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Porlock Bay:
Geomorphological investigation and monitoring

Gravel barrier breaching and tidal lagoon development

R&D Technical Report W5B-021/TR

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Authors: **M.J. Bray and W. Duane**
RACER
Department of Geography
University of Portsmouth

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© Environment Agency, Rio House, Waterside Drive, Aztec West, Almondsbury, Bristol BS32 4UD, Tel: 01454 624400, Fax: 01454 624409, www.environment-agency.gov.uk

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Research Contractor:
RACER, Department of Geography, University of Portsmouth, HAMPSHIRE, PO1 3HE

Agency Project Manager:	**Local Agency Manager:**	**Technical/Admin support:**
Jane Rawson	Nick Stevens	Sue Ford
Environment Agency	Environment Agency	Environment Agency
(Anglian Region)	North Wessex Area Office	North Wessex Area Office
Kingfisher House	Rivers House	Rivers House
Goldhay Way	East Quay	East Quay
Orton Goldhay	BRIDGWATER	BRIDGWATER
Peterborough	TA6 4YS	TA6 4YS
PE2 5ZR		

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EXECUTIVE SUMMARY

The gravel barrier protecting Porlock Bay has been managed since at least the mid-nineteenth Century to reduce the occurrence of tidal flooding of grazing land behind. In the early 1990s this approach was discontinued and a policy of non-intervention was introduced. A severe storm on 28th and 29th of October 1996 resulted in overwashing of a section of the barrier and subsequent formation of a permanent breach channel and a new intertidal lagoon. Due to the variety and scale of subsequent changes that occurred, it became important for the Environment Agency (EA) to extend their monitoring programme and develop an understanding of the evolving geomorphology of the site.

This report explains the research and monitoring of physical processes and landform changes that led to, and followed, the 1996 barrier breaching. It includes the results of detailed field measurements and aerial photography undertaken between January 1999 and January 2001, together with some further observations extending to July 2001. Furthermore, it compares the results achieved with historical data sets extending back to 1888 so as to place the changes recorded into a longer-term context. The report scope covers the morphological changes occurring on the barrier beach, at the evolving breach channel and also the water levels and accretion rates occurring within the lagoon. Results are applied in terms of their implications for coastal defence, habitat conservation and further research. The work is also of wider significance because barrier breaching could increase significantly given a more widespread adoption of non-intervention shoreline management policies around the British coast.

The major changes that have occurred are identified as follows:

1) A barrier subject to overwashing, landward migration, breaching and tidal lagoon development has been the natural condition within Porlock Bay throughout the past 4,000 years.
2) Historical management attempted to maintain a continuous and static barrier by raising and steepening its crest.
3) Following relaxation of management in the early 1990s, a 700m length of the artificial barrier westward of New Works has been reworked back to a natural lower, but wider form and now occupies a position some 20-50m further landward. The natural form is more variable in profile than its managed predecessor, but has retained its wave dissipation capacity by migrating landward to lengthen its dissipative profile
4) During reworking, a breach occurred in the barrier in October 1996. Co-incident factors of gravel depletion, the artificially steepened profile and a storm surge, high spring tide and wave event resulted in major overwashing and landward migration of the barrier. Some 100m west of New Works, it transgressed over a ditch that became exploited by tidal exchange leading rapidly to erosion of a permanent channel in the clay substratum that cannot be sealed naturally by drift.
5) The back barrier lowlands have formed an intertidal lagoon and a strongly accreting and expanding saltmarsh. Rapid headward erosion of the breach channel recently intercepted the main artificial drainage channel so that the lagoon now almost completely empties to 2.0m O.D. at low water, whereas between Oct-96 and Dec-00 it retained water to a level of around 3.8m O.D.
6) The breach introduced a new drift boundary and a local drift reversal. Gravels drift into the channel from the west and the east, creating spits and are flushed seaward to

accumulate in a small ebb tidal delta. The western spit is accreting and extending into the breach channel whereas eastern spit is retreating away from the breach so that the inlet at the breach is slowly migrating eastward.

7) Five partially dependent barrier "cells" including two spits flanking the breach channel have formed. Two cells are decreasing in volume, one is increasing and two are stable. Gravel losses occur from the barrier to the growing ebb tidal delta and also due to erosion of fine sediments from the core as the artificial barrier segments are re-worked back to a natural form. The trend since 1988 has been for slow loss of barrier volume. Landward recession and formation of spits flanking the breach have lengthened the barrier by up to 6%. The diminished materials available are therefore being spread more thinly along the barrier and this could drive continued landward barrier recession in the future.

The changes documented have significantly increased the complexity and dynamism of the geomorphic shoreline system. Changes occur more frequently and there is potential for those occurring in one part of the barrier to have impacts in neighbouring parts. On balance, the changes appear favourable for earth science conservation and habitats as important new landforms and accreting saltmarsh have been created. Although barrier integrity and effective wave dissipation has been maintained since the breach, four potentially vulnerable locations are identified (Section 5.1) and it is important that the changes occurring should continue to be monitored and understood.

It is difficult to determine the extent to which the coastal landforms have adjusted to the cessation of active management and the occurrence of the breach due to the limited time elapsed and the short record of detailed monitoring so far compiled. Major abrupt adjustments such as enlargement of the breach channel and transition from the artificial to a natural barrier form are completed, or substantially in progress, but ongoing changes should continue for the foreseeable future, albeit at reduced rates. The dynamic nature of the landforms involved and the variations likely in sea-level and storm activity due to probable future climate change mean that full adjustment and static stability are unlikely to be achieved. Instead, the continuation of adjustments should be anticipated and accommodated for within the future management of the bay.

Based on the results achieved to date the following recommendations are made:

1) The complexity of the new shoreline system, its continued dynamism and the dependence of important habitats upon its control mean that there is a need to continue the monitoring programme and maintain an understanding of changes into the future. The programme should be flexible and responsive to future landform changes as outlined in the recommendations made in Section 7. Such a programme should enable informed decisions to be made concerning future options for coastal defence, habitats and amenity management.
2) Future management of the site should anticipate and accommodate the likely future adjustments of the landforms. These include continued barrier recession, extension of barrier re-working towards the War Memorial and exposure of lagoon margins to slowly increased inundation due to sea-level rise and storm surges. The net effect is likely to be a pressure for landward migration of landforms and habitats that could lead to "squeeze" at the landward boundary. To maintain the extent and quality of habitats, it may in future be necessary to consider the options for a limited set-back of field boundaries and/or some forms of limited active intervention.

3) Generic aspects of the research methods adopted and the understanding gained should be transferable to other exposed British shorelines experiencing, or at risk of breaching. This is especially important because permanent barrier breaches of the type studied are relatively rare on the British coast and have not previously been monitored directly during their early stages of development. In particular, a holistic approach is required to address the diversity of landforms, their complex morphologies and the range of timescales over which they evolve. Application of GPS surveying and GIS analytic techniques in combination with construction of qualitative models offer effective means of addressing these problems as explained in Section 6. In applying the results elsewhere, appropriate allowances should be made for differing conditions of wave climate, storm surge exposure, tidal range, barrier sedimentology, sediment supply and backshore topography.

KEYWORDS: Porlock, geomorphology, gravel, shingle, barrier, breach, lagoon, monitoring, profile

1. INTRODUCTION

Porlock Bay, West Somerset is occupied by a coarse gravel barrier beach extending for some 5km between the Gore Point and Hurlstone Point headlands (Figures 1 and 2). Historically, the barrier has afforded protection to Porlock Weir village and harbour as well as Porlock Marsh an area of low-lying land susceptible to saline and freshwater flooding. Although Horner Water is the only major stream entering Porlock Bay, its small but elevated and steeply sloping catchment is effective in delivering quantities of freshwater to the back barrier marsh. Since at least the mid 1800s, a sluice at New Works has regulated the water levels within a small predominantly freshwater lagoon. Collectively, the marsh environments comprised a diverse and valuable range of habitat types recognised with biological SSSI status in 1990. Historically, the barrier has been susceptible to overwashing and breaching and for many years its stability was maintained by the active management of the Environment Agency (EA) and its predecessors, involving replenishment and scraping to maintain a continuous, high berm crest (Figure 3).

A severe storm on 28-29th October 1996 resulted in overwashing of a section of the barrier, tidal flooding of the marshland and thereafter the formation of a permanent breach channel and intertidal lagoon by the tidal discharge and subsequent exchange (Figures 4, 5 and 6). Rapid erosion of the clay substratum has significantly enlarged the breach such that it is unlikely to seal naturally. Furthermore, the breach is unlikely to be repaired for specific coastal defence purposes as the EA presently pursues a policy of non-intervention so that the barrier and marsh should develop naturally. The landowner has expressed a desire to seal the breach and attempted unsuccessfully to do so in 1997 (Figure 5).

The site has been studied previously within the following:

i.) Engineering reports focusing upon its coastal defence requirements (Halcrow, 1985 and Posford Duvivier, 1992);

ii.) Ecological studies (Jarman, 1986) and;

iii.) Geomorphological studies focusing upon its late Holocene and contemporary behaviour prior to (Carter and Orford 1993; Jennings *et al.* 1998 and Orford and Jennings, 1998) and following the 1996 breach (Pethick, 1998).

The present report examines the geomorphological behaviour of the barrier over the past 112 years and focuses especially on the changes that have occurred following the 1996 breach. It should be noted that permanent barrier breaches of the type studied here are relatively rare on the exposed British coast and have not previously been monitored directly during their early stages of development. Their occurrence could, however, increase significantly should there in future be a more widespread adoption of non-intervention shoreline management policies.

1.1 Study Aims:

1. To identify and quantify the nature and scale of the changes occurring and to define the key processes involved.
2. To provide valuable baseline data and understanding that should inform future management of the site and contribute towards further programmes of generic research concerning the behaviour and development of barrier breaching at exposed sites.

1.2 Geomorphology of the Site

The following sections introduce the key processes operating and landforms developing. An annotated aerial photograph (Figure 7) and series of illustrations (Figures 8 to 21) accompany this material to identify and explain the key geomorphological features and processes that are the focus of this study. This section is considered an important introduction due to the uniqueness, complexity and dynamic nature of the site.

1.2.1 Processes Operating at Porlock Bay

1) **Hydrodynamic processes:** wave dissipation occurs over a low gradient boulder foreshore (low and mid tide), but reflection occurs as waves strike the steep seaward face of the barrier at mid to high tide. Direct breaking and reflection from the barrier occur at most tidal states in the eastern part of the Bay where the boulder frame is absent. There is a significant tidal exchange at the breach generating strong currents and maintaining a tidal channel. A unique tidal regime has developed within the lagoon controlled by the interaction between: (i) the level of the seaward edge of the clay substratum which forms a lip to the basin within which the lagoon is retained and (ii) the open coast tidal regime. The result is that lagoon levels respond to coastal tides only at high water when levels exceed the clay lip. Otherwise, they are characterised by slow decline as water drains over the lip. Freshwater flows may contribute significantly at low water when much saline water has been removed, especially following heavy rainfall events.
2) **Barrier processes:** The barrier evolves naturally by berm formation during calm conditions, overtopping in modest storms and overwashing in severe storms (Figures 8 and 9). The latter process results in landward migration or “rollover” causing cliffing and erosion of relict gravel and other sedimentary deposits that become transgressed. Active rollover is indicated by the presence of washover fans comprising gravels that have been driven landward from the crest (Figures 6 and 7). Seepage through the barrier may also occur during storm surges causing formation of characteristic “cans” on the landward face (Figure 10) The pace of migration may depend on the backshore elevation and gradient, the beach volume and the availability of a sediment supply. The degree of oceanographic forcing is also important, especially the wave and storm surge exposure and the rate of sea-level rise. Occasionally, the barrier becomes flattened sufficiently for breaching to occur, as was the case in October 1996. Where breaches are maintained, drift aligned gravel spits tend to grow landward from the barrier along the margins of the breach channel (Figure 6). Fossil recurved spits of this type can be identified landward of the present day barrier indicating the occurrence of past episodes of breaching (Figure 7). The Porlock barrier is unusual in not being managed actively, thus affording rare opportunities to observe the full range of behaviour associated with a depleted, receding barrier.
3) **Beach Drift:** observations of sediment accumulations against groynes and other structures indicate that net beach drift of gravels and cobbles is consistently from west to east (Figure 7). The rate of drift is believed to be slow due to: (i) partial swash alignment of the barrier where dominant waves approach with their crests approximately parallel to the barrier crest orientation, (ii) a shortage of new material entering the system at Gore Point and (iii) groyne systems that partly intercept drift.
4) **Breach channel processes:** The tidal prism of the lagoon (defined as the volume of water exchanged at the inlet over a tidal cycle) generates ebb currents sufficient to flush

seaward all gravel drifting into the breach channel. This prevents natural sealing and maintains a permanent breach. The breach channel itself is enlarging and extending by processes of downcutting, cliffing and headward recession within a clay substratum of Holocene lagoon deposits.

5) **Lagoon and marsh:** are characterised by a sudden increase in marine sedimentation, erosion around the breach due to wave penetration, reactivation of tidal channels (Figure 5) and changes from freshwater to salt tolerant vegetation.

1.2.2 Historical Behaviour of Key Landforms:

1) **Coarse gravel barrier:** The barrier is believed to have existed in some form since at least 8,000 years BP. It probably originated from marine reworking of the durable clastic components of extensive spreads of solifluction deposits, concentrated in ancient valleys and lowlands flanking the coastal hills, as they were transgressed by rising sea-levels. Low eroding cliffs at Porlockford expose a remnant of these materials (Figure 11 and 12) Subsequent evolution would have occurred by drifting of the shoreline gravels within and between bays defined by headlands. With rising sea-levels headlands would have become increasingly defined and lowlands such as Porlock would have formed bays occupied by barrier beaches. Knowledge of the late Holocene (past 8,000 years) behaviour of the Porlock Barrier has been inferred from analyses of sediments (and associated flora and fauna remains) which accumulated in the shelter afforded behind the barrier (*e.g.* Jennings *et al.* 1998). Studies reveal a history of transitions between freshwater and saline conditions indicative of a barrier that was periodically breached and resealed as it migrated landward. Actual behaviour appears to have depended upon a delicate interplay between sea-level rise, sediment supply, the frequency of extreme events and the elevation of the backshore over which the barrier migration occurred. Saline conditions predominate within the back-barrier stratigraphic record suggesting frequent breaching and/or maintenance of tidal inlets through the barrier for extended periods.

   Nineteenth and twentieth-century attempts to maintain a continuous barrier through management therefore do not conform to the natural long term behaviour of this landform. In terms of contemporary behaviour, western (Porlockford) and New Works parts of the barrier exhibit periodic flattening and landward movement during major storms with intervals of partial rebuilding by lower energy events. By contrast, some central parts retain much of their artificially steepened morphology (Figures 13 and 14). Following 1996 the barrier has effectively been divided into two major units by the breach channel, although Orford and Jennings (1998) identified three “sub-cells” prior to the breach. The parts eastwards of Horner Water appear to be accreting and exhibit elevated crest levels (Figure 7).

2) **Boulder frame: sloping** gently seaward for over 200m to MLW from the toe of the gravel barrier and representing the surface over which the barrier has migrated over the past 7,000-8,000 years BP (Figures 3 and 7). The frame is absent from eastern parts of the bay where barrier migration has been inhibited by cliffs.

3) **Gravel Spits** have grown into the breach, flanking the channel and extending into the tidal lagoon (Figures 15 and 16)

4) **A Breach Channel** cut within the clay substratum and generally swept clear of gravel by strong tidal currents. The channel is extending by headward erosion into the lagoon (Figures 15, 16, 17 and 18).

5) **Low clay cliffs supporting a platform.** These comprise late Holocene freshwater and marine sediments that were deposited behind the gravel barrier (Jennings *et al.*, 1998) and which become exposed and eroded as the barrier migrates landward. Although soft and easily eroded the sediments are sufficiently coherent to form near vertical cliffs up to 2.5m high (Figures 17 and 19). At the landward extension of the breach channel, a waterfall is produced by drainage of lagoon waters when the open coast tidal level falls below the level of the platform (Figures 18 and 20).
6) **The lagoon** has altered from being a freshwater feature to become intertidal and saline. It occupies an existing depression that is likely to become modified by sedimentation of fine materials delivered in suspension by the exchange of tidal waters. Locally it may also suffer some erosion generated by waves penetrating into the lagoon at high tidal levels. Existing relic tidal channels are becoming reactivated within the surface of the lagoon margins where rapid saltmarsh colonisation is also occurring (Figures 5 and 21).
7) **Active cliffs** cut in gravel rich superficial deposits at Porlockford (Figures 11 and 12).

The landform elements are interdependent and interact to form a complex system. The gravel barrier exerts an active control by affording protection to the marsh against erosion and flooding. The extent to which it is overwashed, migrates landward, or is breached controls the development of the marsh. The breach is now exerting control upon the barrier by intercepting gravel transport. Some material enters the channel and is flushed seaward, the remainder drifts landward along the breach channel flanks resulting in growth of recurved spits which themselves may affect the barrier's sensitivity to overwashing - and so on. The site is extremely dynamic and the processes and landforms are subject to change and interaction at geomorphologically rapid rates - this is the key element of the site's value. The physical changes occurring are such that they control the development of the biological communities. These qualities were recognised formally in 1999 when English Nature nominated the site as a geomorphological SSSI.

1.3 Coastal Defence and Management

Management has involved maintenance of the New Works sluice, provision of several generations of groynes (*e.g*. Figure 22), replenishment (mining of fossil recurves behind the barrier) and reprofiling after washover events to maintain a high steep crest. These approaches were discontinued in the early 1990s due to concerns over their long-term sustainability.

Following the breach in 1996, the coastal footpath has been redirected and a research programme has been established to monitor and measure the changes. The program involves research into the following elements:

1. Landforms and physical changes (presented within this document).
2. Vegetation changes
3. Bird usage changes

Porlock is seen increasingly as a valuable test site for studies to gain insights into processes of barrier breaching and intertidal lagoon development on exposed coasts. The occurrence of these types of event are anticipated to increase significantly around the lowland coasts of England should there in future be a more widespread adoption of non-intervention shoreline management policies.

A listing of key events extracted from previous reports (*e.g.* Halcrow, 1985 and Posford Duvivier, 1992) is presented as follows:

Table 1.1 Porlock Bay: key management events

Date	**Event**
1824	First record of groynes and of seepage through the barrier
1909	Backbarrier reclaimed for use as a golf course, subsequently inundated by a storm in 1910.
Pre 1939	Porlock marsh recorded as "exceptionally good grazing land"
1939	Storm damage to New Works and regular tidal inundation of up to 80 acres
Early 1960s	Low barrier crest and frequent overwashing causing flooding
1967-1971	Construction of 20 timber pile groynes (e.g. Figure 22), replenishment with gravels from fossil recurves inland to provide a mean crest height of 8.5m O.D. and a width of 3m.
1970s-1980s	Reprofiling after storms to maintain crest height and width
1980s	Approximately annual washovers or "breaches" causing flooding of 200-300 acres. Gravels were bulldozed back to rebuild the crest on each occasion. High barrier vulnerability immediately east of Porlockford Cliffs.
1981	Severe storm surge on 13 December
1984-1985	"Overtopping" damage recorded to barrier opposite the war memorial
Early 1990s	Active management of the barrier discontinued
1996	Breach on 28-29 October leading to formation of permanent tidal inlet
1999	Monitoring programme initiated

2. METHODS

A programme of measurement and monitoring was devised to record: (i) the morphological changes occurring at the barrier and breach channel, (ii) the water levels occurring in the lagoon and to provide a baseline against which future evolution of the system could be compared. The following methods were applied:

1. Topographic surveys of the barrier and breach channel using Global Positioning System techniques;
2. Compilation of a GIS enabling mapping of recent measured barrier positions alongside historical Ordnance Survey large-scale map data.
3. Measurement of extreme lagoon water levels;
4. Aerial photographs of Porlock Bay centred upon the breach and lagoon.
5. Erosion pin and stake measurements of clay “cliff” recession at the breach.
6. Insertion and monitoring of accretion plates at lagoon margins and within developing saltmarsh.

2.1 Topographic Surveys of the Barrier

2.1.1. Measurement Techniques

A number of factors were considered before deciding on the appropriate surveying technique. In terms of accuracy, it was considered necessary to be able to identify significant changes in both plan and height to within a resolution of 0.1 metres. The site covers a distance of approximately three kilometres. Using standard optical instruments this would then require multiple instrument set-ups to achieve the desired accuracy resulting in a protracted surveying process and requiring several days. It was also required that the technique selected should also allow comparison of its results with historical data by referencing the data to a common co-ordinate system (i.e. the Ordnance Survey National Grid).

Taking the above points into consideration it was decided to use the Differential Global Positioning System method of surveying. This utilises a suite of polar orbiting satellites to locate the position of the instrument on the earth's surface. Achievable measurement accuracies are dependent upon the instrument used, the operating procedure and the satellite geometry, but are generally less than 0.02 metres in plan and 0.04 in height, well within the tolerances considered for this task. It has the advantages of operating independently of weather conditions and time of day, is capable of being operated by a single person and has the ability to generate results to any defined co-ordinate system. The method employs two receivers, one fixed on a known point and the second in a mobile role, traversing the features to be measured (Figure 23).

For the initial survey set up and the first five surveys a dual-frequency Leica GPS 200 system was used. With this system, all results are stored for processing later off site to calculate the co-ordinates of measured points. A potential disadvantage is that bad data caused by poor satellite geometry (too few above the horizon for brief intervals) cannot be detected in the field. As a result, several of the surveys suffered small losses of data (occasional losses of 15 minutes of measurements) which did not adversely affect the surveys as a whole. One full survey was also written off for this reason, although a repeat survey was completed at a later date.

The final December 2000 survey was completed using a dual frequency Spectra Precision Geotracer 3000 series system. Its accuracy is identical to the previous instrument, but it is able is able to process information in real time via a radio link connecting the static and mobile receivers. It provides immediate warning of poor data quality and enables the operator to record their position in real time and relocate, or trace, previously recorded co-ordinates. Thus, profiles can be revisited and surveyed precisely without using marker posts, which is a major advantage at Porlock where the dynamic portions of the barrier offer no secure foundation.

2.1.2. Survey Set Up and Control

All survey co-ordinates are based upon the values purchased from the Ordnance Survey for the following trig pillar:

Station Name:	Culbone Hill
Station Number:	SS72/9
Eastings:	283 776.202 m.
Northings:	146 636.004 m.
Elevation:	434.0 m.

Control was transferred from the trig pillar to a number of stations within the site area using the base station transfer method. These stations are located within Figure 24 and their co-ordinates and descriptions can be found in Appendix 1. Base transfer involved setting the reference GPS instrument at the trig pillar and the rover instrument at a control station by the gatepost along the backshore at Porlock, (Control 01). The post-processing method initially obtained coordinates at the trig point using a single point position fix, (giving an initial accuracy of +/- 10 metres), and then calculated the base line between the two instruments. The reference station coordinates were then adjusted to fit the published coordinates in Ordnance Survey of Great Britain 1936, (OSGB36) and the datum shift parameters were then applied to the rover station coordinates to give a more precise solution.

A new highly precise method to establish and check control has recently become available. The Ordnance Survey has established 30 GPS stations around the United Kingdom which are on known locations and whose data is now made available over the internet, (*www.gps.gov.uk*). These can be used as reference stations without the need to occupy them and allows baselines to be computed to the rover instrument from more than one location. This tightens the geometry and gives a more reliable solution. Furthermore, the coordinates of the OS GPS stations are quoted on the European Terrestrial Reference System 1989, (ETRS89) and are updated on a monthly basis to allow for any possible tectonic movement. Finally, it is understood that the datum shift parameters between the ETRS89 and OSGB 36 are not constant, and therefore the OS operates a coordinate converter with a parameter spatial resolution of 1 km. These methods are recommended for all GPS surveys at new sites.

The accuracies of each GPS survey were determined by calculating the positional errors between established control points and the individual surveys (each control point was measured for this purpose on every survey). Results presented in Table 2.1 suggest that the mean survey errors were generally within 0.1m, which was the target set at the outset.

Table 2.1 Accuracies in metres between established control points and individual surveys.

	Control Points								
	Control 02			Control 03			Control 05		
Date of Survey	East	North	Elev	East	North	Elev	East	North	Elev
Feb 02-03, 1999	Point established			Point established					
April 15, 1999	-0.01	-0.02	-0.07	0.09	0.03	-0.07			
July 27, 1999	0.09	0.58	-0.05	-0.11	0.13	-0.09			
Mar 09-10, 2000				0.09	0.04	-0.04	Point established		
May 03-04, 2000							0.12	-0.01	-0.03
Dec 07-08, 2000	-0.03	0.12	0.01	-0.04	0.02	0.02	-0.04	0.01	0.04
Average Tie	**0.02**	**0.23**	**-0.04**	**0.01**	**0.06**	**-0.04**	**0.04**	**0.00**	**0.01**

2.1.3. Mapping of Features

Several distinct features were defined as being important indicators in the development of the breach and the barrier (Table 2.2). Monitoring was undertaken by conducting repetitive measurements of these features such that making comparisons of successive surveys could identify changes.

Table 2.2 Description of mapped topographic features

Feature	**Definition**	**Significance**
Profile	Topographic section measured approximately normal to the shoreline orientation	Summarises cross shore form, indicates the amount of material contained within the barrier
Barrier Crest	Highest part of barrier or seaward margin of a flattened crest	Defines position of barrier, resistance afforded to overwashing and indicates barrier migration
Backtoe	Landward extent of shingle barrier	Defines landward extent of washover fans and indicates migration
Clay Cliff	Top of near-vertical faces cut in clay substrata	Indicates erosion and lateral recession of clay substrata as it is uncovered by barrier migration and defines margins of the incised breach channel
Front toe	Break where steep barrier beach face rests upon underlying lower gradient platform or outer boulder frame. Not easy to define consistently.	Defines seaward extent of barrier
Knickpoint	Clay cliff top at axis of breach channel over which tidal waters flow at times forming a waterfall	Indicates landward migration of the breach channel
Strand Line	Flotsam line around parts of landward face of barrier	Indicates extreme water-level within lagoon

Twenty one profiles were located along a stretch of the barrier centred approximately on the breach to determine any changes occurring in the cross-section profile of the beach (Figure 26). The profile spacing was determined as a trade off between the desire for as detailed a survey as possible and the practical requirement that all profiles and features should be surveyed on each visit (Table 2.3). To facilitate comparisons, profiles were located wherever possible at the same positions as those measured during a previous survey in 1988.

Table 2.3 Profile data obtained by survey dates

Date of Survey	Profiles W06	W05	W04	W03	W02	W01	E01	E02	E03	E04	E05	E06	E07	E08	E09	E10	E11	E12	E13	E14	E15
Dec 1988[1]	❼	❼	~	~	~	~	~	~	~	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼
Feb 02-03, 1999[2]	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼		❼	❼	❼
April 15, 1999[2]							❼	❼	❼	❼	❼	❼	❼	❼	❼	❼					
July 27, 1999	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼			❼	❼
Mar 09-10, 2000	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼
May 03-04, 2000	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼
Dec 07-08, 2000	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼	❼

❼ Indicates results obtained for individual profiles

[1] Pre-breach profiles derived from original profiles surveyed by West Country Surveys

[2] Profiles extracted from digital elevation models

~ no analogous profiles on the continuous 1988 barrier

The remaining features listed in Table 2.2 were mapped in planform and relate either directly to the breach or are associated with the long-term development of the beach.

The major feature in the immediate vicinity of the breach consists of a channel cutting through the underlying clay with low cliffs at its margins. As this channel has a major impact on the tidal exchange between the lagoon and the sea, surveys were carried out to map its extent. Associated with the barrier beach are three features that can be used to characterise any change in its overall dimensions. These are the landward and seaward limits of the beach material and the crest, or highest point running along the length of the beach. These planform features were measured as linear attributes using the GPS instruments in kinematic mode (co-ordinates measured automatically at pre-determined intervals as the surveyor traces over the feature with the survey antennae). The dates on which particular features were measured are presented in Table 2.4.

Table 2.4 Plan data obtained by survey dates

Date of Survey	Plan Data Barrier Crest	Backtoe	Front toe	Clay Cliff	Nick point	Strand Line
1888, 1902, 1928 and 1972 *	❼	❼				
Feb 02-03, 1999	❼	❼	❼	❼	❼	
April 15, 1999	❼			❼		
July 27, 1999	❼	❼		❼	❼	
Mar 09-10, 2000	❼	❼	❼	❼	❼	
May 03-04, 2000	❼	❼				❼
Dec 07-08, 2000	❼	❼		❼	❼	❼

❼ Indicates results obtained for plan features

* Data obtained from original mapped data (Ryan, 1999)

2.1.4. Comparison with 1988 Profiles

A series of surveyed profiles dating from 1988 were made available by the EA. These were obtained as a hard copy of the profile plots and a plan of profile locations. Initially, the profile locations needed to be referenced to the same common grid datum in order to compare them with post-breach profiles. This was carried out by overlaying a grid onto the 1988 profile location plan using co-ordinates of surveyed detail points that also appear on the map.

The horizontal accuracy of the grid, obtained by checking surveyed distances against map distances is believed to be +/- 1.5 metres. The profiles given on the location map, however, did not define the end points. These were obtained by using the chainage on each profile of the track (which runs behind the beach barrier and is shown on both the profile plots and the location map), as the reference point from which all the other chainages could be measured. Finally, the 1988 profiles were plotted within the same diagrams as the more recent ones to enable direct comparisons (Appendix 2).

2.1.5 Comparison with Historical Map Data

Historical map data of selected features were obtained in digital form from an MSc Student project (Ryan, 1999). This was derived originally from Ordnance Survey 1:2500 plans (or earlier 25 inch to the mile versions) and covered four dates, 1888, 1902, 1929 and 1972. The features mapped included the mean low and high water marks, the shingle beach backtoe and the barrier crest line (see Table 2.2 for definitions). The latter two features are directly analogous to the features surveyed in the field using GPS in 1999 and 2000. The crest positions of the 1988 measured profiles were also extracted to provide an additional comparative epoch. All features were transferred to a common co-ordinate system (O.S. National Grid). The barrier crest and backtoe were plotted on common maps using the ARCVIEW GIS package to summarise the historical changes occurring over the period 1888 to 2000 (Figures 27 and 28).

The aim of the study by Ryan (1999) was to evaluate the likely errors of the mapped coastal features in order to determine whether the changes evident between the different historical map editions were actually the result of coastal change, or whether they could be explained by discrepancies in the mapping. Errors can arise within the original survey, the map plotting and subsequent extraction of data from maps. Some 60 common static points were identified on each map edition and measured precisely in the field using GPS. The OS mapped points were then compared with their precisely surveyed control counterparts and the relative errors were analysed. Results indicated that the following errors should be applied.

Date of mapping or survey	**Errors (m)**[1]
1888, 1902, 1928 and 1972 (O.S.)	±3.00 to 4.00
1988 profiles	±2.00[2]
1999- 2000 GPS surveys	±0.03

[1] the error was defined by Ryan (1999) as the distance from the plotted feature within which the actual feature was likely to have existed with a 95% probability.

[2] mostly comprises error in conversion to O.S. grid system, whereas survey error is likely to be small.

When undertaking a comparison between any two epochs of mapping it is necessary to add their respective errors so as to define a “truly significant” distance. All differences in plotted pairs of features that exceed the truly significant distance are likely to represent genuine coastal changes with a 95% probability. For example, the truly significant distance for an 1888-1928 comparison would be a maximum of 8m, whereas that for 1988-2000 is only 2.03m due to the higher survey precisions. These distances are small relative to many of the changes recorded at Porlock enabling the historical changes to be established with a high degree of confidence.

2.2 Lagoon Water Level Measurements

Extreme tidal levels occurring within the lagoon were measured using water sensitive tape mounted vertically within specially constructed stand pipes approximately 1.7m in length and 4cm diameter as seen in Figures 29 and 30 (it is a similar arrangement to the "stage recorder" that is commonly used for measuring extreme river flows). The pipe has an opening at the base enabling water to enter freely as the lagoon level rises. The dye within the water sensitive tape is dissolved by direct contact with water providing a permanent record of the maximum water levels attained. The level of base of the standpipe upon which the water sensitive tape rested was measured to Ordnance Datum within the GPS survey.

Three recorders of this type were sited the northeastern lagoon margin (Figure 25). They were located at different levels in close proximity to the level of the mean high water of spring tides (5m O.D.) to ensure that all major variations in extreme level could be recorded without risk of overtopping of all recorders. The base levels of each recorder were measured as follows:

Recorder 1	4.84m O.D.
Recorder 2	5.09m O.D.
Recorder 3	5.94m O.D.

Measurements of extreme levels were taken at two weekly intervals between January 1999 and September 1999. The lengths of water affected tape at each recorder were measured and then added to the relevant base level in order to determine the water level. The recorder was reset with fresh water sensitive tape following each visit. It should be noted that each measurement only comprises the extreme high water level attained since each reset of the tape, it provides no other details of the timing of the level or of any lower levels.

The recorders were destroyed in September 1999, either by deliberate vandalism, or more likely by the arrival of livestock. They were not reinstated due to probability of further losses. Instead, surveying of the levels of strand lines of debris that become located on the landward face of the barrier opposite the war memorial was adopted as a simple alternative method of collecting extreme water level data on subsequent survey occasions. By always making measurements at the same location and clearing strand line debris from a small area it was possible to identify the highest levels achieved between each survey.

2.3 Aerial Photography

Large-scale vertical overlapping stereo colour aerial photography at scales of 1:4,000 (27 photos) and 1:10,000 (6 photos) was flown on a low spring tide at 1200hrs on 01.04.99. The area covered comprised entire bay between Gore Point and Hurlstone Point and extending inland some 1km. Photos were supplied as prints. Examples are presented in Figures 6, 7, 15 and 21.

The photos are intended to provide a baseline monitoring against which future changes may be compared. They were not analysed photogrametrically, although this is identified as a future research option as further photography is acquired. The 1:4,000 scale is considered the optimum for photogrammetric measurement of beaches and is appropriate for identification of vegetation communities. The 1:10,000 photography was also obtained from the same flight.

This gives flexibility in terms of photogrammetric analysis as many fewer models would need to be set up to cover the entire area thus reducing costs.

Additional photography was also acquired for comparative purposes as follows:

1950	10,000 scale black and white (Ordnance Survey)
1999	Digital colour near-infrared (1345 hrs on 4th September by Dr David Livingstone).

Comparisons of the 1950 photography with that of April 1999 indicates the changes in the barrier following the October 1996 breach. The recurved spits and extensive areas of barrier washover are obvious new features. Some features such as the general lagoon area and back barrier tidal creeks are common to the two sets of photography. Suggesting that inundations and episodes of tidal exchange probably also occurred in the past prior to the 1950 photography (Figure 21).

Comparisons of the September 1999 photography with that of April 1999 reveals some modest changes occurring around the breach over this short period (Figures 15 and 16). The Digital colour near-infrared imagery is especially effective for study of vegetation. Algae on the clay platform show up bright red and saltmarsh is darker (Figure 16). Waters around the breach are clearly seen to be turbid due to wave erosion of the clay cliffs.

2.4 Erosion pins and stakes

In order to study more closely the processes involved in the erosion of the breach channel and of its flanking low cliffs cut in the Holocene clay basement, a programme of monitoring of erosion pins and stakes was established. This work was progressed by an MSc student (Cawsey, 2000).

Detailed measurement of the erosion rate of the clay cliffs at the flanks of the breach channel was undertaken by monitoring of erosion pins. These comprised six-inch nails driven in to face of the clay banks of the breach channel. Six monitoring sites were established along the flanks of the breach channel reflecting different wave exposures as located by Figure 25. Each site comprised some 4 to 6 nails in vertical profile extending from the cliff toe to the crest. The lengths of the nails standing clear of the banks where measured on each visit by the surveyor at weekly intervals between March and September 1999. Differences in the lengths exposed from one survey to the next indicated the amount of erosion that had occurred over the intervening period. All measurements at a site were averaged at each survey to remove any bias due to variations in erosion at the cliff toe compared to the crest. It should be noted that the technique was effective in recording the slow erosion associated commonly with abrasion of the clay cliffs, but could not record the losses involved in larger collapses of the cliff where the pins themselves would be removed (Figure 31). It should be noted that the outer parts of the breach channel cliffs were exposed directly to breaking waves (Figure 31).

To measure the headward recession of the waterfall that marked the axis of the breach channel seven 0.5m length marker stakes were driven into the clay platform surface several metres landward of the cliff crest. Erosion pins could not be used here as recession and cliff collapse occurred too rapidly. The stakes where arranged in a half circle around the head of the waterfall (Figure 25). The distance from the stake to the crest of the waterfall was measured at two weekly intervals.

2.5 Accretion Plates

A total of twelve accretion plates were installed in May 2000 along the lagoon margins in order to measure the rates of sedimentation occurring as the lagoon and its saltmarsh vegetation develop (Figure 33). Three plates were inserted in short crosshore profiles at four distinct locations given in Figure 25. Profiles E1 and E2 are located on the northern lagoon margin and provide coverage of open mud and vegetation covered substrates (Figure 34). Profiles W1 and W2 are located within developing saltmarsh to the west of the barrier.

Each plate comprises a 0.2m square of wire mesh buried carefully at up to 100mm depth by cutting and replacing the marsh turf to minimise disturbance (Figure 33). The site is relocated using a metal detector to pin point the wire mesh. To measure accretion, a steel rule is pressed into the marsh surface until it encounters the wire mesh. Over time a picture can be developed of the changing level of the surface with respect to the mesh plate. It is assumed that the plate should remain static while the ground surface will rise or reduce by accretion or erosion. A mesh rather than a solid plate was preferred, as it should be permeable to plant root systems and rapidly become incorporated within the substratum.

The plates were revisited on 2nd of June 2000 and an initial measurement was made from the surface down to each plate. This measurement was adopted as the starting point for subsequent measurement of accretion as it allowed one month for any settling of the accretion plate to occur. The plates were re-measured on 7th December 2000 and further measurements are anticipated at quarterly or six monthly intervals.

Extraction of the turf's to insert the marker plates revealed the presence of a variable surface layer of sticky clay up to 0.04m thick above a relic vegetation surface comprising a mat of root systems (Figures 35 and 36). The interface between these layers was abrupt and clearly defined suggesting that it allows differentiation of the marine sedimentation that has occurred on top of the former vegetation/soil surface of the land surface that existed prior to the October 1996 breach. Cundy *et al.*, (in press) report the existence a similar buried soil associated with the 1910 breaching of Pagham Harbour, West Sussex. If this interpretation is correct, then it should provide a very effective indicator of general accretion that has occurred since the breach. Initial results suggest that total accretion has been significantly more rapid along the vegetated lagoon margins around mean high water than on the muddy non-vegetated lagoon bed at lower elevations (Figure 36).

3. RESULTS: TOPOGRAPHIC SURVEYS

3.1 Planform Changes (1888-2000)

The general historical changes occurring in the barrier crest, high water mark and overwash margin (“backtoe”) between Porlock Harbour and Hurlstone Point have been extracted from the work of Ryan (1999) and other sources as explained in Section 2.1. These historical barrier crest and backtoe positions are then superimposed upon the recent surveyed barrier positions within Figures 27 and 28 that focus on the central area around the breach and New Works. Detailed changes occurring within the breach channel between 1999 and 2000 are presented in Figure 37.

3.1.1 Porlock Bay 1888-1972 (based upon Ryan 1999)

Between 1888 and 1972 the Mean High Water and beach ridge crest have receded landward by 20-40m along the frontage between Porlockford and the National Trust boundary near Profile E15. An exception is a small segment extending up to 100m to the west and 200m to the east of New Works where the sluice constructions and several generations of closely spaced groynes appear to have promoted accretion involving seaward mean high water extension by up to 15m between 1928 and 1972. Over this same period, the beach between Horner Water and Hurlstone Point has accreted and extended seaward by up to 20m. It is considered likely that drift from west to east has transferred material from western and central parts of the bay to accumulate against the Hurlstone Point headland in spite of the various groynes installed to intercept drift. Although, the structures at New Works have anchored the beach locally and have resulted in some accretion between 1928 and 1972, it is probable that episodes of eastward gravel drift would have occurred during the often-lengthy intervals between groyne maintenance. Over time, the relative stability maintained artificially at New Works has produced a discontinuity in the plan form of the barrier as neighbouring parts of the beach have migrated landward.

An enigmatic feature comprises a lobe of gravel that appears to have accreted immediately to the east of Porlock Harbour over the period 1928-1972. This feature is also identified in the analyses of Halcrow (1985) and Posford Duvivier (1992) where the latter quote an accretion rate of $1{,}800\text{m}^3\text{a}^{-1}$ for 1974-1988. Its occurrence is not easily explained other than by drift from the west, suggesting that under some conditions *e.g.* severe storms, the bay may receive to gravel inputs.

Repetitive washover fans involving spreads of gravel extending 30m or more inland from the barrier crest throughout much of its length were evident from inspection of the historical maps. However, no consistent pattern of change at this landward boundary could be discerned. A tendency for general landward recession between 1888 and 1972 was evident in some places, but elsewhere it was interrupted in places by seaward advances. Undoubtedly, this reflects management by periodic bulldozing of washover fans to artificially rebuild the beach crest and keep clear an access track running behind the beach.

3.1.2. 1888-2000 Barrier Crest

To the west of the present breach, the barrier crest has retreated by some 45-55m since 1888 (Figure 27) with the majority of recession occurring by 1988 (approximately 42m giving a mean recession of 0.42ma^{-1}). Since 1988, around 10m of additional recession has occurred (0.83ma^{-1}) indicating that the historical recession rate has doubled. The relaxation of the management policy and cessation of crest maintenance by bulldozing can explain this acceleration.

At the breach, the once continuous barrier has migrated landward and has formed two recurved spits along the margins of the breach channel. This has involved movement of up to 100m, the majority of which is thought to have occurred relatively rapidly following the breach in October 1996. The detailed evolution of these spits between 1999 and 2000 is presented in Section 3.2.

Between New Works and the war memorial, the crest retreated by 10-20m from 1888 to 1928 and then been appeared remarkably stable up to 1988, probably due to the sluice constructions and several series of closely spaced groynes, the latest being constructed in 1967-71 (Figures 38 and 39). Thereafter, the crest has retreated by up to 10m in the proximity of New Works, but has remained stable closer to the War Memorial. A zone of barrier erosion and crest instability therefore appears to be migrating slowly from New Works towards the War Memorial (Figure 14).

Eastward of the War memorial, the crest retreated by 10-20m between 1888 to 1928 and then appears to have maintained a relatively stable position. This stability is apparent from the vegetated landward face that retains its oversteepened profile following cessation of management. In places, the barrier face has accreted several metres seaward (Figures 40 and 41). The greater stability of this frontage may be due to the wide boulder frame that comprises the lower foreshore and is effective at dissipating wave energy (Figure 42). This feature is less well developed to the west of New Works where nearshore water depths are greater.
Measurements suggest that the length of the crest of the Porlock barrier (Porlockford Cliffs to Hurlstone Point) extended by 23m (0.07%) from 1888-1972 and by up to 200m (6%) from 1972-2000. The former results from the barrier migration and reorientation within the bay (see above), whilst the latter is due to the growth of two landward directed spits bordering the tidal inlet that formed following the 1996 breach. It appears that a finite quantity of beach material is becoming spread more thinly along the migrating and lengthening barrier. The 1996 breach significantly accelerated this process.

3.1.3 1888-2000 Washover "Backtoe"

Examination of the December 2000 washover margins ("backtoe") clearly reveals significant landward extensions of the fans to west of the breach (Figure 28). The variable trends reported for 1888-1972 by Ryan (1999) are replaced by a landward extension of some 30-50m since 1972. It is likely that the majority of the extension occurred following cessation of beach management activities in the early 1990s. The production of extensive washover fans is a natural consequence of recent changes by which the formerly oversteepened barrier has been pushed landward and flattened as it seeks to achieve a more dissipative and stable natural profile. It should be noted that the washover fans migrate landward over the developing backshore saltmarsh resulting in slow loss of that habitat (Figure 43).

At the breach, washover fans have extended up to 150m inland in association with the development of the recurved spits, the majority of which is thought to have occurred relatively rapidly in storm events following the breach in October 1996.

Historically, barrier washover appears to have been much less frequent to the east of New Works due to the greater stability of the barrier crest. Four significant fans are apparent in 1928, but management actions had removed them by 1972 to restore the barrier crest. The December 2000 backtoe is more linear following in many places the artificially formed landward barrier face. Areas of renewed washover and landward extension of fans are nevertheless apparent around New Works (Figures 44 and 45) and also to the east of the National Trust boundary.

3.1.4 1999-2000 Breach Channel

Changes occurring in the barrier and clay cliffs of the Breach Channel between the surveys of the period from Feb-99 to Dec-00 are presented in Figure 37 and Tables 3.1 and 3.2. In summary, the breach channel has evolved by very rapid headward cutting and lengthening, but with only modest recession of its flanks.

Table 3.1 Headward recession of the breach channel

Feature	Oct. 96 – Nov. 97		Nov. 97 – Jul. 99		Jul. 99 – Mar. 00		Mar. 00 – Dec. 00	
	dist.	rate	dist.	rate	dist.	rate	dist.	rate
Channel Head	70	5.4	100	5.0	7	0.9	10	1.1

dist. = “cliff” top recession (m)
rate = recession rate (metres per month)
note that annual recession rates are not presented due to the relatively short intervals of measurement.

The main breach channel cut rapidly headward by 70m from October 1996 to November 1997 (5.4m month^{-1}). This estimate is made using the minor waterfall/rapid surveyed in February 1999 as a reference point. This waterfall represented a minor point of resistance afforded by the unsuccessful attempt in August 1997 to seal the breach by constructing a timber pile fence across it (Figure 5). The waterfall is seen clearly at the position of the remains of the fence in photographs dated November 1997. By July 1999, the channel had migrated some 100m inland (5.0m month^{-1}) and bifurcated to produce a northern and a southern channel.

Headward recession within these channels then slowed significantly involving loss of 7m between July 1999 and March 2000 (0.9m month^{-1}) and 10m between March 2000 and December 2000 (1.1m month^{-1}). The northern channel bifurcated around July 1999 (compare Figures 15 and 16), but the overall rates of headward recession of the northern and southern channels were otherwise similar. The reduction of headward recession suggests the channel is moving closer in its configuration to an eventual stable equilibrium form.

By December 2000, the northern channel had eroded to within 4m of the main north south trending drainage dyke. A significant change in lagoon tidal regime is likely when the breach channel connects with this dyke due to improved drainage of the lagoon at low water resulting in a modest increase in the tidal prism and less retention of tidal waters within the lagoon at low water. This could result in some renewed headward and lateral erosion of the channel for a short period until a new equilibrium is approached. *Observations in late July 2001 revealed* *that connection of the dyke and breach channel had occurred resulting in acceleration of channel erosion.*

The clay cliffs exposed on the seaward face of the barrier have receded by some 8 to 12 metres from February 1999 to December 2000, although their recession rate appears to be slowing (Table 3.2). Similar results are recorded for the rather slower recession of the northern bank of the channel that is partly sheltered from direct wave attack. The inner channels around the area of bifurcation seem to be widening extremely slowly. The southern bank of the main channel is not receding as its clay cliffs have been covered by gravel spilling into the channel as the western spit migrates into the channel.

Table 3.2 Recession of the clay cliffs flanking the breach channel.

Feature	Oct. 96 – Feb. 99		Feb. 99 – Mar. 00		Mar. 00 – Dec. 00	
	dist.	rate	dist.	rate	dist.	rate
Outer cliff (NE)	-	-	6.3	0.48	1.4	0.16
Outer cliff (SW)	-	-	8.6	0.66	3.0	0.33
Channel bank (N)	-	-	3.3	0.26	*0	*0
Channel bank (S)	-	-	~0	~0	~0	~0

* recession too small to measure with confidence
~ channel bank covered by eastward migrating gravel from spit

It can be summarised that the rapid recession of the clay banks is attributable to the loss of its protective covering afforded by the barrier as it was breached and migrated landward. The soft clay then became exposed to direct wave action from seaward (Figure 32). Furthermore, as the breach permitted exchange of tidal waters with the lagoon, so the strong currents that were generated greatly accelerated the headward cutting of the channel into the soft clay foundation. These changes are illustrated by Figures 15 to 20. A tentative conclusion is that the generally diminishing rates of recession recorded are indicative of an increasing degree of adjustment of the channel configuration to the hydraulic regime imposed abruptly by the barrier recession and breach.

3.2 Profile Changes (1988 to May 2000)

3.2.1 Analytic Methods

The results of the profile measurements are presented within a series of plots in Appendix 2. For each of the 21 profiles, all reliable surveys are plotted together on the same diagram to enable immediate comparisons. Profiles were plotted in MS Excel and then transferred to a Word document for presentation.

To facilitate comparisons of changes in the effectiveness of the beach as barrier against wave action, the cross section areas of the profiles were calculated and computations were made of beach volumes. To undertake these analyses all profile data were transferred into the Beach Morphology Analysis Package v.2 (BMAP) produced by the US Army Corps of Engineers (Somerfield *et al.*, 1994). This software incorporates a facility for rapid calculation of profile cross section areas above any given horizontal datum (Figure 46). Horizontal datums of 4m above O.D. and 6m above O.D. were selected for these analyses. The volume above the 4m datum approximately represents the amount of loose sediment as it rests on the underlying clay platform. It includes the main bulk of the sediment comprising the barrier ridge, but excludes the relatively thin layer of sediment on the lower seaward face of the barrier (Figure 30). Profile measurements revealed that the majority of changes occurred on the barrier above 4m whereas those occurring below that were controlled by the recession of the underlying clay foundation. The volume above 6m represents the quantity of material that is available above the level of the annual extreme storm surge enhanced sea-level (Posford Duvivier 1992) and that would afford protection against crest overwashing. This is significant for the earlier management policies attempted maintain the crest at some 8 to 9m O.D. so that a significant proportion of the barrier volume was located above the 6m datum. The ratio of volume above 6m to that above 4m was therefore calculated as an indicator of morphology. Higher index values indicate a steep, high crest typical of the oversteepened managed barrier and low values indicate wide, flattened and overwashed crest typical of a natural barrier subject to migration.

The computed cross section areas are presented in Table 3.3 and are plotted in Figure 47 which provides a visual summary of the changes for the whole frontage over the period 1988 to 2000.

Some of the key changes occurring between surveys are quantified within Table 3.4. The profile data were divided into series representing two epochs as follows:

1) **1988 to July 1999** - the period of change from active barrier management to non-intervention and including the breach event.
2) **July 1999 to December 2000** – the continuing natural adjustments to the relaxation of management and the changes in regime associated with the permanent breach.

Changes in the following key parameters were quantified for each epoch:

1. Cross-section area of barrier above 4m and 6m OD contours.
2. Ratio of volume above 6m to volume above 4m.
3. Elevation of the barrier crest
4. Position of the barrier crest

A key element of the profile analysis involved assessment of the stability of the barrier. Overall stability is difficult to define in simple terms, but can be related the frequency and magnitude of changes in crest elevation and position. Three types of stability can be identified as follows:

1) **Static crest**, typically high and steep. This may be relatively stable if well sorted and supplied with gravel (*e.g.* Chesil Beach), or potentially highly unstable if depleted and poorly sorted (*e.g.* Porlock Barrier prior to breaching).
2) **Mobile crest**, subject to regular overwashing, flattening/re-building and steady landward recession.
3) **Transition** between types 1 and 2 in which a steep static crest suddenly experiences overwash and flattening. This is characterised by a major reduction in elevation and a substantial landward displacement. The crest will usually recover and reform a distance landward, although on occasion a temporary or a permanent tidal breach may occur.

It is important to maintain Type 1 stability and avoid Type 3 transition where barriers protect settlements and infrastructure. Where properties are not at risk Type 2 stability is acceptable as major inundations are generally avoided and the natural barrier morphology provides benefits for earth science and habitat conservation.

These stability types were investigated using the following methods:

R: 6:4: see description above.

Barrier Inertia (BI): a concept developed by Orford *et al.* (1995) to indicate the potential sensitivity of a barrier to “rollover.” It is based on the observation that any material in the beach face must be raised to the level of the crest if the classic “rollover” process of barrier recession is to occur.

$$BI = B_h . RV \qquad (1)$$

where: Bh = barrier height measured as the vertical difference between the barrier crest and the seaward edge of the barrier

RV = the rollover volume, comprising the cross section area of the mobile gravel

A larger barrier inertia value therefore indicates that a barrier should be relatively resistant against overwashing and a low value indicates high sensitivity to overwashing. Allowance should also be made when interpreting this index for the level of wave energy to which the barrier is exposed.

The index values can be interpreted in terms of barrier stability as follows:

Table 3.5 Interpretation of barrier stability indexes

Barrier Stability	Index R 6:4	Barrier Inertia
Type 1	>0.25	high values
Type 2	<0.20	moderate values
Type 3	>0.25	low to moderate values

Table 3.3 Profile cross-section areas (m^2) above given contour.

Profile	**1988**		**Feb-99**		**Apr-99***		**Jul-99**		**Mar-00**		**May-00**		**Dec-00**	
	>6m	**>4m**	**>6m**	**>4m**	**>6m**	**>4m**	**>6m**	**>4m**	**>6m**	**>4m**	**>6m**	**>4m**	**>6m**	**>4m**
W06	43.5	119.3	10.3	82.8	*	*	21.0	101.4	25.0	91.2	24.6	91.7	17.7	77.5
W05	41.0	158.6	21.6	150.4	*	*	14.6	137.1	18.7	138.2	23.5	147.6	9.7	122.1
W04	**	**	0.4	92.9	*	*	9.2	100.5	10.5	97.2	12.1	101.4	5.4	82.5
W03	**	**	1.8	46.6	*	*	4.0	49.5	9.6	64.6	12.7	68.5	12.0	67.7
W02	**	**	6.8	57.3	*	*	6.8	55.9	15.7	78.6	16.1	80.3	19.3	89.8
W01	**	**	0	50.6	*	*	0.7	59.8	2.5	62.5	4.3	73.3	4.7	76.7
E01	**	**	8.4	53.4	4.5	35.7	5.2	39.7	0.3	23.8	0	26.2	0.0	35.2
E02	**	**	5.4	58.1	7.6	62.9	0.4	49.6	0.1	39.0	0.3	47.7	3.0	50.6
E03	**	**	8.3	59.2	7.9	56.8	4.8	56.2	2.5	39.6	4.8	47.0	5.0	38.0
E04	20.1	77.4	9.9	91.1	4.9	81.0	1.9	85.4	3.5	69.9	9.0	79.7	6.9	71.6
E05	25.0	82.4	20.3	93.3	15.8	84.9	16.7	89.0	17.7	89.5	9.9	71.9	20.3	86.2
E06	28.3	90.2	17.9	101.9	17.5	103.7	20.5	109.3	16.8	97.5	18.3	104.5	19.1	104.0
E07	30.8	102.5	18.9	85.6	17.9	84.7	19.3	87.5	21.7	90.8	22.2	91.5	20.7	92.1
E08	33.9	98.6	13.8	84.5	18.9	81.7	17.8	81.3	23.8	91.4	25.9	93.8	22.9	93.0
E09	34. 6	93.5	21.9	86.2	18.4	82.6	17.0	77.8	14.8	72.3	19.5	81.9	24.6	92.2
E10	47.4	125.7	57.5	143.9	54.1	140.1	54.8	139.8	51.5	133.7	53.1	136.2	51.5	131.2
E11	33.7	105.1	35.0	102.3	*	*	34.2	102.3	31.2	94.4	33.2	97.1	35.1	99.1
E12	22.1	71.2	*	*	*	*	*	*	27.0	82.6	25.8	84.1	22.7	78.2
E13	30.8	96.5	41.6	116.3	*	*	*	*	37.4	109.0	40.3	112.0	39.2	109.6
E14	42.4	105.1	62.7	134.3	*	*	60.1	129.8	54.0	120.8	57.5	127.8	56.4	123.9
E15	36.9	117.6	26.3	104.4	*	*	26.1	103.8	33.2	110.8	34.8	115.2	37.8	120.4

* incomplete survey due to equipment failure.

** profiles located on spits flanking the breach, so that there were no analogous profiles on the continuous 1988 barrier.

Table 3.4 Summary of Barrier Characteristics

Profile	1988			Feb-99			May-00			Dec-00			Change 1988 - Feb-99					Change Feb-99 - Dec-00				
	vol >4m	R 6:4	C_{elv}	vol >4m	R 6:4	C_{elv}	vol >4m	R 6:4	C_{elv}	vol >4m	R 6:4	C_{elv}	vol >4m	%	R 6:4	C_{elv}	C_{pos}	vol >4m	%	R 6:4m	C_{elv}	C_{pos}
W06	119.34	0.36	8.96	82.79	0.12	6.73	91.74	0.27	8.48	77.53	0.23	7.98	-36.5	-30.63	-0.24	-2.23	-12.20	-5.25	-6.34	0.10	1.25	1.67
W05	158.57	0.26	8.89	150.41	0.14	7.39	147.64	0.16	7.71	122.09	0.08	6.94	-8.16	-5.15	-0.12	-1.50	-13.33	-28.32	-18.83	-0.06	-0.45	-10.59
W04	**	**	**	92.93	0.00	6.03	101.36	0.12	7.57	82.54	0.07	6.74						-10.40	-11.19	0.06	0.71	-8.75
W03	**	**	**	46.57	0.04	6.28	68.53	0.19	7.47	67.71	0.18	7.32						21.14	45.40	0.14	1.04	2.36
W02	**	**	**	57.32	0.12	6.88	80.25	0.20	7.58	89.77	0.22	7.46						32.45	56.61	0.10	0.58	0.66
W01	**	**	**	50.57	0.00	5.97	73.27	0.06	6.54	76.74	0.06	6.42						26.17	51.76	0.06	0.45	3.55
E01	**	**	**	53.44	0.16	6.78	26.24	0.00	6.00	35.23	0.00	5.56						-18.21	-34.08	-0.16	-1.22	-25.67
E02	**	**	**	58.09	0.09	6.63	47.69	0.01	6.16	50.61	0.06	6.61						-7.48	-12.88	-0.03	-0.02	-19.79
E03	**	**	**	59.21	0.14	6.89	47.01	0.10	6.74	38.05	0.13	6.99						-21.16	-35.74	-0.01	0.10	-17.02
E04	77.43	0.26	8.03	91.14	0.11	6.82	79.86	0.11	6.89	71.58	0.10	7	13.71	17.71	-0.15	-1.21	-11.17	-19.57	-21.47	-0.01	0.18	-8.747
E05	82.39	0.30	8.37	93.33	0.22	7.45	71.87	0.14	7.38	86.23	0.24	7.65	10.94	13.27	-0.09	-0.92	-12.40	-7.09	-7.60	0.02	0.20	-0.65
E06	90.23	0.31	8.34	101.92	0.18	7.08	104.48	0.17	7.60	104.00	0.18	7.69	11.69	12.96	-0.14	-1.26	-6.90	2.07	2.03	0.01	0.61	0.54
E07	102.51	0.30	8.28	85.59	0.22	7.80	91.50	0.24	7.85	92.09	0.22	7.94	-16.9	-16.51	-0.08	-0.48	-7.90	6.50	7.60	0.00	0.14	-1.20
E08	98.57	0.34	8.43	84.52	0.16	7.05	93.82	0.28	7.77	92.99	0.25	7.69	-14.1	-14.25	-0.18	-1.38	-7.50	8.46	10.01	0.08	0.64	1.47
E09	93.53	0.37	8.46	86.19	0.25	7.81	81.88	0.24	7.75	92.16	0.27	7.86	-7.35	-7.85	-0.12	-0.65	-6.20	5.97	6.93	0.01	0.05	-2.05
E10	125.69	0.38	8.66	143.93	0.40	9.16	136.19	0.39	9.10	131.17	0.39	9.19	18.23	14.51	0.02	0.50	2.90	-12.76	-8.87	-0.01	0.03	-1.72
E11	105.08	0.32	8.26	102.33	0.35	8.71	97.14	0.34	8.78	99.13	0.35	8.82	-2.75	-2.61	0.03	0.45	-3.10	-3.20	-3.13	0.00	0.11	1.54
E12	71.16	0.31	8.26				84.14	0.31	8.62	78.23	0.29	8.69									8.69	
E13	96.50	0.32	8.23	116.34	0.36	8.91	112.05	0.36	9.00	109.55	0.36	8.98	19.84	20.56	0.04	0.68	-2.12	-6.79	-5.83	0.00	0.07	-2.23
E14	105.06	0.40	8.28	134.33	0.47	9.15	127.81	0.45	9.12	123.91	0.46	9.16	29.27	27.85	0.06	0.87	-3.60	-10.42	-7.75	-0.01	0.01	-0.44
E15	117.56	0.31	8.43	104.38	0.25	7.56	115.20	0.30	8.23	120.42	0.31	8.28	-13.2	-11.21	-0.06	-0.87	-6.20	16.04	15.36	0.06	0.72	-0.13

vol >4m = cross-section area of barrier above 4m OD contour (m^2).
R 6:4 = ratio of volume above 6m to volume above 4m. High values = steep, high crest; Low values = wide and/or flattened, overwashed crest.
C_{elv} = crest elevation (m O.D.).
% = change in volume as % of original volume.
C_{pos} = change in position of crest. Negative values = recession landward; Positive values = accretion seaward.
** = profiles located on spits flanking the breach, so that there were no analogous profiles on the continuous 1988 barrier.

3.2.2 Definition of Behavioral Units or Barrier "Cells"

Inspection of the plotted profiles and the analyses of barrier geometry indicated that the surveyed portions of the barrier could be sub-divided into some five behavioural units or partly connected "cells" identified in Figure 48. It is emphasised that the basis for sub-division primarily involves similarity of barrier morphology and behaviour (1988-2000) and does not necessarily imply discontinuities of sediment transport between "cells," although these are apparent in some instances. The "cells" are defined in Table 3.6.

Table 3.6 Barrier "cells"

Cell	Description	Sediment transport connections with:
1	Western Spit flanking breach channel (W01 to W04)	Cell 3
2	Eastern Spit flanking breach channel (E01 to E04)	Cell 5
3	Western Barrier (Porlockford to E04)	Porlockford cliffs and Cell 1
4	Breached segment – frontage occupied previously by the barrier prior to breaching (W04 to E04).	Not applicable
5	New Works - War Memorial - the interface between the mobile western barrier and spits and the relatively stable Eastern Barrier	Cell 2 and Cell 6
6	Eastern barrier – relatively stable	Cell 2 and Horner Water barrier

Cells 1, 2 and 4 are additional to those identified by Orford and Jennings (1988) based on the pre-breach morphology. The additional cells result from the new discontinuity produced by the breach and its effects on adjoining areas. It should be noted that cell 4 is not a presently functioning behavioural unit. It is identified simply to permit comparison between the former complete barrier segment that existed in 1988 and the products of its subsequent breakdown occupying a corresponding position in 1999 and 2000 (the spits). Its characteristics in 1999-2000 are derived therefore as the mean or sum of the characteristics of the spits comprising cells 1 and 2.

The identification of these units enables some generalisations to be made concerning past behaviour and offers a basis for estimation of likely future changes. The major changes occurring between 1988 and Dec-00 are summarised within Table 3.7. The table is based on the analysis of the profiles and assumes that the measured profiles are representative of the respective behavioural cells.

Table 3.7 Summary of Barrier Changes

Cell	L (m)	Ratio 6:4		Crest elevation (m O.D.)		C_{pos} change (m)
		1988	Dec-00	1988	Dec-00	1988 – Dec-00
1	99	0.25	0.15	8.46	6.99	[†]0.4
2	133	0.25	0.08	8.46	6.54	[†]-17.8
3	452	0.34	0.18	8.93	7.46	-13.4
4	*209 (232)	0.25	0.12	8.46	6.76	-
5	208	0.34	0.26	8.37	7.86	-8.8
6	545	0.35	0.38	8.35	8.85	-3.0
Overall	**1437**	**0.34**	**0.29**	**8.56**	**7.93**	**-8.3**

L = Length (longshore) of cell
* = length in 1988 and (Dec 2000)
R 6:4 = ratio of volume above 6m to volume above 4m. High values = steep, high crest; Low values = wide and/or flattened, overwashed crest.
[†] = Jul-99 to Dec-00

The changes in barrier inertia occurring between 1988 and Dec-00 are presented within Table 3.8.

Table 3.8 Changes in "Barrier Inertia"

Cell	1988			Dec 2000		
	B_h (m)	RV (m^3)	Inertia (m^3m^{-1})	B_h (m)	RV (m^3)	Inertia (m^3m^{-1})
1	-	-	-	2.5	80	200
2	-	-	-	2.5	54	135
3	8.0	154	1,232	6.5	110	715
4	5.3	130	689	2.5	67	168
5	5.0	105	525	4.3	105	451
6	5.2	137	712	5.6	147	823

A compilation of the changes occurring in each "cell" is described as follows based on the summaries above and the results of the analyses detailed in Section 3.2.1.

Cell 1 Western Spit

The western spit has grown in width at its crest from some 5m in Feb-99 to 20 in Dec-00 due to accretion of gravel on its NE face (profiles W01 to W03 in Appendix 2). It has also increased in crest elevation by some 0.5 to 1.0m (Table 3.4). At profile E02, gravel from the spit spills directly into the breach channel and the amount of accretion occurring has narrowed the channel (Figure 19).Although the crest levels and cross section area are significantly smaller than those of most other parts of the barrier the western spit has remained stable for it faces the breach channel and is not exposed directly to frontal wave attack. Due to this shelter and its continuing trend for accretion, the spit is anticipated to remain relatively stable in the immediate future.

Cell 2 Eastern Spit

By contrast to its western counterpart the eastern spit has retreated landward by up to 30m since Feb-99 (Profiles E01 to E03 in Appendix 2). It has also diminished in cross section area and crest width and has reduced in crest elevation by up to 1.5m (Table 3.4). These changes have been produced by major overwashing and "rollover" of the barrier as indicated by the substantial washover fans that have formed (Figures 44 and 45). Changes have been most rapid at its tip (E01) so that the spit has increasingly recurved as it has diminished. The inlet as defined by its flanking spits has therefore migrated along the coast to the NE and has widened even though its incised channel has been narrowed as the western spit has accreted.

Losses of gravel from the spit are thought to have occurred due to drift towards New Works and also to the breach channel from the spit tip where strong tidal currents flush material seaward. The breach channel intercepts all incoming drift from the west so that losses are not replaced. As the spit has lost gravel, it has become increasingly vulnerable to overwashing so that landward recession has continued to occur rapidly in spite of the increasing width of dissipative clay platform that has become exposed in front of the spit. Landward recession has occurred in two distinct phases, from Jul-99 to Mar-00 and from May-00 to Dec-00 (see Profiles E01 and E03). These correspond to periods of winter wave attack and up to 15m of recession have occurred in each season. Parts of the spit face NW and are directly exposed to wave attack from the Irish Sea (Profiles E02 and E03). It is thought that the spit has been able to maintain its integrity in spite of losses due to its continued recession that exposes an increasingly wide dissipative clay platform. At present it is uncertain whether volume will diminish to a critical level rendering the spit liable to repetitive overwashing and breaching, or whether continued spit recession and wave dissipation by the emerging clay platform can maintain the depleting spit. If integrity is maintained in the short term, a critical event in the future could occur if the spit migrates landward into the main N-S drainage channel that exits at New Works. The spit is some 25 to 40m seaward of the channel at present giving longevity of some two to four years at present recession rates. It should be noted that the intersection of the migrating 1996 barrier with an existing drainage channel was sufficient to initiate and maintain the October 1996 breach. *Subsequent observations on 30-31 July 2001 indicated further recession and lowering of the spit concentrated between E02 and E03.*

Cell 3 Porlockford Barrier

The present barrier has changed considerably in comparison to its 1988 counterpart. It has receded landward by up to 20m (Profile W05 and W06 in Appendix 2) and flattened considerably, reducing in cross section and falling in crest height on average by 1.5m (Table 3.7). Barrier inertia has fallen considerably as the barrier stability has altered from Type 1 to Type 2 (Table 3.8). With the relaxation of active management in the early 1990s the former oversteepened crest would have been eroded and eventually overwashed during storms. Overwashing by breaking waves would have pushed the crest material landward generating washover fans and flattening the barrier to create its present form (Figure 22). At profile E05 overwash fans have extended over 50m landward from the “backtoe” of the 1988 barrier. Barrier integrity appears to have been maintained by processes of recession and overwashing which lengthen the profile and increase the zone over which wave dissipation can occur. Additionally, is likely that natural processes of gravel sorting have become re-established on the present barrier crest to result in a permeable framework into which the backwash of waves that reach the crest can infiltrate. Orford and Jennings (1998) reported that the process of bulldozing and artificial profiling by which the pre-1992 barrier was maintained resulted in disruption of natural sorting and reduction of permeability that reduced the efficiency with which the barrier could dissipate the energy of waves reaching its crest.

Significant changes have also occurred recently for the crest built up considerably during the period Jul-99 to May-00, but was then flattened and pushed back by Dec-00. This behaviour is a natural function of barrier “rollover” and would correspond to periods of modest storms (crest building) and severe storms (crest flattening and migration). Autumn 2000 was characterised by several severe westerly storms co-incident with storm surges. Renewed crest building is anticipated prior to the next autumn series of severe storms.

Cell 4 Barrier at location of 1996 breach

If the pre-breach 1988 barrier is compared with its post-breach counterparts (the western and eastern spits), then some significant changes are apparent. Not only have parts of the breached barrier migrated landward by up to 100m, but they have also lengthened, reduced in cross-section area and flattened with up to 2m loss in crest elevation (Table 3.7). Barrier Inertia has reduced significantly (Table 3.8) and barrier stability has altered from Type 1 to Type 3 (at time of the breach) to Type 2 following establishment of the breach. The present barrier is significantly more dynamic than its managed 1988 counterpart, but its integrity under wave attack appears to have been maintained by the dissipative properties of the clay platform that has emerged on the mid beach face as the barrier has receded.

Cell 5 New Works to War Memorial

The barrier in this cell has exhibited the most complex pattern of changes for it represents the interface between the mobile Porlockford barrier and spits and the relatively stable Eastern Barrier as exemplified by Figures 13 and 14. At profile E10 opposite the War Memorial, the barrier has remained stable and has maintained its 1988 position and form (Type 1 stability). At profiles E06 to E09, the seaward face and portions of the crest of the 1988 barrier have been eroded and it would appear that much of this material has been pushed over the remaining 1988 barrier core to create washover fans. The overall effect has been a widening and flattening of the barrier with a modest recession and slight reduction in crest elevation. These changes are best developed in the west (profile E06) and diminish eastward to profile E09 suggesting that a zone of erosion and natural profile reshaping is migrating eastward (Figure 14). At profiles, E04 and E05 closest to New Works the 1988 barrier has been eroded completely and the material reworked to form a new crest (1m lower and 20m landward) and washover fan extending up to 30m landward.

At each profile, the most of the erosion of the 1988 barrier and formation of a flatter, lower and wider form had occurred prior to Feb-99. Subsequently, the crest has tended to increase slightly in elevation and has either remained stable or fluctuated in position with accretion evident on some profiles. Only at profile E04 has the crest continued to retreat rapidly landward by 9m from Feb-99 to Dec-00, although it maintained its form over this period.

It can be summarised that barrier stability has adjusted, or is in process of adjustment away from the artificially maintained static form (Type1) towards a flatter, wider natural barrier with Type 2 dynamic stability. Cross section areas have been maintained and following an initial recession, the net crest position has remained relatively stable since Feb-99. Barrier inertia is relatively unaffected (Table 3.8) and it would appear that the new profile configuration has been well capable of dissipating the wave energy experienced since Feb-99. These conclusions are perhaps surprising given the very obvious “erosion” of the former barrier crest. In fact, the material of the 1988 barrier has been redistributed to create an efficient natural dissipative form.

A potential uncertainty for the future concerns the extent to which the stability of the barrier during the process of profile adjustment was assisted by the presence of the New Works structures and of the existing groyne system that could have “anchored” parts of the barrier (Figures 38 and 39). These structures will become dilapidated and cease to function in the future without maintenance so that drift might operate more freely and cause the barrier to become depleted. Under this scenario, a sharp increase in barrier crest recession could be anticipated.

Cell 6 Eastern Barrier

Over the period 1988 to Feb-99 only relatively modest changes have occurred and the artificial barrier form of 1988 largely remains intact. At profiles E11 to E14, the barrier crest has increased in elevation by at least 0.5m and mixed phases of modest erosion and accretion are recorded on the seaward beach face. Some build-up or accretion of the landward barrier face or backslope is also recorded on most profiles. It is uncertain whether natural processes achieved build up on the crest and backslope, or whether it could have been the result of artificial barrier re-building over the period 1988-92. The latter explanation is indicated by the high R6:4 ratios that have been maintained (Table 3.7). Since Feb-99, the crests have remained stable and only modest fluctuations in profile have occurred on the seaward beach face involving localised phases of accretion (Figure 40) or erosion (Figure 41). Profile E15 has behaved differently for the 1988 profile has suffered overwashing and profile flattening. However, natural crest accretion and beach face re-building occurred after July-99.

Two potentially destabilising influences are identified with this otherwise stable cell. Firstly, a zone of downdrift depletion has developed immediately eastwards of profile E10. It has resulted in thinning of the crest width from 5-8m to only 2-3m over a 25m frontage by Dec-00. If this trend continues the crest at this point is likely to become increasingly sensitive to overwashing. Secondly, at least two seepage "cans" have been identified in the backslope of the barrier around the War Memorial (Figure 10). Although they are natural phenomena typical of gravel barriers elsewhere such as Chesil Beach (Carr and Blackley, 1974), seepage cans do result in the displacement of materials from the backslope and may weaken the integrity of the artificial barrier. At the War Memorial a seepage can appears to have developed in association with the area of crest thinning and clearly indicates a potentially vulnerable location.

To summarise the Cell 6 barrier has maintained its key features including: (a) its artificially steepened artificial profile form; (b) its overall cross section areas and (c) its high degree of barrier inertia. The crest has thus experienced a period of static stability (Type 1) and the barrier has functioned to fully protect its hinterland. The following factors are believed to account for this stability as follows: (i) this cell is protected by a boulder frame forming a dissipative lower foreshore that imposes a depth limitation on the approach of very large waves; (ii) it receives a supply of sediment drifting from Cell 5 during prevailing conditions and is also open to inputs from the east during periods of drift reversal and (iii) it has a high barrier inertia that provides buffering against changes.

3.3 Gravel Volumes and Transport Pathways

3.3.1 Barrier Volumes

Barrier volumes were calculated for each cell based on the profile cross section areas and the longshore distances between profiles. Results are presented in Figure 48 and Table 3.9.

Table 3.9 Barrier beach volumes >4m OD within cells.

Cell	**Dist (m)**	**1988 (m^3)**	**Feb-99 (m^3)**	**Jul-99 (m^3)**	**May-00 (m^3)**	**Dec-00 (m^3)**
1. Western Spit	99	-	5,800	6,132	7,796	7,834
2. Eastern Spit	133	-	8,286	7,278	6,354	6,227
3. Porlockford to W04	452	56,668	43,202	48,743	46,277	38,817
4. W4-E4	209	24,169	14,086	13,410	14,150	14,061
5. New Works to War Memorial	208	20,251	20,372	19,833	19,709	20,316
6. Eastern Barrier	545	56,560	64,856	63,820	62,501	61,784
TOTAL	1437	**157,648**	**142,516**	**145,806**	**142,637**	**134,978**

1988 to Feb-00

From an estimated loose sediment volume of 158,000m^3 in 1988, some 15,000m^3 (9%) was lost by Feb-99. Losses occurred in Cell 3 (13,000m^3) and Cell 4 (10,000m^3), whereas accretion of 8,000m^3 occurred in Cell 6. Although it is difficult to provide definitive explanations of the changes due to the lack of survey data between 1988 and 1999, each of the cells that lost material had been subject to barrier rollover and intense reworking following cessation of active management. The following mechanisms of loss can be postulated:

1) Eastward drift to cells 5 and 6 prior to the breach;
2) Drift into the breach channel and subsequent seaward flushing of materials after Oct. 1996 and
3) Loss of finer sediments from the core of the poorly sorted artificial barrier as it was reworked during processes of "rollover."

Operation of mechanism 1 could additionally explain the accretion of material at Cell 5 and also the stable volume of Cell 5 that was maintained in spite of barrier reworking.

Feb-99 to Dec-00

After Feb-99, overall barrier volume fluctuated between 146,000m^3 and 135,000m^3. Relatively steady volumes were maintained within Cells 5 and 6, but significant changes occurred within Cells 1, 2 and 3.

The volume of Cell 3 varied between 39,000 and 49,000m^3 and the highest values recorded during summer surveys suggesting operation of a seasonally driven variation, perhaps relating to cross-shore exchange of sands and fine gravels. The finer materials could be transported onshore and incorporated within the barrier during calm conditions and then removed seaward to the nearshore during stormy winter conditions. Further surveys covering several future summer seasons are required to confirm this trend. An alternative explanation is that pulses of drift input could occur from the west (*e.g.* the accreting gravel lobe described in Section 3.1.1.) to boost the barrier volume, followed by winter losses by drift to the western spit and breach channel (Section 3.3.2). Changes are unlikely to arise in this instance as a result of reworking of the artificial 1988 barrier since the plots of profiles W05 and W06 (Appendix 2) reveal that this process had largely been completed in this cell prior to Feb-99.

The volume of material retained within each of the two spits flanking the breach channel has altered, although the total within both spits has remained steady. The Western Spit (Cell1) has increased steadily in volume by 2,000m^3 from Feb-99 to Dec-00, whereas the Eastern Spit (Cell 2) has decreased by a similar amount over this period.

3.3.2 Gravel Drift Pathways

To explain these volume changes an understanding was developed of the transport of gravel between the respective cells, especially around the breach channel. Drift pathways and net transport directions are presented in Figure 49, based on evidence of previous studies (Halcrow, 1985; Orford and Jennings, 1998) and morphological indicators such as spit alignment, and beach levels on either sides of groynes of other obstructions (relative beach depletion indicates the downdrift direction). Important additional evidence is provided by distinctive pale masonry clasts derived from disintegration of structures associated with the New Works sluice. These clasts have acted as “tracers” that clearly indicate eastward drift over the past three years or so during which the disintegration has accelerated. Almost all clasts observed on the beach surface were located up to 40m to the east of New Works and very few were observed to the west of their point of origin.

Net eastward drift operates along Cell 3 and supplies gravel to the Western Spit (Cell 1) where some accretes to widen the spit, but the remainder spills into the breach channel and is flushed seaward by ebb tidal currents. South-west and southward drift operates along the short Eastern Spit (Cell 2) and transports gravel to the tip of the spit where it is also thought to be lost to the breach channel. Drift is clearly eastward at New Works and also throughout Cells 5 and 6. A zone of drift division therefore exists a short distance to the west of New Works (Figure 49). Gravel entering the breach channel from the two spits is preferentially transported seaward by the ebb tidal flow that exits from the lagoon. A short distance seaward this transport is counteracted by wave driven onshore movement so that gravels tend to be deposited to form a prototype ebb tidal delta. This feature is evident in aerial photos of the foreshore (*e.*g. Figure 6), but is currently small because it is probably not yet developed fully as it only represents accretion since the breach in 1996. Ebb tidal deltas are typical of mature tidal inlets on the coasts of England and Wales where they store sediments and periodically supply them back to the shoreline as migratory swash bars that detach themselves from the flanks of the delta. It remains uncertain whether this process occurs at Porlock due to the immaturity of the delta and the presence of the clay cliffs that would prevent onshore movement towards Cells 1 or 2. If it were to occur, the most likely site of onshore supply would be around Profile E05 immediately east of New Works as prevailing north-westerly waves would drive gravel in this direction and a clear pathway to the shore exists.

The volume changes recorded between Feb-99 and Dec-00 are now explained as follows and initial estimates of future change are provided in Italics:

Cell 3: short-term fluctuations in volume are likely to occur due to seasonal cross-shore transport of finer sediments as previously explained. Long term sediment volume will depend on the net balance of drift inputs from the west at Porlockford and outputs eastward to Cell 1. Between Feb-99 and Dec-00, a net loss of 4,400m^3 (2,400m^{3}a^{-1}) was recorded providing a minimum estimate for drift to Cell 1 over this period. Drift inputs from the west (Porlockford) have probably been limited for the beach at that location is extremely depleted and the crest has been eroded landward (Figure 50). This conforms to the operation of a process of barrier "cannibalisation" to sustain drift as postulated by Orford and Jennings (1998). *Net loss and slow reduction in volume by further cannibalisation is likely to continue unless new material is introduced at the western end of the cell.*

Cell 1: accretion of some 2,000m^3 between Feb-99 and Dec-00 (1,100m^{3}a^{-1}) is explained by incoming drift from Cell 3, of which at least 2,400 m^3 (1,300m^{3}a^{-1}) would have entered the breach channel. *The spit is likely to continue to accrete, but at a steadily decreasing rate because the breach channel limits lateral expansion.*

Cell 2: loss of 2,000m^3 between Feb-99 and Dec-00 (1,100m^{3}a^{-1}) can be explained by: (a) southward gravel drift to the spit tip followed by loss to the breach channel and (ii) eastward drift to Cell 5. It is not possible to quantify either of these fluxes so it is assumed that drift is evenly divided with 1,000m^3 (550m^{3}a-1) being transported in each direction. Gravel losses are not replaced by any fresh inputs, as the spit is isolated from other drift pathways by the breach channel to the west and the littoral drift divide to the east. Furthermore, the clay cliffs in front of the spit prevent input of any gravels being driven onshore from the developing ebb tidal delta. The drift is therefore sustained by erosion of the spit that will tend to be most significant at the location of the drift divide. Observations on 30-31 July-01 revealed new zone of spit flattening and overwashing exactly at this point. *The spit will continue to reduce in volume, becoming most depleted at the location of the drift divide.*

Cell 5: it is thought that barrier volume has remained static due to control of the seaward face by groynes. The groyne embayments are presently filled with gravel so that any material drifting in from Cell 2, or possibly moving ashore from the ebb tidal delta will tend to overtop them without accreting. The groynes themselves are presently effective in preventing net gravel loss by drift, but they fail to control the cross shore rollover process that leads to reworking of the 1988 barrier and losses of fine material from its core. As rollover occurs gravel is pushed up the beach face and over the reworked crest resulting in depletion of the beach face groyne embayments. At this point the groynes may once again begin to intercept drift and build up the beach face such that net barrier volume is retained in spite of losses at the crest. As the barrier migrates landward the groynes will eventually become outflanked and suffer reduction in their interception efficiency. *Volume loss is likely in the future as the groynes become dilapidated and beach migration causes them to become outflanked. Drift inputs from the west may reduce in the long term as Cell 2 depletes further.*

Cell 6: the slow volume loss recorded is probably the result of a slight difference between drift into this cell in the west compared with that leaving the cell to the east. It is too small (<5% of total cell volume) at present to easily be accounted for, although it could become significant if it persists in the future. *Likely to remain relatively stable in volume.*

Ebb Tidal Delta: the foreshore accumulation is derived from gravels entering the breach channel from Cells 1 and 2 that are then flushed seaward and deposited at the point where seaward ebb current transport is balanced by onshore wave driven transport. A rough estimate of delta volume can be produced based in its plan dimensions (60 x 250m based on the April 1999 air photos) and an assumed thickness of 0.5m. This gives a volume of 7,500m^3 that would have accumulated since the October 1996 breach. This amounts to an accretion rate of 1800m^{3}a^{-1} assuming steady growth. It may be compared with the estimates of losses to the breach channel from Cells 1 (1,100m^{3}a^{-1}) and 2 (550m^{3}a-1) based on barrier volume changes between Feb-99 and Dec-00. Although this comparison is based on several assumptions and involves different time periods, the close correspondence between the delta accretion and the losses estimated to the breach channel provide confidence in the conceptual model developed of gravel transport around the breach. Confirmation of this model ideally requires monitoring of barrier and delta volumes over a longer period. *It is concluded that the delta is likely to grow in future as gravel continues to drift into the breach channel. This has two implications: (i) the delta will tend to store gravel that otherwise would remain on the barrier and (ii) accretion of the delta will build up foreshore levels and improve wave dissipation in front of the barrier.*

3.4 Summary of Barrier Changes

Late Holocene (past 6,000 years).

1) Paleaoenvironmental investigations indicate that the Porlock Bay barrier has been subject to landward migration and breaching such that back barrier areas were dominated over this period by marine sedimentation (Jennings *et al.*, 1998). Breaches became sealed on several occasions enabling freshwater lagoons to form for limited periods, although further breaches always recurred.
2) Inlets have therefore segmented the prevailing barrier form rather than having a continuous crest and due to shortage of sediment supply the barrier has been mobile (landward "rollover") rather than static.
3) The Porlock barrier became isolated from any significant drift inputs of fresh gravel due to the emergence of Gore Point as a headland.

Historical (1888 to 1992).

1) Map comparisons indicate recession of the barrier in western and central parts of the Bay and accretion in eastern parts against Hurlstone Point. These changes are consistent with a west to east drift of sediments and a tendency for the barrier to lengthen and re-orientate slightly westwards. Sediments are therefore becoming spread along an increasing barrier length and those drifting away from western parts are unlikely to be replaced naturally leading to depletion.
2) Active management was undertaken to maintain a continuous barrier with a static crest. This involved an on-going commitment towards groyne building, replenishment and frequent crest re-building to maintain an artificially steepened profile.
3) Frequent barrier overwashing and some recession nevertheless occurred between structures at New Works and Porlockford Cliffs, which acted as hard points that, anchored the barrier.

Relaxation of Management 1992 to Feb-99.

1) The Porlockford barrier between Porlockford Cliffs and New Works experienced complete reworking of its artificially steepened form by overwashing and landward rollover. Some barrier volume was lost due to reworking of finer materials from the old barrier core and a lower, but wider natural form has resulted. The steep narrow crest and its poorly sorted condition appear to have resulted in an often abrupt and uncontrolled transition from the static managed form to a natural dynamic form.
2) Some 200m to the SW of New Works the barrier breached on 26th October 1996. Although details of the event are limited, it appears that the barrier was severely overwashed and retreated over an artificial drainage cut which channeled tidal exchange such that it rapidly cut a channel in the clay substratum enabling a permanent breach to establish.
3) Elsewhere, the transition from static to a dynamic barrier has so far been achieved without breakdown and the new barrier has provided protection against wave attack.

4) As barrier rollover has occurred, a clay platform has been exposed in front of the beach face. This functions to dissipate wave energy, especially where recession has been rapid and the platform has widened. The clay itself suffers cliffing and lowering.

5) The zone of barrier reworking has migrated steadily eastward from New Works. Groynes at this location appear to have assisted the transition as they have controlled drift.

6) The barrier to the east of the War Memorial has remained stable and largely static retaining its steepened artificial form.

Changes Associated with the Breach Oct 1996-Feb-99.

1) Tidal exchange at the breach rapidly cut a channel into the clay substratum. The channel has eroded headward by over 180m such that it now fully drains the back barrier area. There is some evidence that rates of erosion are reducing as the channel evolves towards a more stable form.

2) The breach forms a sediment transport boundary and prevents continuous drift along the barrier. Its influence also results in a pathway of drift reversal and a zone of drift divergence and immediately to its east. A new transport regime has therefore developed following the breach.

3) Gravel spits formed along the flanks of the channel supply gravel into the channel itself. The Western Spit is accreting quite strongly and encroaching into the cut breach channel. The eastern spit is migrating rapidly landward and depleting. The net effect is that the inlet is tending to migrate slowly eastward in the direction of drift.

4) Gravel entering the breach channel is flushed seaward to accumulate in a prototype ebb tidal delta on the lower foreshore. The delta stores gravels that otherwise would remain part of the barrier.

The present situation Feb-99 to Dec-00.

1) The barrier is continuing to adjust to: (i) the relaxation of active management and (ii) the formation of a permanent breach and tidal inlet.

2) The extent of adjustment so far is not easy to determine for the detailed monitoring covers just two years making it difficult to differentiate short term and seasonal changes from longer term trends driven by adjustments to the new regimes.

3) Five partly interconnected barrier cells now operate, each with their own distinct behaviour.

4) Overall barrier volumes have generally been maintained since Feb-99, but patterns have been variable in some cells.

5) To the west of New Works the initial phase of landform adjustment is complete because all traces of the pre-existing barrier are now reworked and new systems of sediment transport and tidal exchange have become established at the breach. However, the new landforms generated (forming Cells 1 to 3) are dynamic and still undergoing organisation within the new system or regime.

6) In particular, Cell 3 (Porlockford Barrier) has adopted a natural dissipative form, but is experiencing active recession due to its continuing depleted state. Cell 2 is losing material due to the presence of the drift divide and the breach and is migrating landward very rapidly such that future breakdown is a possibility.

7) Immediately to the east of New Works there is an eastward migrating zone of reworking where the artificial barrier is steadily being converted to the more natural flattened dynamic form.

8) The barrier to the east of the War Memorial has remained stable and largely static retaining its steepened artificial form.

4. RESULTS: INSTRUMENTATION

4.1 Lagoon Water Level Measurements

The measurements of extreme water levels occurring in the lagoon between January and September 1999 are presented in Appendix 3. All of the recorders functioned effectively over this period although Recorder 3 recorded little data as the water level only reached its standpipe on one occasion. This recorder was sited well above mean high water of spring tides to ensure coverage of major extremes. As no truly exceptional conditions occurred over this period the recorder was effectively redundant. Measurements from Recorders 1 and 2 generally showed a very close correlation with each other and tended generally to reflect the stage covered of the spring-neap cycle of the tides in Porlock Bay. An additional extreme level of 6.3m O.D. was obtained in May-00 by surveying strand line debris within the lagoon. This is believed to represent the extreme water level for winter 1999/2000.

Results are summarised within Table 4 .1 that presents the maximum water level occurring within each month of measurements. Comparisons of measured extremes with the predicted "astronomic" tides within the bay outside of the lagoon revealed that these tides strongly determined the lagoon levels. For example the equinoctial tides of March and April have clearly generated the highest levels recorded within the lagoon. On exceptionally high tides the lagoon extremes tended to be slightly lower than the open coast predictions. This could reflect a tendency for the narrow inlet to control extreme tidal exchange. However, on five occasions the lagoon levels were some 0.5 to 1.4m higher than the predictions for the bay. These instances could be explained by the occurrence of: (i) storm surges due to combinations of low atmospheric pressure and strong onshore winds and/or (ii) periodic strong freshwater inputs that can elevate lagoon levels. Neither of these phenomena is incorporated within the tidal predictions. It should be noted that large storm surges can be generated within the Bristol Channel for during a severe storm on 13 December 1981 a surge of 1.34m was recorded at Hinkley Point increasing to 1.89m at Avonmouth. Occurring in combination with a high spring tide this surge caused major flooding along the Somerset coast (Procter and Flather, 1989).

Table 4.1 Monthly extreme lagoon later levels.

Period	Extreme lagoon level (m O.D.)		
	Mean	Predicted	Residual
5-25 Feb. 1999	5.75	5.87	-0.12
19-26 March	6.07	6.13	-0.06
16-23 April	6.19	6.21	-0.03
14-21 May	5.82	6.10	-0.28
18-25 June	5.81	5.66	0.15
23-30 July	5.53	4.91	0.62
13-20 Aug. 1999	5.50	5.50	0

Mean = mean lagoon level based on data from Recorders

Predicted = highest tidal level predicted for Porlock Harbour based on UK Hydrographic Office data without allowance for meteorological effects.

Residual = the difference between the observed lagoon level and the predicted Porlock Harbour level.

For comparison the following tidal levels are extracted from previous studies:

Mean High Water Neap Tides (predicted)	2.6m O.D.
Mean High Water Spring Tides (predicted)	5.0m O.D.
Porlock Bay extreme (1yr return period)	6.0m O.D.
Porlock Bay extreme (20 year return period)	6.3m O.D.
Porlock Bay extreme (100 year return period)	6.4m O.D.
Porlock Bay 13 Dec 1981 (estimated by adding the surge to the corresponding predicted tidal level at that time of day)	6.6-6.9m O.D.

Some inconsistencies are apparent in these data because there has been no regular tide gauge measurements at Porlock Harbour and the tidal predictions and extreme level estimates given are extrapolations based on measurements from Avonmouth and Hinkley Point. The extremes quoted from the Posford Duvivier (1992) report are certainly underestimates by at least 0.1m for each return interval since they based on analyses that were completed prior to the 1981 event. Nevertheless, it is clear that the maximum levels measured in the lagoon exceed MHWS by over one metre and correspond to at least the annual bay extreme water level.

The conclusion derived from this analysis is that the lagoon extreme water levels are related strongly to those in the Bay.

Measurements by Cawsey (2000) of lagoon levels recorded over a high tide are presented in Figure 51 to indicate the nature of the lagoon tidal regime that operated over a typical tidal cycle. The clay platform at the breach margin acted as a dam that enabled a permanent lagoon to be retained at about 3.8m O.D. The lagoon levels therefore only responded to the open coast tide as it exceeded these levels. In Figure 51, the lagoon level appears to rise early, although this is due to the bay tide rising slightly earlier than was predicted. Otherwise, there is very good agreement between the two curves until the bay tide falls towards the platform level. At this point, water is retained within the lagoon so that the two curves differ increasingly as the bay tide falls below 3.8m O.D. Note also that the lagoon tide is asymmetric in that it falls more slowly than it rises due to the retaining influence of the clay platform. A water surface gradient is therefore produced by the lowering of the bay tide generating a strong ebb flow and a waterfall over the clay platform at the headward part of the breach channel.

The lagoon therefore experienced a mean tidal range of around 1.2m increasing to an annual extreme of 2.4 or 2.5m during high spring tides and/or storm surges. *This regime has now altered due to the connection of the breach channel with the main drainage dyke. The main change is that the lagoon drains by at least an additional metre so that much of the previous standing water is now replaced by new low gradient intertidal foreshore. Measurements of lagoon levels during this new regime indicate that they remain very strongly correlated with the bay tide once that has risen into the upper breach channel (Cope – personal communication).*

The results reported here indicate that although the tidal regime of the evolving lagoon would appear to be unique, it can be represented adequately by the predicted bay tidal cycle at levels above that of the upper breach channel. Additional allowances would be needed to represent the effects of storm surges and possible flash flood events from the steep catchments behind the bay.

The importance of this work on tidal levels is that in conjunction with knowledge of ground elevations it enables estimation of tidal inundation durations and frequencies (hydroperiod) for the back barrier area. Previous studies have suggested that hydroperiod is critical in defining the type of intertidal vegetation community that is likely to develop in areas experiencing breaching. As such, it can provide a valuable basis for prediction of future changes at Porlock and other similar sites.

4.2 Breach Recession Measured by Erosion Pins and Stakes

The results of monitoring of the erosion pins are presented in Appendix 4 and are summarised within Table 4.2.

Table 4.2 Summary of breach channel lateral erosion measured by erosion pins.

	Mean loss by erosion in (mm)					
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Total	112	74	222*	100	182*	101
mm month^{-1}	20	13	40*	18	33*	18

* includes a single major loss of 120mm.

Losses by small-scale abrasion processes were extremely slow amounting to 0.015 to 0.020m per month excluding two instances where large bank failures removed all pins. No significant differences were recorded according to the relative wave exposure of the sites (sites 1 and 6 were most exposed – see Figure 25). By comparison with the results of repeated GPS surveys of the breach channel flanks (Section 3.1.4) the erosion pin rates account for only some 10% of the total recession recorded. It suggests that bank failure rather than small-scale abrasion is the major mode by which the breach channel has enlarged laterally.

The headward recession of the breach channel recorded by monitoring of erosion stakes located in Figure 25 is presented in Table 4.3.

Table 4.3 Breach channel headward erosion measured using stakes.

Date	Cliff top recession recorded at stake (m)							
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Total
05-Mar	0.45	0.00	1.00	1.00	0.00	0.00	0.00	2.45
19-Mar	0.73	0.00	0.30	0.00	0.00	0.00	0.00	1.03
09-Apr	0.38	0.48	0.00	0.44	0.30	0.35	0.00	1.95
23-Apr	0.22	0.00	0.35	0.35	0.40	0.00	0.10	1.42
07-May	0.00	0.00	0.35	0.20	0.00	0.27	0.10	0.92
21-May	0.00	0.30	0.30	0.50	0.00	0.10	0.00	1.20
04-Jun	0.20	0.10	0.00	1.00	0.00	0.10	0.00	1.40
18-Jun	0.60	0.10	0.35	0.00	0.00	0.00	0.00	1.05
09-Jul	0.00	0.71	0.00	0.60	0.30	0.00	0.15	1.76
23-Jul	0.00	0.20	0.30	0.10	0.40	0.00	0.20	1.20
06-Aug	0.10	0.15	0.60	0.20	0.40	0.30	0.00	1.75
20-Aug	0.00	0.00	0.35	1.00	0.00	0.00	0.00	1.35
Total	2.68	2.04	3.90	5.39	1.80	1.12	0.55	17.48
m month^{-1}	0.45	0.34	0.65	0.90	0.30	0.19	0.09	0.42

Recession was highly variable and controlled primarily by the occurrence of failures of the bank that could involve loss of a metre of crest in a single event over a limited frontage (Figure 31). The most rapid recession of up to 1m per month occurred in central parts (Sites 4 and 5) and was comparable to the slower post July-99 rates recorded by the GPS surveys (Table 3.1). It suggests that much of the rapid erosion identified in Table 3.1 was achieved prior to March-99. It should be noted that these stake measurements did not cover the full winter period when wave energy would be highest so that the mean rate of 0.42m per month is probably typical only of recession occurring over the spring and summer period. Indeed, it is apparent that recession was more rapid in March and April than in later months. This could relate also to the occurrence of equinoctial tides that would increase the tidal exchange occurring over this period.

4.3 Backbarrier Accretion Measurements

The accretion recorded on the five transects located in Figure 25 is presented in Table 4.4. Highly variable thicknesses of clayey sediment ranging from zero to 25mm were recorded. The variation is likely to be the result of site specific factors such as exposure, vegetation and elevation. W2 and W3 were rather more sheltered, but vegetation, especially presence of algae varied considerably in spite of efforts to maintain some consistency between the lower (no anchored vegetation) mid (pioneer species of variable density) and upper sites (dense vegetation). No accretion was recorded at Transect W3 as it appeared to be located too high (>5.0m O.D.) to experience any sustained inundation. This transect was relocated on 31st July 2001 as it had been disturbed by grazing cattle.

Table 4.4 Accretion measurements between 2nd June and 7th December 2000.

Transect	Lower site		Mid site		Upper site		Mean
	mm	m O.D.	mm	m O.D.	mm	m O.D.	
E1	13	3.82	25	4.03	0	4.72	13
E2	0	3.78	10	4.00	25	4.56	12
W1	0	3.93	20	4.09	10	4.50	10
W2	25	4.05	15	4.33	0	4.82	13
W3	0	-	0	-	0	-	-
Mean*	10	3.90	18	4.11	9	4.65	

* transect W3 excluded as it was located too high to experience frequent inundation

The most consistent and rapid accretion was recorded from the mid sites located at elevations of between 4.0 and 4.3m O.D. that experience sustained inundation (three hours over a typical spring tide according to Figure 51) and possess pioneer vegetation that can encourage sedimentation.

Averaging of accretion within each transect revealed greater consistency with 10 to 13mm being recorded (Table 4.4), equivalent to an annual rate of around 20mma^{-1}. This rate is extremely rapid by comparison with accretion studies elsewhere that invariably relate to more mature marshes.

An estimate can be derived of the total accretion that has occurred since the October 1996 breach according to the level beneath the present surface of a fossil soil thought to represent the back barrier surface immediately prior to the breach. This fossil soil is described in Section 2.5 and examples of the accretion layer are provided in Figures 35 and 36. The thicknesses of sediment that have accreted are presented in Table 4.5.

Table 4.5 Accreted sediment thicknesses at 7th Dec-00 above October 1996 surface.

Transect	Lower site*		Mid site*		Upper site*	
	mm	mma^{-1}	mm	mma^{-1}	mm	mma^{-1}
E1	42	10	5	1	38	9
E2	8	2	35	8	40	10

* measurements taken adjacent to the corresponding accretion plate

Up to 42mm of sediment has accreted over the 50-month period from occurrence of the breach to Dec-00 ($10mma^{-1}$), although some variations are evident within the limited sample of sites measured. The rates calculated are around half as rapid as those estimated from the accretion plates. Although it could be that accretion has accelerated between Jun-00 and Dec-00, it is also possible that some of the measurements from the accretion plates could be overestimates due to: (i) poor compaction of recent sedimentation or (ii) settling of the accretion plates. These uncertainties should be resolved by continuing to monitor the plates so as to lengthen the accretion record and by sampling more widely across the sediment layer above the October 1996 land surface so as to assess spatial variations in accretion.

Irrespective of these uncertainties, the accretion rates recorded are very rapid. The literature suggests that newly inundated marshes tend to accrete rapidly at first, although this declines over time as the marsh surface accretes vertically to approach its equilibrium level. In North Norfolk, studies have shown that this equilibrium level is located some 0.6 to 0.8m below the highest astronomical tide. If this simple relation is applicable to Porlock, then a potential exists for rapid accretion of all intertidal back barrier areas up to between 5.0 and 5.5m O.D. Other studies have suggested that accretion rates most frequently exceed rates of sea-level rise on coastlines subject to large tidal ranges. At Porlock, the bay mean tidal range is very large (7.0m), but within the lagoon the effective mean tidal range is only around 1.2m. Accretion is also dependent upon sediment availability. At Porlock, the erosion of the breach channel and recession of the clay substratum exposed by barrier migration generates abundant suspended sediment at the breach (see Figures 16 and 32). Flood tidal currents transport much of this material into the lagoon where it may be deposited on the accreting saltmarsh and lagoon margins. Prior to the recent connection of the breach channel with the main drainage dyke, the impounding of lagoon waters at around 3.8m O.D. for up to 9 hours during the bay tide low water would have further assisted the deposition of fine sediments.

In summary, the conditions at Porlock appear conducive to accretion, but the availability of sediments from the eroding breach channel and clay platform is probably the major factor in explaining the rapid rates recorded. A comparison of the orange-brown colour of the sediments deposited (Figures 35 and 36) with that of the eroding platform and channel (Figure 17) clearly supports the probability of a linkage between the two materials. It would appear therefore that the erosion of the clay platform and breach channel is beneficial to the development of the backbarrier saltmarsh. Furthermore, as the marsh accretes vertically it will in turn form an improved foundation for the landward retreating barrier enabling the landform assemblage to become self-regulating.

A comparison of accretion rates may be made with Pagham Harbour, West Sussex that was breached in 1910 following some 36 years of reclamation (Cundy *et al.*, in press). Accretion rates of between 4 and 8 mma^{-1} (1910-94) were estimated according to thicknesses of sediment layers measured above the buried 1910 soil. Further studies based on ^{137}Caesium dating of fallout from nuclear weapon testing indicated accretion of 4-6mma^{-1} since 1963. The broad correspondence with the Porlock rates and the tendency identified for slowing of accretion over time following the breach suggest that clearly that generic principles with potential wider application may be derived from study of sites such as Porlock and Pagham.

5. IMPLICATIONS OF CHANGES

This report has attempted to establish and explain in some detail the complex geomorphological changes that have occurred within Porlock Bay and to provide a baseline for future studies. In this section the understanding gained is applied in terms of the implications for the present and future qualities and uses of the site. The specific implications are identified in Italics.

5.1 Coastal Defence

1) Over much of the study area there has been a change in barrier stability from a managed static form to a more dynamic type of stability that maintains the overall integrity of the barrier, but increases the frequency of changes in its form and position. New pathways and boundaries of drift have been produced and the complexity of the geomorphic shoreline system has increased considerably. The monitoring completed to date, reveals that processes or changes occurring in one part of the barrier are likely to have impacts in neighbouring behavioural cells and potentially also in back barrier areas. *It means that there will be a continuing need to monitor changes and to appraise their implications.*
2) The barrier continues to function as a coastal defence structure, but it is more responsive to forcing and adjusts its form to achieve the optimum wave energy dissipation with the gravel volume that is available. Its adjustments involving recession, widening and flattening are beneficial for they introduce portions of the underlying substrata into the active profile allowing it to lengthen and become more dissipative so reducing the possibility of catastrophic barrier breakdown. The October 1996 breach occurred during an abrupt transition from the steepened artificially maintained form rather than due to the breakdown of a natural barrier. There is a possibility that other parts of the barrier undergoing this transition between the managed and natural forms could breakdown catastrophically *e.g*. Cell 5 between New Works and the War Memorial. *However, the monitoring undertaken to date has provided confidence that excepting the 1996 breach, the process has not been catastrophic and the changes were tolerable in coastal defence terms. The implication is clearly that the natural barrier form can tolerate periodic overwashing so making any return to the previous high maintenance management policy unnecessary.*
3) The barrier has maintained its integrity and function as an effective wave dissipator at all locations except at the breach. Even here, the development of the flanking spits and exposure of the clay platform strongly inhibits wave penetration into the lagoon. The monitoring undertaken to date enables four key locations to be identified where the continued barrier integrity could be threatened as follows: (a) the Eastern Spit (Cell 2) that is becoming depleted due to its interaction with the breach channel; (b) Porlockford barrier (Cell 3) at its attachment to Porlockford cliffs for it loses gravel by drift to Cell 1 and the breach channel more rapidly than it receives fresh inputs; (c) Cell 5 as the barrier undergoes transition from the artificial to the natural form and (d) a small zone of crest thinning and seepage opposite the War Memorial that renders the artificial barrier susceptible to overwashing. *The implications in areas (b) and (d) would be for landward spreads of gravel and an increase the frequency of inundation at sites where inundation is already experienced via the established breach. At areas (a) and (c) the backshore is sufficiently low that a new breach could form if the protective barrier becomes severely depleted. Sediment depletion and barrier thinning are most apparent at areas (a) and*

(b). Areas (a), (c) and (d) are covered well by the existing monitoring, but two or three additional profiles ideally need to be established to monitor area (b).

4) Several co-incident factors contributed to the occurrence of the breach *e.g.* natural gravel depletion, an artificially re-profiled static defence line, cessation of active management, a storm surge, a high spring tide and a wave event. Its subsequent development as a permanent feature appears related to transgression over a discontinuity in the clay substratum that became exploited by tidal exchange. The processes of drift inferred by the monitoring undertaken to date appear insufficient to naturally seal the inlet that has formed such that it is likely to be maintained naturally for the foreseeable future. *The implication is that the breach channel will continue to intercept drift along the barrier and the ebb tidal delta associated is likely to grow such that additional gravel becomes stored on the lower foreshore rather than on the barrier. Together with steady erosion of old barrier core sediments as the artificial barrier in Cell 5 is re-worked, the barrier as a whole is likely to continue to reduce in volume, albeit at a diminishing rate.*

5) In its present breached condition the barrier provides little protection at all against flooding due to efficient tidal exchange at the breach inlet. Measurements suggest that lagoon levels follow closely the tidal levels of the bay, especially during extremely high sea-level events. *The implication is that the backbarrier intertidal margins will remain sensitive to the effects of storm surges and sea-level rise, although the barrier will inhibit wave penetration. It suggests that there are needs to plan back barrier land uses according to surface elevation and make allowances for the combined effects of future sea-level rise and storm surges. The zone affected is likely to be modest and unlikely to include any properties for there is a natural rise in topography inland of the area already subject to tidal flooding.*

6) A potential benefit is that marsh accretion appears likely to outstrip sea-level rise to produce a net gain in backbarrier land levels. This gain will tend to be at the expense of backbarrier areas that are likely to reduce due to barrier migration. It is probable that present rapid rates of barrier recession result from the transition from an artificial to a natural barrier form. Thus, it is postulated that recession should reduce slightly as the transitions are completed. As yet, the monitoring record is to short to determine any reliable trends due to short term, or seasonal profile variability.

5.2 Habitats and Earth Science Conservation

1) New dynamic landforms including mobile barriers and spits, an ebb tidal delta and an evolving inlet have formed. They have great value for earth science conservation because they are at a very early stage of their development and their freedom of movement is almost totally unconfined by management. The monitoring undertaken to date adds to this value for it establishes a baseline against which future changes can be compared and further studies developed. *The implication is that continued free behaviour and natural development of coastal landforms is desirable within Porlock Bay.*

2) The newly formed dynamic barriers are likely at present to be too active to permit development of significant shingle vegetation communities.

3) The former freshwater back barrier lagoon has been exchanged for an intertidal lagoon, although the regime of the latter has altered recently such that it now almost completely empties at low water, whereas between Oct-96 and Dec-00 it retained water to a level of

around 3.8m O.D. A strongly accreting marsh with expansion of saltmarsh vegetation has developed area around the fringes of the lagoon at elevations of between 4 and 5m O.D. *The recent change in lagoon regime may have implications for bird usage for the open water of the lagoon is reduced and replaced by intertidal mudflats. However, the increased intertidal area provides opportunities for a considerable expansion of saltmarsh providing that vertical accretion continues.*

4) Landward extension of washover fans and migration of the barrier as it has developed a natural form has resulted in transgression of backbarrier areas. The developing marsh is being squeezed between the migrating barrier and static field boundaries inland. *The implication is that to maintain the extent of the backbarrier habitat, opportunities should be sought to move back these field boundaries and allow regular tidal inundation where there are suitable low-lying lands. The areas involved are likely to be modest for topography rises inland. Furthermore, this fringe is probably already subject to periodic inundation due to coincidence of storm surges with high spring tides e.g. Figure 4.*

5) Pressures due to future climate change induced acceleration in rates of sea-level rise may not be a problem for the developing saltmarsh for it appears capable of accreting vertically to keep up with, or exceed even the most rapid predicted rates of rise. Sea-level rise may affect the habitat more significantly if it causes acceleration of barrier migration (see implication no. 4 above). *The implication is that the backbarrier habitat has the potential to develop into a resilient natural system during a period when other similar habitats elsewhere may experience environmental pressures and suffer losses of extent and quality.*

6. CONCLUSIONS

The research and monitoring undertaken has achieved a synthesis of the geomorphological changes occurring within Porlock Bay over a range of timescales as follows:

1) A long term depletion and reorientation of the barrier has been identified. This is due to a reduction of gravel inputs into the bay and the continued operation of a west to east drift on the barrier.
2) The natural response to this depletion has been for barrier migration, beaching and long-term maintenance of intertidal lagoons. This is the natural state of the coastal landforms of the bay given present environmental conditions.
3) Management over at least the past two centuries has sought to maintain a continuous and static barrier to prevent inundation of land behind. Over time it created an artificially heightened and steepened barrier profile.
4) With the relaxation of management in the early 1990s a significant portion of the artificial barrier has been reworked back to its natural lower, but wider form. Landward migration of the crest by up to 20m and extension of gravel washover fans by up to 50m have accompanied this transition.
5) The natural barrier has generally retained its integrity during the transformation from the steepened managed form. The static stability of the managed barrier has been exchanged for the dynamic stability of the new natural form. The new barrier retains its wave dissipation capacity by migrating landward to lengthen its dissipative profile.
6) Immediately to the west of New Works a breach occurred in the barrier in October 1996. It appears that co-incident factors of gravel depletion, the artificially steepened profile, cessation of active management, and a storm surge, high spring tide and wave event resulted in major overwashing and landward migration of the barrier at this point. Its subsequent development as a permanent feature appears related to its transgression over a discontinuity in the clay substratum that became exploited by tidal exchange.
7) The quantity of tidal exchange at the breach resulted in rapid cutting of a channel into the clay substratum that has further concentrated tidal currents such that the new inlet cannot be sealed by drift and should now be considered permanent.
8) The inundated back barrier lowlands have formed an intertidal lagoon and a strongly accreting and expanding saltmarsh. Rapid headward erosion of the breach channel recently intercepted an artificial drainage channel so that the lagoon now almost completely empties at low water, whereas between Oct-96 and Dec-00 it retained water to a level of around 3.8m O.D.
9) The breach has significantly affected the behaviour of the barrier for it has introduced a new drift boundary and a local drift reversal. Gravels drift into the channel from the west and the east and are flushed seaward to accumulate in a small ebb tidal delta. Drift appears greater to the west of the breach such that the western spit is extending into the breach channel. The eastern spit is retreating away from the breach. The net result is that the inlet at the breach is slowly migrating eastward in the direction of prevailing drift within the bay.
10) Some five partially dependent barrier “cells” including two spits flanking the breach channel have formed. The behaviour of these cells has been defined in terms of changes in profile and barrier volume. Two cells are decreasing in volume, one is increasing and

two are stable. Gravel losses occur from the barrier to the growing ebb tidal delta and volume loss also occurs due to erosion of fine sediments from the core as the artificial barrier segments are re-worked back to a natural form. The trend since 1988 has been for slow loss of barrier volume.

The changes documented since the cessation of active management have significantly increased the complexity and dynamism of the geomorphic shoreline system. Changes occur more frequently and there is potential for those occurring in one part of the barrier to have impacts in neighbouring barrier cells (within Porlock Bay) and potentially also in back barrier areas. Although the net result to date has been the maintenance of barrier integrity (excepting the breach) and its continued effective wave dissipation function, it is important that the changes occurring should continue to be monitored and understood.

An important question concerns the extent to which the coastal landforms have adjusted to the cessation of active management and the occurrence of the breach and whether there is evidence for reduction in rates of change as adjustment progresses. Firm conclusions cannot yet be drawn concerning this issue due to the limited time elapsed since these key events and the short record of detailed monitoring so far compiled. Nevertheless, the following observations are made:

1) The barrier between Porlockford and New Works is now totally re-worked and has assumed a natural form. The transition involved a significant landward migration and this rapid migration has continued where the barrier has become depleted *e.g.* Cell 2. Elsewhere, barrier position and elevation has fluctuated since the transition. Although this is indicative of a greater degree of adjustment, it may also be due to short term or seasonal variations making the longer-term stability difficult to establish at present. This can be clarified by lengthening the monitoring record enabling detection and elimination of short-term variations.
2) The barrier to the east of the War Memorial has yet to react in any significant manner to the cessation of active management and retains its steepened form.
3) Recession rates of the clay cliffs of the breach channel have reduced considerably, although some renewed erosion is anticipated following its recent connection with a lagoon drainage channel. The tidal regime and extreme levels of the lagoon correlate strongly with those of the bay. Thus, a reasonable adjustment has already been achieved between the breach channel and the lagoon.
4) Rapid accretion is recorded in the back barrier marshes and lagoon. Although this primarily reflects lack of adjustment between the intertidal lagoon and its tidal regime it is beneficial to habitat development and over time should build surface levels upwards towards their preferred equilibrium.

A tentative conclusion is that the changes associated with the cessation of active management are such that adjustment of landforms to the new conditions will require at least several decades. Many of the rapid and abrupt changes are completed or substantially in progress, but ongoing changes should continue for the foreseeable future, albeit at lesser rates. The dynamic nature of the landforms involved and the variations likely in environmental forcing due to probable future climate change mean that full adjustment and static stability are unlikely to be achieved. Instead, the continuation of adjustments should be anticipated and accommodated for within the future management of the bay.

The programme of monitoring and research has adopted a holistic approach to address the diversity of landforms now present within the bay, accommodating their morphological complexity and the range of timescales over which they evolve. As such, this study could serve as a model approach to the geomorphological investigation of exposed shorelines experiencing, or at risk of breaching. The following are regarded as key elements in the methods applied:

1) The GPS survey method enabled rapid measurements of complex features. Furthermore, its capability to relocate co-ordinates in the field is a major advantage in conducting repetitive surveys of highly dynamic features where maintenance of large numbers physical profile markers is impossible.
2) Even with the advantages of GPS survey it was preferable when tackling the complex morphological features to survey a combination of fixed profiles and defined morphological features rather than attempting to collect sufficient data with which to construct digital ground models. Remote sensing approaches are preferable for acquisition of the high data densities required for ground modelling of complex coastal morphologies.
3) Integration of survey information and historical data within a GIS was advantageous for it enabled overlay of any combination of a wide range of morphological features and different survey dates. Furthermore it can incorporate the results of additional studies of land elevations, tidal levels, vegetation and accretion in backbarrier areas.
4) Volumetric analyses of defined behavioral cells were effective in simplifying the complex changes that were occurring on the barrier.
5) The “Barrier Inertia Index” provided a quick assessment of relative stability and should be applicable to barriers elsewhere.
6) Preparation of a qualitative model of the barrier and breach system greatly assisted the explanation of the complex changes that were recorded.

It is emphasised that the work discussed here represents a unique study of a single site. However, it establishes a basis for identifying some of the generic principles governing the behaviour and development of similar sites elsewhere. Permanent barrier breaches of the type studied are relatively rare on the exposed British coast and have not previously been monitored directly during their early stages of development. Their occurrence could, however, increase significantly should there in future be a more widespread adoption of non-intervention shoreline management policies. It is therefore important to continue the monitoring at Porlock, to study additional sites and to extend research towards quantification of the forcing parameters as well as recording the landform responses.

7. RECOMMENDATIONS

The following comprises a brief summary of recommendations for further research and monitoring at Porlock based directly on the results and lessons learnt:

1) A check is recommended of the baseline transfer that relates the surveys undertaken to the O.S. National Grid. A new precise method of achieving this is now available as described in Section 2.1.2.
2) Barrier surveys are appropriate at three-monthly intervals until there is clear evidence that short-term variability can be defined and longer-term rates of change are reducing. Once the features of the barrier and breach channel have achieved some sort of equilibrium status, the interval between monitoring dates can be extended.
3) Two or three additional profiles are required to provide coverage of the western part of Cell 3, especially at its interface with Porlockford Cliffs where a zone of crest erosion has developed.
4) Surveys every two years should be undertaken to monitor the development and integrity of the barrier beach as a whole (air photos would suffice). However, if the barrier is breached at another site a more concentrated monitoring framework could be considered.
5) There is no longer a need to monitor lagoon levels as they have been shown to relate closely to the bay tidal predictions. Furthermore this correlation was confirmed for the new tidal regime by Cope (personal communication) on 30th July 2001 as part of her doctoral research.
6) Continued monitoring of the installed accretion plates should be undertaken to lengthen the record of measurements. New plates should be considered to extend the monitoring to the newly exposed lower intertidal areas.
7) Wider sampling of the lagoon sediment thickness that has accreted above the Oct. 96 soil surface would help to establish the spatial variation in accretion and could enable a calculation of the total volume accreted.
8) There is an opportunity to link data on ground levels, tidal levels accretion rates and vegetation development. This work is currently being progressed by S. Cope as part of her doctoral studies.
9) Opportunities for wave monitoring, a back analysis of the 1996 breach event and application of the Bradbury barrier profile prediction model are set out in a research proposal submitted in conjunction with Dr Andrew Bradbury in February 2001.

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FIGURES 1-51

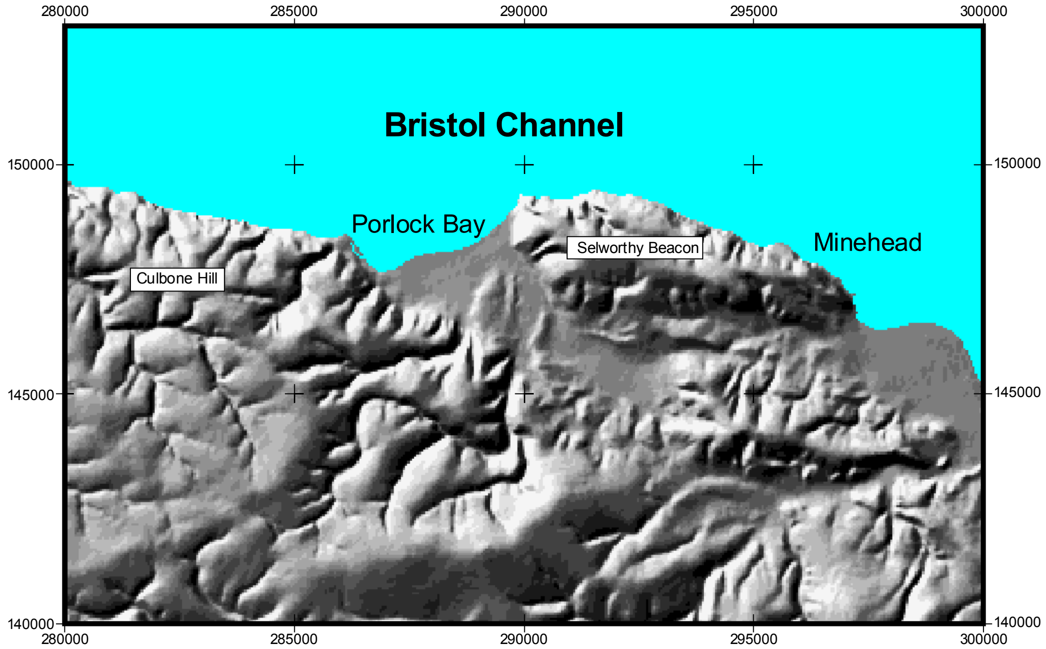

Figure 1 Site of Porlock Bay, North West Somerset. Note that the bay is confined by headlands and high relief. Several small streams with steep catchments feed freshwater to the low-lying areas of the Bay behind the barrier. (5km grid tics are depicted)

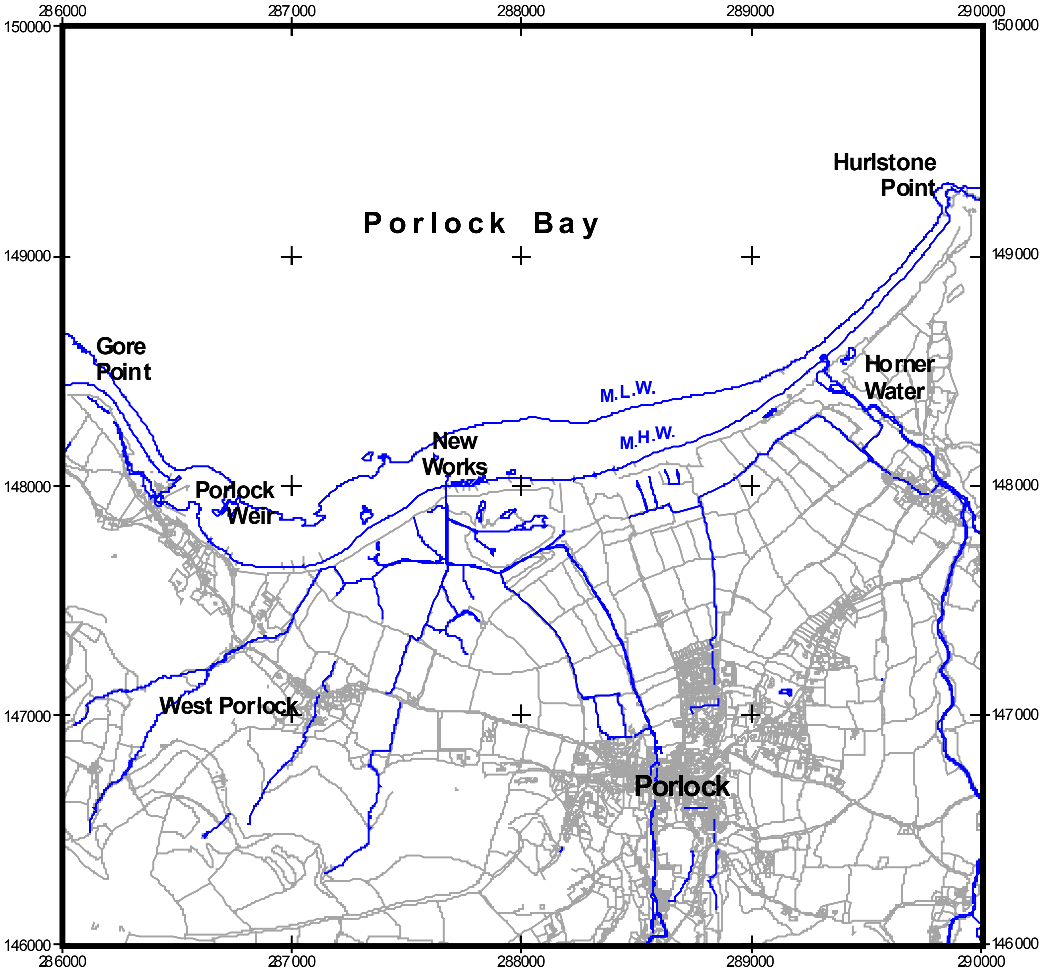

Figure 2 Porlock Bay location map. Note the small streams draining into the bay, the network of drainage channels converging on New Works and the lack of settlements in central parts.

Figure 3 View westwards across Central Parts of Porlock Bay demonstrating the artificially maintained barrier with its steep and high crest. During this time, the back-barrier area was a freshwater grazing marsh drained by the sluice at New Works (mid distance). The exposed foreshore represents land transgressed by the retreating barrier.

Figure 4 Porlock breach and lagoon revealing extent of flooding during an extremely high tide on 01.03.98.

Figure 5 Barrier and breach channel demonstrating landowner's unsuccessful effort to seal the breach with a 'fence' in September 1997. Note the position of the waterfall at the breach some 20m seaward of the fence and also New Works outlet functioning to drain the lagoon. Relic tidal channels in the foreground have been reactivated and are functioning to distribute and drain tidal waters within the developing saltmarsh.

Figure 6 Vertical aerial photograph mosaic of the breach and lagoon at 1216hrs on 1st April 1999. Note that the photos are non-rectified and should not be used for direct measurement of features.

Figure 7. Geomorphology and processes of Porlock Bay, 1st April 1999.

→ net beach drift direction

1. Gore Point headland – partly eroded solifluction lobe that permits a small input of gravel from the west.
2. Mature tidal creek and saltmarsh – provides a possible analogue for the environment that may form following the breach within the Bay.
3. Porlock Weir harbour groyne or breakwater that intercepts drift to assist maintenance of a navigable channel. Has promoted beach accretion immediately updrift
4. Lobate gravel and cobble bank formed in lee of breakwater – has experienced several recent episodes of growth.
5. Porlockford sea wall constructed to protect the B3225 road as the shore has eroded.
6. Porlockford Cliffs cut in solifluction deposits eroding at 0.5-0.6 ma^{-1} (1889-1962) and yielding small quantities of gravel. Remaining active, but eroding more slowly recently.
7. Porlock gravel barrier identifying portions subject to overwashing and retreat. The beach crest has been pushed landward forming a lower, but wider crest profile.
8. Area of marsh subject to regular saline inundation and/or intrusion identified by darker vegetation colour associated with transition from freshwater to saline communities.
9. "Fossil" gravel spits and recurves containing late-Holocene beach material. Some were mined for gravel to sustain the 1968-71 barrier reconstruction.
10. Intertidal lagoon formed following the 28th October 1996 breach and establishment of the permanent tidal inlet.
11. Stable barrier retaining earlier artificially reconstructed form and accreting in places.
12. Boulder frame representing the eroded surface transgressed by the barrier. It is wider and higher in central areas affording more effective wave dissipation.
13. Seepage of the Horner Water stream through the breach. Breaches the barrier from landward during high discharge events when it may transport beach materials seaward.
14. Steep cobble beach (accreting up to 20m, 1888 to 1972) , higher and wider than the barrier to the west. Exposed to WNW waves and lacking a dissipative boulder frame.
15. Hurlstone Point headland. Hard rock headland thought to form a total barrier to gravel drift, although it fails to retain sand within Porlock Bay.

Figure 8. Overwashing in progress on Hurst Spit, Hampshire on 18.12.89 (photo courtesy of Dr Andrew Bradbury). Similar processes occur at Porlock and would have initiated the 1996 breach.

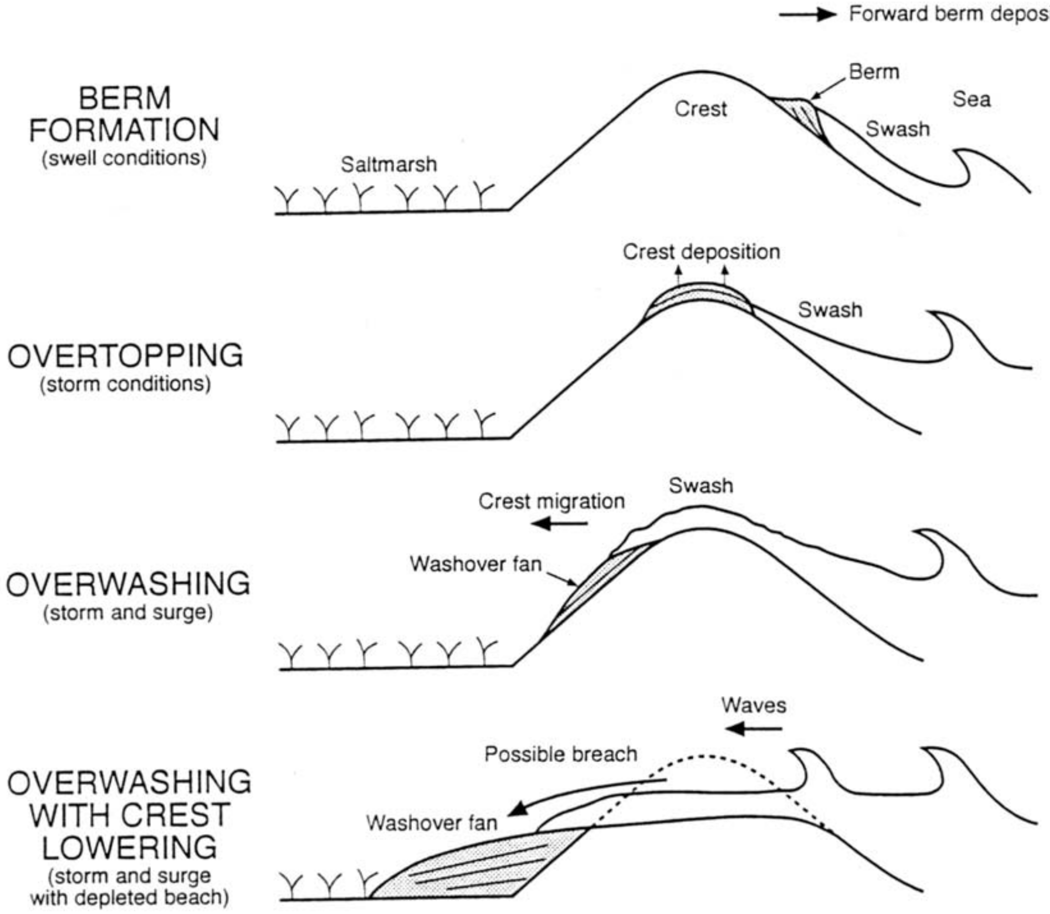

Figure 9 Processes of gravel barrier development. The 1996 breach at Porlock was generated during an episode of overwashing with crest lowering.

Figure 10 Seepage “cans” on the backslope or landward face of the barrier near to the War Memorial close to profile E10. These features are charactersistic of active gravel barriers and are formed by seepage of sea water through the barrier during periods of high water level in the bay. Note that seepage pressure is sufficient to displace material resulting in deposition of debris fans a short distance landward. A strand line of flotsam indicates a recent maximum extreme water level of 6.3mO.D. in the lagoon, possibly during the event that formed the can. This level is almost certainly lower than the corresponding Bay extreme level so the hydrostatic gradient thus produced may explain the high seepage pressures generated. Note that flooding of the lagoon partly equalises these pressure gradients reducing seepage and maintaining barrier integrity. Seepage is also inhibited by poorly sorted sediments, wider barriers and vegetation.

Figure 11. Low cliffs at Porlockford cut in solifluction deposits. Eroding at 0.5 - 0.6ma^{-1} between 1888 and 1972, they remain active, although recession has slowed. The beach here is relatively sheltered by the coast immediately to the NW and drift is thought to operate slowly in a net eastward direction. The timber pile groynes were constructed in 1967-68 and have effectively trapped material.

Figure 12. The solifluction deposits of Porlockford Cliffs. They comprise poorly sorted angular sands, grits, gravels and cobbles up to 100mm diameter. The larger clasts are hard sandstones similar in type to those forming the barrier beach so that cliff retreat yields small quantities of beaching forming materials. It is thought that the Porlock barrier was formed from the erosion of previously more extensive deposits of this type in the mid and late-Holocene as sea-levels rose towards their present elevation.

Figure 13. Flattened and overwashed barrier at New Works viewed from profile E03 on 14th Jan 1999. Note that the barrier is lower, but wider than the more static and vegetated sections visible in the mid distance. The wide low-gradient boulder frame is seen comprising the lower foreshore.

Figure 14. Erosion cutting into the crest of the "stable" barrier at Profile E09 on 4th May 2000. Note the vegetated backslope in the foreground and a less well vegetated section in the mid-distance close to the war memorial. Such areas indicate parts of the barrier that are becoming increasingly subject to seepage and occasional overwashing. The disturbance produced is such that a continuous vegetation cover cannot become established.

The two photographs clearly illustrate the differences between the high, narrow, steep and static artificial barrier form (*e.g.* Figure 14), as opposed to the flatter dynamic landward migrating natural barrier that has become established in many parts as the management practices were relaxed (Figure 13). The latter state is likely to become increasingly prevalent in the future.

Figure 15. Close view of breach approaching low water at 1216hrs on 1st April 1999. Lagoon waters are draining out of the breach channel forming distinct waterfalls over the retreating clay cliffs that define the incised channel. The recurved spits and spreads of overwash gravels rest upon the clay platform. The western spit is migrating towards the incised channel such that its gravel spills into it becoming entrained by currents and transported seaward forming banks in the outer channel.

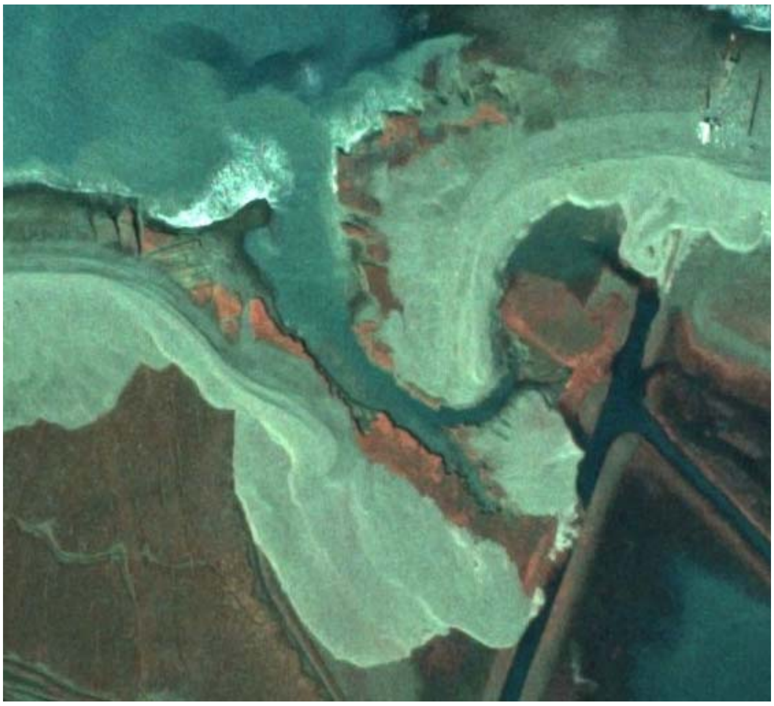

Figure 16. Near-infrared digital image of the breach approaching high tide at 1345hrs (GMT) on 4th September 1999. Note that the tide has yet to rise above the clay cliffs and platform and that the two "waterfalls" have retreated closer towards the main artificial drainage cut. Gravel entering the incised channel has formed a small temporary spit on the western flank. This imagery is especially effective for study of vegetation. Algae on the clay platform show up bright red and saltmarsh is darker (bottom left). Waters around the breach are turbid due to wave erosion of the clay cliffs.

Figure 17. View eastwards over breach channel from the western gravel spit. Note the incision of the channel into the underlying clay and the slow retreat from June-98 to May-00 of the clay cliffs forming the channel flanks. The western spit (foreground) has grown and migrated towards the breach channel covering the clay platform. By contrast, the eastern spit has diminished and migrated NE away from the breach channel. Barrier losses are especially noticeable around New Works in the mid distance in May-00. The headward parts of the breach channel bifurcated in late 1998 and a well established NE arm is seen at the landward tip of the eastern spit in May-00. Note the linear furrows on the clay platform which are interpreted as the remains of previous drainage ditches/channels on the old marsh surface now transgressed by the barrier and eroded. It is thought that a major NNW – SSE trending ditch existed previously at the breach and was exploited by the exchange of tidal waters resulting in the formation of a permanent rather than temporary inlet. View is from W03.

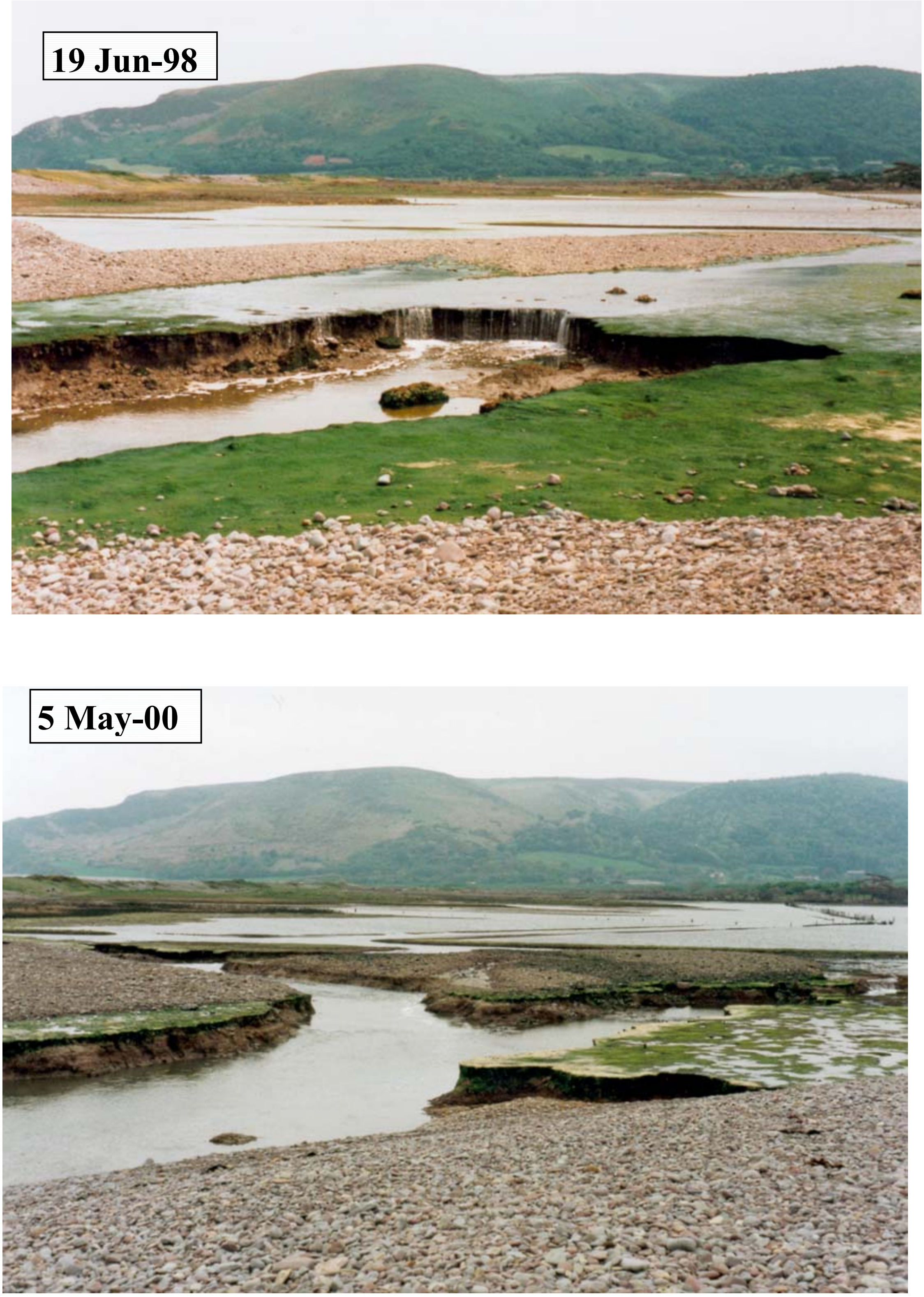

Figure 18. The landward extremity of the breach channel cut into Holocene clay back barrier deposits. The lagoon is flooded as the tide rises above the level of the clay platform at about 4m O.D. and then drains as it falls below that level forming a waterfall. The tidal exchange results in strong headward erosion of the clay cliffs. The channel bifurcated in late 1998 forming prominent north eastern and southern tributaries as seen in May-00. Also evident is the encroachment upon the channel of the western spit. Viewpoint is at profile W01.

Figure 19. Breach Channel 5th May 2000 – view seaward. Note the western gravel barrier to the left spilling into the channel and the platform swept clear of gravel to the right by the retreat of the eastern spit. The clay cliffs flanking the channel have continued to retreat slowly.

Figure 20. The NE arm of the breach channel on 5th May 00. It has eroded rapidly headward since late 1998 and by Summer 2000 appeared to have assumed dominance over the southern arm which has evolved more slowly. Continued headward erosion would by July 01 result in linkage to the deep north-south trending drainage ditch that formerly directed flood waters towards the New Works sluice. Such linkage should result in more effective drainage of the lagoon altering its tidal regime.

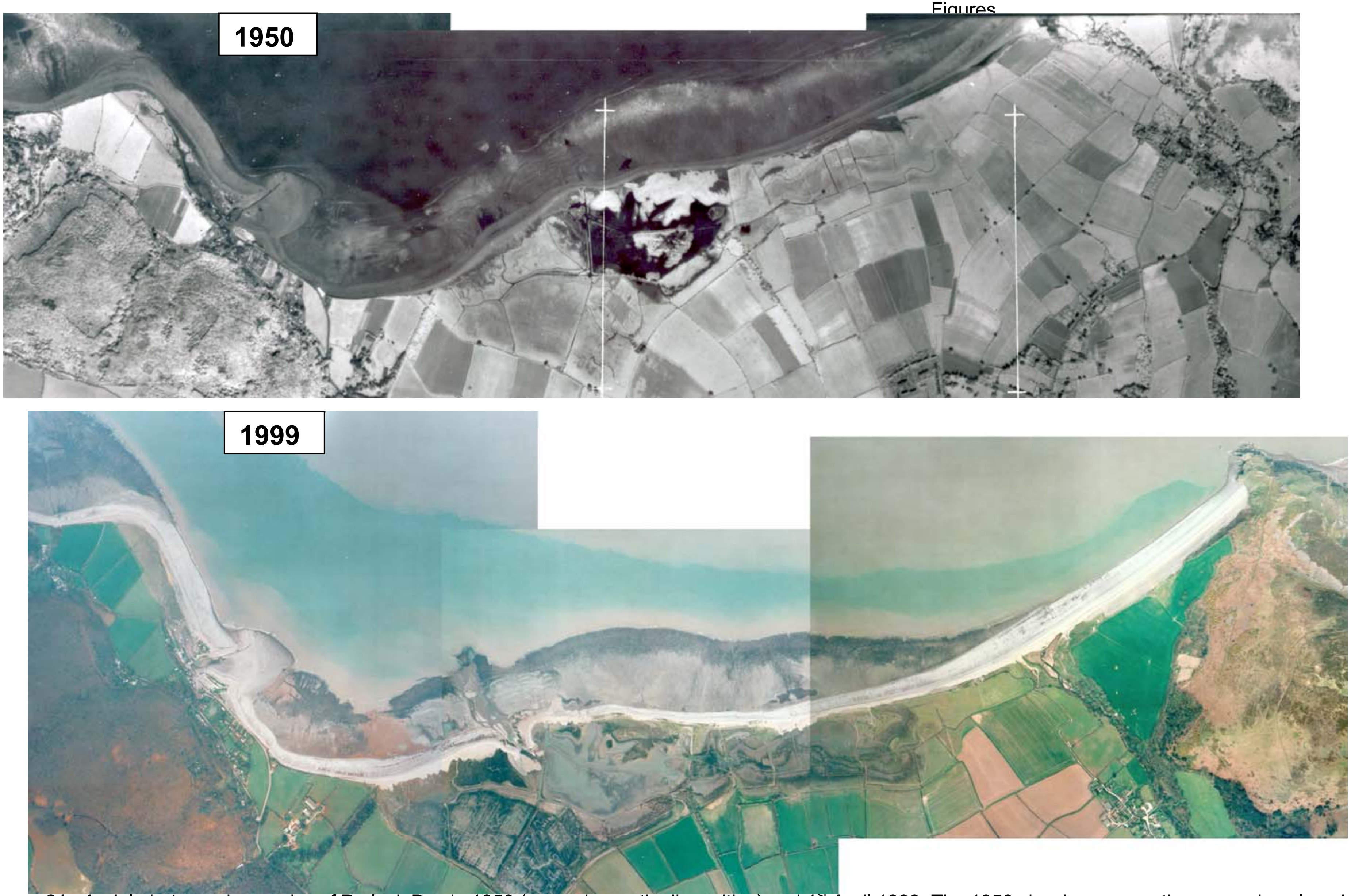

Figure 21. Aerial photograph mosaics of Porlock Bay in 1950 (monochromatic diapositive) and 1st April.1999. The 1950s barrier was continuous and enclosed a freshwater lagoon. Note the relic tidal channels discernible within the 1950s back-barrier marsh that provide evidence of previous intertidal episodes.

Figure 22 Views eastwards from Porlockford Cliffs showing the western extremity of the barrier. Note the timber pile groynes – nos. 4 (foreground), 5, 5a and 6 - that have been deliberately lowered in places to permit eastward drift. The May-00 beach appears to have accreted around groynes 4 and 5, but has suffered losses around groynes 5a and 6 by comparison with Jun-98. The crest also appears to have retreated by several metres. This area was one of the most vulnerable in the 1980s when significant “breaches” occurred on an annual basis. Since 1998, this area has suffered overwashing rather than serious breaching. Crest flattening is followed by natural rebuilding a short distance inland. Overall, the barrier is lower, flatter and wider than its 1980s counterpart and is potentially a more effective dissipater of wave energy.

Figure 23 GPS survey equipment in operation. A static receiver is set up at a known point and the surveyor operates a roving receiver measuring profiles and other features of detail to complete the survey. Note that a radio link operates between the two enabling the surveyor to measure all points in real time.

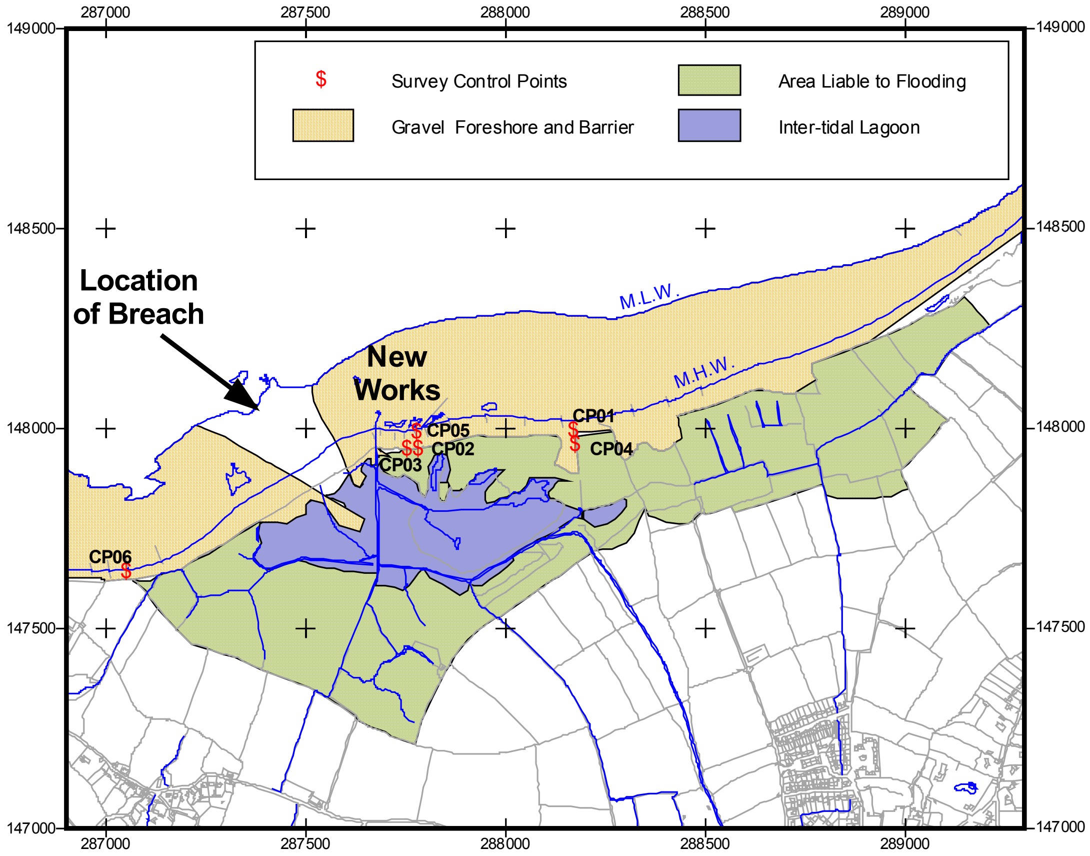

Figure 24 Location of survey control within the study site

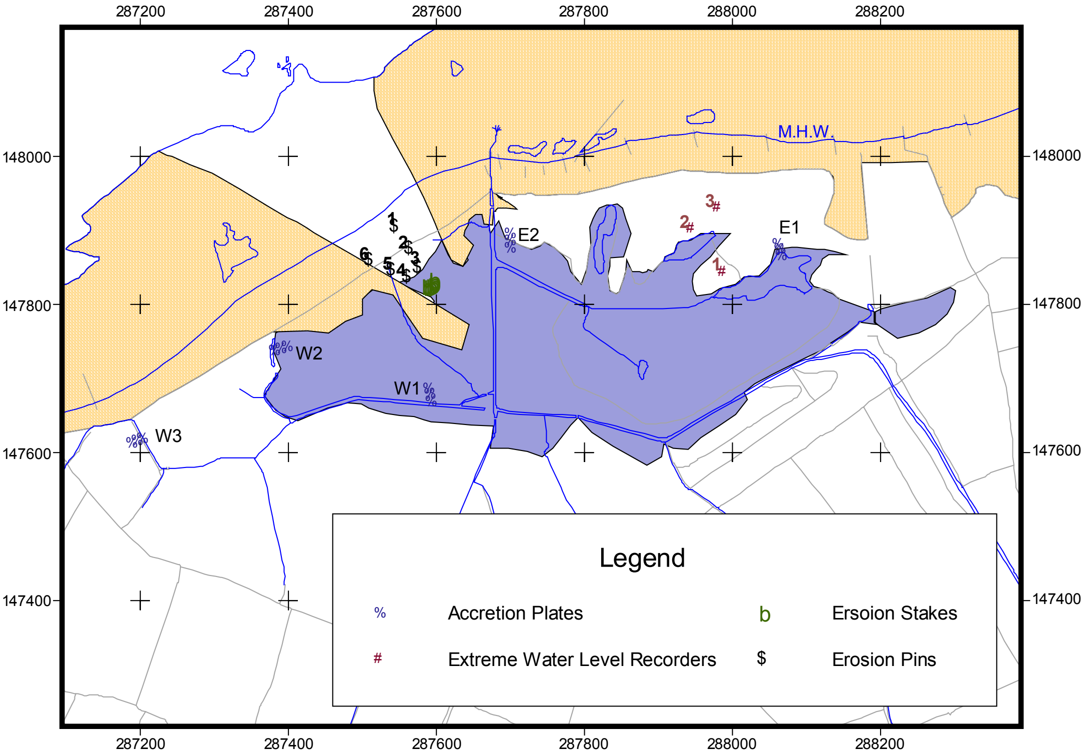

Figure 25 Location of monitoring instrumentation within the study site. Note that the three accretion plates are located in short cross shore profiles at each mapped site.

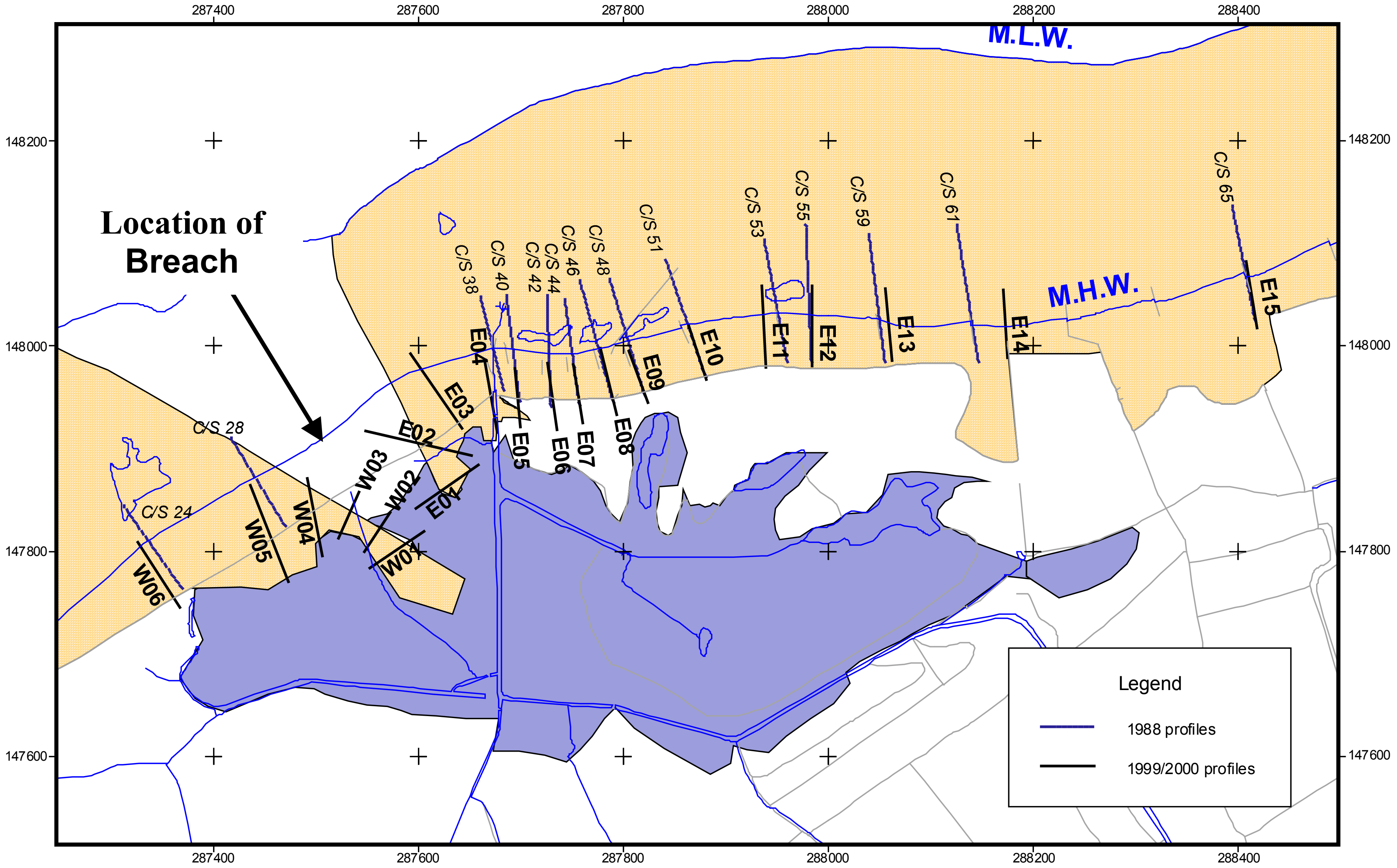

Figure 26. Location of profiles surveyed across the barrier

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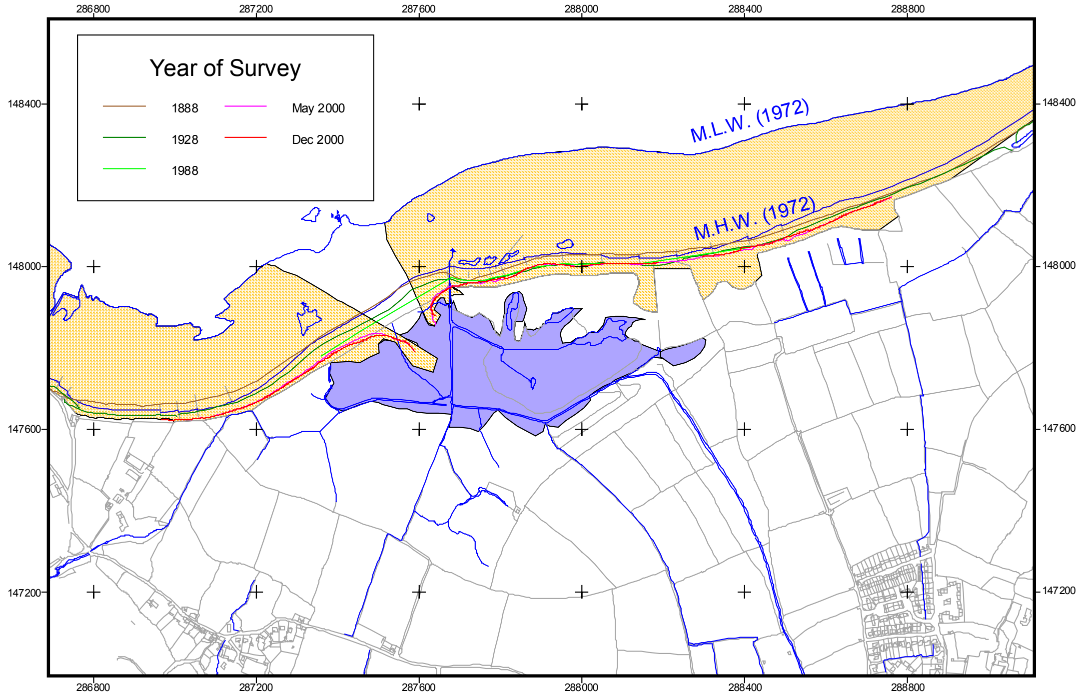


Figure 27 Historical positions of the barrier crest derived from OS plans (1888 and 1928), profiles (1988) and GPS surveys (2000).

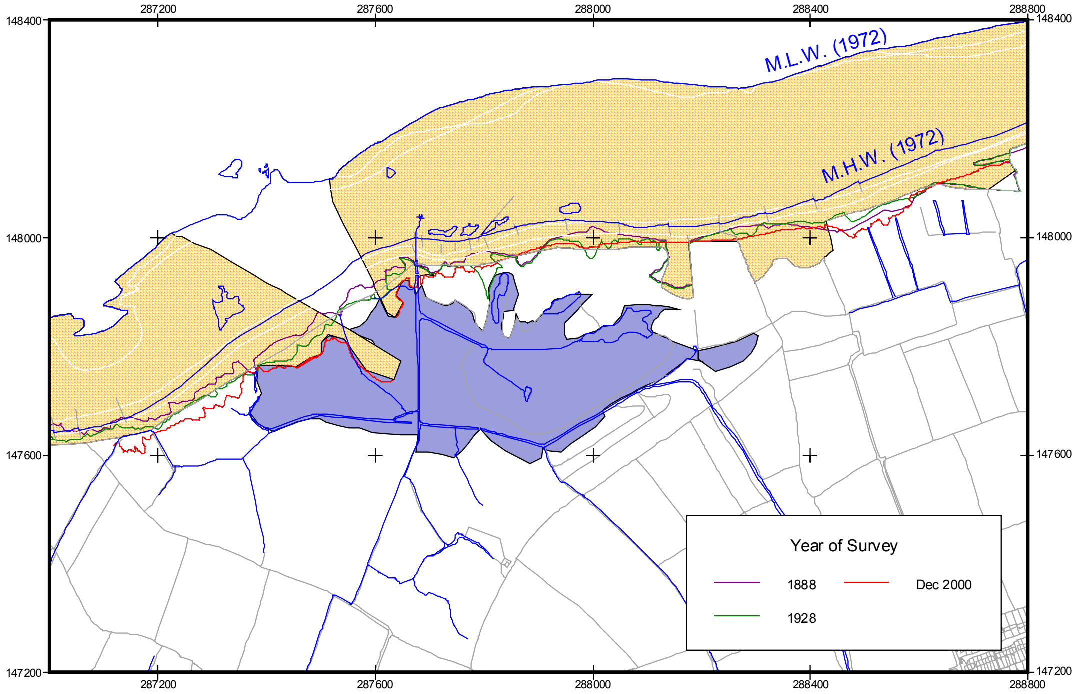


Figure 28 Historical positions of the barrier landward gravel margin (backtoe) derived from OS plans (1888 and 1928), and GPS survey (2000).

Figure 29. Extreme water level recorder sited on the margin of the lagoon close to MHWST. The water sensitive tape is attached to a rod that is held vertically within the standpipe. Water can only enter at the base of the standpipe and dissolves the dye of the tape as the lagoon level rises. The rod and tape are withdrawn from the pipe for measurement and a fresh tape is attached to the rod following each measurement. The standpipe is weatherproof so preventing entry of water except as the lagoon level rises.

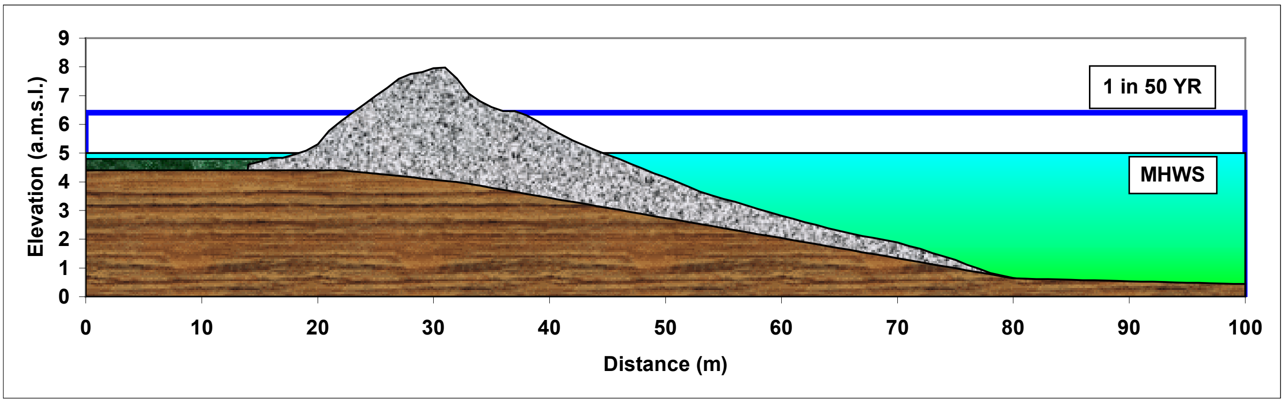


Figure 30 Generalised profile across the Porlock gravel barrier in the vicinity of the War Memorial. The barrier comprises a relatively thin veneer of gravel resting upon a Holocene clay foundation. Mean and extreme tidal levels are indicated. Much of the barrier crest is less than 3m above MHWST and within 1.5m of the 1 in 50 year extreme water level. The lagoon margins are generally at a level of 4.0 to 5.5m O.D. - the extreme water level recorders were sited within this zone.

Figure 31. Marker stake located at the margin of the breach channel. Note the cliff fall immediately in front of the stake. The stakes were moved back from the cliff edge as recession progressed.

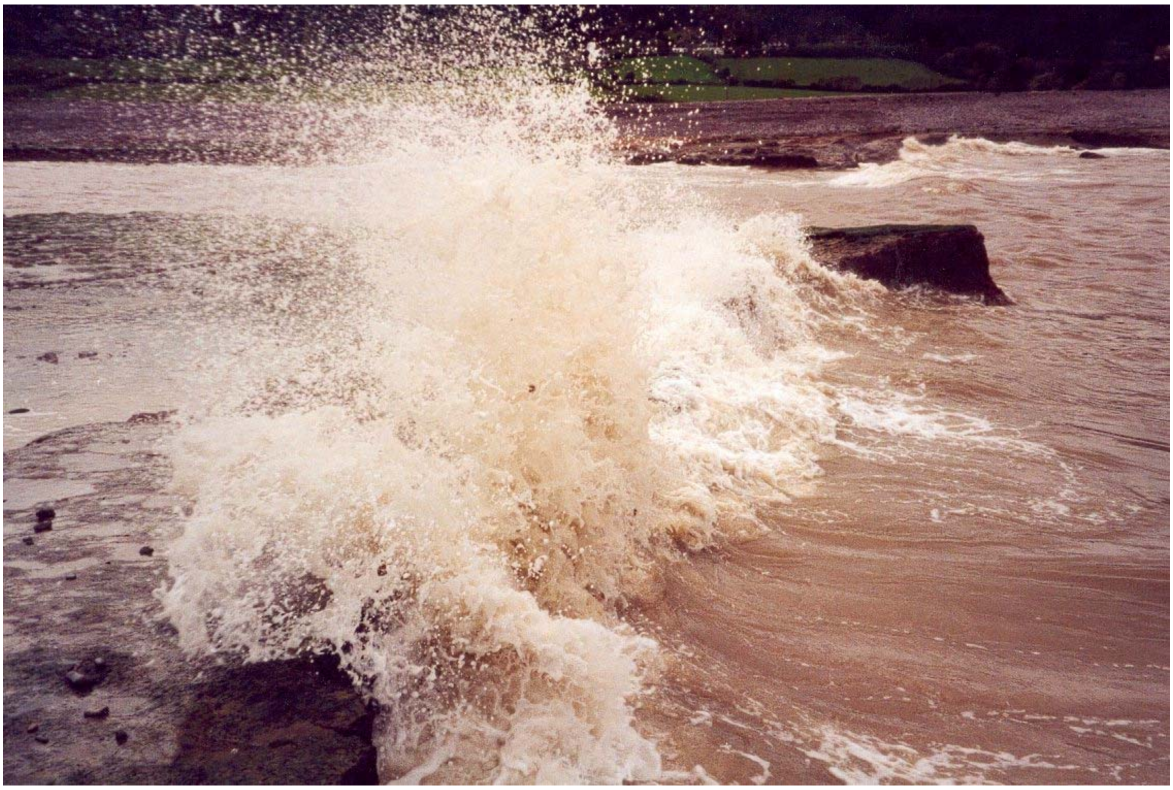


Figure 32. Direct wave breaking upon the clay cliffs of the outer part of the breach channel. The cliffs at exposed locations such as this retreated significantly more rapidly than those along to more sheltered inner channel flanks. Note the turbid waters due to the suspended sediments derived from the ongoing erosion processes.

Figure 33 Insertion of accretion plate B (mid lagoon margin) at accretion ptofileE2. The wire mesh was buried carefully at 100mm depth by replacing the marsh turf to minimise disturbance. The site is relocated using a metal detector to pin point the wire mesh. To measure accretion a steel rule is pressed into the marsh surface until it encounters the wire mesh.

Figure 34 Accretion profile E1 at the lagoon margin. Arrows indicate the locations of the buried accretion plates. The aim is to record accretion occurring at different elevations and with different levels of vegetation cover.

Figure 35. Turf cut from profile E2 upper site showing the clearly defined 30-40mm thick clay layer above a former vegetation/soil surface. This is believed to represent the thickness of marine accretion that has occurred following the breach in October 1996.

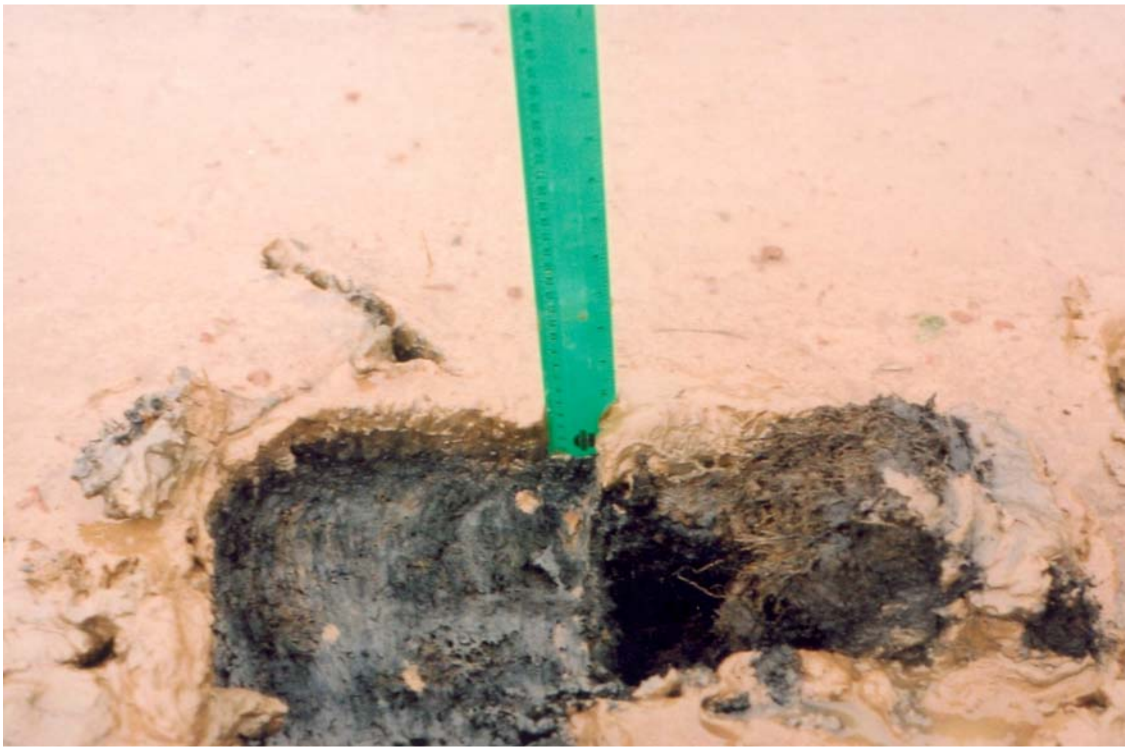


Figure 36. Turf cut from the lagoon bed showing the clay layer to be only 20-30mm thick above the former vegetation/soil surface. Note the relic root systems clearly indicating a buried land surface.

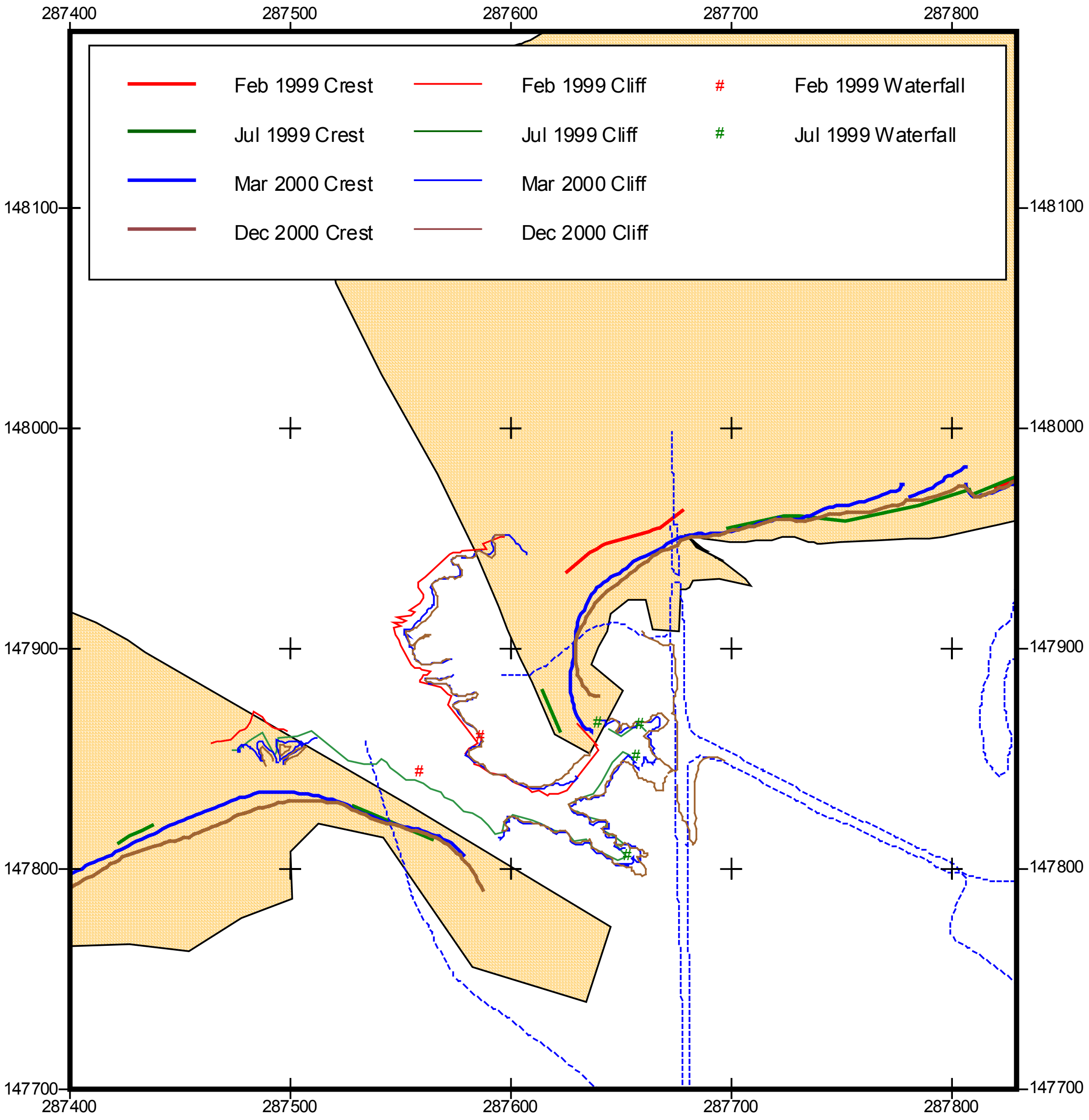


Figure 37 The breach inlet. Surveyed features include the clay cliffs of the incised channel and also the crest of the gravel barrier. The waterfall marking the headward limit of the breach channel has migrated inland by over 100m since Nov. 1997 Note the modest recession of the clay cliffs flanking the channel and the greater recession of the seaward facing clay cliffs. Note also the significant recession of the north-eastern spit or barrier crest. The twin landward 'arms' of the inlet channel are eroding headward towards the main pre-existing drainage ditch. All features could not be surveyed on each occasion due to constraints of time, tidal levels and tidal flows, which made surveying parts of the breach difficult.

Figure 38. View west towards New Works from E08 on 19th June 1998. The barrier is controlled by a series of timber pile groynes constructed in 1967-68 and which have promoted some beach accretion.

Figure 39. View west towards New Works from E08 on 4th May 2000. Note that there has been accretion at the barrier crest and around the groynes in the foreground. However, foreshore lowering and crest recession is evident around the structures at New Works leading to their progressive destruction (compared with the June 98 situation). The barrier in this area is relatively low and is subject to overwashing although it has migrated much more quickly landward to the west of new works than here to the east.

Figure 40. Barrier crest at E15 view westwards on 19th June 1998. The crest is relatively wide and stable although subject to some erosion of the vegetated scarp in the foreground. It retains much of the form of the previous artificially managed barrier. Note the high cliff headlands in the distance that prevent any major eastward drift of fresh sediments into Porlock Bay.

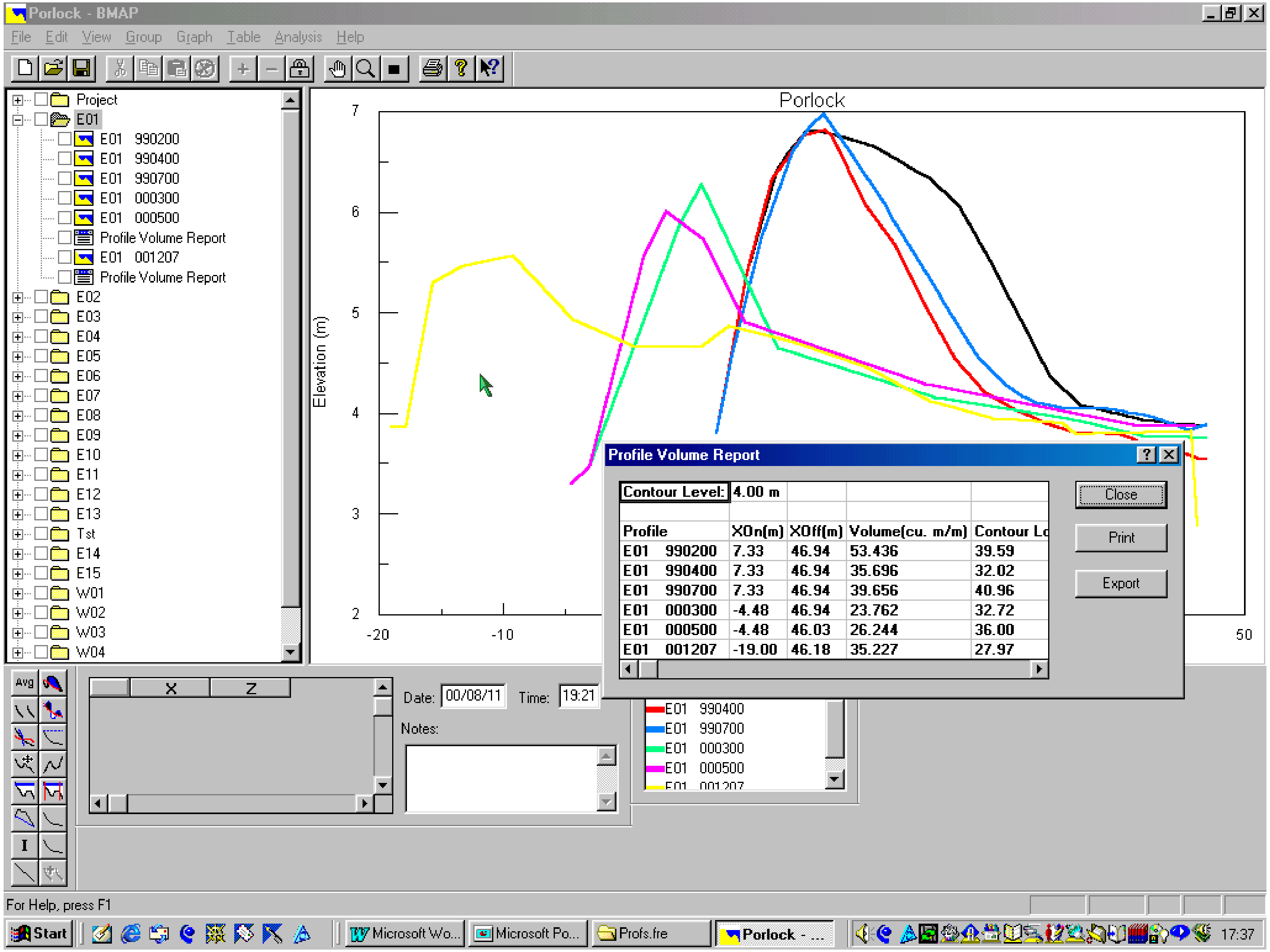
Figure 41. Barrier crest between E 14 and E15 viewed westwards on 14th January 1999. The crest is relatively stable, and a secondary crest has accreted some 3-4m seaward of the original storm crest. Note the extensive low gradient boulder frame forming a dissipative lower foreshore. This feature imposes a depth limitation on the approach of very large waves, except for during high storm surge events.

Figure 42. View east from E 13 over a stable portion of the barrier that has accreted at the crest (note the new berm deposited 1-2m seaward of the previous barrier crest). The wide low gradient boulder frame is seen comprising the lower foreshore and is effective at dissipating wave energy, perhaps contributing towards the stability of this portion.

Figure 43. Newly formed washover fans extending over the developing saltmarsh behind the barrier at Porlockford, 8th December 2000. Note that the landward margins of these fans are surveyed using GPS and plotted as the "backtoe."

Figure 44. Washover fans on the backslope of the active gravel barrier at New Works 14th January 1999. During overwashing the crest is flattened and its material pushed landwards for form the washover fans. Note that the barrier is especially flattened to the immediate left (New Works), but becomes higher, steeper and narrower eastwards into the distance. Viewpoint is from midway between profiles E02 and E03.

Figure 45. Washover fans on 5th May 2000 viewed from approximately the same location as in January 1999. The general morphology has remained unchanged and the flattened barrier has remained stable over the intervening period. Note that the eastern spit from which the photo was taken has migrated further into the lagoon such that the photo viewpoint has moved slightly closer to the washover fans.

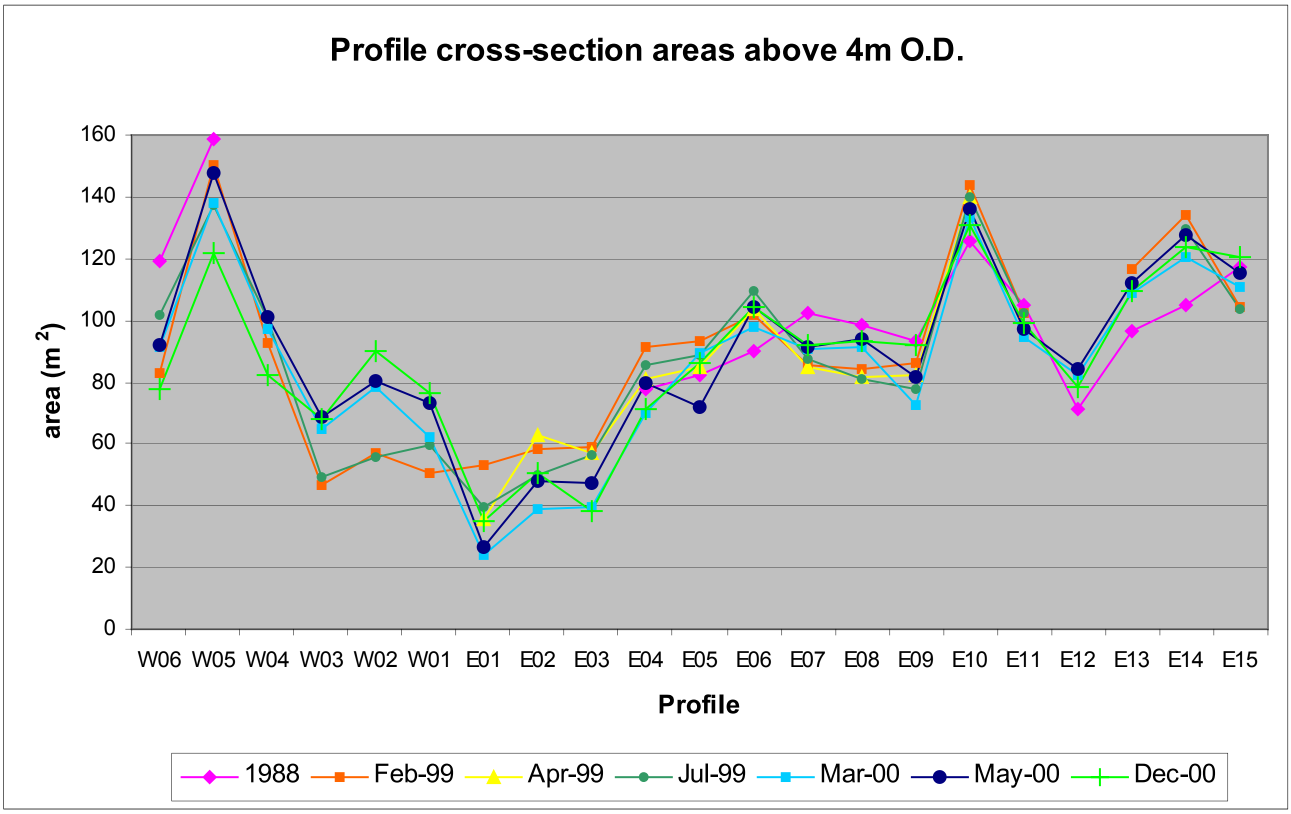


Profile Volume Report

Contour Level:	4.00 m			
Profile	XOn(m)	XOff(m)	Volume(cu. m/m)	Contour Lc
E01 990200	7.33	46.94	53.436	39.59
E01 990400	7.33	46.94	35.696	32.02
E01 990700	7.33	46.94	39.656	40.96
E01 000300	-4.48	46.94	23.762	32.72
E01 000500	-4.48	46.03	26.244	36.00
E01 001207	-19.00	46.18	35.227	27.97

Date: 00/08/11 Time: 19:21

Figure 46. Screenshot of Porlock barrier volume analysis using BMAP software (US Army Corps of Engineers).



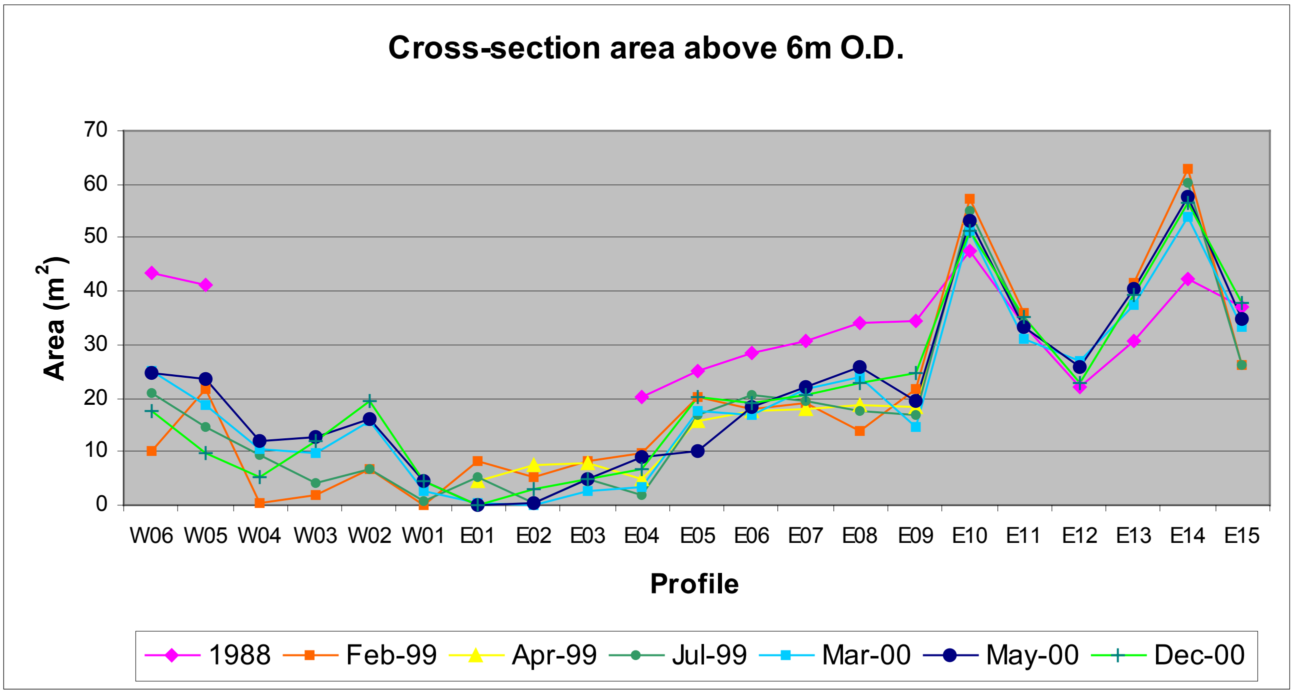


Figure 47. Cross-section areas of the gravel barrier above the 4m and 6m contours. Volumes above 4m indicate the approximate quantities of loose gravel available and volume above 6m indicates resistance against overwashing during extreme events.

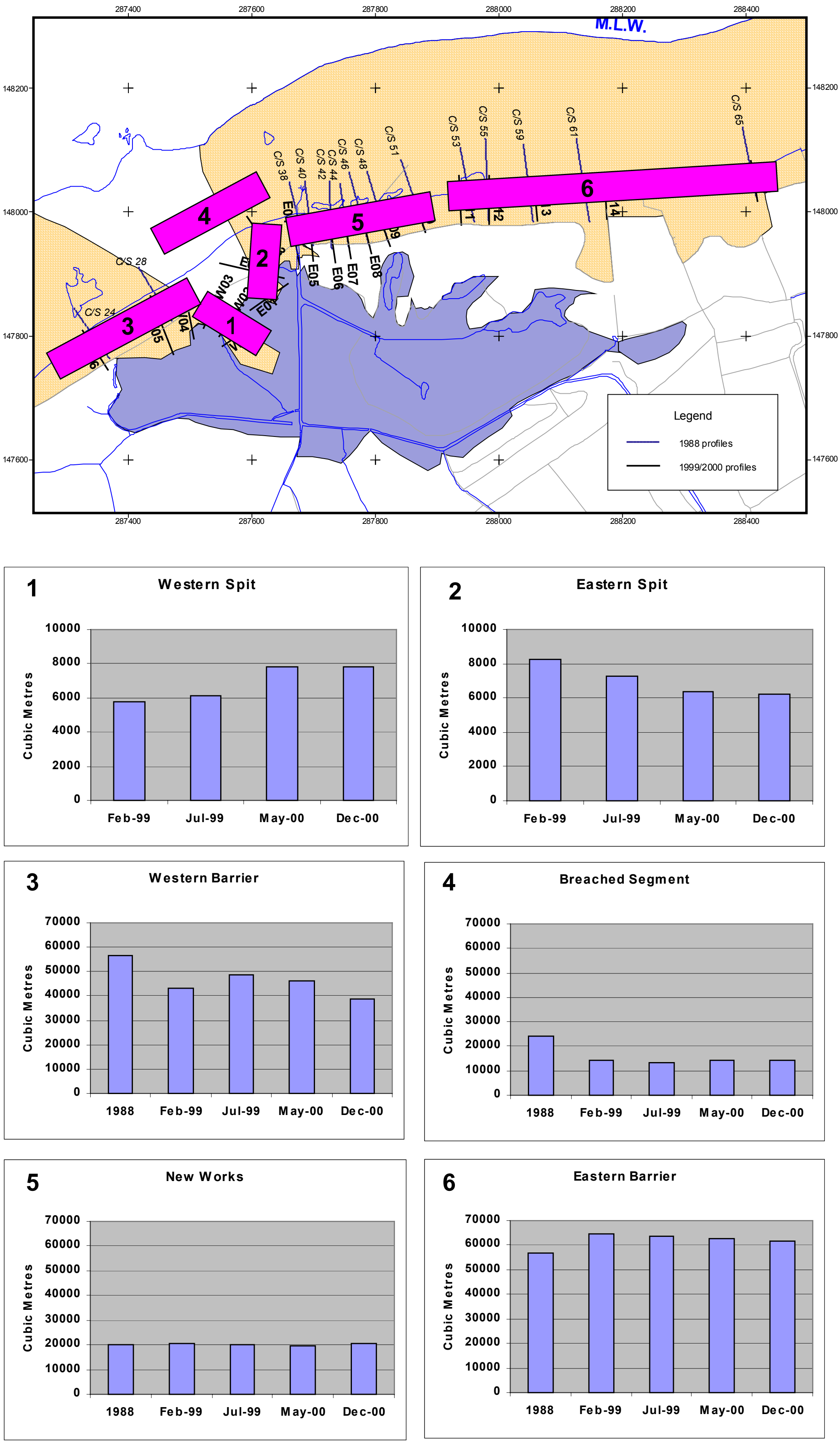


Figure 48. Barrier volume changes within defined behavioural "cells"

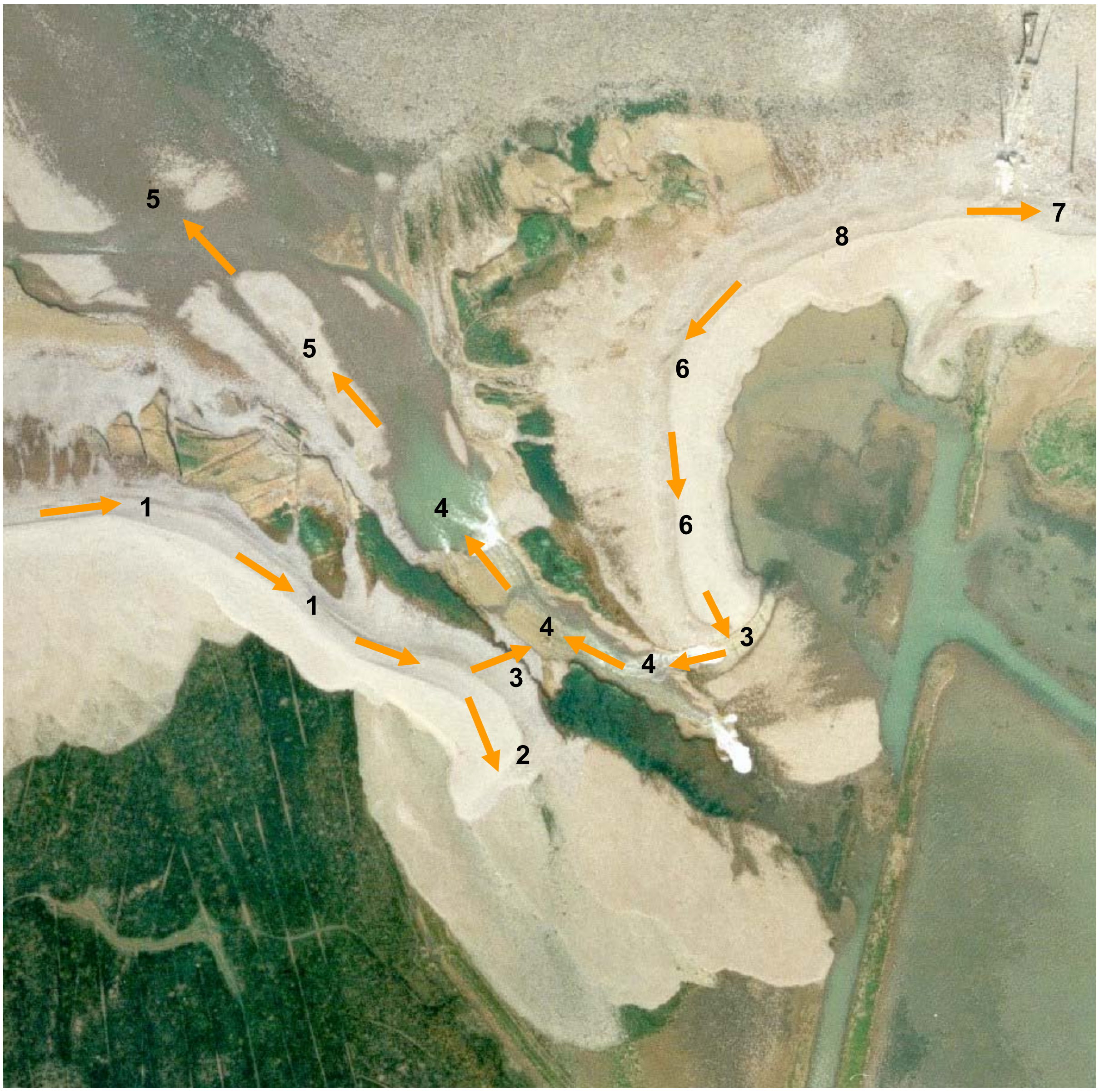


Figure 49. Gravel drift pathways around the breach channel. Details are as follows:

1. Eastward drift from the Porlockford barrier onto the Western Spit.
2. Deposition on the Western Spit.
3. Drift from spits into the breach channel.
4. Ebb tidal current transport seaward along the breach channel.
5. Deposition of seaward moving gravels to form shoals in the outer breach channel.
6. SW and southward drift along the Eastern Spit.
7. Eastward drift at New Works to Cell 5.
8. Approximate location of drift divide.

Figure 50. Depleted upper beach and eroded crest at Porlockford at the western extremity of Cell 3, 8th Dec-00.

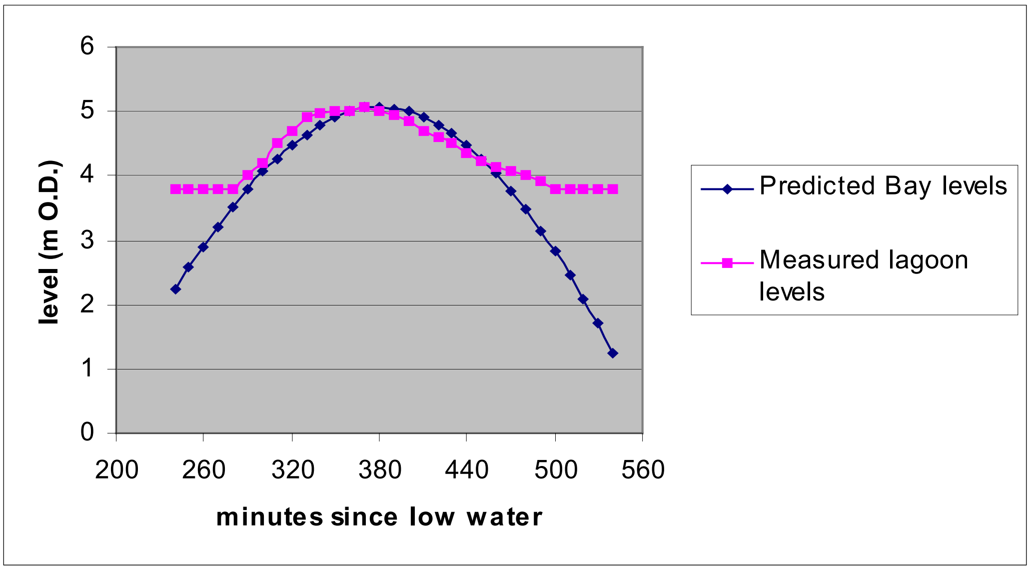


Figure 51. Comparison of measured lagoon levels and predicted bay tidal levels between 1630 hrs and 2130hrs on 24th September 1999.

APPENDIX 1 Locations of Survey Control Points

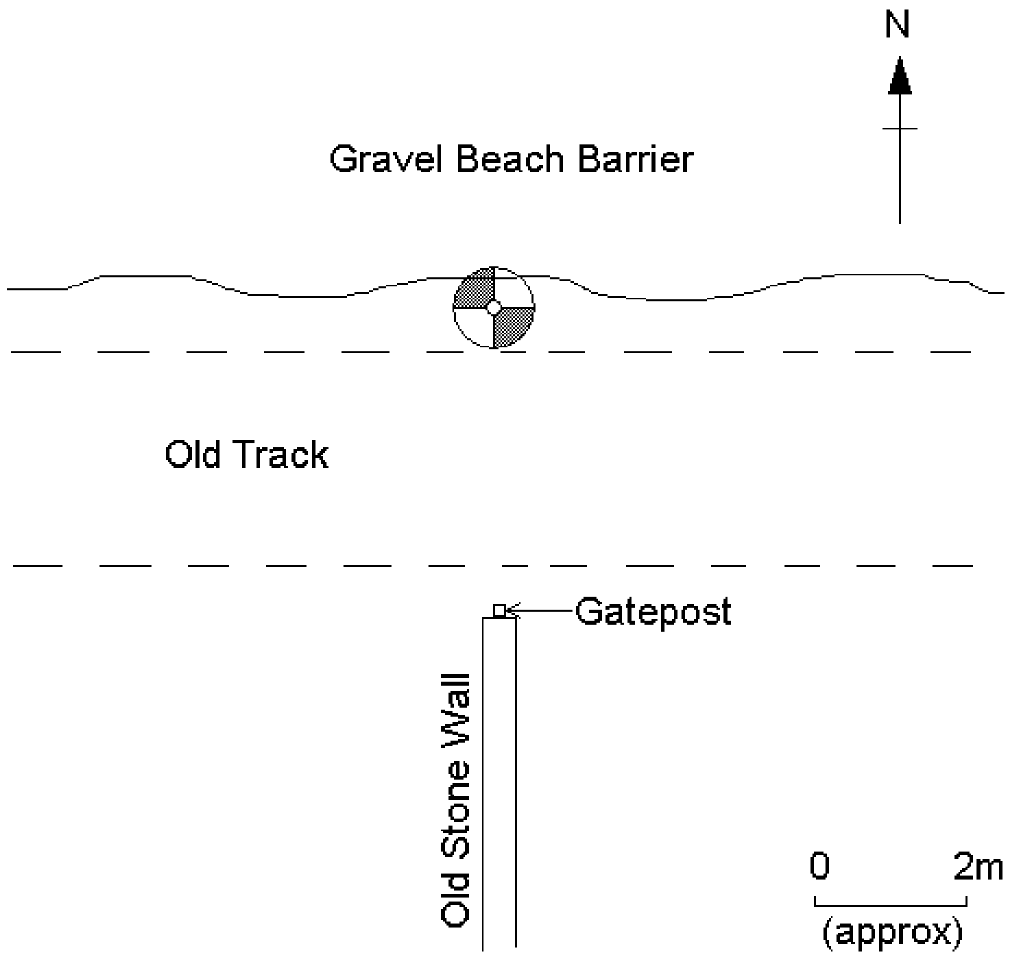
(see also Figure 24)

Station Name	**Control 01**
Eastings	288175.088
Northings	147992.737
Elevation	7.26

Spheroid	**Airy 1936 (OSGB36)**	**Projection**	**UKTM**
Semi-major axis (a)	6 377 563.396	Latitude of Origin	49° 00’ 00” N
Semi-minor axis (b)	6 356 256.909	Longitude of Origin (CM)	02° 00’ 00” W
Flattening (1/f)	299.324 964 5	Eastings at Origin	400 000.00
		Northings at Origin	-100 000.00
Elevation Datum	**MSL at Newlyn**	Scale Factor at CM	0.9996012717

Description Ground level at wooden stake.

Plan View



Survey Date	Feb 1999

Station Name	**Control 02**
Eastings	288786.006
Northings	147948.921
Elevation	5.94

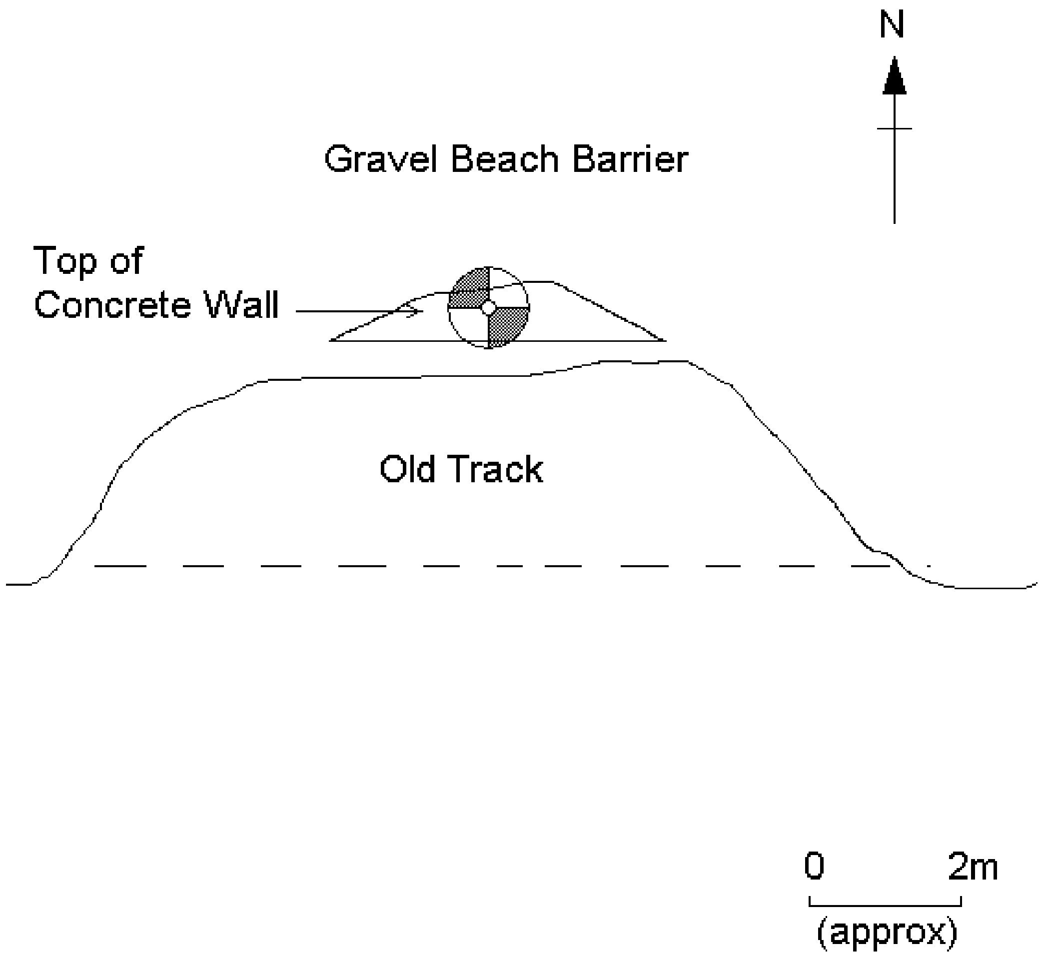
Spheroid	**Airy 1936 (OSGB36)**
Semi-major axis (a)	6 377 563.396
Semi-minor axis (b)	6 356 256.909
Flattening (1/f)	299.324 964 5

Projection	**UKTM**
Latitude of Origin	49° 00’ 00” N
Longitude of Origin (CM)	02° 00’ 00” W
Eastings at Origin	400 000.00
Northings at Origin	-100 000.00
Scale Factor at CM	0.9996012717

Elevation Datum	**MSL at Newlyn**

Description Chiselled mark and paint on concrete wall.

Plan View



Survey Date	Feb 1999

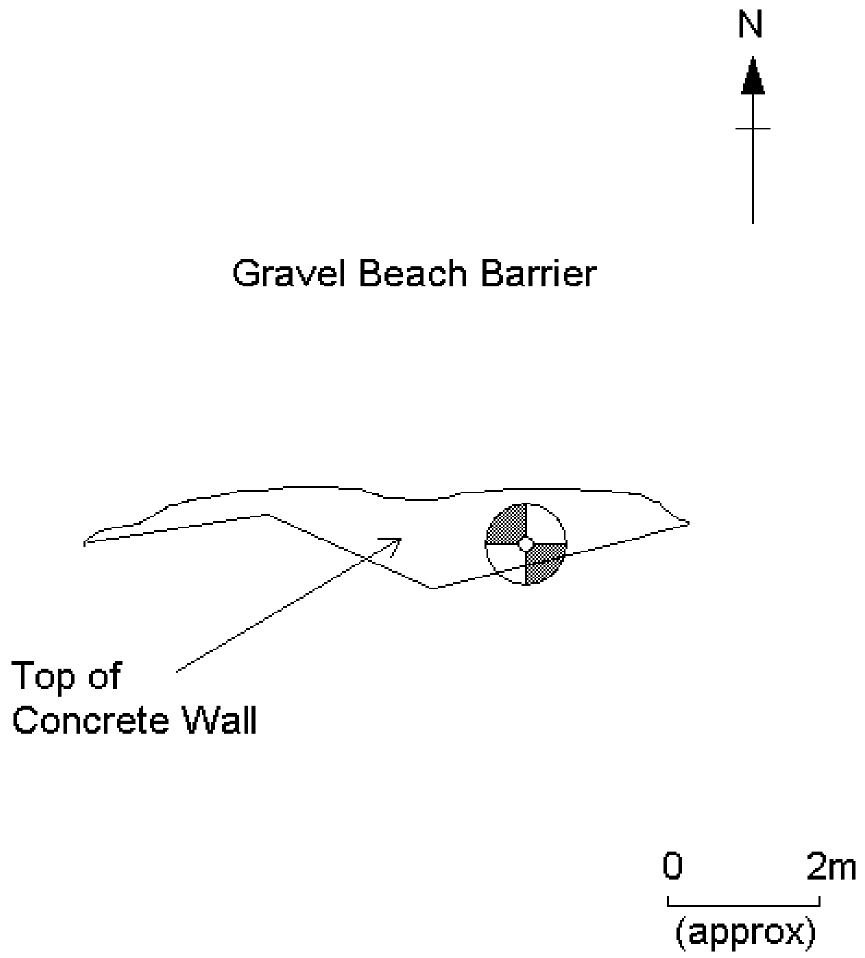
Station Name	**Control 03**
Eastings	287758.912
Northings	147948.669
Elevation	6.15

Spheroid	**Airy 1936 (OSGB36)**
Semi-major axis (a)	6 377 563.396
Semi-minor axis (b)	6 356 256.909
Flattening (1/f)	299.324 964 5
Elevation Datum	**MSL at Newlyn**

Projection	**UKTM**
Latitude of Origin	49° 00’ 00” N
Longitude of Origin (CM)	02° 00’ 00” W
Eastings at Origin	400 000.00
Northings at Origin	-100 000.00
Scale Factor at CM	0.9996012717

Description Nail in top of concrete wall

Plan View



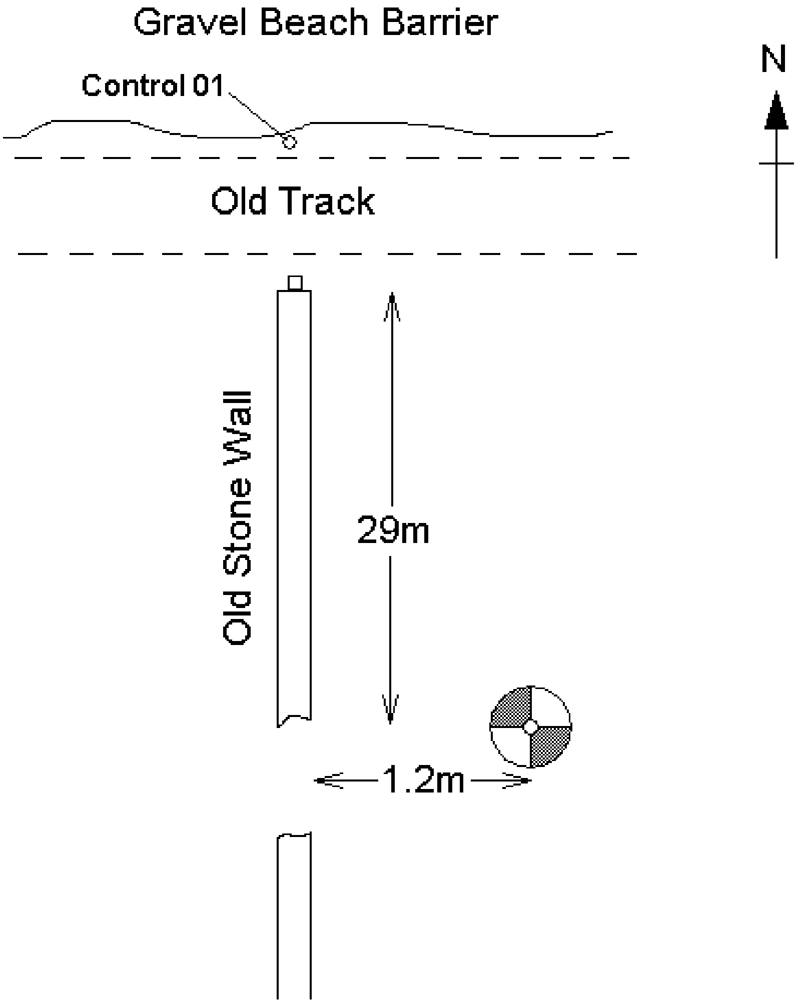
Survey Date	Feb 1999

Station Name	**Control 04**
Eastings	288179.327
Northings	147958.262
Elevation	6.41

Spheroid	**Airy 1936 (OSGB36)**	**Projection**	**UKTM**
Semi-major axis (a)	6 377 563.396	Latitude of Origin	49° 00' 00" N
Semi-minor axis (b)	6 356 256.909	Longitude of Origin (CM)	02° 00' 00" W
Flattening (1/f)	299.324 964 5	Eastings at Origin	400 000.00
		Northings at Origin	-100 000.00
Elevation Datum	**MSL at Newlyn**	Scale Factor at CM	0.9996012717

Description Nail in wooden stake

Plan View



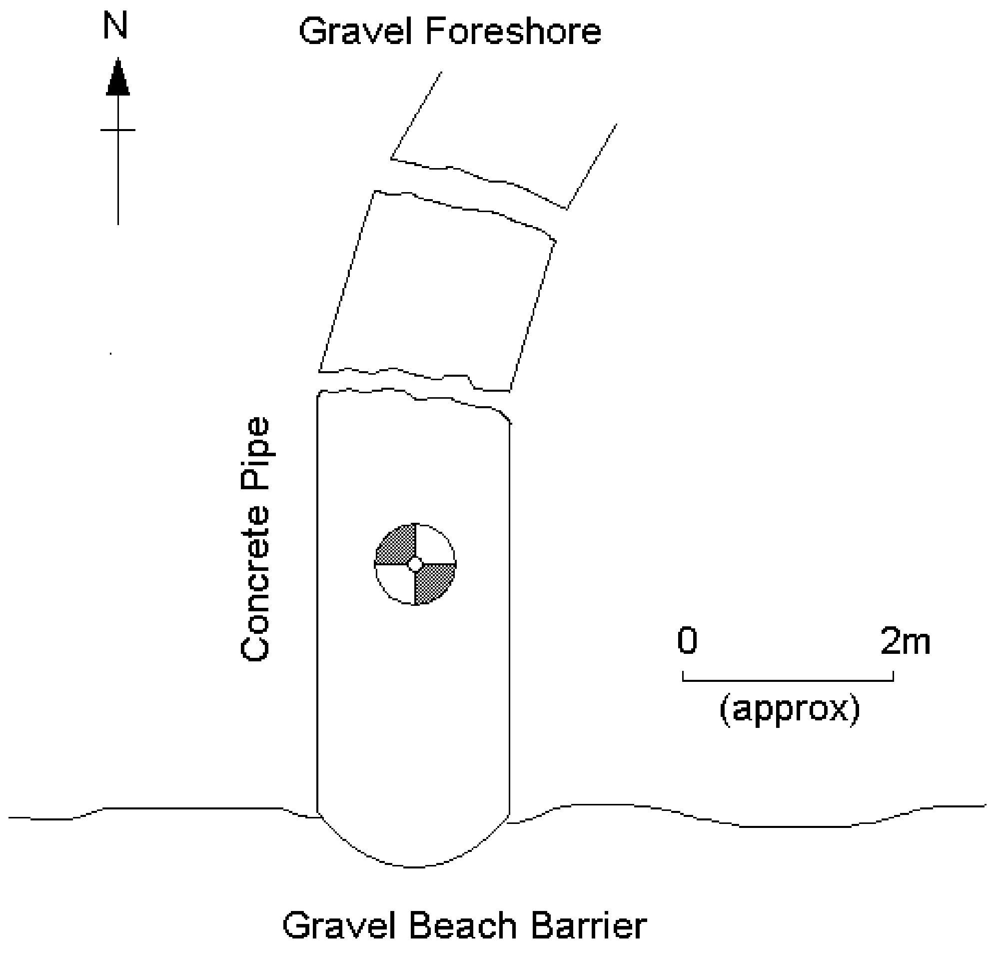
Survey Date	May 2000

Station Name	**Control 05**
Eastings	287780.942
Northings	147990.279
Elevation	3.60

Spheroid	**Airy 1936 (OSGB36)**	**Projection**	**UKTM**
Semi-major axis (a)	6 377 563.396	Latitude of Origin	49° 00’ 00” N
Semi-minor axis (b)	6 356 256.909	Longitude of Origin (CM)	02° 00’ 00” W
Flattening (1/f)	299.324 964 5	Eastings at Origin	400 000.00
		Northings at Origin	-100 000.00
Elevation Datum	**MSL at Newlyn**	Scale Factor at CM	0.9996012717

Description Iron pin in concrete pipe

Plan View



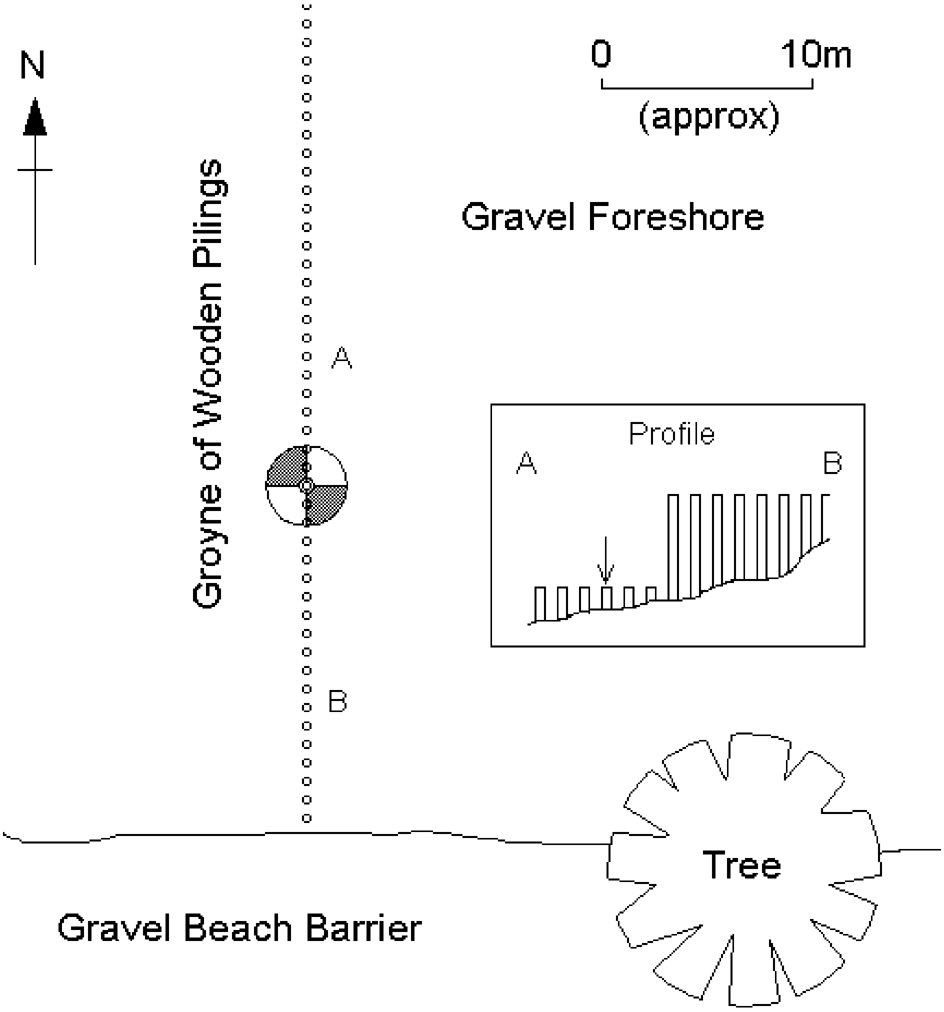
Survey Date	Mar 2000

Station Name	**Control 06**
Eastings	287056.362
Northings	147641.598
Elevation	5.45

Spheroid	**Airy 1936 (OSGB36)**	**Projection**	**UKTM**
Semi-major axis (a)	6 377 563.396	Latitude of Origin	49° 00’ 00” N
Semi-minor axis (b)	6 356 256.909	Longitude of Origin (CM)	02° 00’ 00” W
Flattening (1/f)	299.324 964 5	Eastings at Origin	400 000.00
		Northings at Origin	-100 000.00
Elevation Datum	**MSL at Newlyn**	Scale Factor at CM	0.9996012717

Description Small nail in centre of third sawn-off piling from landward end on fifth groyne eastward from Porlock Weir

Plan View



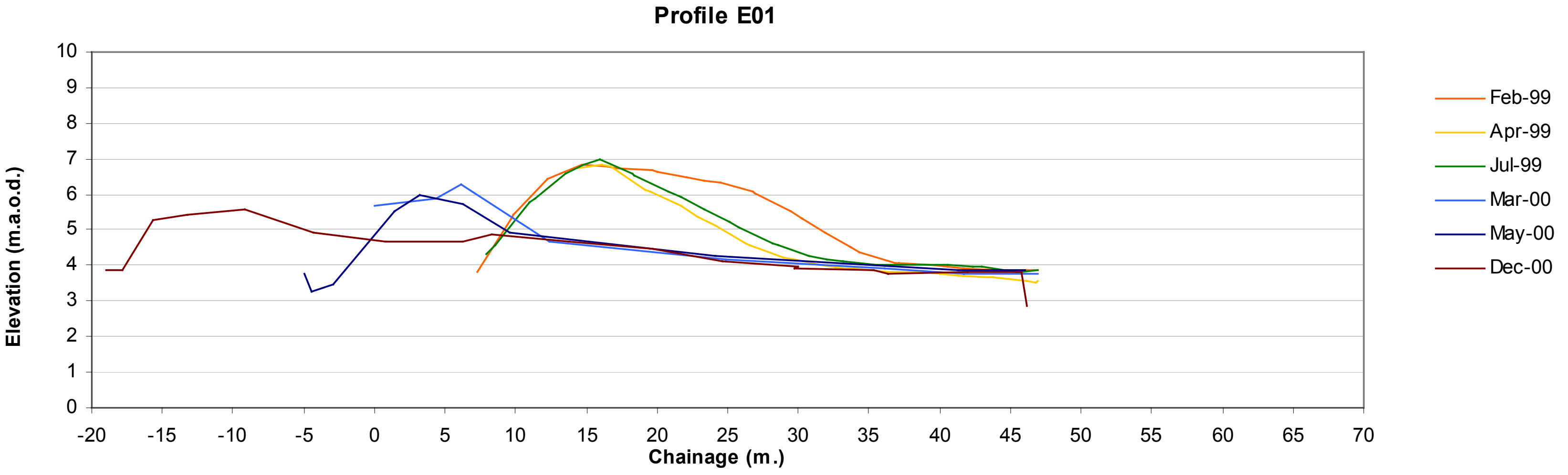
Survey Date	May 2000

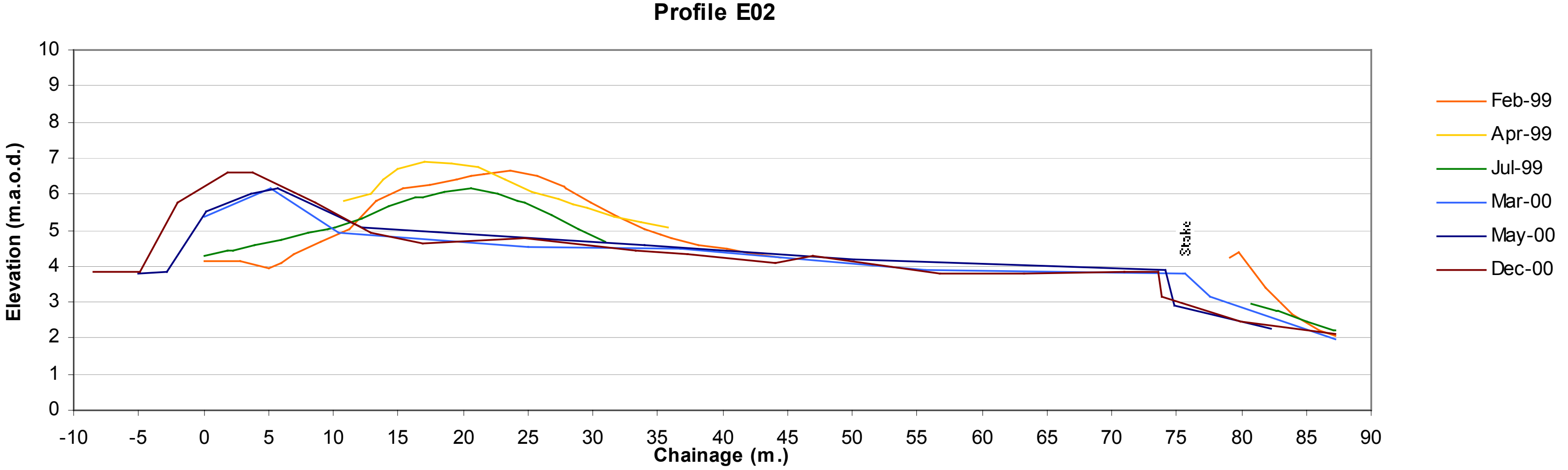
APPENDIX 2 Topographic Barrier Profile Plots

Survey Dates:

Dec 1988
Feb 02-03, 1999
April 15, 1999
July 27, 1999
Mar 09-10, 2000
May 03-04, 2000
Dec 07-08, 2000

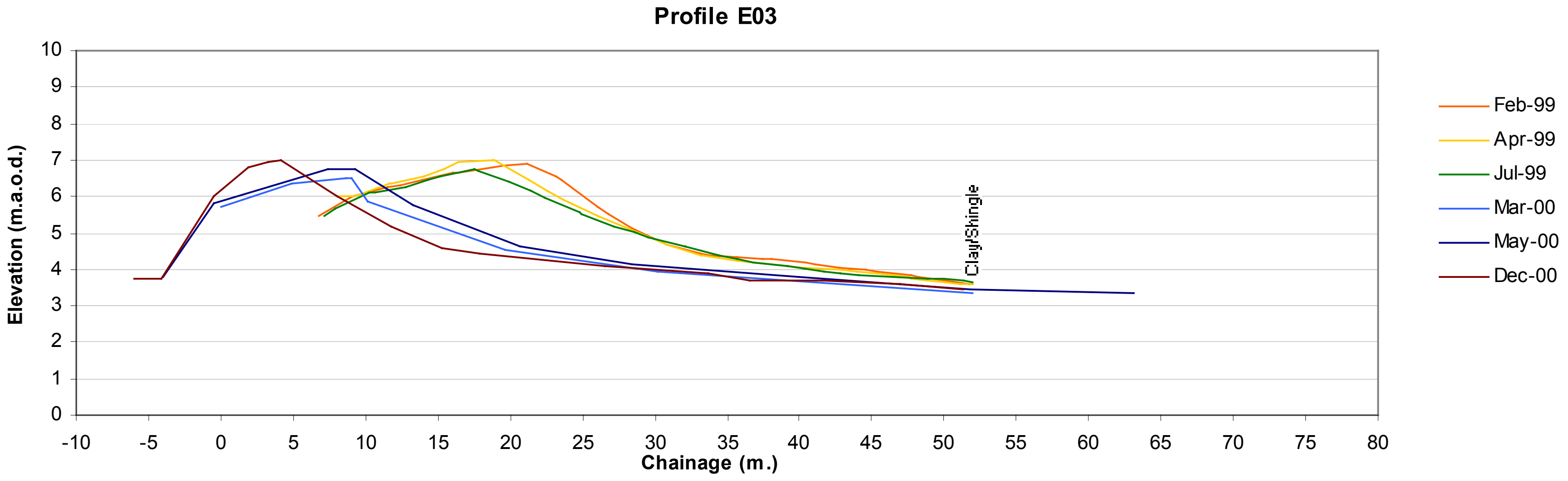
Appendix 2 - Topographic Barrier Profile Plate

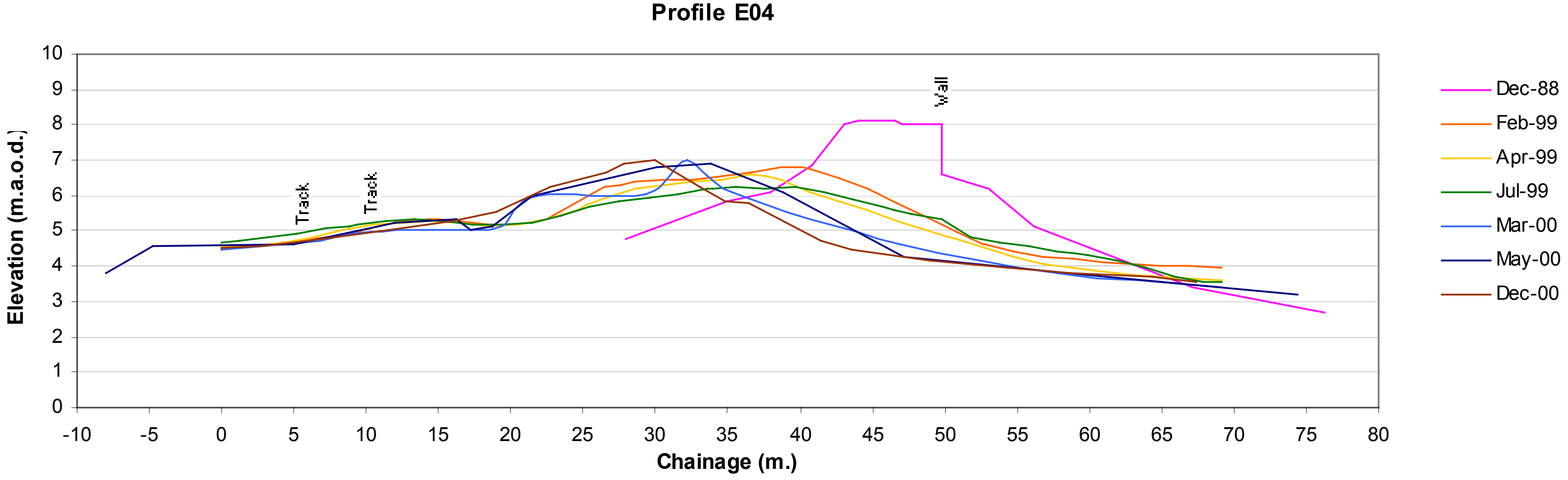




Profile locations given in Figure 26

Appendix 2 - Topographic Barrier Profile Plate

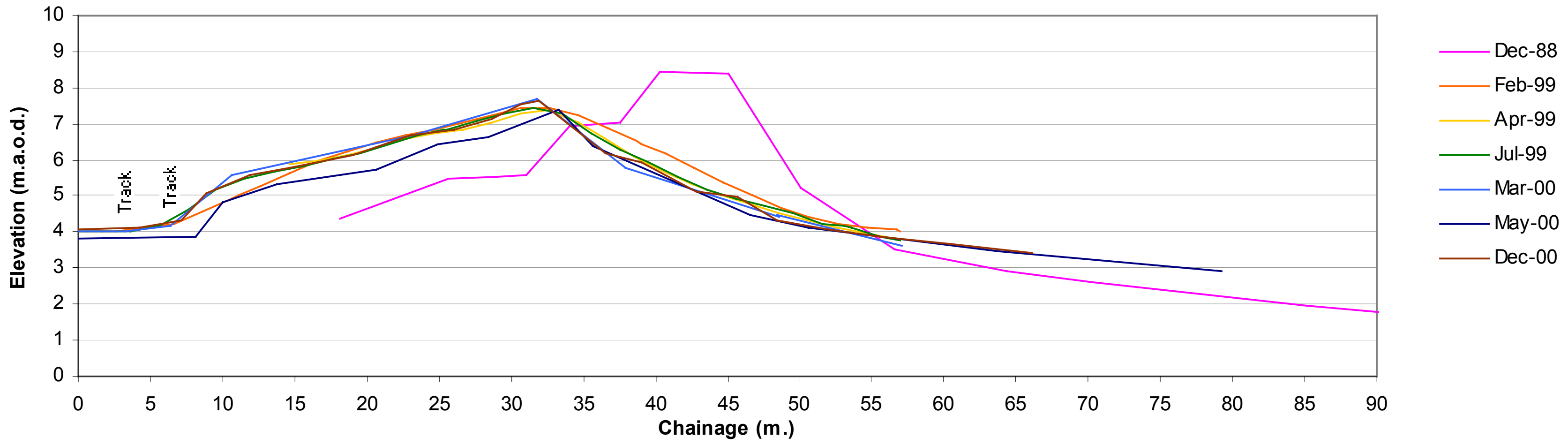




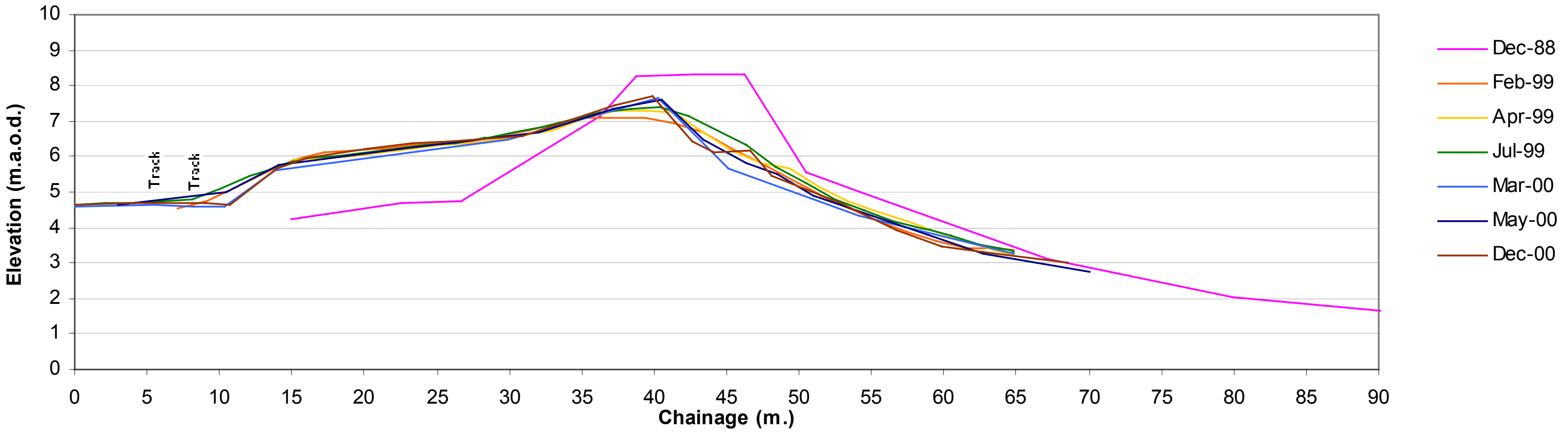
Profile locations given in Figure 26

Appendix 2 - Topographic Barrier Profile Plate

Profile E05

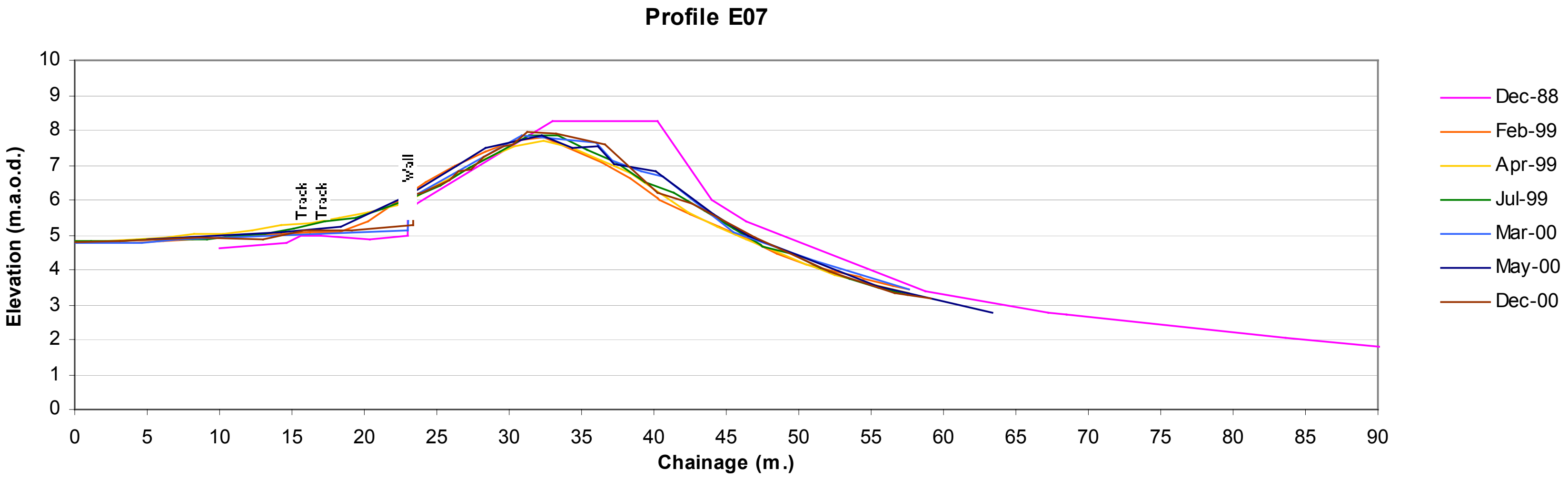


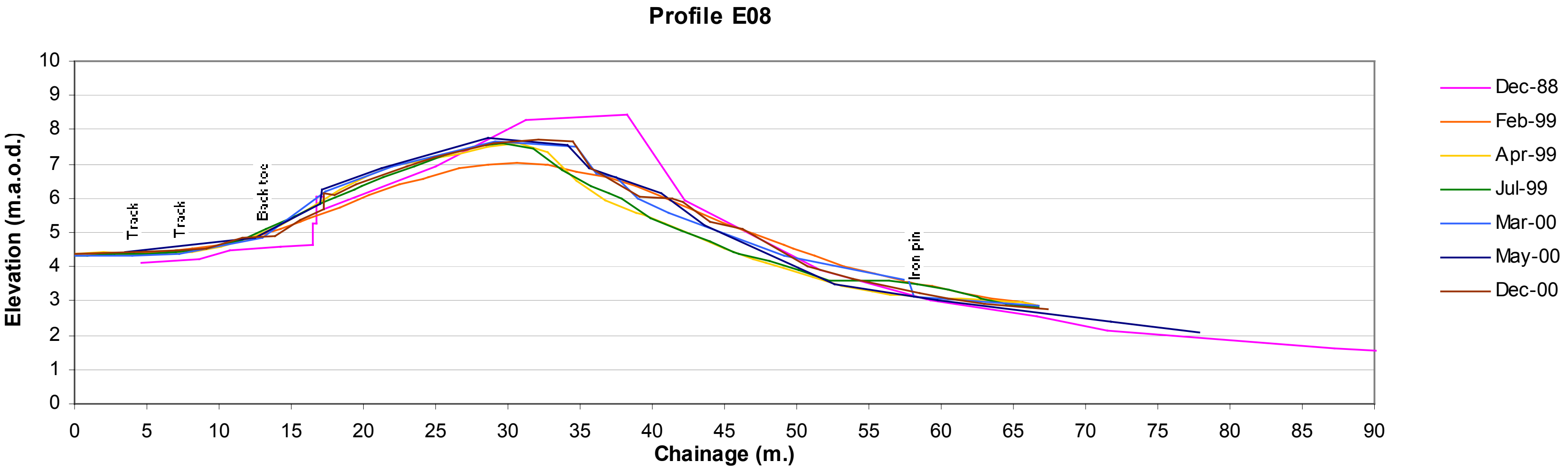
Profile E06



Profile locations given in Figure 26

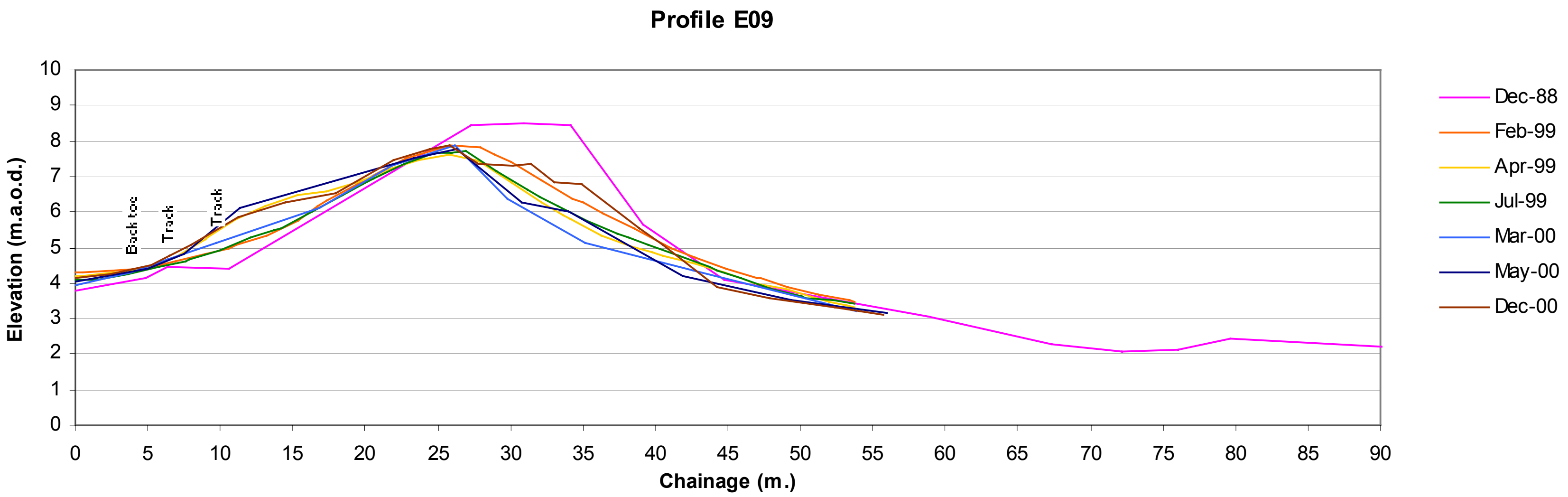
Appendix 2 - Topographic Barrier Profile Plate


Profile E07

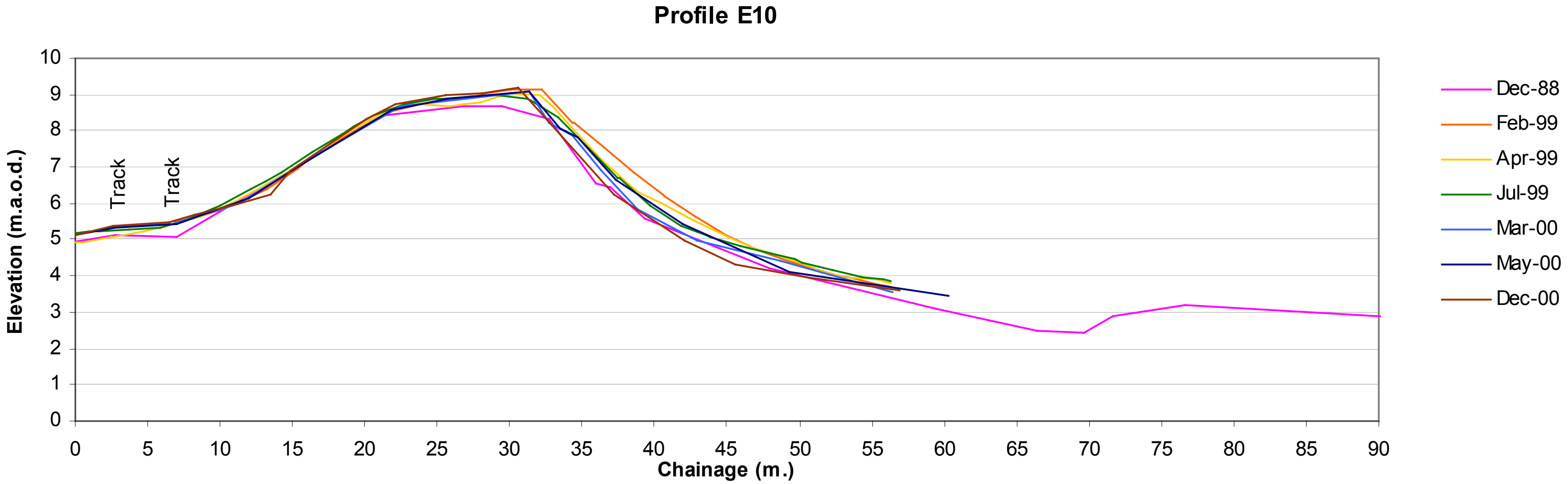

Profile E08

STCG 024 Porlock Bay: Geomorphology

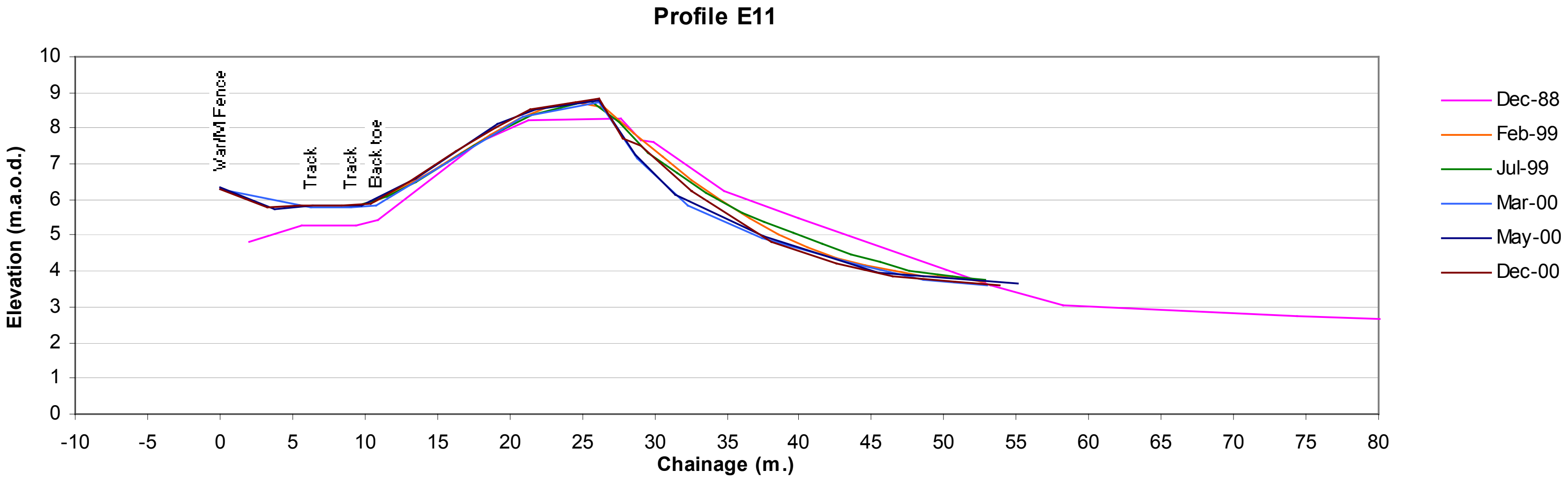
Appendix 2 – Topographic Barrier Profile Plate

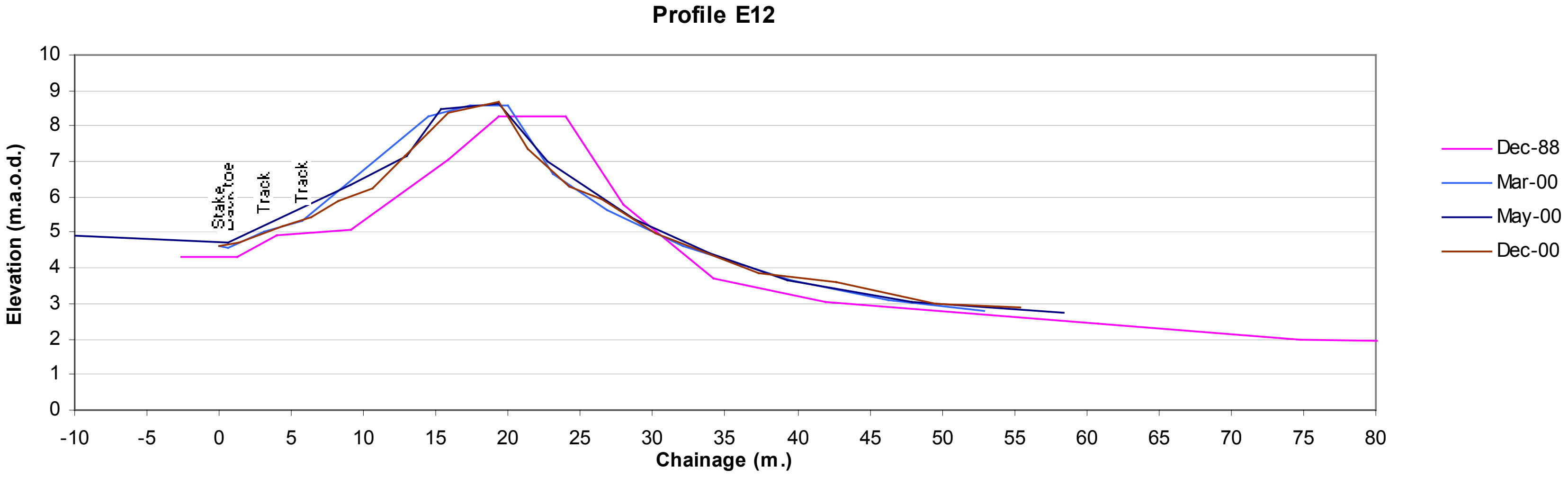


Profile locations given in Figure 26



Appendix 2 - Topographic Barrier Profile Plate

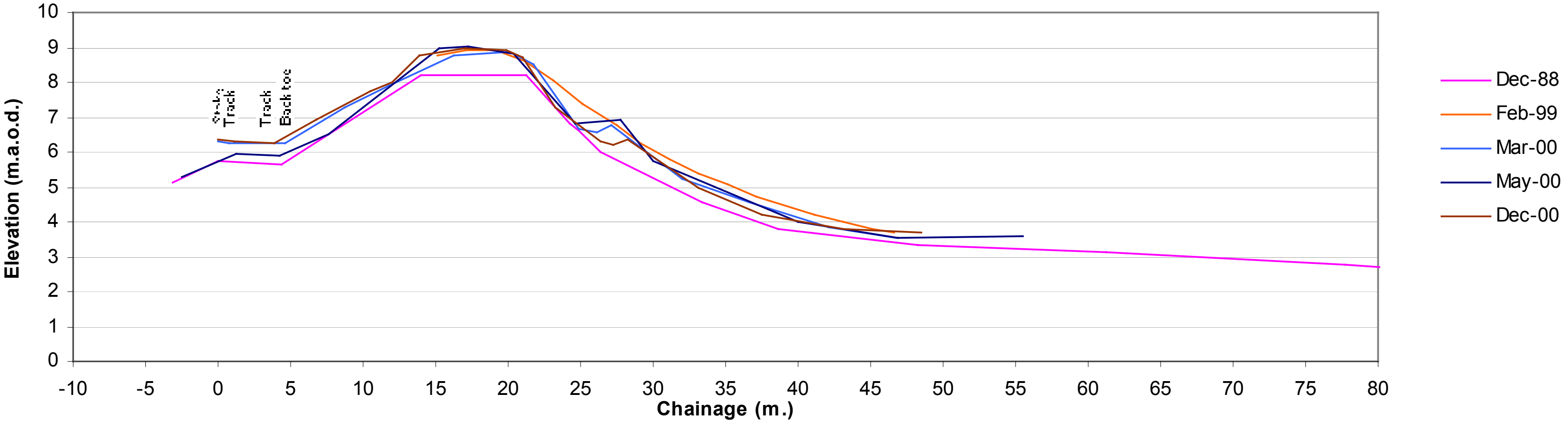




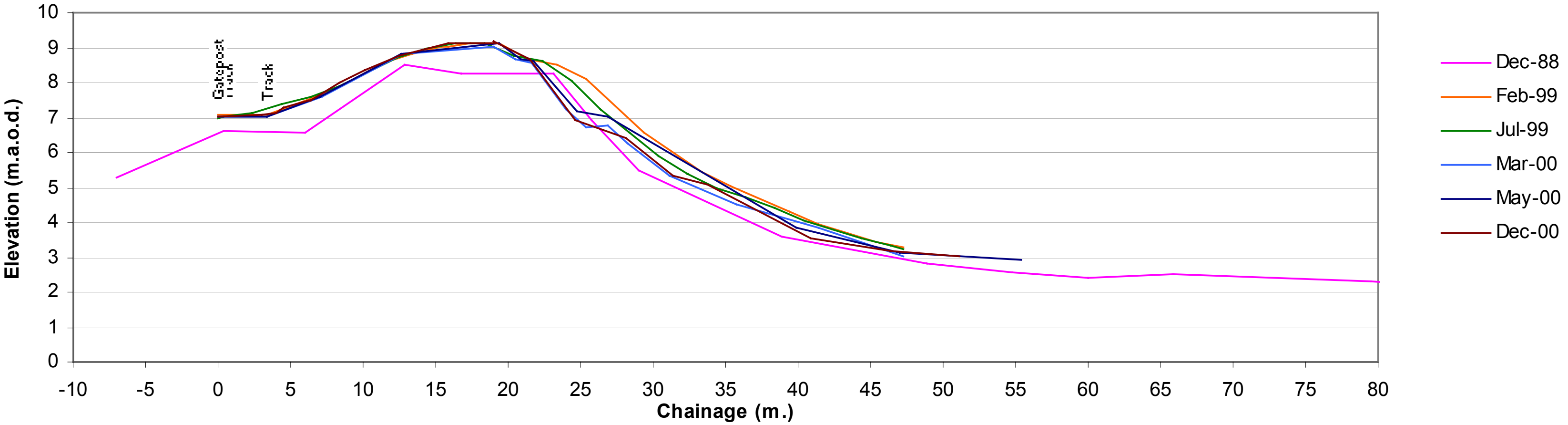
Profile locations given in Figure 26

Appendix 2 - Topographic Barrier Profile Plate

Profile E13

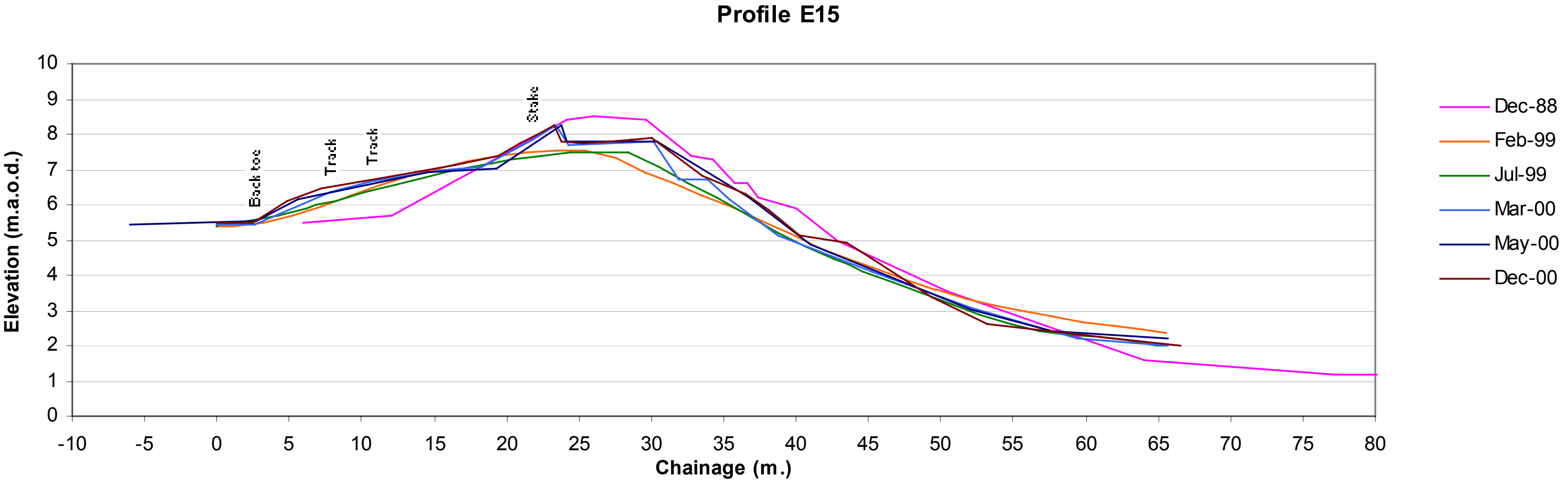


Profile E14



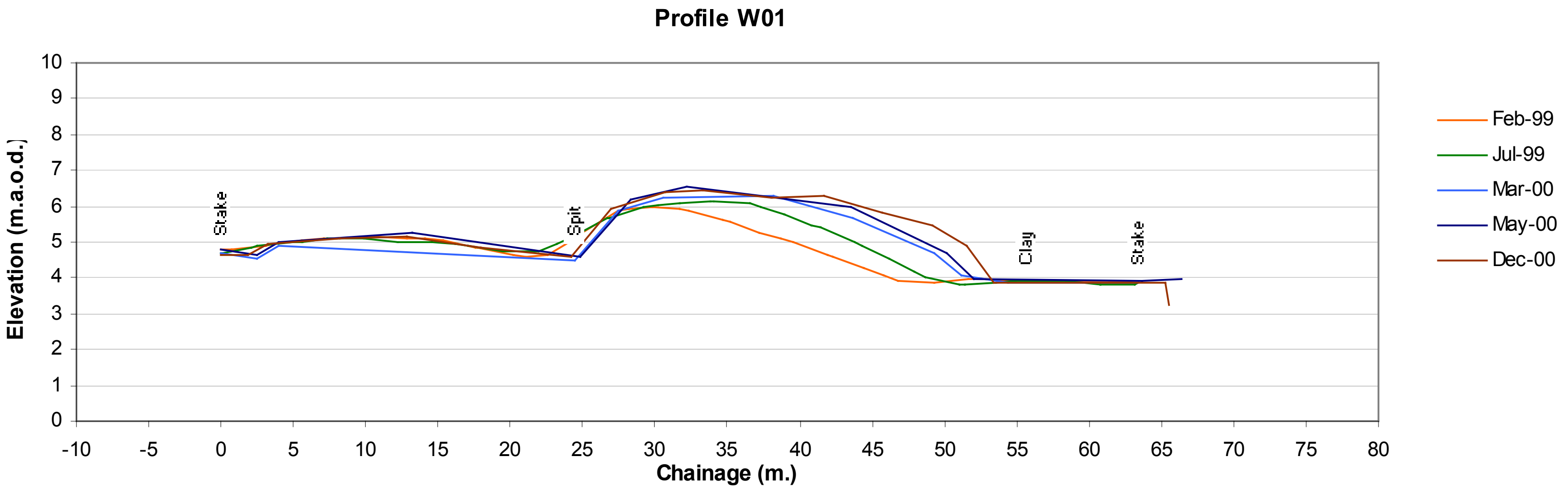
Profile locations given in Figure 26

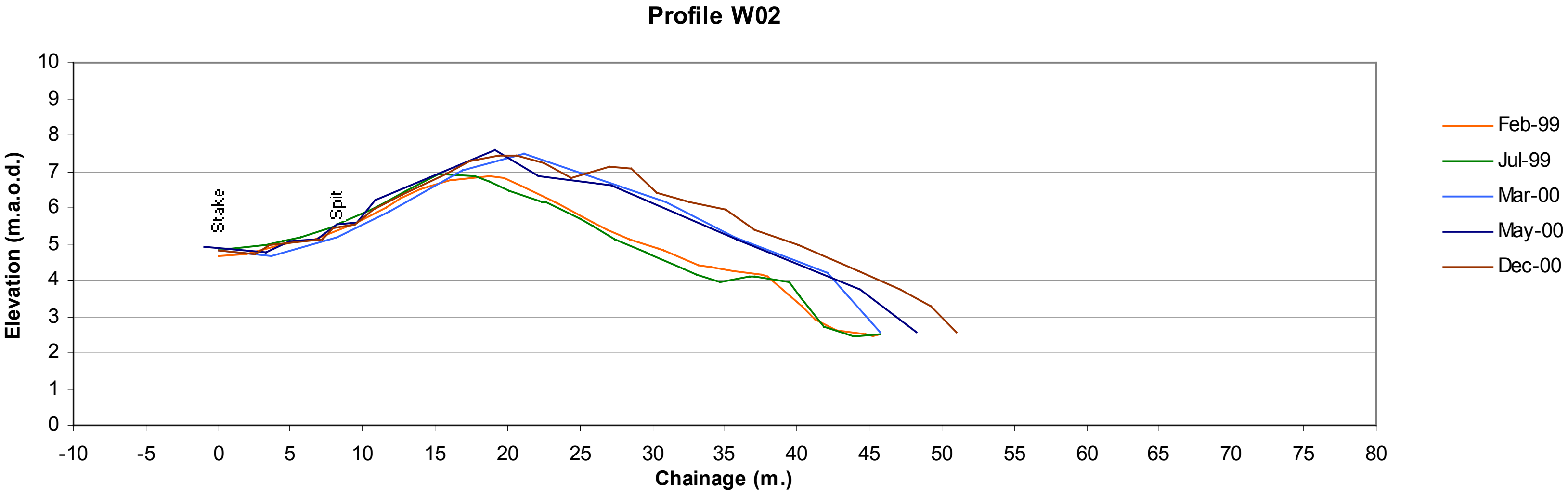
Appendix 2 - Topographic Barrier Profile Plate



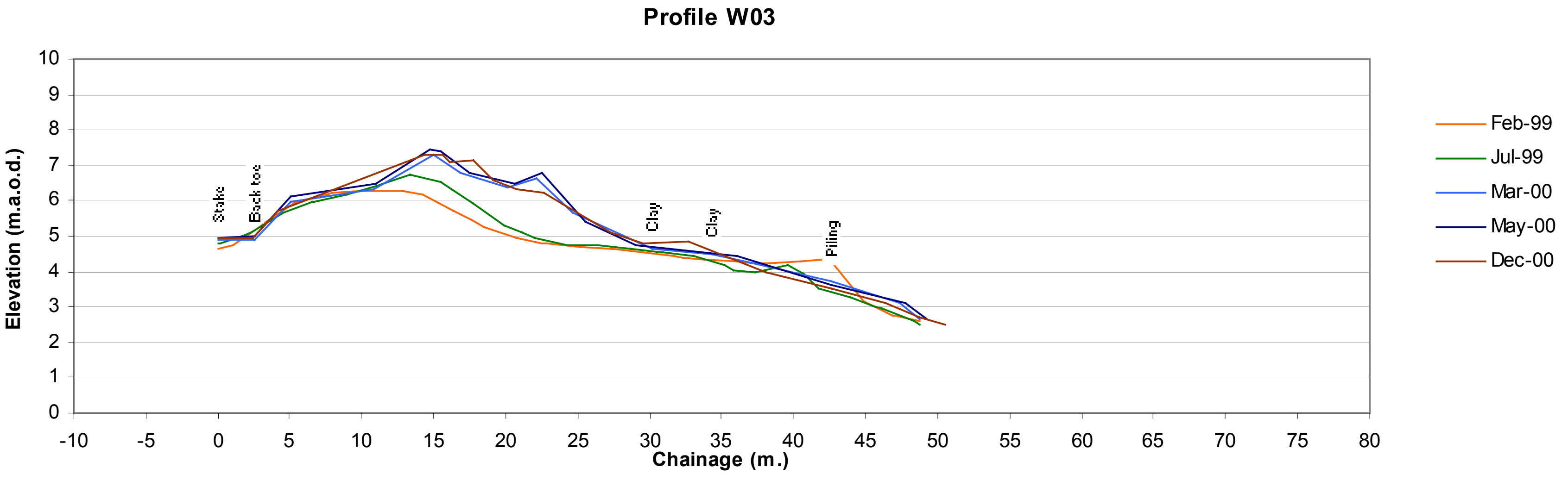
Profile locations given in Figure 26

Appendix 2 - Topographic Barrier Profile Plate





Appendix 2 - Topographic Barrier Profile Plate

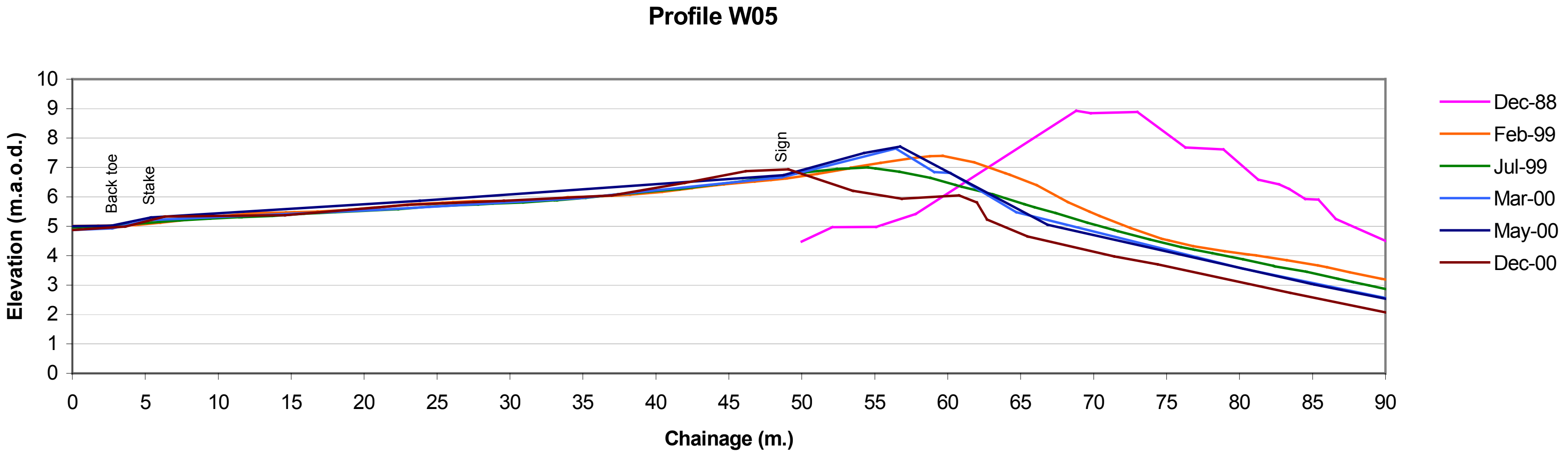

Profile W03

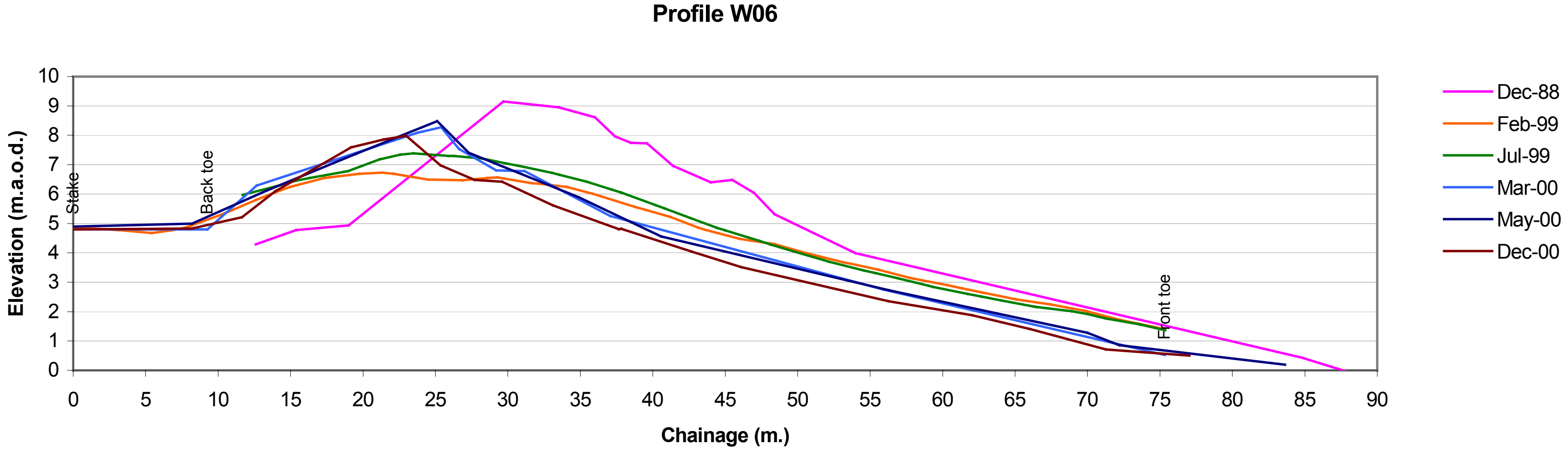

Profile W04

Profile locations given in Figure 26

STCG 024 Porlock Bay: Geomorphology

Appendix 2 - Topographic Barrier Profile Plate





Profile locations given in Figure 26

APPENDIX 3 Measured Extreme Lagoon Levels

Measurement Date	Extreme lagoon level (m O.D.)					
	Recorder 1	Recorder 2	Recorder 3	Mean	Predicted	Residual
16-29-Jan99	5.53	5.53	-	5.53	5.36	0.17
02-Feb	5.16	5.18	-	5.17	5.48	-0.31
05-Feb	5.18	5.19	-	5.19	5.38	-0.19
28-Feb	5.77	5.73	-	5.75	5.87	-0.12
05-Mar	5.68	5.73	-	5.71	5.33	0.38
12-Mar	5.04	5.09	-	5.07	4.84	0.23
19-Mar	5.68	5.84	-	5.76	5.91	-0.15
26-Mar	6.10	6.04	-	6.07	6.13	-0.06
09-Apr	5.30	5.32	-	5.31	5.12	0.19
16-Apr	6.09	5.87	-	5.98	5.98	0
23-Apr	6.15	6.15	6.27	6.19	6.21	-0.03
29-Apr	-	-	-	-	-	-
07-May	5.06	5.12	-	5.09	4.87	0.22
14-May	5.63	5.79	-	5.71	5.26	0.45
21-May	5.80	5.84	-	5.82	6.10	-0.28
28-May	5.39	5.33	-	5.36	3.95	1.41
04-Jun	5.31	5.33	-	5.32	4.64	0.68
11-Jun	5.07	5.21	-	5.14	4.39	0.75
18-Jun	5.85	5.76	-	5.81	5.66	0.15
25-Jun	5.52	5.54	-	5.53	4.38	1.15
09-Jul	-	-	-	-	-	-
16-Jul	5.50	-	-	5.50	5.63	-0.13
23-Jul	5.52	-	-	5.52	5.13	0.39
30-Jul	5.53	-	-	5.53	4.91	0.62
06-Aug	5.03	-	-	5.03	5.11	-0.08
13-Aug	5.07	-	-	5.07	5.56	-0.49
20-Aug	5.59	5.41	-	5.50	5.50	0
27-Aug 1999	5.49	5.22	-	5.36	5.31	0.045

Note that the value given refers to the period between the measurement date and the previous recording date.

There is little data for Recorder 3 because the lagoon level only reached the toe of the standpipe on one occasion.

Mean = mean lagoon level

Predicted = highest tidal level predicted for Porlock Harbour based on UK Hydrographic Office data without allowance for meteorological effects.

Residual = the difference between the observed lagoon level and the predicted Porlock Harbour level.

APPENDIX 4 Erosion of Breach Channel: erosion pin measurements

Date	Mean loss by erosion (mm)					
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
05-Mar 99	3	6	1	4	3	6
12-Mar	4	0	13	0	1	5
19-Mar	3	4	*120	3	6	9
26-Mar	4	3	0	3	0	3
09-Apr	3	0	4	4	0	0
16-Apr	5	4	4	4	0	5
23-Apr	3	1	0	5	3	5
29-Apr	38	3	5	6	5	32
07-May	1	4	3	4	1	1
14-May	5	4	4	0	3	1
21-May	4	3	1	4	0	0
28-May	3	4	1	5	3	0
04-Jun	4	1	3	4	4	1
11-Jun	3	0	9	5	4	0
18-Jun	0	3	9	8	5	5
25-Jun	3	1	3	4	1	4
09-Jul	5	5	9	6	*120	4
16-Jul	0	3	5	6	4	4
23-Jul	5	5	4	4	4	3
30-Jul	4	4	6	8	4	1
06-Aug	4	3	4	4	4	4
13-Aug	3	1	3	1	1	1
20-Aug	1	4	5	4	5	4
27-Aug 99	4	8	6	4	1	3
Total	112	74	222	100	182	101
mm week^{-1}	4.67	3.08	9.25	4.17	7.58	4.21
mm month^{-1}	20.00	13.21	39.64	17.86	32.50	18.04

Values given are the average of measurements from up to six pins in vertical profile up the cliff face at each site.

* major bank failure involving loss of pins and consequent underestimation of total recession