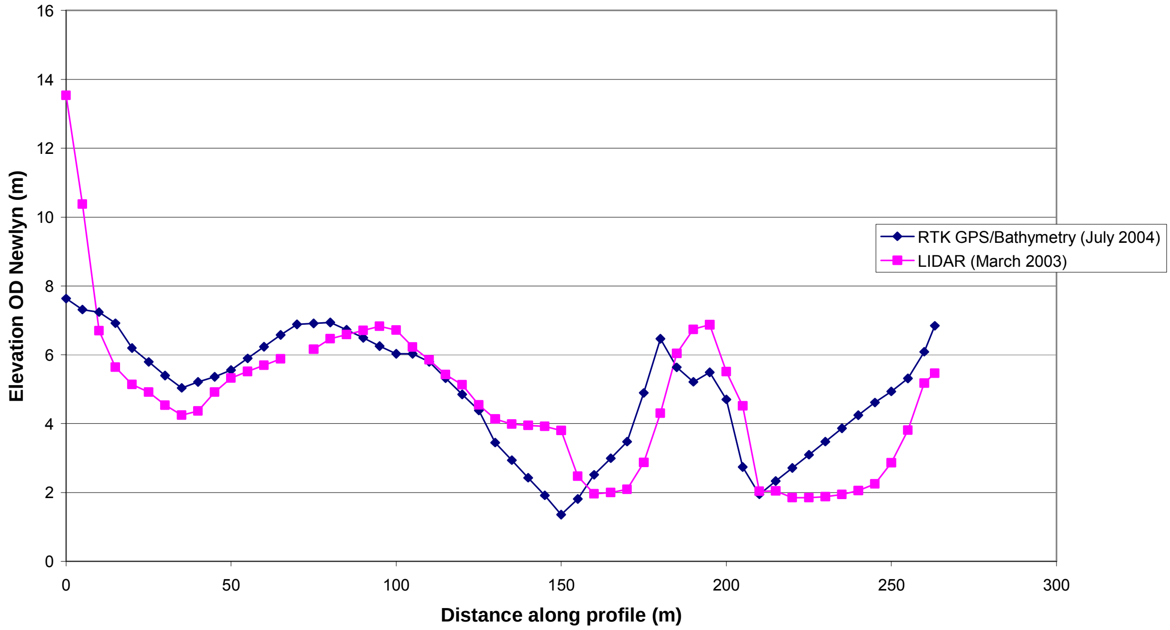


Figure 6.7: LIDAR and RTK GPS/Bathymetry survey profiles along profile A.

Moving away from the origin it looks as though sediment accretion has occurred between the 10m and 85m mark along the profile. Substantial sediment erosion (where LIDAR 2003 elevations > RTK GPS/bathymetry 2004 elevations) is observed from the 125m to 155m mark along the profile at the deepwater channel location very close to the location of recent dredging operations.

The large elevation spike about the 180m mark resembles the Hayle Estuary training wall which varies in position between the LIDAR and RTK GPS survey data (~5m). This seems odd given it would not be expected to have shifted in position at all let alone in the space of 16 months. This indicates a presence of systematic error between the two survey data sets. Towards the end of the profile, the far bank of the Hayle Estuary appears to have experienced a significant amount of accretion.

6.2.3 Profile B

Dune erosion is apparent between March 2003 and July 2004 along the first 20m of profile B (see Figure 6.8).

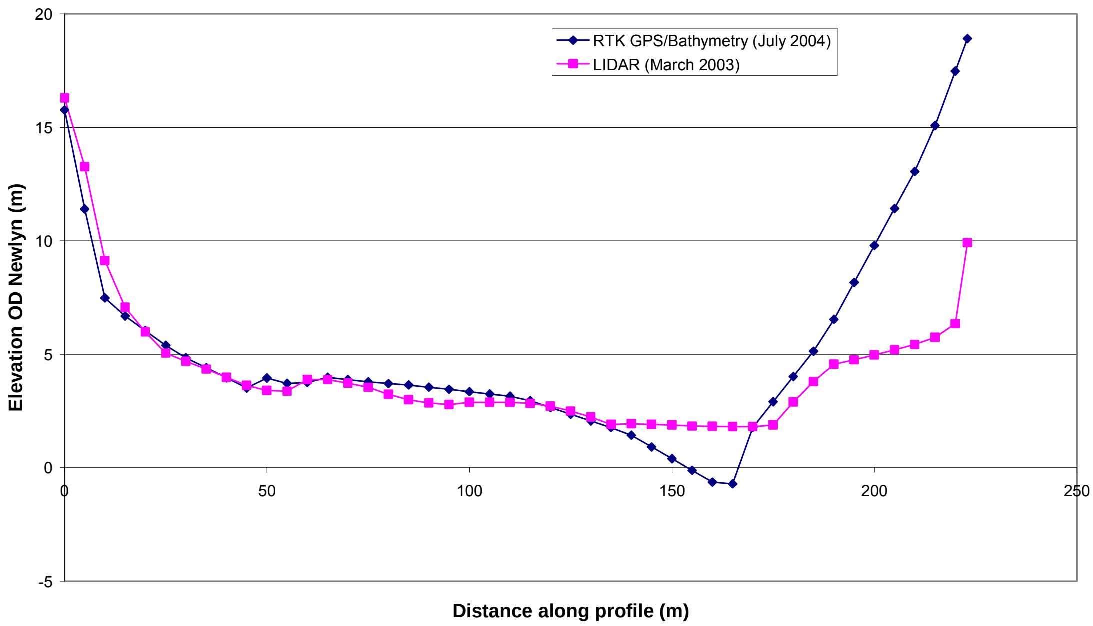


Figure 6.8: LIDAR and RTK GPS/Bathymetry survey profiles along profile B.

The profile remains relatively stable with slight accretion occurring about the 50m mark and between the 70m and 115m mark. Channel depths along the profile, about the 160m mark, differ between the LIDAR (2003) and RTK GPS/Bathymetry (2004) survey data. This may be evidence of erosion or scouring of the channel and may indicate limitations in accuracy of the LIDAR elevation data.

The initial part of the far bank indicates an increase in beach levels, however from the 190m mark onwards, inaccurate extrapolation of the RTK GPS survey data may account for the steep rise towards the end of the profile.

6.2.4 Profile C

In the first 45m of profile C, a substantial amount of accretion is observed where the dune face and toe both shift approximately 20m towards the estuary channel (see Figure 6.9).

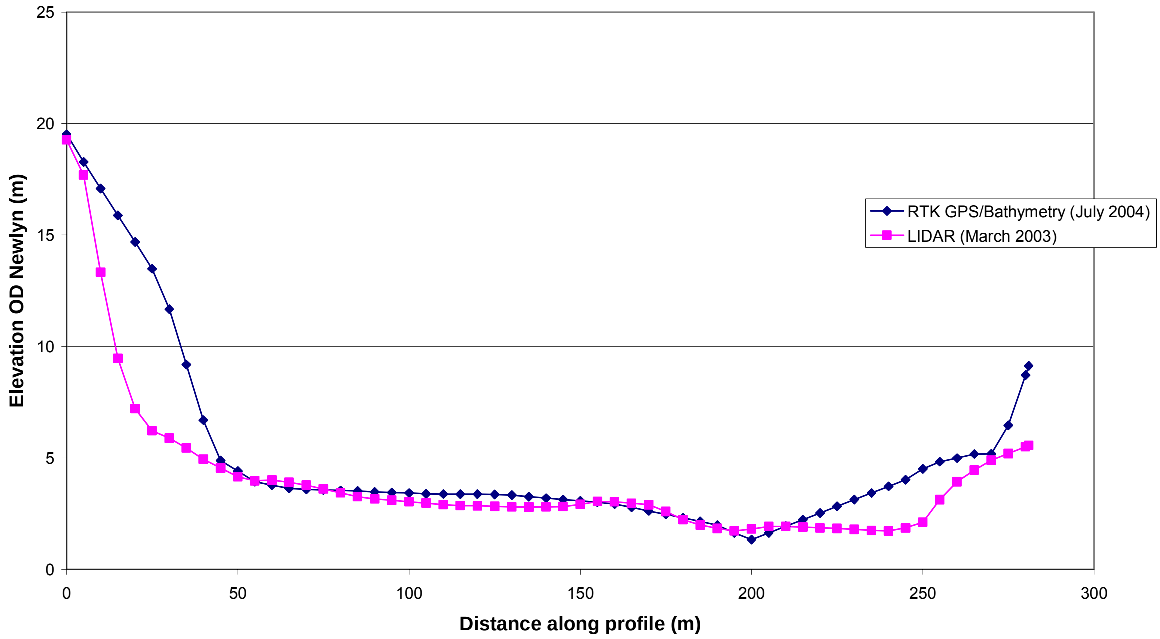


Figure 6.9: LIDAR and RTK GPS/Bathymetry survey profiles along profile C.

A slight increase in beach levels between 85 and 150m mark is observed between 2003 and 2004. At the channel (~200m along profile C) the 2004 (bathymetry data) beach level is slightly below that of the 2003 (LIDAR data) level by about 0.48m, before accretion is observed on the far bank of the deepwater channel.

6.2.5 Profile D

The first 40m of profile D (see Figure 6.10) is very similar to that of profile N11 (apparent accretion on dune face and seaward shift of dune toe) which is logical considering they originate from the same point. An increase in beach levels has occurred between the 45m and 215m mark for the period between the 2003 and 2004 survey, before a noticeable reduction in beach levels as the profile approaches the deepwater channel. Little change in the 2003 profile is observed at this point, however the 2004 profile dips significantly to an elevation of -1.40m OD Newlyn, before rising just as rapidly to the observed accretion at the 325 to 340m mark.

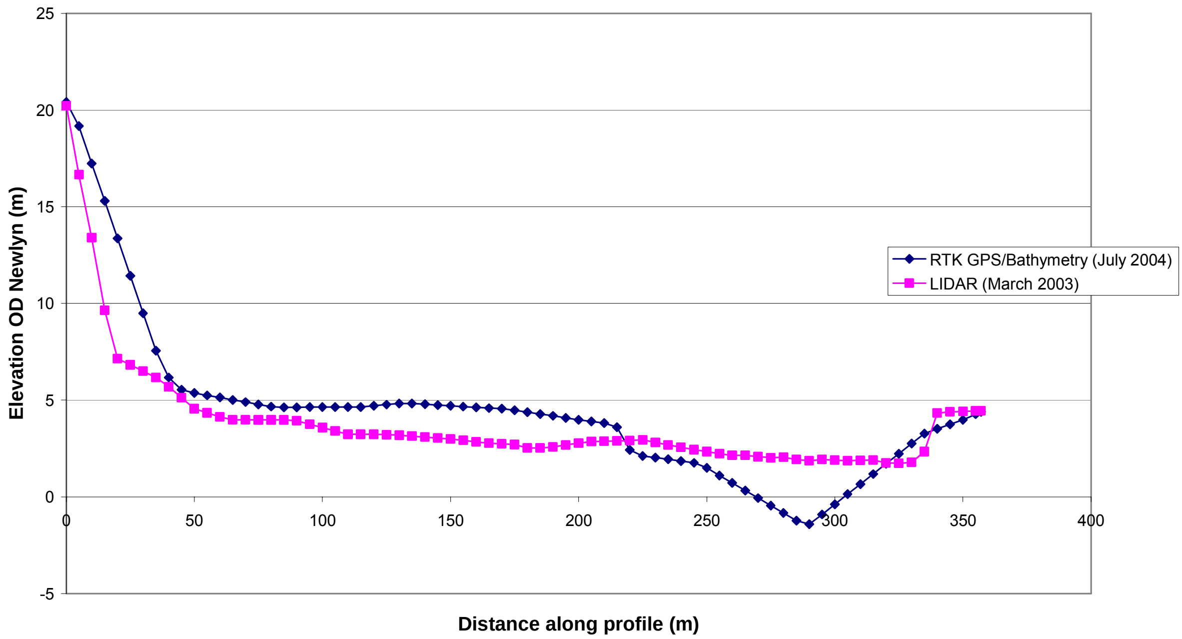


Figure 6.10: LIDAR and RTK GPS/Bathymetry survey profiles along profile D.

6.2.6 Volumetric Analysis with RTK GPS / Bathymetric Survey Data and LIDAR Data

Figure 6.11 reflects the results from the previous section, but also illustrates areas of accretion and erosion on a much larger scale. On initial inspection, it appears that the whole of the area surveyed is subject to some degree of erosion or accretion. It is accepted that, due to errors and assumptions within the data collection and processing (see Section 7.2.3), differences will exist between the RTK GPS/Bathymetry and LIDAR survey data regardless of erosion and accretion events.

The extreme edges of the overlaid difference analysis maps (Figure 6.11 and 6.12) are the outer edges of the RTK GPS survey, and therefore interpolation errors present, show up large differences in elevation for features such as cliffs, and steep hills.

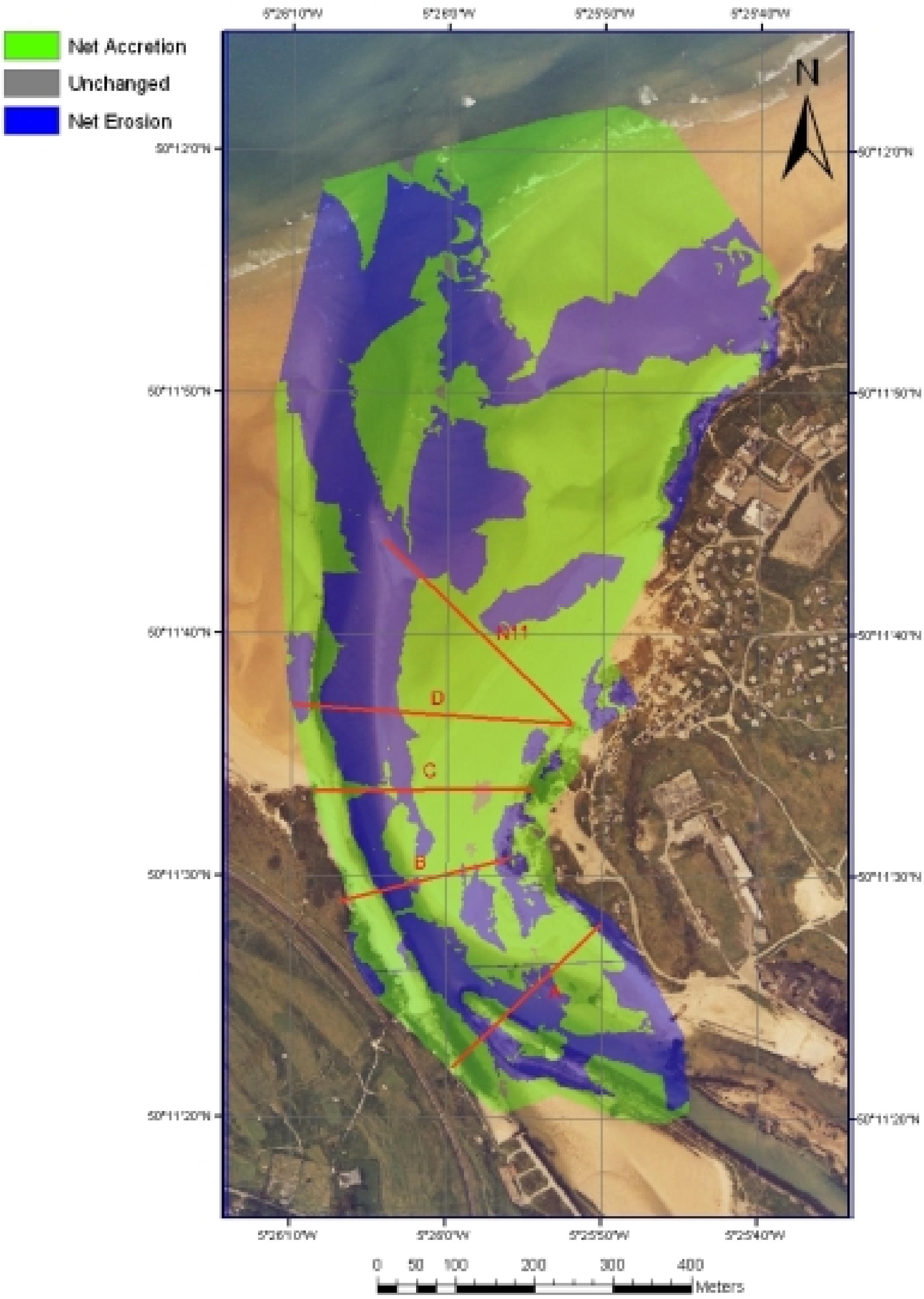


Figure 6.11: Net accretion and net erosion of beach sediment between March 2003(LIDAR) and July 2004 (RTK GPS/Bathymetry).

Between March 2003 and July 2004, the most obvious widespread area of elevation reduction occurred the length of the deepwater channel from Hayle Harbour through to St Ives Bay. Approximately 100m north and 300m west of Black Cliff, two relatively large areas respectively, have experienced an apparent reduction in beach levels. A large proportion of upper Hayle Beach is observed to have increased in beach levels which may be a result of seasonal time scale and not long term coastal processes.

6.2.7 Elevation Difference Analysis - RTK GPS / Bathymetric Survey Data and LIDAR Data

Figure 6.12 provides a clearer representation of the quality and quantity of beach change over the Hayle Estuary mouth and beach area. Disregarding the deep red areas on the eastern edge of the chart, the largest losses in beach elevations (approximately 3.0 and 4.0m) between March 2003 and July 2004, occurred along the deepwater channel from the estuary mouth training wall through to St Ives Bay. This amount of sediment reduction seems unlikely in the space of 16 months, and may be an indication of limitations in collecting LIDAR surface elevation data over submerged areas (see Section 7.3).

Other apparent erosion events occur at the foredune location about profile B (latitude 50º11’30” N and longitude 5º25’57” W). Significant sediment reduction in this area ranges from 1.5 to 4.0m. Another noticeable reduction in elevation (2.0 – 2.5m) occurs just inside the estuary mouth, close to the area where recent dredging operations have been observed.

Again, ignoring the western edge of the chart, the most significant areas of sediment deposition has occurred at the toe of the Hayle Towans dune system. This is indicated by the dark blue (3.6 – 4.0m) ‘triangle’ shaped areas. Further indication of deposition has occurred inland at the tops of the dunes at the origin to profile D and N11. This occurs over an area lacking in vegetation cover since at least 1988 (see Figure 6.1) and would be vulnerable to wind erosion.

At the Hayle Estuary entrance, just south of profile A (50º11’25”N and 5º25’51”W) a zone of increased elevation (2.5 – 4.0m) has occurred. This result indicates that, even with dredging operations taking place, sediment is still being deposited within the estuary entrance. At the nearby training wall, varying levels in elevation changes (negative and positive) are evident which in reality, would be unlikely, given it is an artificial topographical feature. This further asserts the view of acute random errors occurring during the data digitising process.

According to the data, the remainder of Hayle Beach has experienced slight increases levels in elevations (0 – 1.5m) which may indicate presence of seasonal influences on the beach levels.

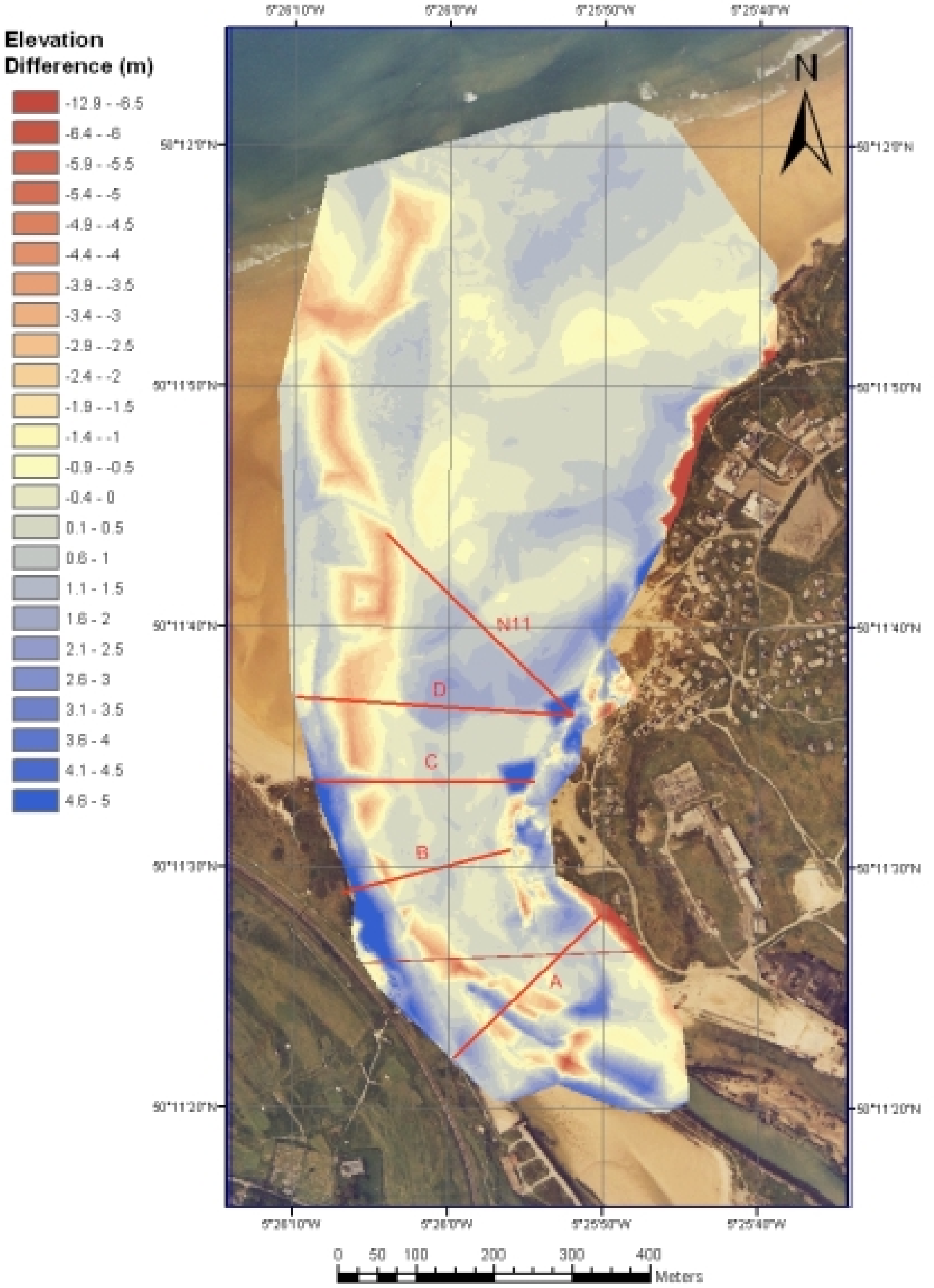


Figure 6.12: Changes in beach elevation between March 2003 and July 2004.

Chapter 7

7 Discussion

7.1 Aerial Photograph HWL Analysis

7.1.1 High Water Shoreline Positions

The results described in Section 6.1 confirm the observations of previous studies of the sediment transport processes observed at Hayle. Historical evidence suggests whole estuaries may undergo long periods of accretion followed by long periods of erosion (Penwith District Council 2002), and in particular, Hayle Harbour being periodically swamped with sand and erosion of Towans dunes (Halcrow Maritime 1999). The aerial photograph shoreline analysis (Section 6.1) confirms these observations with the HWL shorelines along profile A retreating and advancing episodically between 1946 and 1996.

Sluicing of the deepwater channel ended in 1971 due to a ceasing of shipping operations within the harbour. This event could perhaps explain the significant amount of accretion observed in the 1979 aerial photographs (see Figure 6.1) with Halcrow Maritime (1999) reporting sand deposits rapidly accumulating in the seven years after sluicing ceased.

Natural coastal processes have since been re-established at Hayle Beach which, being wave dominated, have resulted in sediment transport to the mouth of the estuary resulting in loss of foredune sand and consequent reduction beach levels (Penwith District Council 2002). This is consistent with the results of the HWL analysis for profiles A and B (Sections 6.1.1 and 6.1.2) with shoreline advance observed between 1979 and 1988. Other studies conducted by Allan (2003) along the Oregon coast demonstrated estuaries as likely sinks of beach sand. Once the sediment becomes suspended by wave action, tidal currents transport it into bays and estuaries.

However, while foredune retreat rate is relatively constant over the years across all profiles, from 1979 to 1988, the HWL shorelines at profiles A, B and C have shown to advance seaward. A reverse trend is observed from 1988 to 1996 with rapid retreat of HWLs across all profiles. This may be an indication of natural sediment transport process, at the estuary mouth, reaching a form of equilibrium around 1988 before a significant change in the hydrological regime, such as due to an increase in swell wave activity, resulting in rapid shoreline retreat. Dail *et al* (2000) confirms this view where it was found sand volume of a sub-aerial beach is negatively correlated with wave energy flux (-0.88) and highly correlated (0.96) with shoreline position. Further analysis of historical wave climate patterns at Hayle Beach would be recommended in providing a clearer picture of shoreline changes at Hayle.

The most recent trends (1988 to 1996) along profile D exhibits shoreline retreat of 104.8m indicating a significant reduction in beach levels. This is consistent with the findings of the Penwith District Council (2002) and may be explained by a reduction in the level of Hayle Beach resulting in changes to the flood and ebb velocities at the mouth of the estuary (see Section 2.4.1), and a consequent potential landward movement of sand.

7.1.2 Foredune Retreat

The vegetation line, also used as a shoreline indicator, in this case marks the location of the foredune position and subsequent dune erosion when compared over time (see Figure 6.1). This can be used as an alternative shoreline indicator in areas with large tidal ranges and relatively flat beaches. These tend to cause large fluctuations in wave run-up and hence the variable position of the HWL (Leatherman 2003). Significant dune retreat of 55.4m occurred between 1946 and 1979 along profile C (Figure 6.4) which exceeds the maximum dune the retreat (45m) estimated by Halcrow Maritime (1999). This may reveal a prior underestimation in the magnitude of the coastal processes at work at Hayle Beach.

Beach foredune positions from 1988 to 1996 show very little signs of transition across all profiles. This may be explained by a model proposed for dune erosion by Komar *et al* (1999) where the amount of erosion is determined by the cross-offshore distance that extreme wave run-up exceeds the position of the initial dune scarp. This leads to the assumption that the erosion process is independent of time and that the dune scarp retreats until it is no longer impacted by wave run-up. By this rationale, from 1988, the dune scarp or foredune position at Hayle was possibly no longer impacted by wave run-up.

Profiles B, C and D, showing signs of dune crest regression with corresponding shoreline advance, suggests the dunes have an active role in the beach's natural protection to wave attack by providing a reservoir of sand to broaden the surf zone and protect the remaining dune (Penwith District Council 2002). This is confirmed by a study of erosion on the Californian coastline, conducted by Sallenger *et al* (2002). It was revealed that beach width is a significant factor for protection of the beach by wave attack and performed better than an increase in beach elevation for preventing dune erosion.

7.1.3 Sources of Error

Random errors can be introduced to shoreline interpretation from aerial photographs including during the digitising and geo-referencing process (Leatherman 2003). The use of OS lines to geo-reference key features on the image is limited due to oblique tilting at the edge of every photograph (see Section 3.1.2), and some parts of the photograph will be assigned more accurate coordinates than other parts.

The quality of the original photograph may have contributed to errors when identifying the correct HWL. For example, poor image quality for the 1946 photographs, and being black and white, the HWL was difficult to identify from the surrounding beach. Therefore, there was potential in identifying a false HWL from the image, and hence false shoreline measurements may have been made.

7.1.3.1 HWL Shorelines

Use of the HWL as a shoreline indicator is not without controversy. However, with decades of historical shoreline data based on HWL, studies of shoreline change are always going to make use of such data.

The HWL is not a morphological feature but an ephemeral line in the sand sensitive to short term fluctuations in wave and tide conditions (Leatherman 2003). As the horizontal position of the HWL varies from tide cycle to tide cycle, the next logical step is to reduce this variability by attaining a mean high water (MHW) value (Parker 2003). This step was not possible given the lack of information on the aerial photographs and tidal records available.

Even if the use of MHW was possible, variation in shoreline position would still exist. Parker (2003) demonstrated that determination of MHW position from 1 year of tidal records would contain 4% to 11% variation in heights due to not accounting for the 18.6 year lunar nodal cycle.

For shoreline change analysis purposes in this study, the stage of the tide (neap or spring), and hence the position of the last HWL preceding the time of the photograph, the HWL was considered as a consistent indicator. However changes in beach slope can drastically affect the results. The gentler the slope of the inter-tidal zone the greater the change in shoreline position with changing water level (Parker 2003).

For example, taking a summer inter-tidal beach profile (N11 beach profile for the RTK GPS survey data (see Figure 6.6)) with a beach slope of 1.26º and taking the difference between spring and neap high water values of 6.45m (1946 photo) and 4.97m (1979 photo) respectively, the horizontal shoreline position has the potential to vary up to 126.6m along that profile. This reveals large potential for error in use of HWL in shoreline change analysis.

Further, beach slope depends on temporal variability on a seasonal basis (steeper summer profiles and flatter winter profiles) (see Figure 2.8) and shows often dramatic reaction to storm events (Parker 2003). Therefore changes in

HWL shoreline position will also vary depending on what time of year the photographs were taken.

Another discrepancy arises with the use of predicted tidal heights for the elevations of the HWL shorelines. Predicted tides may differ from observed tidal heights by up to 0.3m before they are even termed a surge (Abbott 2004). In addition to the errors present in the example above, even slight variations in HWL elevation (0.3m) would produce significant horizontal HWL position deviations (13.6m). Therefore the total error potential in horizontal HWL position at Hayle could be as much as 140.2m.

7.2 RTK GPS / Bathymetry (2004) and LIDAR (2003) Survey Inter-comparison

The assumed horizontal position of the 1998 profile N11 (see Figure 6.6), conducted by Halcrow Maritime (1999), is an approximation of the details provided in Figure 4.15. The apparent mean vertical offset of -1.66m between the LIDAR (2003) and 1998 profile suggests possible discrepancies with regard to the datum of each data set.

It is possible that the 2.84m offset applied to the whole LIDAR survey data set (see Section 1.5.1.2) was an overestimation, however, by observing dune crest (zero point of origin) elevations for profiles B, C and D (Figures 6.8, 6.9 and 6.10 respectively), very little differences between the LIDAR and RTK GPS surveys exist. This suggests that the vertical offset value of 2.84m applied to the LIDAR data may not be far off the mark. It is recommended further statistical analysis between the original LIDAR data and RTK GPS survey data to determine a closer approximation to the true elevations.

7.2.1 Dune Erosion

Erosion of the dune face between 1998 and 2003 may well be the result of regular pedestrian foot traffic and strong winds causing a dune blow-out. Due to possible restrictions on public access, allowing vegetation growth and dune regeneration, subsequent dune face accretion has taken place between 2003 and 2004. Investigation of wind records over this period may confirm this view.

Reasons discussed above may well be a factor in dune face accretion occurring across profiles C and D between 2003 and 2004. Present dune erosion at profile B is consistent with observations by Halcrow Maritime (1999) where dunes further east of the estuary are accumulating sand, and general deterioration of dunes directly adjacent to the estuary channel (Profile B), is believed to be due to damage caused by public access. Figures 6.11 and 6.12 support this observation with dune erosion contained to mainly to the southern end of the Towans dune system.

7.2.2 Beach Level Changes

Spatial variation in beach volume change is found to closely track shoreline change (Sallenger *et al* 2002), indicating that the beaches maintain their general form during redistribution of sand. Between 2003 and 2004 a general increase in beach levels was observed, with the area about profile D experiencing the greatest amount of accretion. This could be explained by changes in the seasonal beach profiles since the LIDAR survey was flown at the end of winter and the RTK GPS survey was conducted at the end of summer. During winter, energetic swell events result in rapid erosion and subsequent accretion of the berm being the primary subaerial beach response (Dail *et al* 2000).

The seasonal change in wave heights, and hence wave energy, that occurs on the North Cornish coast (refer Figure 2.4) would correspond to a significant cross-shore movement of sand and reshaping of the beach face during large swell events (winter). Subsequent beach recovery would occur when weak to moderate wave conditions (summer) would favour onshore sediment transport (Dail *et al* 2000).

The observed accretion just south of profile A (Figure 6.12) supports Halcrow Maritime's (1999) and Penwith District Council's (2002) observations where sediment transport mechanisms are resulting in more sand entering the estuary than leaving it. It is likely that sand transported into the estuary during the flood tide (refer Section 2.4.1) is retained in the estuary, as falling water levels during the ebb tide leave newly formed sand banks exposed, resulting in the gradual accumulation of sand within the estuary.

Penwith District Council (2002) believes this process is a direct consequence of bathymetric changes occurring at Hayle Beach. To confirm this, further long term monitoring of beach levels need to be conducted as seasonal patterns in the results are likely to be producing masking effects over the longer term beach changes which are believed to be occurring.

Wave directions in St Ives Bay occur predominantly from the northwest (refer Figure 2.6) causing net movement of sediment by littoral drift mechanisms in a predominantly west to east direction (Penwith District Council 2002). Longshore drift deflection, created by Hayle River, has subsequently resulted in the growth of the spit extending across the estuary mouth. The consequent lack of sand supply to the east of Hayle Beach down-drift of the spit, has enabled erosion by localised tidal currents transporting suspended sediment from Hayle beach and into the estuary.

7.2.3 Limitations of LIDAR and RTK GPS Survey Inter-comparison

Sediment budgets can be derived through pair wise comparison of DEMs, producing maps of difference to visualise and quantify the pattern of beach change (Brasington 2003). However, errors inherent to volumetric based analysis are related to survey and DEM data quality. Therefore accurate detection of shoreline change is dependent on consistent and precise measurement techniques so that apparent changes in the shoreline are not merely manifestations of inconsistencies in the measurement technique (Parker 2003).

7.2.3.1 Survey Technique

The results of the LIDAR and RTK GPS data comparison make it clear errors are present. Initially, errors can stem from the accuracy of the measurement technique. Brasington (2003) revealed that elevation change detection is 6 – 7 times more precise with RTK GPS rather than LIDAR surveying method.

The apparent erosion occurring along the length of the deepwater channel in Figures 6.11 and 6.12 mainly occurs where the bathymetric survey was conducted. It is quite possible that this observation is a result of the LIDAR survey technique not used lasers designed for water penetration. Also, LIDAR system performance degrades rapidly with heavy surf action due to white water foam and suspended sediment in the water column (Leatherman 2003).

7.2.3.2 Sources of DEM Error

Systematic errors, including minor differences in the datums between two surveys, are always a problem in survey inter-comparison. This can be minimised by employing the same sample datum control and WGS 84 transformation parameters. It is unclear as to what transformation parameters were applied to the LIDAR data before use in this study.

Fundamental differences in the mode of data acquisition may also give rise to similar effects (Brasington 2003). Measurement intervals in LIDAR are very dense and regular compared to a personal RTK GPS survey. Gaps in terrain measurement would affect grid spacing and ultimately lead to errors in surface interpolation. Buonaiuto (2003) also revealed that if bathymetric change is poorly resolved by larger grid spacing, large scatter and a decrease in accuracy of determined slopes and depths result. However in attempting to minimise this effect with RTK GPS, a compromise must occur between spatial resolution and survey duration.

Figure 6.7 (profile A) is a good example of the errors associated with survey data inter-comparison. The large difference in elevation at the profile origin (5.9m) occurred due to a lack of heights surveyed by RTK GPS above the beach, consequently, surface interpolation of existing survey points results in inaccurate portrayal of the true elevations at the edge of the survey area. The same effect is observed at the end of the profile.

The 5m horizontal displacement of the Hayle Estuary training wall that intersects profile A, suggests an error in the horizontal positioning of the LIDAR survey data. A study of the accuracy between LIDAR and RTK GPS beach surveys conducted by Sallenger *et al* (2003), involving multiple surveys carried on a given day, revealed the largest source of error was attributed to drift in the DGPS system used during the LIDAR survey. This could explain some of the discrepancies observed in this study.

Volumetric sediment budget analyses are doubly sensitive to DEM quality as it is inherently incorporates errors in both surface models. This is evident in Figures 6.11 and 6.12 where permanent artificial features exhibiting unrealistic elevation changes in the space of 16 months. A study on LIDAR and RTK GPS survey data inter-comparison by Brasington (2003) concluded DEM quality lies well below the level required to accurately quantify channel dynamics and sediment budgets.

7.3 Impact of Dredging

Dredging within the Hayle Estuary is necessary in order to maintain a safe navigable channel for vessels which frequently use the harbour. The presence of accretion within the estuary as shown in Figure 6.12 is persisting even though dredging of the channel is still occurring, indicating that a losing battle is being fought with higher volumes of accretion taking place than artificial sediment removal.

Due to a lack of reliable dredging data made available, and inaccuracies present in the results, it is difficult to make quantitative judgments on the amount of sediment artificially removed from the coastal cell system. However, modelling studies of impact of dredging on the shoreline by Hobbs (2002) predicted dredging will have extremely small impact on ambient tidal currents and potential storm surges.

Patterns of dune retreat, beach erosion and accretion of sand in Hayle Estuary mouth have been observed well before dredging operations commenced at Hayle, with considerable fluctuations in depths of the entrance channel observed since 1848 (Halcrow Maritime 1999). The sluicing operation at Hayle was an effective method of clearing the channel of sediment. Since it has ceased, and without artificial sand removal, it is believed continued loss of sand at Hayle Towans and infilling of the estuary will persist if natural processes are allowed to continue. Sea level rise is considered as the underlying cause of pervasive worldwide beach erosion with global warming exacerbating the existing problem by accelerating erosion rates (Leatherman 2003). With this in mind, existing coastal processes observed at Hayle may well be signs of long term (decadal or larger) changes and will continue as long as natural coastal processes persist.

Chapter 8

8 Conclusion

This study attempts to fill a niche in assessing beach change at the Hayle Estuary mouth and the impact of local dredging operations. Historical shoreline data was derived from archived aerial photographs spanning from 1946 to 1996. In addition, combined RTK GPS / bathymetric survey data from July 2004 was also compared to LIDAR survey data flown in March 2003.

Aerial photograph shoreline analysis at Hayle Beach has revealed dramatic changes in beach morphology since 1946. Gradual retreat of the Towans dune system between 1946 and 1988 has accompanied significant amounts of sand deposition at the estuary entrance, coincident with the termination of the sluicing operation in 1971. Dredging operations commenced from 1973 in an attempt to clear the subsequent sand deposits. More recently (1988 – 1996), little change in dune positions has accompanied a reduction in beach levels.

LIDAR and RTK GPS survey data comparison revealed very recent (2003 – 2004) dune accretion events at Towans possibly attributed to a decrease in wave run up during the summer. Dune deterioration towards the channel entrance and observed exposure of rocks on the beach indicates the occurrence of shoreline retreat. Sand accretion to the east of the estuary entrance is continuing, despite the ongoing dredging activities. This suggests, further narrowing of the navigation channel will occur if the present natural coastal processes persist. It is unclear whether dredging operations are contributing to the observed erosion and accretion patterns at Hayle. Therefore further analyses involving historical wave data, dredging data, and beach surveys are recommended.

Accuracy and precision errors in the survey technique, and subsequent DEM creation, significantly impacted on the quality of shoreline and beach change assessment. Seasonal variations in beach levels also may have produced masking effects over the longer term beach changes occurring. Therefore further detailed accuracy analysis is recommended of remote survey DEM measurements against a comparable high resolution topographic data set based on an RTK GPS survey conducted during similar times of year.

9 Appendices

Appendix 1: Levelling data for the tide gauge used for the hydrographic survey on 28th July 2004.

Station	Back sight	Foresight	Station height
	0.482		
1 (BM 9.85mOD)	0.929	2.247	
2	1.263	1.75	
3	0.174	2.218	
4 (Tide Gauge)	1.602	2.024	
		1.785	
	4.45	10.024	-5.574
	1.888		
1 (Tide Gauge)	2.282	0.107	
2	2.278	0.529	
3 (BM 9.85mOD)		0.245	
	6.448	0.881	5.567
difference	**Ht tide gauge below BM 9.85OD**		
-0.007	5.570m		
Therefore all tide values 9.85m - 5.570m			

Appendix 2: Table of bathymetric survey data manually extracted from the HYDROpro NavEdit software.

Easting (m)	Northing (m)	Measured Depth (m)	Reduced depth (m) CD	Height above Chart Datum (m)	Height relative to OD Newlyn (-3.14m)
155283.14	37861.49	2.64	-1.84	1.84	-1.3
155130.52	37892.06	4.16	-0.4	0.4	-2.74
155075.42	37923.03	2.95	-1.62	1.62	-1.52
155055.91	37935.95	3.56	-1.03	1.03	-2.11
155019.57	37963.88	3.52	-1.09	1.09	-2.05
155368.82	37846.25	2.53	-1.93	1.93	-1.21
155328.63	37861.24	2.08	-2.38	2.38	-0.76
155310.38	37865.79	2.74	-1.73	1.73	-1.41
155285.86	37863.21	2.64	-1.84	1.84	-1.3
155007.48	37976.32	3.3	-1.33	1.33	-1.81
155000.08	37979.6	3.63	-1	1	-2.14
154982.72	37989.96	5.21	0.58	-0.58	-3.72
154964.83	38001.31	3.04	-1.59	1.59	-1.55
154947.89	38009.81	3.58	-1.05	1.05	-2.09
154928.95	38028.17	2.99	-1.65	1.65	-1.49
154923.59	38036.56	3.06	-1.6	1.6	-1.54
154913.29	38061.68	3.37	-1.3	1.3	-1.84
154894.78	38096.35	2.86	-1.83	1.83	-1.31
154886.97	38124.17	3.68	-1.01	1.01	-2.13
154968.42	38195.89	3.6	-1.11	1.11	-2.03
154857.41	38257.14	3.77	-0.95	0.95	-2.19
154854.22	38316.83	3.2	-1.54	1.54	-1.6
154852.7	38335.47	3.1	-1.64	1.64	-1.5
154854.85	38381.51	2.93	-1.81	1.81	-1.33
154859.06	38446.82	2.81	-1.94	1.94	-1.2
154863.32	38494.74	2.74	-2.02	2.02	-1.12
154903.37	38447.72	3.56	-1.24	1.24	-1.9
154907.23	38486.65	3.46	-1.41	1.41	-1.73
154907.38	38538.32	3.53	-1.41	1.41	-1.73
154912.23	38546.91	3.53	-1.42	1.42	-1.72

154840.38	38624	3.3	-1.67	1.67	-1.47
154873.33	38629.11	3.67	-1.32	1.32	-1.82
154846.56	38674.32	3.62	-1.4	1.4	-1.74
154850.29	38735.69	3.88	-1.15	1.15	-1.99
154839.78	38765.01	3.93	-1.14	1.14	-2
154813.19	38845.56	2.83	-2.28	2.28	-0.86
154864.74	38815.28	4.02	-1.09	1.09	-2.05
154873.3	38831.28	4.07	-1.06	1.06	-2.08
154914.66	38826.79	3.95	-1.2	1.2	-1.94
154930.92	38837.84	4.01	-1.15	1.15	-1.99
154937.35	38863.41	4.19	-0.98	0.98	-2.16
154947.12	38900.1	4.14	-1.04	1.04	-2.1
154961.24	38928.91	4.26	-0.93	0.93	-2.21
154943.43	38968.01	4.38	-0.81	0.81	-2.33

Appendix 3: Table of profile data prepared during the aerial photograph analysis.

	1988 (Neaps)			1996 (Springs)		1979 (Neaps)		1946 (Springs)	
Point Description	**Distance along profile (m)**	**Height relative to OD Newlyn (m)**	**Chart Datum (m)**	**Distance along profile (m)**	**Height relative to OD Newlyn (m)**	**Distance along profile (m)**	**Height relative to OD Newlyn (m)**	**Distance along profile (m)**	**Height relative to OD Newlyn (m)**
height at starting point (Lidar)	0	9.44	12.58	0	9.44	0	9.44	0	9.44
HWM	31.7	1.71	4.85	6.48	2.57	11.1	1.83	14.5	3.31
1st water mark	75.24	-1.02	2.12	6.8	2.47				
2nd water mark	164.4	-1.02	2.12	167.48	2.47				
1st weir edge (RTK)	175.64	5.94	9.08	175.64	5.94				
2nd weir edge (RTK)	191.12	5.21	8.35	191.12	5.21				
3rd water mark	200.75	-1.02	2.12	190.15	2.47				
4th water mark	247.24	-1.02	2.12	245.14	2.47				
HWM	256.7	1.71	4.85	248.7	2.57	236.6	1.83	258	3.31
height at end point (Lidar)	271.5	7.9	11.04	271.6	7.9	271.6	7.9	271.6	7.9
height at starting point (RTK)	0	16.09		0	16.09	0	16.09	0	16.09
(1979/1946 - top of dune position (assumed same height as initial dune position))	-	-	-	-	-	33	16	45.1	16
HWM	111.91	1.71		89.6	2.57	57.2	1.83	57.6	3.31
1st water mark	123.68	-1.02		93.1	2.47				
2nd water mark	178.37	-1.02		201.5	2.47				
HWM	190.3	1.71		205.9	2.57	200.1	1.83	205.6	3.31
end pt (Lidar)	226.96	11.97		226.96	11.97	226.96	11.97	226.96	11.97
height at starting point(rtk)	0	19.65		0	19.65	0	19.65	0	19.65

height at starting point (at equivalent top of dune position)	8.75	19.65		8.75	19.65				
(1979/1946 - top of dune position)						22.4	19.65	77.8	19.65
HWM	152.71	1.71		69.7	2.57	74.7	1.83	130.7	3.31
1st water mark	192.54	-1.02		73.66	2.47				
2nd water mark	250.5	-1.02		283.5	2.47				
HWM	264.7	1.71		287.8	2.57	262.8	1.83	274.2	3.31
end pt (lidar)	291.2	9.06		291.2	9.06	291.2	9.06	291.2	9.06
height at starting point	0	20.43		0	20.43	0	20.43	0	20.43
(1979 - top of dune position)						22.5	20.4	65.6	20.4
HWM	151.26	1.71		46.5	2.57	134.1	1.83	126.1	3.31
1st water mark	254.61	-1.02		51.02	2.47				
2nd water mark	336.1	-1.02		462.8	2.47				
HWM	442.5	1.71		468.2	2.57	699	1.83	549.3	3.31

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