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Coastal Cells in Scotland: Cells 8 & 9 – The Western Isles

D L Ramsay & A H Brampton

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REPORT

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Note: *Due to their size, the maps in Appendix 2 have not been reproduced within this report, but are available for inspection, by prior arrangement, at the Earth Science Group, Advisory Services, Scottish Natural Heritage, 2 Anderson Place, Edinburgh EH6 5NP.*

Summary

This report reviews the coastline of Cell 8 between Barra Head and the Butt of Lewis on the Minch coastline and Cell 9 between the Butt of Lewis and Barra Head on the Atlantic coastline of the Western Isles. In it are described the various coastal characteristics and processes which affect the regime of this particular stretch of shoreline. These include a description of the major coastal features, processes, and defences along with other aspects of beach development. The stretches of coastline which, for coastal management purposes, can be treated as independent or semi-dependent cells are also identified.

The study was carried out for Scottish Natural Heritage, Scottish Office Agriculture, Environment and Fisheries Department and Historic Scotland by the Coastal Group at HR Wallingford. The contract was administered by Dr George Lees of Scottish Natural Heritage. For further details of the study please contact Mr Douglas Ramsay or Dr Alan Brampton of the Coastal Group at HR Wallingford.

Note

This contract was undertaken prior to the establishment of The Scottish Executive. The report therefore contains references to The Scottish Office and The Secretary of State for Scotland. The following changes therefore apply and should be borne in mind when reading the report.

Previous terminology	*Present*
The Secretary of State for Scotland	The First Minister
The Scottish Office Agriculture, Environment and Fisheries Department	The Scottish Executive Rural Affairs Department

1 *Introduction*

1.1 General

In January 1996, HR Wallingford was commissioned by Scottish Natural Heritage (SNH), the Scottish Office Agriculture, Environment and Fisheries Department (SOAEFD) and Historic Scotland (HS) to extend an existing study, (HR Wallingford, 1997) to define Coastal Cells and Sub-cells around the coastline of Scotland. This report, which reviews the coastline of Cell 8 between Barra Head and the Butt of Lewis (Minch coast) and Cell 9 between the Butt of Lewis and Barra Head (Atlantic coastline), is one of a series of 11 reports covering the entire coastline of mainland Scotland, the Western Isles, Orkney and Shetland. The study concentrates on identifying and describing the various natural and man-made characteristics and processes which affect the behaviour of this particular stretch of coastline. The report includes a description of the dominant hydraulic processes, areas of erosion and accretion, coastal defences and various other aspects of the coastal regime. The aim of the report is to provide an overall understanding of the character and processes occurring within each sub-cell to allow as full an appreciation as possible of the coastal regime on a macro scale.

1.2 Terms of reference

The terms of reference for this study were detailed by Scottish Natural Heritage in Annex A of their Project Specification. The aims are to provide:

(i) a basic description of coastal cells and their significance,

(ii) maps of each cell showing the location and boundaries of all sub-cells contained therein and the nature of the cell boundaries,

(iii) a map of each sub-cell showing the general direction(s) of littoral drift therein and known areas of erosion and accretion,

(iv) a map of each sub-cell showing the location of all sites designated for their nature conservation interest,

(v) a map of each sub-cell showing the location of sites designated for their historical or archaeological interest,

(vi) a map of each sub-cell showing the location of all principal coastal protection works and beach monitoring schemes,

(vii) descriptions for each sub-cell of the following characteristics and processes:

- geology and geomorphology
- wave and tidal regime
- areas of erosion and accretion and, where information exists, details of any rates of change
- assessment of existing erosion problems
- a summary of the relevance or implications of the littoral processes identified to sites of nature conservation interest
- a summary of the susceptibility of the historical and archaeological sites to coastal erosion

- existing coastal protection and management measures (including dredging and spoil disposal)
- present monitoring arrangements
- assessment of sensitivities of sites to climatic change and sea level rise.

1.3 Outline of report

A general introduction to the concept of coastal cells, and how the concept has been applied to the coastline of Scotland is provided in Chapter 2. Chapter 3 provides general background information on the coastal environment in Scotland in the context of coastal cells. Chapter 4 provides reference to data sources of relevance to coastal management in Cells 8 and 9. Chapters 5 and 6 form the main body of the report. A brief description of Cells 8 and 9 detailing all the cell and sub-cell boundaries is given. For each sub-cell, a description of its character and the processes occurring there is detailed. An assessment of climatic change, sea level rise, and the likely effects on the coastline of Cells 8 and 9 is given in Chapter 7, with Chapter 8 listing the references used. A listing of Sites of Special Scientific Interest (SSSIs), the locations of noted historical and archaeological sites, useful addresses and a glossary of terms used are contained within the appendices of this report.

2 *Coastal Cells*

2.1 Coastal Cells

The concept of Coastal Cells was introduced in an initial document identifying the main cells around the coastline of Scotland, (HR Wallingford, 1997), and in a similar document for the coastline of England and Wales, (HR Wallingford, 1993). The description below summarises the significance and importance of such cells in managing the coastline with regard to the naturally occurring processes acting upon it.

The processes which shape and alter a coastline show no respect for administrative boundaries. Coastal defences installed by one local authority have, at some sites in the UK, contributed to erosion along frontages under the care of an adjacent authority. These difficulties can be avoided by recognising the natural divisions of a coastline, often called coastal "cells". Where the main concern in managing a shoreline is to defend against erosion or flooding, then the most useful definition of a cell is based on a consideration of the longshore drift of beach material (sand and shingle). This is because most cases of severe coastal erosion are caused by interruptions to the natural longshore transport of sediment.

A recent study of the coastline of England and Wales, (HR Wallingford, 1993), resulted in its suggested division into 11 main cells, each of which was further divided into sub-cells. An ideal cell would be entirely self-contained from a sediment transport viewpoint, i.e. there would be no nett import or export of beach material. Then, although coastal defence works could affect the whole cell by interrupting the longshore drift, they cannot affect beaches in other cells. Once established, these cells (and sub-cells) have proved to be a useful basis for shoreline management purposes. In England, the Ministry of Agriculture, Fisheries and Food (MAFF) have introduced Shoreline Management Plans; these are drawn up to provide a strategic basis for planning future coastal defences. Apart from considering aspects such as waves, tidal levels and coastal erosion/accretion, these Plans consider wider issues. Typically these include land use, ecological and geological conservation, tourism and recreation etc. As a consequence, in England and Wales, these plans provide a useful input into wider Coastal Zone Management initiatives. Each Plan is normally carried out for one or more sub-cells as defined above. An initial study has just been completed into defining coastal cells around the coastline of mainland Scotland, Orkney, Shetland and the Western Isles, (HR Wallingford, 1997).

On rocky coastlines, like many of those in the Western Isles, where sediment is sparse, and beaches are often confined to deeply indented bays, then "cells" are often small and numerous. It becomes impractical in such areas to draw up a management plan for each cell; as a result it is sensible to group a number of these small bays together, to form a more convenient "cell" for management purposes. Considerations other than just the longshore transport of beach material are used to define cells in these situations. These include general orientation of the coastline and its hydraulic environment. Cells 8 and 9 have been defined in this manner.

Bearing the above description of cell boundaries in mind, the coast of Scotland has been divided up into 11 main "cells" as shown in Figure 1. These major cells not only reflect beach sediment units, but also divide the coast into regions where the geology, physical character and orientation are similar.

For the purposes of coastal defence management, however, these major cells may be rather large, and contain too many conservation organisations, local authorities etc. for a single group to manage. Within these major cells, therefore, a number of "sub-cells" have been defined, and the description of the coast in this report is arranged using these smaller units. At many sites, the sediment transport around a headland or a large harbour only moves in one direction, and is often of small volume. Engineering works on the updrift side of such a feature may therefore have some impact on the downdrift coast, but such impacts may be small or totally insignificant. Interference with the beaches downdrift of such a "one-way" valve will not affect beaches updrift. We can regard such sub-cells as being "partly dependent", with the understanding that the cell boundary between them is not totally "sediment-tight". An idealised cell is shown in Figure 2.

The definitions of cells and sub-cells in this report are principally derived from the viewpoint of movement of sand and shingle along the beaches, and taking into account the likely consequences of interfering with that movement, i.e. sediment movement in the littoral zone, Figure 3. A particular difficulty arises, however, in estuaries, which are often 'sediment sinks' and hence suitable cell boundaries. For those interested in the biological aspects of an estuary, or the movements of cohesive sediments, this separation of the estuary into two cells is inconvenient. To avoid this, we have preferred to define cell, (and sub-cell) boundaries, around Scotland on the basis of 'drift divide' points (e.g. headlands). The inner portions of several major firths have then been defined as sub-cells.

Identification of such coastal cells is intended to help planners determine the length of coastline likely to be affected by coastal works in a particular area. It is hoped that this type of 'overview' will assist in the understanding of the coastal system as a whole and may lead to a more unified approach to the planning of coastal defences, and hence assist in wider Coastal Zone Management.

2.2 Coastal planning and development

In England and Wales, Shoreline Management Plans co-ordinated with other initiatives can provide useful information in informing decisions on Statutory policies, for example in areas which face particular pressures such as in estuaries where competing usage is often experienced. An example, from England and Wales, of the inter-relationship between some of these initiatives is shown in Figure 4. Local authorities are required to produce a structure and local plan which together provide the Development Plan for an area. The Development Plan provides the statutory framework within which development control decisions are made. Shoreline Management Plans should be integrated within the work of the local authority and can have an important role in informing development plan policy.

There are several documents available which highlight the Government policy on key issues affecting the coastal zone. Of most relevance to the coastline of Scotland is the recently published discussion document from the Scottish Office on *Scotland's Coast* (Scottish Office, 1996) and *National Planning Policy Guidelines (NPPG)13: Coastal Planning* (Scottish Office, 1997). Similar publications in England and Wales, despite being geared to the legislative framework in these countries, are also of use in highlighting the key issues affecting the Scottish coastline. Of particular note, in the context of this report, is the Department of Environment (DoE) publication on *Policy guidelines for the coast* (DoE, 1995) and the MAFF publication, *Shoreline Management Plans - A guide for coastal authorities* (MAFF, 1995).

2.3 Coast protection legislation in Scotland

The new Unitary Authorities with a coastal frontage are known as coast protection authorities under the Coast Protection Act 1949 and have powers under the Act to undertake such coast protection works as they consider necessary to protect any land in their area. Where coast protection work proposed is not maintenance and repair, the coast protection authority is required to follow the procedures defined in the Act. This may lead to approval by the Secretary of State. Once a scheme is approved by the Secretary of State, government grants are available towards the eligible cost of the works at a rate dependant on the authority promoting the scheme. The grant level can vary from between 20% to 80% at present.

The seabed below the Mean Low Water Mark of Ordinary Spring Tides is owned by the Crown Estate *prima facie* in law. The Crown Estate also owns much of the foreshore between Mean High and Mean Low Water Springs but does not hold a title to the foreshore and ownership can be displaced by anyone who can show a title derived from a Crown Grant. As part of the process required to enable consideration of schemes for approval under the Coast Protection Act 1949, consultation with the Crown Estate Commissioners is required. Approval must be obtained from the Commissioners before any coastal defence works, or any works on Crown Estate property is carried out.

Planning permission will be required for all new coastal defence works above Mean Low Water Mark of Ordinary Spring Tides and for any associated works such as borrow pits. In addition, building warrants are normally required for the construction of all walls and structures over a certain height. The exceptions to this are where work is being conducted within harbour limits and are covered by the Harbour Act 1964; for maintenance work; and for emergency works. There are a number of other consents which may be required before coastal defence work can be undertaken. Some of these are detailed in the table below:

Table 1 Required consents for proposed coast protection works

Consent	Application
Planning Permission (TCPSA 1997)	• All new works above MLWS • Associated works such as borrow pits above MLWS
Coast Protection Authority (CPAu) consent (CPA 1949)	• All coast protection works other than those carried out by a CPAu in its own area • New works carried out by a CPAu in its own area require consent of SoS (Scotland)
FEPA Licence (FEPA 1985, part II)	• Licence required for all operations entailing construction or deposition on seabed below MHWS
Environmental Statement (ES) (EA 1988/1994)	• If Planning Authority considers significant environmental effects to a "sensitive location" [1] will result from proposed works, it can require an ES with planning application
Notice of Intent (WCA 1981 Sn28)	• If works are permitted development on an SSSI

Notes

[1] Indicative criteria for assessing the significance of such impacts are contained within the Environmental Assessment legislation referred to.

Abbreviations used:

- CPA 1949: Coast Protection Act 1949
- CPAu: Coast Protection Authority
- EA 1988/1994: Environmental Assessment (Scotland) Regulations as amended
- ES: Environmental Statement
- FEPA 1985: Food and Environment Protection Act 1985
- SoS: Secretary of State
- TCPSA 1997: Town and Countryside Planning (Scotland) Act 1997
- WCA: Wildlife and Countryside Act 1981

Details of the statutory designations, and consultees, of conservation, historical and archaeological sites are described in Section 3.6.

3 The marine environment

3.1 Introduction

This chapter provides a brief general introduction to the coastal environment of Scotland in the context of this report. For more detailed information the reader is referred to the recently published CIRIA manuals *The use of rock in coastal engineering* (CIRIA, 1991) and the *Beach management manual* (CIRIA, 1996).

3.2 Geology and geomorphology

Scotland is composed of a particularly wide range of different rock types, representing most periods of geological time. Sedimentary rocks (those formed by the consolidation and lithification of sediments deposited in different marine and non-marine environments), igneous rocks (those formed by the solidification of lava erupted on the surface of the land or of magma which consolidated within the earth's curst) and metamorphic rocks (those formed by the alteration or deformation of other rock types) are all well-represented around the coastline.

In geological terms, Scotland can be considered as being formed of five distinct units or divisions, each separated by a major fault or fracture in the Earth's crust:

- the north-west Highlands and Islands west of the Moine Thrust, composed of "ancient" Lewisian gneiss;
- the Northern Highlands between the Moine Thrust and the Great Glen Fault, composed of the eroded roots of the Caledonian Mountain Belt, consisting primarily of 1 Ma old metamorphosed sediments of the Moine;
- the Central Highlands between the Great Glen Fault and the Highland Boundary Fault, composed of 800 Ma old Dalradian sediments and intruded with granites now forming the Cairngorms and other mountains and hills;
- the Midland Valley, composed of sediments deposited in tropical seas 300 Ma ago, extensive lava fields of the Ochils and Clyde plateau and the volcanic rocks of Edinburgh and the Laws of Fife and East Lothian; and
- the Southern Uplands, composed of sediments deposited in the former Iapetus Ocean which, for over 100 Ma, separated Scotland and England.

The geological structure and the lithological variability exert a strong influence on the morphology of the coastline. However, it is the processes which have occurred over the last ca. 2 Ma (during the period known as the Quaternary) that have left a major impact on the coastline, in particular those during the last (Late Devensian) glaciation (ca. 26,000-10,000 years) and in the postglacial period or Holocene.

The last ice sheet, which reached a thickness of 1500 metres in places, advanced from the Highlands over the entire Scottish mainland and most of the islands. Ice extended off-shore and local ice-caps may have existed on the more remote island groups such as Shetland and the Western Isles. Sea level, world-wide, was up to 140 metres lower than it is today. This, and earlier ice sheets, extensively scoured and eroded the bedrock, particularly in the west where it carved out the fjords and sea lochs along lines of pre-existing geological weakness. By 13,000 years ago the ice sheet had melted, depositing a variable cover of drift off-shore in the process. On-shore the ice deposited a thick cover of till in the more eastern areas. Meltwater from the retreating ice also deposited glaciofluvial deposits in the major eastern valleys and coastal lowlands. As sea level rose during deglaciation, some of the glacial sediments in the off-shore zone were reworked and moved into the present coastal zone, and fresh material was eroded from the glacial deposits on the coast. It is the material derived from these glacial deposits which supplied the majority of the sediment for the sand and shingle beaches of the present coastline.

As the ice sheet melted, the loading it applied on the Earth's crust was removed, resulting in the land recovering, or rising, typically at rates of a few millimetres per year (known as isostatic uplift). Rates varied, however, being greater where the ice was formerly thickest and less where the ice had been thinner, as was the case, for instance, around the Northern and Western Isles. At the same time, melting of the ice sheets caused global sea level to rise (known as eustatic rise). Accordingly, the patterns of relative sea level change during and since the ice age have varied around the country depending upon each location's proximity to the centre of the former ice sheet.

When the ice first began to melt, between approximately 17,000 and 15,000 years ago, global or eustatic sea level rose, flooding over the continental shelf and engulfing many coastal areas. In some western areas, such as Jura and Arran, "raised" beaches were deposited on the coast at heights of up to 40m above present day high water mark. Thereafter, isostatic uplift gradually overtook eustatic rise causing a relative fall in sea levels around most of the country. This trend continued, with local variations, until around 8,000-9,000 years ago, bringing sea level down to around or below present day levels in most areas. At that time, eustatic rise once more overtook isostatic uplift and relative sea level rose again (known as the Postglacial Transgression) to attain a maximum height relative to the land, in most areas, around 5-6,000 years ago.

Since that time eustatic rise has tailed off and so isostatic uplift has caused, in general, a gradual fall in relative sea level of around 1-2 millimetres per year in Scotland, though recent studies suggest that changes in sea level related to global climate change may now be counteracting this. Moreover, in areas remote from the centre of the main Scottish ice cap, such as the Northern and Western Isles, eustatic rise in sea level has continued to outpace isostatic uplift and so gradual submergence has dominated in these areas in recent millennia, rather than emergence.

3.3 Hydraulic processes

In understanding the recent (and past) evolution of the coastline a knowledge of the prevailing tidal levels, currents, wave and swell conditions is necessary.

Tidal levels

Tidal levels experienced around the Scottish coastline are generally made up of two components, an astronomical component and a residual component due to weather effects. The main tidal driving forces are the "astronomical forces"'- the major contribution being due to the relative motions of the Earth, Moon and Sun. The differential gravitational effects over the surface of the oceans cause tides with well defined "semi-diurnal" and "diurnal" periods (actually about 12.38 and 24.76 hours respectively).

In addition to the contribution to the tides which results from the earth's rotation, other periods are apparent in the fluctuation of tidal levels, for example the fortnightly spring-neap cycle, corresponding to the half period of the lunar cycle. Due to the slight ellipticity of the earth's orbit around the sun, there is also an annual variation of tidal effects. The solar tidal components are increased due to declinational effects giving rise to the equinoctal tides in September and March. Even longer variations can also be identified, such as that of approximately 18.6 years which corresponds to the changing angle between the axis of the earth and the plane of the moon's orbit.

Analysis of tidal measurements takes advantage of the knowledge of these precisely known periods, and uses a "harmonic" analysis of the measured data to derive information on the phase and magnitude of each tidal constituent, i.e. a component with a defined period. By analysis of the range (i.e. the vertical difference between high and low water levels), and the timing of the arrival of high/low waters, considerable light can be shed on the propagation of tides around the coast. All the tidal energy experienced around the coastline of Scotland stems from the Atlantic and were it not for the openings to the Atlantic, there would be no noticeable tide in the North Sea. Once the tidal energy reaches the shallow waters of the north-west European continental shelf, however, it becomes concentrated by both the reducing water depth and the converging land-masses. A large number of complex processes then occur, including reflections and complicated swirling motions around areas of little or no tidal range (so called *amphidromic points)*.

Sufficient information to predict tides with reasonable accuracy can be gathered in as little as four weeks (a Spring-Neap tidal cycle) in most locations. However, longer periods of recording are necessary to accurately determine all the components. Some of the most influential components, or "harmonics", are normally presented in Tide Tables. It is possible to purchase software (a) to analyse tidal measurements, and/or (b) to use the resulting (or published) harmonics to make your own predictions of water levels. Yearly predictions of water levels are published in the Admiralty Tide Tables. The tide tables also tend to give levels relative to "Chart Datum" and the relationship between the particular "Chart Datum" and a more "universal" vertical datum, e.g. Ordnance Datum Newlyn (ODN) in the UK, must always be carefully established. **For the design of coastal works, it is better to use information derived from analysis of recorded water levels (see below), related to a land-based vertical datum, e.g. ODN.**

Actual water levels experienced around the coastline will vary from those predicted in the Admiralty Tide Tables. Generally speaking the differences between the levels of highest astronomical tide and, say, the largest predicted tide in any year is rather small (i.e. a few centimetres). In practice, this difference is unimportant, at least in Scotland, when compared with the difference between predicted and observed tidal levels due to weather effects. As a very simple example, a static depression with a pressure 38 millibars lower than average can produce an increase of 0.3m in tidal level above that predicted. Such static barometric effects, however, are usually less important than dynamic ones.

A rapidly changing weather pattern will often produce short period fluctuations in atmospheric pressure, which in turn produce fluctuations of a similar timescale in the tidal curve. A good example is provided by the passage of a series of squalls. As a result, undulations in tidal level are caused, with a typical period of a few minutes. These undulations are usually called 'seiches', and on the open coast they normally present no great problems, since the associated changes in water levels, velocities and accelerations are small. However, in enclosed or partly enclosed bodies of water such as harbours, bays or sea lochs the periodicity of the seiches can cause a resonance which amplifies their effect. This rarely occasions any distress to coastal defences but can cause problems to moored ships.

The most important meteorological effects which alter water levels are generally known as 'storm surges'. Such surges result from the effects of wind stress on the surface of the sea. In shallow seas, such as the North Sea, a strong wind can cause a noticeable rise in sea level within a few hours. As one result, tidal levels at the coast can be increased (at both high and low water) until the wind abates. If the wind suddenly drops and then reverses in direction, the excess water held in an area by the wind can then be released, usually as one or more long waves. If such waves are amplified by a narrowing estuary, they can attain a significant amplitude and if the resulting surge arrives at a coast at the same time as the high water of an astronomical tide, the nett result can be devastating.

In the North Sea, such effects can regularly produce a "residual", i.e. a difference between predicted and actual water levels of a metre or so. In severe events, a "surge" can be produced, i.e. a long wave-like disturbance which can add several metres to the tidal level, although fortunately not often at high tide. "Negative surges" can also occur, for example under an anti-cyclone, producing much lower levels than expected.

It is often the combination of a surge and a predicted high tide which causes flooding or damage along a coast. Both the height of surges, and the time of their arrival relative to (predicted) high water are very variable. A considerable amount of research into such events has been carried out, with the main objective of predicting extreme tidal levels. Such predictions are usually expressed in a probabilistic manner, using the idea of "return periods". For example the 100-year (return period) tidal level is that level expected to occur or be exceeded only once, on average, in each century.

For sites where there is insufficient measured data, it is necessary to use numerical modelling to predict such extreme levels (by interpolation from nearby sites), or to "hindcast" tidal levels that have occurred in the past. This latter task is important if information on a particular severe event is required, for example to analyse the causes of flooding or of damage to coastal structures.

Tidal currents

The tides occurring around the coastline of Scotland also result in significant tidal currents, even in areas where the tidal range is small, e.g. off the coast of Islay. Where the shape of the coast allows the tide to fill and empty a large area during each cycle (e.g. estuaries, tidal inlets), the effects of the currents often dominate the hydraulic and sedimentary regime of the area. Even on an open, wave dominated coastline, such currents have a variety of effects. They act together with the waves to transport sediment more efficiently, both on beaches and over the nearshore seabed. As a result of this capacity to transport sediment, the tide can produce shifting banks of sediment which affect coastal processes. The currents also interact with the waves, altering their character, especially where they are similar to the wave propagation speeds. Finally, although the currents tend to be roughly equal on flood and ebb in most places, the small asymmetries can be fundamentally important in a large number of ways, particularly in the transport of fine-grained sediments (muds and clays), together with any adsorbed pollutants, for example heavy metals. In terms of sediment transport in the nearshore zone, the direction and velocity of currents acting at High Water Level may be more important than higher current velocities acting at mid tide. Similarly the tidal residual (vectorial displacement over the period of one tidal cycle) may also be important in the transport of nearshore sediments, particularly in estuaries.

While tidal levels vary slowly in space, and can be represented by a single value for each location at a specified time, tidal currents are much more complex. Very substantial changes in speed and direction can occur over a few tens of metres. Also, currents can change significantly with depth. In the open sea, such changes are often modest, i.e. a gradual reduction in speed below the water surface, but maintaining a consistent direction. However, in shallow water close to a coast, in estuaries, and in the vicinity of structures, the situation is often much more complex. Indeed flows can be in very different, sometimes entirely opposing, directions at the surface and near the seabed.

Waves and swell

The action of waves on the coastline is normally the dominating process influencing the littoral regime. The main wave influence on much of the Scottish coastline is from wind generated waves. Such waves have periods in the range 1-25 seconds, but in Scottish coastal waters the important range is usually between 4 and 20 seconds. The size and period of waves which strike a coast depend on the wind speed, its duration and the 'fetch', that is the unobstructed distance over the sea surface that the wind has travelled. On open coasts where the fetch is very large but the wind blows for only a short period, the wave height is limited by the duration of the storm. Beyond a certain limit, the total fetch length becomes unimportant. Where fetch lengths are restricted, e.g. by offshore islands, a short storm may produce the largest potential waves and any increase in the duration will not cause extra wave growth. Such waves are described as "fetch limited".

On oceanic shorelines, including some of the Scottish coastline (especially the exposed west and north coast), the situation is usually more complicated. Where both the fetch and durations are extremely large waves then become 'fully developed' and their height depends solely on the wind speed. In such situations the wave period usually becomes quite large, and long period waves are able to travel great distances without suffering serious diminution. The arrival of "swell', defined as waves not generated by local and/or recent wind conditions, presents a difficulty in wave forecasting which it is only now becoming possible to overcome, using for example a global wave forecasting model.

Swell waves are of nearly constant period and direction (although the height of successive waves does vary). Swell can be measured easily and accurately gauged "by eye", but is difficult to predict numerically. In contrast, waves generated locally (i.e. over a few hundred kilometres, during a day or so) are much more variable in direction and period. These waves are more difficult to measure, or gauge accurately by eye, but much easier to forecast numerically.

As waves approach the shoreline they are altered as shallow water processes become important. Around much of the UK this starts to affect waves in water depths of around 20m (more off the north and west coasts of Scotland, where larger wave conditions are experienced). In shallow water the main processes in the transformation of waves are shoaling, depth-refraction, current refraction, seabed friction, wave breaking, diffraction and reflection. In general terms this results in a decrease in wave heights as they travel into shallow water but little change in wave period. Whereas offshore wave conditions vary gradually in space, inshore wave conditions are normally site-specific with considerable variation often experienced over relatively short distances. Similarly around the coastline of the UK, offshore wave conditions are experienced from every directional sector. However, the range of wave directions experienced in shallow water will be much smaller and some offshore wave directions may be unimportant.

For coastal engineering purposes, both offshore and inshore wave conditions are normally defined in terms of the significant wave height, H_s (which is the average height of the highest one third of the waves in a given sea state), the wave period, T_m (which is the time taken for two successive wave crests to pass the same point), and the wave direction, θ.

3.4 Littoral processes

The concept of coastal cells is concerned with sediment movements in the littoral zone (see Figure 3). The rate and direction of such movements are influenced not only by the prevailing hydraulic processes, such as swell and wind waves and tidal, wind and wave induced currents, but also by the bathymetry and the physical characteristics of the beach and seabed (e.g. sediment size).

On a sand or shingle beach, the influence of the natural processes, particularly the wave action, will result in the beach attempting to attain an equilibrium profile. This profile will normally vary depending on the incident conditions. For example there is often a distinct summer/winter cycle where storm wave action in winter months draws beach material further down the beach to below the low water mark resulting in a flatter beach slope. This material is then transported back up the beach during the summer (resulting in a steeper beach slope) during milder wave conditions. Where there is little long term change in the beach morphology the beach system is said to be in dynamic equilibrium. In general, drawdown of the beach occurs at a much quicker rate, e.g. over the period of a single storm, than beach build-up, which may take a number of months. Hence, beach material may appear to have been eroded when it may simply be removed due to a recent storm with there being insufficient time for the material to be moved back onto the upper beach.

Where waves break obliquely at the coast a longshore current will be created in the surf zone which, when acting with the stirring action of the waves, will result in the longshore transport of material. Littoral drift is a dominant influence in shaping the coastline and is the major cause of coastal erosion (or accretion) particularly where the dynamic equilibrium of the drift regime is altered in any way (either due to natural changes or due to other external influences, e.g. human). On most of Scotland's beaches, sediment will move in both directions along a beach due to waves from different directions. However, it is normally the nett sediment transport rate and direction which is of greatest importance. A nett transport of material may be evident at the coastline, e.g. where there is a build up against a harbour breakwater, or a groyne over a length of time (years). However, it is often difficult to determine the direction and magnitude of any littoral transport confidently, particularly around the coastline of Scotland where the magnitude and direction of wave conditions are variable. To do so normally requires the use of numerical models which predict longshore transport using a time series of wave data. In certain situations, other hydrodynamic processes can cause littoral drift, either adding to or opposing the drift caused by waves breaking obliquely to the beach contours. These processes include tidal currents and longshore variations in breaking wave height. The former can be important when currents are still strong at high (and low) water, especially on straight coastlines (e.g. north of Aberdeen). The latter process is well demonstrated by the shelter provided by an offshore island. This provides substantial spatial variations in wave height, leading to a strong drift from the more active areas into the sheltered water.

In addition to an understanding of sediment movements, a knowledge of the inputs and outputs of sediment into the littoral regime is required. This is known as the sediment budget. It is important to know whether there is any fresh source of beach material being input to the system, e.g. from fluvial sources, cliff erosion or offshore deposits, or whether existing material is being reworked by coastal erosion. Similarly knowledge of whether material is being lost completely from the beach system, e.g. offshore, or if it is moved by wind action into a dune system, or whether it is accreting on the beach, is also important.

To assess the possible impacts and requirements of future coastal protection works, and to understand the likely future evolution of the shoreline, a quantitative understanding of these littoral processes is required.

3.5 Coastal defence, monitoring and management

There are two main types of coastal defence - "Coast Protection" where engineering works are used to protect an eroding coastline from further erosion, and "Sea Defence" where works are provided to prevent flooding of the coastal hinterland due to extreme wave and/or tidal conditions. In assessing existing defences along a frontage there are three main criteria which need to be examined:

- the structural condition of the defence,
- its capacity to prevent overtopping or flooding,
- the impact of the defence on the surrounding littoral regime.

The standard of protection provided by a section of coastal defence depends on the margin of safety it provides against structural collapse or unacceptable high overtopping discharge for example, both of which are highly influenced by the level and condition of the beach in front of the defence. Each of these criteria are interrelated with structural failure a consequence of the hydraulic forces as well as structural and geotechnical aspects. Overtopping and flooding, as well as depending on the severity of storm conditions, is also a function of the crest level of the structure and cross-sectional profile. Similarly the condition of the beach in the locality of the defence is a function of the sediment supply, hydraulic conditions and also of the type and design of the structure.

Construction of coastal defences, either to prevent flooding or to control coastal erosion, can have a variety of effects on the coastline and the development of beaches. Linear structures built along a frontage can have various detrimental effects on a beach. For instance, structures constructed in front of eroding cliffs or links areas can prevent the contribution of fresh material to the beaches, with resulting sediment starvation of the coast downdrift, known as downdrift erosion. Where wave action interacts with a linear defence, wave reflections from the structure can lower the level of the beach in front of it, and hence allow greater wave attack on the structure itself.

Of greater impact on the littoral regime is the effect of interrupting or altering the longshore transport of beach material, e.g. by the construction of a harbour breakwater or construction of a groyne system. The long-term effects of either reducing or stopping all drift along a coastline can be an increase in erosion at beaches further along the coast due to sediment starvation.

3.6 Natural and cultural heritage

There are a number of statutory and non-statutory forms of designations which are used to protect terrestrial sites with natural and cultural heritage value. Statutory designations, or areas which have some form of 'custodial' ownership, have mechanisms which protect them, to a limited extent, from certain development or harmful activities. There is also a wide range of conservation legislation protecting individual habitats and species which may affect future shoreline management. Further information on natural heritage sites can be obtained from Scottish Natural Heritage with information on cultural heritage sites from Historic Scotland.

The range of national and international designations afforded to the coastal areas of Scotland of direct relevance to shoreline management, the designating organisations, and a short description of each taken from the Scottish Office discussion paper, *Scotland's Coasts* (Scottish Office, 1996), are detailed below:

<u>Sites of Special Scientific Interest (SSSI)</u> — <u>Scottish Natural Heritage</u>

Designated by SNH under the Wildlife and Countryside Act 1981 Section 28 to protect areas of important flora, fauna, geological or physiological features. Extensive parts of the coast are included within the SSSI network but the legislation only applies to land above MLWS. SSSIs provide the basis for other national and international designations e.g. NNRs and SACs. SNH requires to be consulted on developments, or notified of potentially damaging operations, which may affect the SSSI interest.

National Nature Reserves (NNR) Scottish Natural Heritage

Declared by SNH under the National Parks and Access to the Countryside Act 1949 Section 16. NNRs are owned or leased by SNH or managed under agreement to protect and enhance their outstanding nature conservation interest. Public access may be controlled through bylaws. NNRs are also SSSIs, and some have coastal frontage or are offshore islands.

Marine Nature Reserves (MNR) Scottish Natural Heritage

Provision is made in the Wildlife and Countryside Act 1981 Sections 36 and 37 to designate marine areas to conserve their marine flora and fauna. This is the only statutory designation which specifically relates to marine areas below the low water mark. Designation procedures involve extensive consultation and protection is by bylaws. There are currently no MNRs in Scotland but a voluntary Reserve operates at St Abb's Head in Berwickshire.

Local Nature Reserves (LNR) Local Authorities/Scottish Natural Heritage

Section 21 of the National Parks and Access to the Countryside Act 1949, and Section 10 of the Local Government (Scotland) Planning Act 1982, give powers to local authorities in conjunction with SNH to establish Local Nature Reserves for their conservation and amenity value and for the public enjoyment of the countryside. They are controlled by bylaws. To date three coastal LNRs have been established in Scotland.

Special Areas of Conservation (SAC) Scottish Office

SACs are to be designated under the 1992 EC Directive on the Conservation of Habitats and Species. The special interest of SACs must be strictly protected. SACs, together with SPAs classified under the EC Wild Birds Directive (see below), will form a European-wide network of sites known as Natura 2000. The main aim of the network is to maintain the relevant species and habitats in a favourable conservation status. Coastal and marine sites are among the areas which, following consultations, are being proposed to the European Commission for SAC designation.

Special Protection Areas (SPA) Scottish Office

The 1979 EC Directive on the Conservation of Wild Birds requires special measures to be taken to protect wild birds and their habitats, including the designation by the Secretary of State of Special Protection Areas to safeguard vulnerable species and regularly occurring migratory birds. Scotland is particularly important for cliff-nesting seabirds, waders and wildfowl. SPAs are subject to the same strict protection of their special interest as SACs.

Ramsar sites Scottish Office

The Ramsar Convention requires wetlands of international importance to be protected to safeguard wetland habitats and species including those which contain large numbers of wildfowl. Several coastal or marine areas are designated or proposed Ramsar sites. The Secretary of State, on the advice of SNH, designates Ramsar sites and the Government has decided that as a matter of policy these sites should be accorded the same strict protection as for SPAs and SACs.

National Scenic Areas (NSA) Scottish Natural Heritage

National Scenic Areas were introduced by circular in 1980 (amended in 1985) to safeguard areas of outstanding landscape importance as identified by SNH (formerly CCS). Policies for protecting NSAs are set out in development plans and planning authorities are required to consult with SNH on specific categories of development. A number of NSAs incorporate part of the coast.

Natural Heritage Areas (NHA) Scottish Natural Heritage
The Natural Heritage (Scotland) Act 1981 Section 6 makes provision for the designation of NHAs, although none has been introduced to date. These will cover extensive areas including the coast within which nature conservation, landscapes and cultural issues will be managed under a single integrated management plan which will be approved by the Secretary of State.

Areas of Great Landscape Value (AGLV) Local Authorities
Under the provisions of Circular 2/1962, AGLVs are identified by local authorities in development plans with appropriate policies to protect areas of regional or local landscape importance. AGLVs vary in area and may include parts of the coast.

Environmentally Sensitive Areas (ESA) Scottish Office (SOAEFD)
These are designated by the Secretary of State under the 1986 Agriculture Act to encourage landowners to manage their land to safeguard and enhance the nature conservation, landscape and cultural interest of the land for which a grant is available.

Marine Consultation Areas (MCA) Scottish Natural Heritage
These are non-statutory areas introduced in 1986 where SNH wish to be consulted on developments, in particular fish farms, which are likely to have an impact on the marine environment. There are 29 sites within Scotland, most of which are on the West Coast or the Islands.

Regional Parks and Country Parks Local Authorities
These are promoted by the local authorities under the provision of Section 48 of the Countryside (Scotland) Act 1967 to provide informal outdoor recreation and to protect local landscape and amenity for the enjoyment of the public. Country parks are relatively small areas used intensively for informal recreation. Regional parks are extensive areas where existing land use continues but also accommodates recreational activities. Some of these parks incorporate coastal areas.

RSPB Reserves Royal Society for the Protection of Birds
Private reserves owned by the Royal Society for the Protection of Birds where the main interest is ornithology but where there are often other important conservation interests.

Scheduled Monuments Historic Scotland
Ancient monuments surviving in both town and country are tangible reminders of Scotland's long history. Because of the evidence they can provide about Scotland's past many ancient monuments are given legal protection against deliberate or accidental damage or destruction by being "scheduled". A scheduled monument is a monument which the Secretary of State considers to be of national importance and has included in a set of records (known as the Schedule) maintained by him under the Ancient Monuments and Archaeological Areas Act 1979.

4 The Western Isles - information sources

4.1 General

Information on the physical characteristics and coastal regime is available from a variety of sources and organisations. The purpose of this section is to provide general details on the availability of such information and of any data sources of relevance to shoreline management. Further, site specific information, particularly on littoral processes and coastal defences, is contained within each of the sub-cell sections in Chapters 5 and 6.

Three general sources of information exists for the coastal environment of the Western Isles. The UK Digital Marine Atlas (UKDMAP) which was developed by the British Oceanographic Data Centre, Birkenhead provides a reference database on the marine environment for the whole of the UK. It provides general information on a wide range of subjects including geology, hydrography, conservation and ecology. A review of information relating to the natural environment, the current protected status of coastal and marine habitats, communities, species and activities around the Western Isles is detailed in *The Minch Review* (Bryan, 1994) which was produced by Scottish Natural Heritage and Western Isles Islands Council, and in *Coasts and Seas of the United Kingdom: Region 15 & 16: The Western Isles and West Highland* (Barne et al, 1996).

Details of physical oceanographic and meteorological (metocean) data collected around the British Isles on behalf of the UK energy industry is summarised in a report by Metocean (1994). This includes details on organisations who have collected information on winds, waves, currents, water levels and other associated parameters. Further information sources of physical data are detailed in the following sections.

4.2 Geology and geomorphology

The geology of the Western Isles is described in several studies, for example (*British Regional Geology: The Northern Highlands of Scotland* (Johnstone & Mykura, 1989), *Outer Hebrides: Localities of Geological and Geomorphological importance* (Black, 1977) and *The Outer Hebrides: The Shaping of the Islands* (Angus, 1997)). These reports reference a large number of more detailed localised studies conducted within the Western Isles. The British Geological Survey have also produced four solid geology 1:100,000 scale maps and a 1:625,000 solid and Quaternary map covering the Western Isles.

The Geological Conservation Review was a 12 year research programme initiated by the Nature Conservancy Council in 1977 to identify the key onshore Earth science sites in Great Britain using available survey and research information. Site classification was completed in 1989 and the review is currently being published through a series of approximately 40 volumes, 14 of which are now available.

The geomorphology of the Western Isles coastlines is described in several studies, the main texts being *The coastline of Scotland* (Steers, 1973); *The beaches of Lewis and Harris* (Ritchie & Mather, 1970); *The beaches of Barra and Uist* (Ritchie, 1971) and *The shaping of the islands* Angus (1997). Other, more localised studies have also been conducted. These include a review of coastal erosion in the Western Isles (HR Wallingford, 1995b).

4.3 Bathymetry

The bathymetry off the coast of the Western Isles is illustrated in detail on the following Admiralty Charts:

Table 2 Available Admiralty Charts

Chart No.	Location	Scale
1127	Outer approaches to the North Channel	1:500,000
1785	North Minch - Northern Part	1:100,000
1795	The Little Minch	1:100,000
1796	Barra Head to Point of Ardnamurchan	1:100,000
2529	Approaches to Stornoway Harbour	1:25,000
		1:10,000
2642	Sound of Harris	1:20,000
2720	Flannan isles to Sule Skerry	1:200,000
2721	St Kilda to Butt of Lewis	1:200,000
2769	Barra Head to Griean Head	1:30,000
		1:12,500
2770	Sound of Barra	1:30,000
		1:12,500
2825	Lochs on the east coast of Uist	1:12,500
		1:15,000
2841	Sound of Harris to Ard More Mangersta	1:50,000
2905	East Loch Tarbert	1:25,000
3381	West Loch Roag	1:12,500
3422	East Loch Roag	1:12,500

The charts are produced by the Hydrographic Office, Taunton, and also include information on tidal streams, tidal levels and other information of use to the navigation of sea vessels.

4.4 Wind data

The islands are well served with anemometer records with winds having been recorded (and the information passed to the Met Office) at Butt of Lewis and Benbecula, Figure 6. In addition wind records from Stornoway and from Tiree could also be potentially useful in estimating wave conditions on the eastern coastline. At present the recorders at Stornoway and Benbecula are equipped with Digital Anemograph Logging Equipment (DALE), which logs wind data onto magnetic tape, and which is sent to Bracknell for incorporation into the Climatological Data Bank there. The recorders at Butt of Lewis and Tiree use graphical recorders, which have to be hand-analysed to provide suitable data for archiving. Our latest information (1994) states that all these stations, except the Butt of Lewis, are soon to be equipped with Semi-Automatic Meteorological Observing Systems (SAMOS) which produce wind statistics continuously for immediate archiving. A summary of the available known wind data is provided in the following table:

Table 3 Cell 8 - Availability of wind data

Location	Period covered	Anemometer Type
Benbecula	01/70-Present	Analysed anemograph from SAWS/SAMOS/CDL station
Butt of Lewis	03/86-Present	Data on Metform 6910
Stornoway	01/70-Present	Digital anemograph logging equipment (DALE)
Tiree	01/70-Present	Data on Metform 6910
North Rona	Unknown	Unknown

An automatic weather station is also situated on North Rona (about 50km north of the Butt of Lewis).

4.5 Tidal data

Stornoway has an A-class tidal gauge, installed and maintained as part of a national network of tide-gauges organised by the Proudman Oceanographic Laboratory (POL) situated at Bidston, Birkenhead (Figure 6). Long term measurements from this gauge have been analysed to produce 'harmonic constants' from which predictions of tidal levels can be made for any desired time. Harmonic constants have also been calculated for several other locations within Cells 8 and 9. These too can be used to provide local tide predictions, either by POL, or other organisations who have obtained the relevant computer programs to make such predictions. It should be realised, however, that the harmonic constants derived for these sites may not be as reliable as those from an A-class gauge. **Care must also be taken in the Western Isles as some levels on older Admiralty Tide Tables and Charts are referred to a local datum and not to Ordnance Datum Newlyn.**

Information on mean sea level can be obtained from the Permanent Service for Mean Sea Level (PSMSL) which is located at the Bidston Observatory in Birkenhead. This was set up in 1933 and is responsible for collecting monthly and annual mean values of sea level from approximately 1450 tide gauge stations around the world. The contents of the PSMSL data set are described in the report *Data holdings of the PSMSL* (Spencer & Woodworth, 1993) which can be obtained from the Bidston Observatory. Within Cell 8 mean sea level is recorded at the A-class gauge in Stornoway.

Actual tidal levels, however, can and often do vary significantly from those predicted using harmonic analysis due to the influence of meteorological effects (surges) see Section 3.3. The UK Met Office Storm Warning Service operates a surge prediction model provided by POL. This has a 12km spatial resolution around the coast of the UK, and can provide information on surge conditions offshore from the Western Isles. To provide predictions at the coastline a more detailed numerical model would be required. There are no known localised tidal models within Cells 8 and 9.

A number of studies have been conducted into extreme (surge) water level predictions (e.g. Graff, 1981; Woodworth, 1987; Coles & Tawn, 1990). The latest research into trends of extreme sea levels (Dixon & Tawn, 1994) provides a site by site analysis of extremes around the coast of the UK. This research has been extended to produce a spatial analysis of extreme water levels every 20km around the mainland coast of the UK (Dixon & Tawn, 1997). However, this study does not include the Western Isles.

The Admiralty has always provided information on tidal currents to assist in navigation. The Admiralty Charts usually have a selection of 'Diamonds', i.e. locations indicated on the chart by a diamond symbol, with accompanying lists of current speeds at that point throughout the tide. In UK waters, this information is given for both Spring and Neap tides. The currents are usually 'depth-averaged', i.e. an average value of the speed throughout the water column.

In addition the Admiralty also produce 'Tidal stream atlases' with the offshore zone of The Western Isles covered in the North coast of Ireland and west coast of Scotland Atlas (Hydrographer of the Navy, 1962). These show the currents over a wide area at various states of the tide. The flows are represented by arrows, annotated with the approximate speeds (again for Spring and Neap tides). However, this information is aimed at those navigating ships; it is rarely of much use in very shallow coastal waters or away from the main channels in estuaries.

Tidal current measurements are normally made over relatively short periods of time (usually less than 1 year), often in connection with a particular study. There are two main sources of such data. Firstly the British Oceanographic Data Centre have a digital inventory of current meter data around the British Isles collected from a large number of both national and international organisations. The digital directory contains information up to 1991 and is available directly from BODC. The other source is from commercial survey companies carrying out site-specific studies.

Within the Minch little current meter recording has been conducted apart from a small number of recordings in the Sea of the Hebrides. Some current meter recording has been conducted to the west of Uist and Barra but little current data has been collected offshore of Lewis and Harris. No further information from commercial organisations was located.

4.6 Wave data

Information on offshore wave conditions can be obtained from two sources, either from measured wave data or from synthetic wave data generated using numerical models. The only detailed record of instrumentally recorded wave data in Scotland is the MIAS catalogue (MIAS, 1982) which was compiled in 1982 and a catalogue compiled by Metocean (1994). An updated digital version of the MIAS catalogue is presently being developed. Other wave recording has been conducted by commercial organisations normally in connection with a marine construction project, e.g. harbour development. The Minch and the Sea of the Hebrides are poorly served with measured wave data with no known locations where such recording has been conducted.

Measured offshore wave conditions to the west of the Western Isles are detailed in Table 4 and the locations shown in Figure 6. The percentage of data collected from the waverider buoy situated offshore of the Butt of Lewis was extremely poor with only approximately 5-6% of possible records collected and analysed. The measurement of wave conditions offshore of South Uist was conducted as part of the UK Wave Energy Programme with a number of waverider buoys deployed between March 1976 and April 1984. This deployment included a number of buoys in relatively shallow water depths.

The records listed in Table 6 contain only details of wave height and period. No details of the wave direction were recorded. It is unlikely that this wave information will be in a suitable format to be of much use in coastal management. A more effective use of this data would be in the calibration of wave numerical models to predict wave climates and extremes. Details of the above recorded wave information can be obtained from BODC.

Table 4 Recorded wave information

Location	Lat/Long	Period covered	Mean Water Depth (m)	Contact
Butt of Lewis	58°34.5'N 06°28.0'W	01/79-04/80	80	MIAS
Tiumpan Head	58°15.0'N 06°09.0'W	08/69-10/69 05/71-03/72	15.2 15.2	MIAS
South Uist	57°17'48"N 07°53'54"W	08/80-12/83*	100	MIAS
South Uist	57°18'42"N 07°29'06"W	03/76-04/83	42	MIAS
South Uist	57°19'36"N 07°29'06"W	08/79-07/82	23	MIAS
South Uist	57°17'24"N 07°29'06"W	03/81-08/81*	25	MIAS
South Uist	57°19'48"N 07°27'12"W	06/78-08/79	15	MIAS

Note: Some of the buoys were moved, for part of the recording period, to nearby locations; it is assumed that these small changes in position did not seriously affect the measured wave conditions.

*The exact dates at which recording finished at these sites is not known.

Information on wave conditions can also be obtained from the VOS (Voluntary Observations from Ships) archives. Many ships of passage make regular observations of wind and wave conditions as part of their routine duties. This information is collected worldwide and collated by the UK Meteorological Office. The records include date, time, location, wind speed and direction, significant wave height (H_s), zero-crossing period (T_m) and wave direction. Although not scientifically measured, VOS records have been found to be a useful source of data where there has been a large number of records spanning over many years, e.g. major shipping lanes. VOS data is available in the form of monthly, seasonal and annual frequency tables of wave height and period in 30° sectors for sea areas specified in 1° latitude and longitude squares. Details of the density of VOS data can be obtained from the Met Office.

When using VOS data it is important to ensure that the selected area is large enough to contain sufficient data in each sector for a reliable analysis of extreme conditions, but small enough to ensure that conditions are representative of the region of interest. In addition, for an analysis based on VOS observations to be valid, it is necessary to ensure that the exposure of the location of interest is the same as that of the VOS area used.

In many locations offshore wave prediction using numerical modelling techniques is difficult. Around much of the UK coast it is necessary, as a minimum, to have a model which can predict the generation of waves over a substantial part of the sea or ocean, and then to 'follow' those waves as they develop into swell. This is particularly important in deriving wave conditions to the west of the Western Isles where swell wave energy is a significant component of the total wave energy. A number of such numerical models exist, all run by national meteorological offices, or other governmental departments. In the UK, the most appropriate model to use is the Meteorological Office European Wave Forecasting Model.

Two surface wave models are run at present on an operational (daily) basis at the UK Meteorological Office. These are the result of an evolving series of such models, in use since 1976. They were designed primarily for offshore application, for example in ship routing and operation of offshore structures. The model calculations are carried out on a polar stereographic grid, whose exact spacing varies from one latitude to another. The European

Wave Model (grid spacing about 30km) is nested within the Global Model (grid spacing about 150km) from which it takes its boundary wave conditions. The 30km grid size means that shallow water effects are not well represented in the model, and grid points closest to the land are not used for prediction purposes. Before use, the model predictions therefore need to be transformed from 20-50km offshore to the shoreline (see below).

Both models are run twice daily, driven by wind fields extracted from operational global weather forecasting models. They produce wave forecasts from 12 hours prior to the run-time ('T') up to 36 hours ahead, at 3 hourly intervals. As well as noting the time, date, latitude and longitude, each forecast gives the wind speed and direction, and the significant wave height, mean wave period and wave direction for the separate wind-sea and swell components and overall. The data from T-12 hours to T+0 hours is permanently stored in an archive, whilst the data from T+0 hours to T+36 hours is immediately disseminated for forecasting purposes. Sea state observations from fixed buoys, oil platforms, Ocean Weather Ships, and more recently satellite wave measurements, are used for real-time 'calibration' of the models, and also for periodic validation. The archived information provides a very useful 'synthetic' offshore wave climate. Figure 6 shows the grid point locations offshore of the Western Isles. Due to the coarse resolution of the grid, offshore wave conditions in The Minch can only be generated for locations to the north east of Lewis and to the south of the islands. The model grid resolution is not accurate enough to predict conditions within The Minch.

Within much of The Minch, the total wave climate (i.e. the swell and wind wave climate) will be dominated by locally generated wind waves. Due to the shelter provided by the islands from Atlantic swell, swell waves will not be as significant as on the more exposed west coast. Modern numerical methods are capable of accurate predictions of 'wind-sea', especially if there is good quality, sequential wind data available to provide the basic input conditions. This technique has been used to derive the offshore wave climate off the east coast of Lewis at Gob Shilldinish (HR Wallingford, 1986). Hourly wind measurements from Stornoway were used, and adjusted to allow for the somewhat faster wind speeds that would be expected over the sea. The generation area was represented by radial fetches, with their origin at the point where wave information was required; this being more accurate than taking a single fetch length in the direction of the wind.

The final stage in numerical wave prediction is to transform such offshore wave information into corresponding nearshore conditions. This may be carried out just for a few offshore conditions (e.g. waves expected to occur only in exceptional storms), or for a whole wave 'climate'. For further details of the range of numerical techniques available, the reader is referred to a recent report by Dodd and Brampton (1995). However, in outline all such models start from a digital representation of the water depths between the offshore point at which waves are predicted, and the stretch of coastline under consideration. A number of alternative techniques are available that calculate the way that the wave energy propagates shoreward; they all include the processes of refraction and shoaling, and many can include other effects such as frictional dissipation, the shelter provided by offshore islands or headlands, the effects of tidal currents or the continuing growth of waves as they travel across the area being modelled. The accuracy of such transformation methods is generally good, provided an appropriate model has been chosen. Off the western coast of South Uist, for example, it would be necessary to incorporate the effects of friction caused by the shallow sloping offshore rock platform, in order to obtain reliable results. Further north, however, the western coastline of Harris and Lewis is less well protected, as water depths increase more rapidly as one travels offshore. Along the western coastline there are no known locations where detailed inshore numerical modelling has been conducted .

Table 5 Sources of numerically modelled wave conditions

Location	Offshore/Inshore Position	Period	Mean water depth (m)	Wave data	Contact
On a regular grid 0.25° lat. by 0.4° long.	Offshore: First point is normally less than 20km from the coast	1986 onwards	variable	Wind, swell and total sea climate and extremes	UK Met Office or HR Wallingford
5km S of Branahuie Bay	Offshore: 58°11.3'N 6°21.8'W 58°11.69'N 6°21.76'W	1970-1993	65m -1.8m CD -15m CD	1, 10, 50 extreme wave conditions	HR Wallingford
Off Gob Shilldinish	Offshore: 58°9.55'N 6°17'W Inshore: 58°11.47'N 6°18.8'W	1976 - 1984	unknown	Wave climate and 1, 10 &100 year extreme conditions	HR Wallingford
Broad Bay	Inshore: 58°16'N 6°17.3'W	1986 - 1984	-	Wave climate, 0.05, 0.1, 1 & 50 year extreme conditions	HR Wallingford
Brevig Harbour entrance	Inshore	-	-	0.1,1,50 &100 year return period wave conditions	HR Wallingford

Off the east coast of the Western Isles, inshore wave climates and extreme wave conditions have been derived at Stornoway Harbour, Gob Shilldinish and Brevig (HR Wallingford, 1995a,1986, 1996) and are detailed in Table 4. These are shown in Figure 6. A joint probability study of extreme wave and water levels was also conducted at Stornoway Harbour.

4.7 Natural and cultural heritage

Information on statutory designations and protected sites of natural heritage importance, and on certain non-statutory sites, is provided by Scottish Natural Heritage. A description of the various designations is given in Section 3.6.

Within Cells 8 and 9 the number of designated natural heritage sites is given in the Table below:

Table 6 Natural heritage designations

Designation	Number	Designation	Number
SSSI	29*	NSA	2
NNR	2	NHA	-
MNR	-	AGLV	-
LNR	-	ESA	1
SAC	-	MCA	6
SPA	2	RSPB	1
RAMSAR	-	LWT	-

* Seven of these SSSIs exist on offshore islands not embraced by this study.

Note: Data correct to September 1996. Supplied by Scottish Natural Heritage.
The distribution of designated SACs and SPAs has changed significantly since these data were compiled. Details of recent additions to this network can be obtained from Scottish Natural Heritage.

The locations of SSSIs are shown in Figure 7 with further information detailed in Appendix 1. Other natural heritage designations are shown in Figure 8.

Advice on historical and archaeological matters is provided by a number of organisations which are detailed in the following table:

Table 7 Cells 8 & 9 - Information sources for sites of cultural heritage

Advice or information on:	Contact
Scheduled monuments	Historic Scotland
Designated wrecks	Historic Scotland
The protection & management of sites and monuments	Historic Scotland or Regional Archaeologist
Sites or monuments already known	Historic Scotland/Regional Archaeologist/RCAHMS
Archaeological remains discovered during development	Historic Scotland/Regional Archaeologist
The discovery of a site	Regional Archaeologist/RCAHMS
An isolated artefact find	Regional Archaeologist/National Museums of Scotland/Local Museum
Damage to a scheduled monument	Historic Scotland
Damage to an unscheduled monument	Regional Archaeologist

Adapted from *Archaeological and Historical Advice in Scotland* available from Historic Scotland.

The Royal Commission on the Ancient and Historical Monuments in Scotland (RCAHMS) maintain a GIS database (National Monuments Records of Scotland, NMRS) with the locations of scheduled Archaeological and historical sites. Only the location of sites within 50m of the coastline was requested from RCAHMS in this study. However, the RCAHMS advised that to locate all coastal sites would require a resolution of 500m from the coastline. Figure 9 shows the density of scheduled archaeological and historical sites within 500m wide by 10km strips along the coastline of Cells 8 and 9 extracted from the NMRS database. Because of the low resolution these will include a large number of sites which are not truly coastal. Only where more detailed surveying has been conducted can an assessment of the number of coastal sites be determined, but such a study does not appear to be available for any part of the coastline in Cells 8 & 9. There are also a large number of sites, e.g. Listed Buildings, which do not appear in the NMRS database. Appendix 2 shows the actual locations of scheduled sites within 500m of the coastline obtained from the RCAHMS.

1 Cell 8: Barra Head to the Butt of Lewis (Minch coastline)

1.1 General

Cell 8 has been defined, (HR Wallingford, 1997), as the coastline between Barra Head, at the southern end of the island of Berneray, and the Butt of Lewis, at the northern tip of the island of Lewis. The cell encompasses all the beaches occurring on the eastern (Minch) seaboard of the Western Isles. The exceptions to this are the east facing beaches on the Eoligarry peninsula of Barra and the isthmus on Vatersay as these beaches are strongly dependent on coastal processes which affect the western seaboard of these islands and are therefore incorporated within Cell 9.

Both boundaries have been defined on account of the hydraulic climate, with this cell much less exposed to the harsh wave environment of the North Atlantic than Cell 9 on the western coast. For the purpose of future management, Cell 8 has been further divided into four sub-cells, the boundaries of which are presented in Figure 5. The coastline between Barra Head in the south to Stornoway Harbour is dominantly rocky. There are few beach areas and no evidence of any significant macro scale littoral processes. Hence, this has been designated as Sub-cell 8a. Sub-cell 8b is designated between Stornoway Harbour and Tiumpan Head. This is exposed predominantly to wind waves generated from the south and south east. The main beach areas are centred around Braigh na h-Aoidh with few beach areas found on the southern coastline of the Eye Peninsula. Sub-cell 8c, between Tiumpan Head and Tolsta Head, is designated on account of the hinterland drift geology. This sub-cell contains most of the beach areas on the eastern freeboard of the Western Isles the sediments for which have, in part, been derived from erosion of these drift deposits. The headland at Tolsta Head forms a sediment drift divide with Sub-cell 8d defined as between Tolsta Head and the Butt of Lewis. Within each sub-cell relatively self contained beach units can also be identified. For example, Port of Ness, where there is unlikely to be significant interchange of beach material with other beach units. The locations of these "semi-independent beach units" are shown on the relevant littoral process maps.

Sections 5.2-5.6 describe the coastal regime within Cell 8.

5.2 Cell 8: Physical characteristics

5.2.1 General

The characteristics of Cell 8 and processes occurring within it are described under the headings of Geology and geomorphology, Hydraulic processes, Littoral processes and Coastal defences and monitoring.

The geology and geomorphology of the coastline of Scotland is an extremely complex topic with few detailed texts on the subject. Only a brief description is provided within this report in the context of the influence of the solid geology on present day coastal processes, and the geomorphological features evident around the coastline. The drift deposits occurring at the coastline are shown in Figure 10.

Details of the dominant hydraulic processes, i.e. the tides, currents and waves are described. Tidal elevations within each sub-cell are described and, where known, details of any surge information. The directions of the main tidal currents and magnitude of tidal velocities are also detailed. Any areas where significant tidal flooding occurs are noted. Information on tidal currents within Cell 9 is also summarised in Figure 11. The offshore wave climate (both total sea and swell) has been predicted from the Met Office Wave Model along with a range of extreme wave conditions at a number of offshore regions around the Western Isles. The dominant nearshore processes which affect the transformation of offshore to inshore wave conditions are also described.

The next section within each sub-cell describes the main littoral processes. The dominant beach sediment sources and sinks are described. Where possible the main nett longshore transport directions are detailed with an indication of the dominant forces causing this drift. Areas of long term nett erosion and accretion are also described. Where more detailed engineering studies have been conducted, these have been referred to for any indication of erosion or accretion rates. Locations where man-made development in the coastal zone has altered the littoral regime are also described. Details of the foreshore and hinterland characteristics are shown in the relevant figures for each sub-cell along with the dominant littoral processes. Locations where maintenance dredging is conducted are listed, and where possible, any known dredging rates and source of siltation detailed.

The final section details the location, type and influences of coastal protection work. Where possible the length of coastline protected has been given along with a brief indication of the present state of the defences and any significant impacts on the coast due to these works. Locations where any beach monitoring or coastal surveys have been conducted are mentioned and where possible details of the length of such records and monitoring authorities given.

5.3 Sub-cell 8a: Barra Head to Stornoway Harbour

5.3.1 Geology

The underlying hard geology of the Western Isles is dominated by Lewisian gneiss, the oldest rock formation in Britain. This gneiss was derived from igneous and sedimentary rocks during the Precambrian 2900-1100 Ma ago. These rocks were affected by two major episodes of deformation and metamorphism. The first, known as the Scourian, occurred around 2500-2900 Ma and formed the undifferentiated gneisses exposed over much of these islands. The main types are acid-biotite gneisses, hornblende biotite gneisses and hornblende gneiss. The second major episode, the Laxfordian cycle (1900-1100 Ma), resulted in many of the structural and most of the metamorphic features evident. Towards the end of this episode the Outer Hebrides Thrust Zone was formed along the eastern seaboard of much of the Western Isles.

The hard geology dominates with cliffs and intertidal rock platforms, mainly of Lewisian gneiss, outcropping along most of the coastline. Around Renish Point in South Harris the hard geology becomes much more complex. The region known as the South Harris Igneous Complex occurs in a south east-north west belt and consists of a number of metabasic rocks, such as gabbro, anorthosite, norite and diorite and belts of metasediments. Erosion of these cliffs is extremely low and does not supply any material for the formation of beaches. There are a number of major inlets along this coastline, generally running in a north west-south east direction or west to east direction. Most of these lochs lie along lines of weaknesses, but their formation is thought to be only partly due to glaciation (unlike the north west coastline of the mainland).

During glaciation ice flowed outwards from the centre of the islands, in an easterly direction in the Uists and Lewis, and to the south east in Harris. The last glacier to affect the sub-cell retreated around 13,000 years BP. Glacial deposits in this sub-cell are rare and are restricted to localised deposits of boulder clay which cap the bedrock. Such deposits occur at Usinish in South Uist and around Tarbert and Loch Seaforth in Harris. These deposits are not affected by marine processes and hence supply little sediment into the coastal environment. The lack of beach areas in this sub-cell is directly related to the lack of glacial and postglacial deposits.

5.3.2 *Hydraulic processes*

The tidal range is mainly semi-diurnal with a Spring tidal range which varies from 3.2m at Barra Head to 4.1m at Stornoway, Figure 11 and Table 8. Within the sea lochs, such as East Loch Tarbert, Loch Maddy and Loch Skipport, the range can be magnified slightly. Between the islands the tidal cycle can be variable, for example within the Sound of Harris tides are semi-diurnal during Springs and diurnal during Neaps.

Table 8 Sub-cell 8a - Predicted tidal levels and ranges

Sub-cell	Location	MHWS (m CD)	MLWS (m CD)	Spring Range (m)	MHWN (m CD)	MLWN (m CD)	Neap Range (m)	CD to OD* (m)
8a	Barra Head	4.0	0.8	3.2	3.0	1.8	1.2	-
8a	Castle Bay	4.3	0.6	3.7	3.1	1.7	1.4	-2.25
8a	Barra (North Bay)	4.2	0.6	3.6	3.2	1.8	1.6	-
8a	Loch Boisdale	4.1	0.5	3.6	3.0	1.7	1.3	-2.32
8a	Loch Skipport	4.6	0.5	4.1	3.3	1.7	1.6	-
8a	Loch Carnan	4.5	0.6	3.9	3.2	1.9	1.3	-2.50
8a	Loch Maddy	4.8	0.7	4.1	3.6	1.9	1.7	-2.59
8a	East Loch Tarbert	5.0	0.8	4.2	3.7	2.1	1.6	-2.74
8a	Loch Shell	4.8	0.7	4.1	3.6	1.9	1.7	-
8a	Stornoway	4.8	0.7	4.1	3.7	2.0	1.7	-2.71

*Ordnance Datum (local)

In Table 8, due to Ordnance Datum being relative to a local and not relative to Ordnance Datum Newlyn in the Western Isles, the tidal levels are quoted relative to Chart Datum with the conversion factor to Ordnance Datum (local) provided in the final column (where known).

Little information is available on extreme tidal elevations in Cell 8 with the only predictions having been made at the A-class gauge at Stornoway (Dixon & Tawn, 1994). Predicted tidal elevations for various return periods (years) at Stornoway are detailed in the table below:

Table 9 Extreme water levels at Stornoway

Approximate Location	Return period levels (m CD) calculated for 1996							
	10	25	50	100	250	500	1000	10000
Stornoway	5.94	6.05	6.11	6.19	6.27	6.31	6.36	6.50

The main flood stream flows in a northerly direction through the Minch and in the opposite direction on the ebb. Current speeds in the main tidal streams are relatively low but can be much greater in channels between the many islands with peak Spring speeds of up to $2.5ms^{-1}$, and eddies and complex flow patterns common.

The total and swell wave climates for the offshore region to the south east of Barra are shown in Figures 12 and 13. The dominant wave direction for both swell and total sea is from the westerly sector. However, the influence of waves from this sector will reduce significantly to the north although swell conditions generated in the North Atlantic will diffract into the Sea of the Hebrides. Extreme total and swell wave conditions based on data from the Met Office European Wave Model are shown in Table 10:

Table 10 Total sea and swell extreme significant wave heights

Return Period (Years)	Total Sea Significant Wave Height (m)	Swell Significant Wave Height (m)
1	12.41	6.45
10	14.82	8.15
100	17.09	9.82

Within much of the Sea of the Hebrides offshore wave conditions are dominated by local wind generated waves. Fetch lengths to the east are limited but variable in length. However, a narrow wave window extends to the south between 180°N and 220°N where fetch lengths exceed 200km. At the northern end of the sub-cell 40% of wave conditions offshore of Gob Shilldinish occur between 150°N and 190°N with a maximum 50 year return period significant wave height of 3.5m from 162°N.

Along much of the frontage deep water extends close to the outer edge of the nearshore zone with little wave energy dissipation occurring before offshore wave conditions reach the outer sections. However, the coastline is highly irregular with islands, rock outcrops and reefs common in the nearshore region resulting in significant wave energy dissipation occurring before such conditions reach the shoreline. Due to the irregular nature of the nearshore zone the wave climate along this shoreline is highly variable.

5.3.3 Littoral processes

The coastal edge of this sub-cell is dominated by the hard Lewisian gneiss bedrock with few beach areas (Figures 14 & 15). The main deposits of sand material occur between both North and South Uist and Benbecula. These tidal strands have been derived from offshore deposits to the west of the islands which have been transported by tidal current action through the narrow channels and deposited on the nearshore seabed between these islands. In present times, there is unlikely to be any significant nett sediment movement from west to east through these channels (Figures 17 & 24) due to the construction of the causeways linking the islands.

The largest beach system, at Besdarra on the east coast of Berneray is protected from wave action from the easterly sector by numerous rock reefs and islands within the Sound of Harris. The beach system appears to be stable, although storm erosion has occurred at the southern end due to locally generated wind waves during high winds from the east. The Reef, a sand and gravel spit which extends approximately 1.25km south-east at the southern end of the beach at Besdarra, is likely to be a relict deposit reworked by tidal currents flowing through the Sound of Berneray and around the north of the island within the Sound of Harris.

At Rossinish, on the east coast of Benbecula, the supply of sand from the west has formed one of the few beach and dune areas on the eastern seaboard. However, there is no present day supply of sand to the system. Offshore islands protect much of the beach from wave attack with tidal currents running parallel to the beach dominating intertidal littoral processes.

Along much of the east coastline of Harris and Lewis the coastline is dominantly cliffed. Some shingle/cobble/boulder fringe beaches occur along the inner areas of the sea lochs on Harris and also within Loch Maddy on North Uist. Littoral processes do occur on these fringe beaches but there is little information on any significant beach sediment movements.

There are no locations in this sub-cell where maintenance dredging is conducted; the maintenance dredging within Stornoway Harbour is discussed in Section 5.4.3. A small amount of capital dredging was conducted at Lochmaddy in 1985.

Summary of erosion and accretion

There is little notable erosion or accretion within this sub-cell due to the hard nature of much of the coastline. Any erosion occurring on the few beach areas will be predominantly linked to episodic storm events.

5.3.4 Coastal defences

There is little coastal defence work other than harbour and pier structures, Figures 18 & 25.

5.4 Sub-cell 8b: Stornoway Harbour to Tiumpan Head

5.4.1 Geology

The solid geology of sub-cell 8b is dominated by crushed Lewisian gneiss. These rocks outcrop in the form of irregular cliffs and platforms, along much of the Eye Peninsula coastline to the east of Gob na Creige. West of the headland at Gob na Creige, intertidal outcrops of Lewisian gneiss occur, which have a considerable influence on the development of the coastline by dissipating wave energy through bed friction and wave breaking processes before waves reach the softer, more easily erodible, coastal edge.

Overlying the gneiss wave cut platforms around the isthmus to the Eye Peninsula are deposits of conglomerate and sandstones, known as the Stornoway Beds. Erosion of these deposits has provided much of the material for the development of the beaches surrounding Branahuie.

5.4.2 Hydraulic processes

The tidal cycle within the sub-cell is semi-diurnal. The mean Spring tidal range at the A-class gauge at Stornoway is 4.1m with a mean Neap range of 1.7m, Figure 10 and Table 11:

Table 11 Sub-cell 8b - Predicted tidal levels and ranges

Sub-cell	Location	MHWS (m CD)	MLWS (m CD)	Spring Range (m)	MHWN (m CD)	MLWN (m CD)	Neap Range (m)	CD to OD* (m)
8a	Stornoway	4.8	0.7	4.1	3.7	2.0	1.7	-2.71

*Ordnance Datum (local)

In Table 11 the tidal elevations are quoted relative to Chart Datum. Ordnance Datum in the Western Isles is relative to a local datum and not to Ordnance Datum Newlyn. The conversion factor from Chart Datum to Ordnance Datum (local) is provided in the final column.

Little information is available on extreme tidal elevations in Cell 8 with the only predictions having been made at the A-class gauge at Stornoway (Dixon & Tawn, 1994). These predictions are detailed in Table 9 in Section 5.3.2.

The main tidal stream flows through The Minch along the eastern seaboard of the Eye Peninsula with tidal streams and tidal currents within Branahuie Bay and Stornoway Harbour insignificant.

The wave climate within this sub-cell is dominated by local wind waves generated within the southern Minch. The wind wave climate for a location offshore of Gob Shilldinish is shown in Figure 16 (HR Wallingford, 1986). As fetch lengths in all directions to the south and east are limited due to the proximity of mainland Scotland to the east and the Inner Hebrides to the south extreme wave heights are also limited. The maximum 50 year return period significant wave height likely to occur is approximately 3.5m. The easterly facing coastline of the Eye Peninsula will be exposed to larger wave conditions from a narrow wave window which extends past Cape Wrath to the north east.

Swell wave energy will propagate into the Minch, both from the north and from the south. Little quantitative information is available on swell wave conditions experienced within the Minch. As the dominant swell wave direction in the North Atlantic is from the south west, heavy swell will propagate into The Minch from the south when strong winds occur from the south west.

In Stornoway Harbour seiches (standing wave oscillations) of up to 0.5m in amplitude and period of 20 to 25 minutes can occur. These usually occur when a depression is passing north (and occasionally when a depression is passing south).

5.4.3 Littoral processes

Beach areas within this sub-cell are mainly located along the isthmus connecting the Eye Peninsula to mainland Lewis. On most of the Eye Peninsula, the coastline is rock-dominated with few beach areas, Figure 15. The main sediment source for the formation of the isthmus and beach areas has been past erosion of the surrounding conglomerate cliffs which overlie the basement rock. The input of sediment from this source is now restricted due to the protection from wave attack provided by the intertidal rock platform which fronts these soft cliffs. This erosion, and release of beach sediment, will now be restricted to times of high water levels and/or severe wave conditions. However, under such conditions sediment will tend to be lost offshore. In particular shingle sized material moved offshore under storm wave conditions is unlikely to be moved back onshore during periods of constructive swell wave activity. From the back shore erosion evident along the beach areas, the volume of material lost offshore is now much greater than is supplied by these eroding cliffs. The dominant littoral processes occurring within this cell are shown in Figure 17.

A small amount of material (mainly silt with a high percentage of peat) is deposited into the Stornoway Harbour via the Bayhead River during spate flows. This material is trapped within the harbour. Dredging due to this siltation is required occasionally, the last time being in 1993 (4,500m^3-5,500m^3 *in situ*) and before this, 1983 (6000m^3 in situ). This material, either from the source or from the dump location, would not have provided a source of material to any of the beaches.

The main beach fronts the isthmus joining the Eye Peninsula to the mainland of Lewis. This has a thin upper shingle beach which increases in width to the western end of the isthmus with coarse sand occurring over much of the intertidal lower beach. There is a low rate of wave induced nett drift of shingle to the west where it has built up against a concrete outfall. Four groynes at the eastern end have had little impact in maintaining material on the upper beach. On the mainland, to the west of the isthmus, the orientation of the coastline is to the south-east and hence faces the dominant wave direction. Little littoral drift is evident to the west of the isthmus. Due to a lack of available beach material, the thin shingle ridge between the seawall and Holm is frequently breached. All of the beach areas within this region have suffered from an insufficient supply of sediment for some time. Back shore erosion and landward retreat of unprotected frontages will continue.

<u>Summary of erosion and accretion</u>
Erosion of the conglomerate cliffs on the Eye Peninsula is on-going but is now limited to episodic storm erosion or high tidal level events. The nett westerly drift of material resulting in loss of material from the eastern end of the isthmus connecting the Eye Peninsula the Lewis mainland is a long term problem and the lack of material along the frontage between the western end of the isthmus and Holm is also resulting in retreat of the coastal edge.

5.4.4 Coastal defences

Back shore erosion of much of the 'soft' frontage around Branahuie Bay has resulted in a number of coastal defence schemes, Figure 18. The main defence is a sloping concrete seawall initially constructed in the 1950s and strengthened after damage in the 1980s which protects the isthmus linking the Eye Peninsula to the Lewis mainland. Lowering of beach levels at the eastern end has occurred due to the westerly drift and the effect of the seawall on the immediate upper beach. Four groynes placed to control this westerly drift at the eastern end have had little effect and are now in a poor state of repair. At the western end of the seawall an outfall acts as a groyne trapping the westerly movement of shingle. This has resulted in downdrift erosion to the west and the construction of a low rock wall to prevent erosion of the coastal edge. This structure is unlikely to prevent wave erosion of the back shore under a severe wave event directly from the south.

A maintained shingle ridge protects low lying land from flooding between the seawall and Holm. This ridge does not receive sufficient shingle material from further east and is breached regularly. At Holm a rock revetment protects the east facing coastline of the isthmus to Shilldinish. This defence is in a good condition and has little significant impact on the surrounding littoral regime.

5.5 Sub-cell 8c: Tiumpan Head to Tolsta Head

5.5.1 Geology

The coastal geology surrounding Broad Bay is varied. Much of the northern coastline of the Eye Peninsula replicates the southern coastline, with crushed gneisses forming an irregular cliffed coastline fronted by an abrasion platform. To the east of Garrabost on the Eye Peninsula, this gneiss is overlain by less resilient Permo-Triassic conglomerates, known as the Stornoway Beds, which also extend along the north coast of Broad Bay to around Sheilavig Mor. Beyond this, crushed Lewisian gneiss, forming an irregular cliffed coastline, is dominant. The southern side of Tolsta Head is of geomorphological importance with the exposure containing evidence of past glacial and climatic conditions. The site is notified as an SSSI.

The effect of the underlying rock types can be seen in the planshape of this coastline. Abrasion platforms formed of gneiss afford some protection to the softer overlying conglomerates resulting in the rate of erosion being slower there than in parts of the frontage where this bedrock does not outcrop. This has formed a series of headlands which separate the sand and shingle beaches which border much of the inner part of Broad Bay. Most of the beach material found on the beaches in this region has derived from erosion of these soft deposits.

5.5.2 *Hydraulic processes*

There is little information on the tidal range in this sub-cell. The mean spring range is between 3.5 and 4.0m. The tidal range may increase marginally towards the inner part of Broad Bay. The flood stream travels northwards up the Minch with high tide occurring at roughly the same time throughout this sub-cell. As in other parts of the Western Isles information on extreme water levels is sparse and restricted to a prediction at Stornoway, Table 9 (Dixon & Tawn, 1994).

The main tidal stream flows across the mouth of Broad Bay and is generally weak with a peak Spring rate of less than $0.3ms^{-1}$. Within the bay tidal streams are also weak. During the ebb tide, which flows to the south off Tolsta Head, there is a low anti-clockwise rotation within the bay. On the flood there is little tidal stream along the north coast of the Eye Peninsula, and a weak NNE flowing stream along the north coast of the bay which increases in strength towards Tolsta Head.

The offshore wave climate to the north-east of Lewis is shown in Figure 19. The dominant wave direction is from the north-west with the largest offshore wave heights also occurring from this sector. The 50 year return period significant wave height from the direction sector centred on 330°N is approximately 12.4m. The smallest extreme conditions occur from the directional sector centred on 60°N with a significant wave height of 6.2m for the 50 year return period. However, waves from the north-east will have more of a direct effect upon the coastline of this sub-cell than the more extreme offshore wave conditions from the north-west.

Wave energy within Broad Bay occurs due to both short period waves generated locally within Broad Bay and The Minch and larger period swell conditions which propagate into the Bay from the North Atlantic and Norwegian Sea. The largest wind-generated waves occur from a narrow wave window to the north east where there are long fetch lengths. From other directions fetch lengths within the bay are restricted limiting the magnitude of wind-generated wave conditions.

5.5.3 *Littoral processes*

As on the southerly facing coastline of sub-cell 8a, much of the Eye Peninsula is rocky with few beach areas apart from the western end where softer, conglomerate cliffs occur and have provided material for the formation of beaches. These rocks also occur along much of the northern coastline of Broad Bay resulting in a number of long sandy beaches, intersected by rock headlands, Figure 15. The majority of the material for the development of these beaches will have derived from erosion of the conglomerate and till. However, much protection is now provided by the intertidal rock platforms which have become exposed due to the landward retreat of these soft deposits. Erosion of these cliffs is now limited to times of high water levels and/or severe wave conditions. Much of the seafloor of Broad Bay is covered in sediment and it is likely that offshore deposits have also produced a significant input of beach sediments. These resources appear to have been particularly important for the formation of beaches on the northern coastline of Broad Bay, with a high percentage of the beach sediments at Traigh Chuil and Traigh Ghrais derived from shell material. Along the beach at the northern side of the Branahuie isthmus and the Stornoway Airport frontage, the percentage of shell material on the beaches is much lower indicating that a greater percentage of beach sediments has derived from erosion of the glacial cliffs. It is unlikely that offshore deposits supply a large present day volume of beach material despite a high amount of constructive swell wave activity experienced within Broad Bay.

Littoral drift is most evident on the south coastline of Broad Bay, with a westerly wave-induced drift transporting sediment eroded from the cliffs at Aiginish and along the beach at Branahuie, Figure 17. A low northwesterly drift has also been noted along the beach at Melbost. Calculations of dune recession and spit development at Melbost have indicated an average nett longshore drift of less than 4000m^3 per year, (HR Wallingford, 1980). This is due to both a low wave induced nett transport and to a nett northward aeolian transport of beach material. Analysis of the volume of material within Melbost spit indicates that it is of the same order of magnitude as that eroded from the frontal dunes along the length of Melbost Sand. Since the construction of the airport runway extension there is little evidence of sediment build-up on the updrift side of the breakwater due to longshore transport to the north. However, there has been some retreat of the dune face on the downdrift side possibly caused by an increase in wave reflections from the structure rather than due to an interruption in the drift.

On the north coastline of Broad Bay, there is little evidence of longshore drift. The shingle spit at Tong is no longer active. There will be a low rate of beach material transported from erosion of the conglomerate cliffs at Aird Tunga to the sand flats at Tong and Melbost. At Traigh Chuil and Traigh Ghriais, protection afforded by headlands to the north of these beach units may result in nett northerly drift resulting from heavily diffracted swell waves causing a wave- induced northward current and locally generated wind waves from the south-easterly sector. However, any present day nett drift is of an extremely low rate.

Summary of erosion and accretion

The lack of sediment input to the beach areas within this sub-cell is resulting in erosion of most of the frontal dunes which back the beach areas. This is most evident at Traigh Chuil and Traigh Ghriais.

5.5.4 Coastal defences

Most of the coastal defences in this sub-cell occur around the inner part of Broad Bay protecting the narrow isthmus joining the Eye Peninsula to the mainland, Figure 18.

A short length of sloping revetment and vertical upstand protects the access road to Port nan Giuran on the north-eastern coastline of the Eye Peninsula. The structure has minimal impact on the surrounding coastline and provides adequate coastal protection to the road. However, the crest of the structure is relatively low and will be overtopped resulting in flooding of the road and storm debris being deposited behind the structure.

To the east of Aiginish a short rock wall and constructed till ridge protects low lying land. This defence is likely to be overtopped frequently and is unlikely to withstand a severe storm event. Rock has also been dumped down some of the most severely eroded sections of the cliffs fronting the access road at Aiginish. Despite this the road is still under considerable threat.

The northern coastline of the isthmus connecting the Eye Peninsula to the Lewis mainland is protected along most of its length by a stepped concrete seawall with wave recurve. Fronting St Columba's church a low concrete apron is in a relatively poor state and has been outflanked at the eastern end where approximately 10m in length of rock protection has been provided. Beach levels at the eastern end of this frontage are low, partly due to a lack of supply of beach material from the east and due to wave reflections from the hard structure. Groynes, placed to control the westerly drift at the eastern end of the beach are now badly deteriorated and serve no purpose. At the western end of the isthmus a low vertical concrete wall prevents overwashing of the low hinterland.

The rock breakwater protecting the airport extension at the northern end of Melbost Sands appears to have little influence upon the beach apart from some erosion of the spit to the north which is probably caused by increased localised wave reflections.

At Tong a stretch of gabion wall and rock revetment protect a sewage outlet and the access road to Tong Moorings. A short low vertical concrete wall protects an eroding conglomerate outcrop to the north of the river outlet on Traigh Chuil. Waves will reflect off this wall resulting in localised beach lowering.

5.6 Sub-cell 8d: Tolsta Head to Butt of Lewis

5.6.1 Geology

Crushed and undifferentiated Lewisian gneiss form the solid geology of this coastline, as in much of the Western Isles. To the north of Tolsta Head these cliffs back the sand beach of Traigh Mhor but become directly exposed at the coastline in the form of steep high cliffs to the north of Traigh Geiraha, extending to beyond Cellar Head. The coast north of Cellar Head is indented, particularly to the north of Meall Geal with inlets and geos common.

The section of the coastline around Port of Ness is of considerable geological importance displaying a complex sequence of interbedded shelly tills, sands, silts and gravels. These deposits are easily erodible and will have provided much of the beach material for the sand beach at Port of Ness. The site is a designated SSSI on account of these exposures.

5.6.2 Hydraulic processes

There is little information on the tidal range in this sub-cell. The Mean Spring Range is between 3.5 and 4.0m. The flood stream travels northwards up the Minch with high tide occurring at roughly the same time throughout this sub-cell. As in other parts of the Western Isles information on extreme water levels is sparse and restricted to a prediction at Stornoway, Table 7 (Dixon & Tawn, 1994).

Tidal streams flow in a northerly direction on the flood and southerly during the ebb. Tidal streams generally occur well offshore with little movement nearshore. Only around the Butt of Lewis do current velocities become significant with a peak Spring rate of $1 ms^{-1}$ occurring off the headland. Due to the low tidal streams, wind induced currents may be significant, particularly where they act in the same direction as the tidal stream.

The total sea offshore wave climate to the north-east of Lewis is shown in Figure 19. Over 60% of wave conditions occur on average from the north-west sector. The largest wave conditions occur from the directional sector centred on 300°N with a 1:50 year return period wave height of 12.4m. The smallest wave conditions occur from the directional sector centred on 60°N with a 1:50 year return period wave height of 6.2m. However, it is winds from the north-easterly sector which will produce the most severe wave conditions experienced on the coastline within this sub-cell. The coastline will also experience a large amount of swell wave conditions generated further afield in the Norwegian Sea.

5.6.3 Littoral processes

There are only two self-contained beach units within this sub-cell, at Traigh Mhor and Traigh Geiraha and at Port of Ness. The sand beaches of Traigh Mhor and Traigh Geiraha are situated between gneiss headlands (Figure 15). The upper beach is split by the short headland of Gob Hais. The offshore seabed is shallow sloping and is predominantly covered with sand. These deposits will have provided the major source of beach material which will have been moved onshore under swell waves. Some shingle and coarse sand occurs at Traigh Geiraha derived from fluvial deposits washed down during spate flows. The entire unit appears to be extremely stable (in terms of marine processes) with no significant nett loss or gain of sediment presently evident. At Port of Ness the till cliffs which back the beach are an important sediment source and are still being actively worked during times of high tidal elevations.

The beach unit at Traigh Mhor shows little evidence of any nett longshore drift (Figure 17). The orientation of the beach and the shallow sloping nearshore zone results in wave crests approaching the beach parallel to the beach contours. Hence, the potential for wave induced longshore transport is minimal. Instead, cross-shore processes will tend to dominate with beach material being moved seawards during storm conditions and then moved back up the beach under swell waves. Due to the abundance of sand on the upper beach there is a significant volume of material transported from the beach into the dunes by aeolian transport.

At Port of Ness, the beach is slightly more exposed to conditions from the south easterly sector than from the north-easterly sector. This appears to result in a low northerly drift due to both wave and wind action which has caused some siltation within the harbour.

Summary of erosion and accretion
The soft cliffs backing the beach at Port of Ness are experiencing episodic erosion. Despite this the beach unit at Port of Ness appears to be relatively stable as do the beach units at Traigh Mhor and Traigh Geiraha.

5.6.4 Coastal defences

There is no coastal defence work within this sub-cell. The vertical concrete wall of the harbour at Ness does cause a slight increase in erosion of the adjacent cliffs due to increased wave reflection from the structure.

6 Cell 9: Butt of Lewis to Barra Head (Atlantic coastline)

6.1 General

Cell 9 has been defined, (HR Wallingford, 1997), as the coastline between the Butt of Lewis, at the northern tip of the island of Lewis, and Barra Head, at the southern end of the island of Berneray. The cell encompasses all the Atlantic (west) facing beaches in the Western Isles. Both boundaries have been defined on account of the hydraulic climate with this cell exposed to the harsh wave environment of the Atlantic compared to the relatively milder conditions experienced on the easterly facing coastline of these islands. For the purpose of future management, this cell has been further divided into six sub-cells, the boundaries of which are presented in Figure 5. There is little evidence of significant present day nett longshore drift along any section of this coastline. Many of the individual beach units can be considered as self-contained sediment cells. Hence, sub-cell boundaries have been defined at locations where there is likely to be significant changes in the nearshore wave climate, i.e. mainly where the slope of the nearshore seabed changes significantly. Within each sub-cell relatively self contained beach units can also be identified. For example there is unlikely to be significant interchange of beach material between the individual beach areas in sub-cell 9a. The locations of these "semi-independent beach units" are shown on the relevant littoral process maps.

Sections 6.2 to 6.8 describe the coastal regime occurring within Cell 9.

6.2 Cell 9: Physical characteristics

6.2.1 General

The characteristics of Cell 9 and processes occurring within it are described under the headings of Geology and geomorphology, Hydraulic processes, Littoral processes and Coastal defences and monitoring.

The geology and geomorphology of the coastline of Scotland is an extremely complex topic with few detailed texts on the subject. Only a brief description is provided within this report in the context of the influence of the solid geology on present day coastal processes, and the geomorphological features evident around the coastline. The drift deposits occurring within Cell 9 are shown in Figure 10.

Details of the dominant hydraulic processes, i.e. the tides, currents and waves are described. Tidal elevations within each sub-cell are described and, where known, details of any surge information. The directions of the main tidal currents and magnitude of tidal velocities are also detailed. Any areas where significant tidal flooding occurs are also noted. Information on tidal currents within Cell 9 is also summarised in Figure 11. The offshore wave climate (both total sea and swell) has been predicted from the Met Office Wave Model along with a range of extreme offshore wave conditions. The offshore total sea and swell climates in the region to the north west of Lewis and Harris are shown in Figures 20 and 21 respectively and to the west of the Uists in Figures 22 and 23. The dominant nearshore processes which affect the transformation of offshore to inshore wave conditions are also described.

The next section within each sub-cell describes the main littoral processes. The dominant beach sediment sources and sinks are described. Where possible the main nett longshore transport directions are detailed with an indication of the dominant forces causing this drift. Areas of long term nett erosion and accretion are also described. Where more detailed engineering studies have been conducted, these have been referred to for any indication of erosion or accretion rates. Locations where man-made development in the coastal zone has altered the littoral regime, are also described. Details of the foreshore and hinterland characteristics are shown in the relevant figures for each sub-cell along with the dominant littoral processes.

The final section details the location, type and influences of coastal protection. Where possible the length of coastline protected has been given along with a brief indication of the present state of the defences and any significant impacts on the coast due to these works. Locations where beach monitoring or coastal surveys have been conducted are mentioned and, where possible, details of the length of such records and monitoring authorities are given.

6.3 Sub-cell 9a: Butt of Lewis to Tiumpan

6.3.1 Geology

The underlying solid geology is dominated by Lewisian gneiss, the oldest rock formation in Britain. This gneiss was derived from igneous and sedimentary rocks in the Pre-Cambrian approximately 2900-1100 Ma. These rocks were affected by two major episodes of deformation and metamorphism. The first, known as the Scourian, occurred around 2900-2500 Ma and formed the undifferentiated gneiss material exposed at present. The main types are acidbiotite gneisses, hornblende biotite gneisses and hornblende gneiss. The second major episode, the Laxfordian cycle, resulted in many of the structural and most of the metamorphic features evident. At the northern end of the unit, around the Butt of Lewis, an outcrop of metasedimentary gneiss occurs. This belt displays a diversity of lithologies and has considerable geological importance.

The hard geology is exposed in the form of sea cliffs only around the Butt of Lewis and from around the township of Shawbost to the southern boundary of the sub-cell at Tiumpan. However, much of the coastline is fronted by exposed intertidal rock platforms. These outcrops have a significant influence on the development of the coastline by dissipating wave energy through bed friction and wave breaking processes before waves reach the softer, more easily erodible, coastal edge.

During glaciation ice flowed outwards from the centre of mainland Lewis. The last glacier to affect the sub-cell retreated around 13,000 years BP. Glacial deposits of boulder clay overlie the gneiss bedrock in various thicknesses along this coastline particularly between Eoropie and Shawbost, Figure 15. At Swainbost wave erosion has resulted in this deposit being cut into sea cliffs up to 20m high. Deposits of between 1m and 5m in thickness occur along much of the coastline. However, at Swainbost Sands and Traigh Chumil wave erosion has created till cliffs up to 20m in height. Erosion of these cliffs has exposed what is considered to be one of the best examples of a possible interglacial beach in Scotland. Further south, between North Dell and Borve, possibly the same beach rests on a pre-Devensian shore platform and a variety of superficial deposits have been identified. There is little other evidence of inter- or postglacial geomorphological features within this sub-cell.

Erosion of the till material is the main source of material for the many cobble beaches occurring along this coastline and probably also much of the sand sized material. For instance a high proportion of the shingle and cobble beach material at Barvas will have derived from postglacial erosion of the till cliffs to the north. Other Quaternary deposits are rare, apart from postglacial deposits of blown sand at Eoropie, Swainbost and Borve.

6.3.2 Hydraulic processes

The tidal cycle along this coastline is semi-diurnal with a mesotidal range. The spring range measured at Carloway to the south of the sub-cell is 3.6m with a neap range of 1.6m, Figure 11 and Table 12. The high and low water elevation at Carloway is measured relative to Chart Datum which is 2.33m below Ordnance Datum Newlyn.

Table 12 Sub-cell 9a - Predicted tidal levels and ranges

Sub-cell	Location	MHWS (m CD)	MLWS (m CD)	Spring Range (m)	MHWN (m CD)	MLWN (m CD)	Neap Range (m)	CD to OD* (m)
-	STORNOWAY	4.8	0.7	4.1	3.7	2.0	1.7	-2.71
9b	Carloway	4.2	0.6	3.6	3.2	1.6	1.6	-2.20

* Ordnance datum (local)

In Table 12 the tidal elevations are quoted relative to Chart Datum. Ordnance Datum in the Western Isles is relative to a local datum and not to Ordnance Datum Newlyn. The conversion factor from Chart Datum to Ordnance Datum (local) is provided in the final column.

The flood tide runs in a south-west to north-east direction parallel to the coastline with the ebb tide in the opposite direction. Tidal currents are relatively low and generally insignificant. The exception is close to the Butt of Lewis where maximum Spring current speeds can reach $1ms^{-1}$. During the ebb tide an eddy runs in a north east direction along the coastline to the west of the Butt of Lewis due to the north going stream along the east facing coastline. Tidal flows in this region may be responsible for a shallow bank which extends in a WSW direction from the south-west extremity of the Butt of Lewis, offshore of Eoropie.

The offshore total and swell wave climate for the offshore region to the west of Lewis and Harris is shown in Figures 20 and 21 respectively. The dominant wave conditions occur between 230° and 270°N. However, extreme wave conditions (significant wave heights of greater than 8m) are experienced from every direction apart from the south-easterly quartile. Extreme total sea wave conditions have been predicted from the Met Office Wave Model and are detailed in Table 13.

Swell wave condition contribute a large proportion of the total wave energy experienced in this region. The dominant direction is from 250°N to 270°N although extreme swell wave conditions can occur from any westerly sector direction. Extreme swell wave heights for this offshore region are also detailed in Table 13.

Table 13 Total sea and swell extreme significant wave heights

Return Period (Years)	Total Sea Significant Wave Height (m)	Swell Significant Wave Height (m)
1	12.80	5.67
10	15.14	6.90
100	17.32	8.06

The wave climate inshore is dominated by the nearshore bathymetry and, due to the extreme nature of the wave conditions, is very sensitive to tidal level. Along much of the frontage between the Butt of Lewis to Tiumpan the nearshore seabed shelves relatively steeply (1:40 to 1:70 slope) to the -20m CD contour. Between the -20m CD and the -50m CD contour the seabed slope is more gentle (approximately 1:110 at the northern boundary and about 1:250 to the south of this sub-cell). The contours run approximately parallel to the shoreline resulting in larger wave conditions occurring at a small angle of incidence at the coastline due to refraction processes. Less extreme wave conditions, which are affected less by the seabed bathymetry, will occur at the coastline from between 230°N to 50°N. The wave cut platform which fronts much of the coastal edge within this sub-cell will dissipate much of the wave energy. Hence more severe wave conditions will only be experienced on the upper beach and coastal edge during times of high tidal levels.

6.3.3 Littoral processes

The foreshore and hinterland characteristics occurring in Sub-cell 9a are shown in Figure 15. Littoral processes are dominated by wave and wind action with tidal currents having very little influence within this sub-cell. The dominant littoral processes are shown in Figure 17.

Present day fresh sediment sources are limited. The major input has been from reworking of glacial deposits of wind blown sand and boulder clay which back the beach areas between Eoropie and Barvas. Erosion of these till cliffs will previously have provided most of the beach material found along this coastline. Input of beach material from erosion of these cliffs will now be limited to times of high tidal elevation and severe wave conditions due to the protection afforded by gneiss outcrops and a cobble and boulder upper beach which is found along much of this frontage. A previous beach sediment source is also likely to have come from offshore deposits of sand and gravel. This is most evident at Traigh Sanda. This beach has a high shell content indicating that a large percentage of the beach material will have been derived from offshore deposits. However, it is unlikely that these deposits are a significant present day sediment source. At Traigh Sanda there is also likely to be a low input of sand-sized material from erosion of the till deposits to the south. Present day fluvial sediment sources are not significant within this sub-cell.

There are two dominant sediment loss mechanisms within this sub-cell. Firstly, the most significant loss will be due to storm wave action which will result in an offshore movement of beach material. This material is likely to be trapped on the rocky seabed and is unlikely to be returned onshore under more constructive swell wave conditions. The second loss of sediment from this sub-cell is from commercial sand extraction from the dune and machair systems at Traigh Sanda and Barvas.

There is little gross or nett longshore sediment transport within this sub-cell. Most of the beach units can be considered as independent sediment cells. There is likely to be a low northerly drift rate to the north east at Traigh Sanda with material from the eroding till cliffs to the south providing some input of material. There is also likely to be a healthy cyclic onshore/offshore movement of beach material due to storm/swell wave action on this beach unit. Wind action will also result in sand transport from the beach to the dune systems.

Between Swainbost and Barvas nett sediment transport is dominantly an offshore movement of material under storm conditions. There may be some gross longshore transport but due to the rocky nature of the foreshore such a rate is likely to be temporally and spatially variable. At Barvas, the orientation of the beach would tend to suggest a south-westerly nett movement of material. However, this rate will be extremely low and confined to storm conditions due to the coarse nature of the beach material. To the south of Barvas the beach units are all self contained units with little input/output or movement of beach material.

The coastline of this sub-cell is dominantly eroding with little accretion occurring. The shingle and cobble upper beaches will protect the coastal edge under all but the most severe storm conditions. It is under these conditions that erosion of the beach and coastal edge will be most noticeable. The main characteristics will be a continued retreat of the coastal edge between Traigh Sanda and Barvas as the till cliffs are eroded and the likelihood of breaching and flattening of sections of the shingle ridges which front many of the brackish lochs within this sub-cell. Wind erosion is evident on all the dune areas within this sub-cell. At Traigh Sanda and Barvas much of this has been initiated by quarrying activities. Erosion of the dunes and machair is also being initiated by livestock at Swainbost and Barvas. Due to the extreme wind climate this erosion will increase with areas unable to be stabilised unless appropriate erosion control measures are taken. A detailed study of the system at Barvas was conducted by Harris & Ritchie (1989).

Summary of erosion and accretion

Most of this coastline is experiencing long-term erosion due to the severity of the wave climate. This is most apparent along the till cliffs between Eoropie and Barvas.

6.3.4 Coastal defences

Coastal protection work is limited to Dalmore Bay where timber breastwork protects the car park and cemetery backing the beach. There is no significant impact due to the defences on the beach system, with the structures presently in good condition. The beach fronting the coast protection works is relatively narrow and steep and damage is likely if storm conditions cause beach levels to drop. Some erosion of the machair is occurring at the western end due to the coast defences restricting pedestrian access to the beach at this location. Backshore erosion of the machair edge is continuing along the short stretch of beach which is unprotected to the west of the protected frontage.

Some rock has been placed at the eastern end of the beach at Loch Shawbost to protect the track from wave attack. There is no other coastal protection work within this sub-cell with no routine beach surveys conducted. The location of coastal defence work is shown in Figure 18.

6.4 Sub-cell 9b Tiumpan to Hushinish Point

6.4.1 Geology

The coastline of this sub-cell is dominated by the solid geology with very few beach areas. As in most of Lewis the bedrock is mainly Lewisian gneiss. At the eastern end of Glen Valtos an area of granite migmatite (rock consisting of pre-existing gneiss and granite), outcrops at the coast. To the south of Gallan Head, the area known as the Uig Hills has the greatest abundance of granite in the Western Isles. This granite is in the form of a network of veins and sheets, which can be hundreds of metres in thickness, surrounded by extensive migmatite.

This area underwent intensive erosion due to glaciation. The last glaciers formed in the highlands of Lewis and Harris and moved in a north westerly direction in this area. Previously the Western Isles had been glaciated by the mainland ice sheet. The effect of this can be seen in the rocky, indented appearance of the coastline with a number of fjord like sea lochs, such as Loch Roag. Much of the coastal topography is high, in the form of steep sea cliffs. Where the relief is lower, wave abrasion platforms and offshore rock reefs are common. This results in the coastline of much of this sub-cell being relatively resilient to marine erosion despite the severity of the wave climate.

Glacial deposits within this cell are largely absent and restricted to a few localised areas. The most notable are the fluvio-glacial deposits at Uig where sand and gravel were deposited by glacial meltwater. This deposit has been the main source of beach material for the sand beach system at Uig and is the only significant fluvio-glacial deposit in the Western Isles. Offshore glacial sand deposits cover parts of Loch Roag and were probably the main source of beach material for the sand beaches at Cliff and Berie. Thin layers of glacial till overly the bedrock at very few locations, the most noticeable being at Valtos.

6.4.2 Hydraulic processes

As along the sub-cell to the north the tidal cycle is semi-diurnal and mesotidal in range. The spring tidal range at Carloway is 3.6m and at Little Bernera 3.8m with the corresponding neap ranges 1.6m and 1.5m respectively, Table 14.

Table 14 Sub-cell 9b - Predicted tidal levels and ranges

Sub-cell	Location	MHWS (m CD)	MLWS (m CD)	Spring Range (m)	MHWN (m CD)	MLWN (m CD)	Neap Range (m)	CD to OD* (m)
9b	Carloway	4.2	0.6	3.6	3.2	1.6	1.6	-2.20
9b	Little Bernera	4.3	0.5	3.8	3.1	1.6	1.5	-

* Ordnance datum (local)

In Table 14 the tidal elevations are quoted relative to Chart Datum. Ordnance Datum in the Western Isles is relative to a local datum and not to Ordnance Datum Newlyn. The conversion factor from Chart Datum to Ordnance Datum (local) is provided in the final column (where known).

Tidal current information is shown in Figure 11. The flood tide flows in a south-west to north-east direction with the ebb tide flowing in the reverse direction across the mouth of East and West Loch Roag. South of Gallan Head tidal current patterns are indiscernible. Currents velocities at an Admiralty Diamond west of Gallan Head do not exceed $0.5ms^{-1}$ during the Spring tide and elsewhere along the exposed sections of this coastline current speeds are barely perceptible. Within East Loch Roag tidal velocities can be up to $0.75ms^{-1}$ within some of the narrow channels between islands and at the entrance to Little Loch Roag can be a maximum of $2.5ms^{-1}$ during Spring tides. Elsewhere current speeds are generally negligible.

The offshore total and swell wave climate for the region to the west of Lewis and Harris is shown in Figures 20 and 21 respectively. The dominant wave conditions occur between 230° and 270°N. However, extreme wave conditions (Significant wave heights of greater than 8m) are experienced from every direction apart from the south-easterly quartile. Swell wave conditions contribute a large proportion of the total wave energy experienced in this region. The dominant direction is from 250°N to 270°N although extreme swell wave conditions can occur from any westerly sector direction. Extreme wave heights for the total sea and for swell waves for this offshore region are detailed in Table 13 in Section 6.3.2.

The -50m CD contour extends across the mouth of East and West Loch Roag and occurs close to the shoreline along the west facing coast. The steepness of the nearshore bathymetry results in little attenuation of wave conditions before they reach the shoreline. Hence, the wave climate is very severe with waves affecting the coastline between Tiumpan and Gallan Head from between 270°N and 40°N, and to the south of Gallan Head from between 210°N to 0°N. Rock reefs and outcrops occur over much of the nearshore seabed. Friction effects here are extremely important in affecting wave transformation from offshore to inshore. Due to the extreme wave conditions experienced at the coastline, beach areas are restricted to sheltered bays.

6.4.3 Littoral processes

The foreshore and littoral characteristics in Sub-cell 9b are shown in Figure 15. Littoral processes within this sub-cell are dominated by wave and wind action with tidal currents having no influence on beach processes. The dominant littoral processes are shown in Figure 17.

The few beach units to be found within this sub-cell are restricted to relatively sheltered regions. The source of beach material has been dominantly glacial sands and deposits probably moved onshore during times of lower sea levels. The exception to this is at Uig where the beach material is derived from a large fluvio-glacial deposit. This source is likely to still supply a low input of sand material to the beach system. Offshore sand deposits may still supply a low rate of sand to the beach at Traigh na Berie where a number of offshore islands provide protection from severe wind wave attack. This will increase the relative influence of swell waves which would tend to move sand onshore. Some input of material is also provided from the reworking of blown sand deposits backing the beaches at the western end of Traigh na Berie and Camas na Clibhe. At Traigh na Berie this results in an anti-clockwise rotation of the entire beach system. Erosion of the till deposits at Valtos would have contributed sediment to the beaches during times of higher sea levels.

Sediment losses are also relatively low. There will be some offshore losses at Camas na Clibhe and at Mangersta Sands, but the rates will be minimal.

Most of the beach systems within this sub-cell can be considered to be in dynamic equilibrium with the incident hydraulic conditions. Little nett longshore drift is evident with each of the beach systems acting as self-contained sediment cells. At Traigh na Berie drift occurs in both direction with there being a low nett drift to the east. At Camas na Clibhe and Mangersta onshore/offshore cyclic sediment transport will dominate.

Wave erosion of the coastal edge is most evident at the western end of Traigh na Berie and along most of the frontage at Camas na Clibhe with the car park on the machair now under threat. The beach systems at Cnip and Camas Uig are well sheltered with little long term wave erosion evident. Wind erosion is also relatively limited, restricted to the face of the machair at Camas na Clibhe and a few small blowouts towards the eastern end of Traigh na Berie. At Mangersta the deflated machair surface is now relatively stable due to the sand now deflated down to the high water table reducing the potential for wind erosion.

Summary of erosion and accretion

Wave erosion is most noticeable at Camas na Clibhe and at the western end of Traigh na Berie. The only significant accretion is within the beach and dunes at the eastern end of Traigh na Berie.

6.4.4 Coastal defences

Coastal defence work within this sub-cell is limited to a short length of low rock wall which protects a house at the eastern end of Crip. The wall appears to have little affect on the beach and is presently functioning adequately preventing wave erosion of the machair edge. However, it is unlikely to withstand direct storm wave attack. No other coastal defence work has been conducted within this sub-cell with no routine beach monitoring conducted. The location of the coastal protection work is shown in Figure 16.

6.5 Sub-cell 9c Hushinish Point to Sound of Harris

6.5.1 Geology

The granite migmatite rocks of the Uig Hills are exposed along much of the northern half of this sub-cell with few beach areas. As in the sub-cell to the north the coastal edge of West Loch Tarbert is dominated by the solid geology, being rugged with sloping sea cliffs of varying elevation fronted by wave abrasion platforms. Consequently, little present day marine erosion occurs.

To the south of West Loch Tarbert the hard geology becomes much more complex. The region known as the South Harris Igneous Complex occurs in a south east-north west belt to the south of Borve. The area also consists of a number of metabasic rocks, such as gabbro, anorthosite, norite and diorite. The influence of the structural and lithological variations is seen on the coastline with rock outcrops creating a series of headland-dominated bay beaches.

Quaternary deposits are restricted to localised areas. Glacial deposits of boulder clay occur on the coastline around Glen Meavaig on the north coast of West Loch Tarbert. Such deposits also cover much of the area to the north and east of Luskentyre. The main sediment source for the development of the Harris beaches is likely to have been offshore deposits which were moved onshore during times of lower sea levels. Fluvial deposits may also have been a significant source, particularly at locations such as Luskentyre and Borve.

6.5.2 Hydraulic processes

The tidal cycle is semi-diurnal with a Mean Spring range which varies from 3m at West Loch Tarbert to 4m at Leverburgh, Table 15.

Table 15 Sub-cell 9c - Predicted tidal levels and ranges

Sub-cell	Location	MHWS (m CD)	MLWS (m CD)	Spring Range (m)	MHWN (m CD)	MLWN (m CD)	Neap Range (m)	CD to OD* (m)
9c	West Loch Tarbert	3.7	0.7	3.0	2.8	1.5	1.3	-
9c	Leverburgh	4.6	0.6	4.0	3.5	1.9	1.6	-2.93

* Ordnance datum (local)

In Table 15 the tidal elevations are quoted relative to Chart Datum. Ordnance Datum in the Western Isles is relative to a local datum and not to Ordnance Datum Newlyn. The conversion factor from Chart Datum to Ordnance Datum (local) is provided in the final column (where known).

The main tidal streams occur well offshore with tidal current patterns in the nearshore zone in this sub-cell showing no particular direction. Tidal velocities are extremely low and are not a significant littoral process. Wave-induced currents will have more influence on the littoral zone due to large changes in the degree of exposure of the beach to wave conditions over relatively short stretches of coastline, leading to large gradients in longshore wave energy at the shoreline. Wind-induced currents may also be important, particularly over the sandflats of Traigh Luskentyre.

The offshore total and swell wave climates for the region to the west of Lewis and Harris are shown in Figures 20 and 21 respectively. The dominant wave conditions occur between 230° and 270°N. However, extreme wave conditions (significant wave heights of greater than 8m) are experienced from every direction apart from the south-eastern quartile. Swell wave conditions contribute a large proportion of the total wave energy experienced in this region. The dominant direction is from 250°N to 270°N although extreme swell wave conditions can occur from any westerly sector direction. Extreme wave heights for the total sea and for swell waves for this offshore region are detailed in Table 13 in Section 6.3.2.

The wave climate affecting this coastline is less severe than to the north due to the dissipative influence of the relatively gently sloping nearshore bathymetry. The amount of wave energy dissipation and wave refraction which takes place as waves travel inshore will be very dependent on the tidal water elevation along much of the coastline within this sub-cell. Most of the beach areas occur to the south of the sub-cell in South Harris with much shelter provided from direct wave attack by the island of Taransay and by Toe Head. Direct wave attack in this area will only occur from a narrow wave window between approximately 250°N and 300°N. However diffraction effects of both swell and wind waves will be significant.

6.5.3 Littoral processes

The main beach areas occur in the southern half of the sub-cell and are characterised by a sandy foreshore, backed by dunes and machair. Details of the foreshore and hinterland characteristics are shown in Figure 15. Beach material is abundant with large sandy tidal strands at Luskentyre and Scarasta. Beach material will have derived from seabed glacial deposits moved onshore during periods of lower sea levels. At present offshore sand deposits are unlikely to supply any significant amount of fresh beach material. Fluvial deposits may also have been significant in the past with sediment transported by the steep fast flowing river systems which drain to the coastline. However, present day fluvial supplies are unlikely to be significant.

At present the sediment budget is relatively stable. A moderately low amount of material will be lost offshore during storm conditions, particularly from the more exposed beaches, such as at Northton and Traigh na Cleavag. A greater loss from the foreshore is due to aeolian transport of sand into the dunes and machair.

In general there is little evidence of any major nett longshore sediment transport pathways. Figure 17 shows the dominant mechanisms. Both swell and wind waves are much modified by the shallow sloping nearshore bathymetry with the planshapes of the beach areas in dynamic equilibrium with these conditions. However, the beach areas within this sub-cell, particularly the systems at Luskentyre and Scarasta, will be extremely sensitive to changes in sea levels due to the influence of the nearshore bathymetry, and hence wave conditions (and direction) at the coastline.

At Luskentyre sediment movement is complex, but overall nett movement is likely to be relatively low. Features such as Corran Raah on the island of Taransay and the corresponding spit at Rosamol indicate a number of sediment circulation cells, most probably caused by swell wave induced longshore currents. There is likely to be a weak movement of sediment along both sides of the spit feature of Corran Raah. There is also likely to be a northward drift along Traigh Seilebost but the absence of any recurve at the distal end of the spit feature indicates that any drift rate is low. Aeolian transport will also tend to move sediment in a northward direction towards Luskentyre. Traigh Seilebost does not appear to be a true spit. It is suggested (Ritchie & Mather, 1970) that it is a remnant dune and machair complex which has been drowned forming the tidal flats of Traigh Luskentyre. River flows from Faodhail Luskentyre will have a significant effect in redistributing this sediment. Current velocities within the river channel may also be contributing to erosion of the coastal edge to the south of Luskentyre. This part of the coastline is also exposed to more severe wave attack through a narrow wave window which exists to the south west between the island of Taransay and Toe Head and it is considered that wave erosion is the dominant erosion mechanism in this area. A detailed study of the system at Luskentyre was carried out by Harris & Ritchie (1989).

At present wind action is an extremely dynamic mechanism for the movement of sediment along the coastline. All the beach areas are backed by dunes and machair which all display dynamic features such as blowouts. Due to the severity of the winds experienced on this coastline, the dunes are extremely sensitive to any external influences.

Summary of erosion and accretion

Wave erosion is most noticeable at Northton and Traigh na Cleavag. The beach systems between Scarasta and Luskentyre appear to be relatively stable in terms of hydraulic processes with the exception of the southern coast of Luskentyre where erosion of the coastal edge is occurring due to the effects of the main river channel passing through Traigh Luskentyre. The effects of wind action appear to have a greater effect than hydraulic action. Most of the dune systems are affected by wind action, particularly at Luskentyre, Traigh Iar, Scarasta and Traigh na Cleavag.

6.5.4 Coastal defences

A rock wall has been constructed to prevent erosion of the machair edge backing the beach at Northton, Figure 18. The wall will have little influence on the beach except during storm conditions, where increased wave reflections may cause an increase in offshore beach sediment movement. It is likely that, due to the size of rock used and the near vertical construction, severe damage to the structure will occur under storm conditions. No routine beach monitoring of beach areas or coastal defences is conducted within this sub-cell.

6.6 Sub-cell 9d Sound of Harris to Griminish Point

6.6.1 Geology

The underlying geology both onshore and offshore is dominated by Lewisian gneiss. This has a considerable influence on the coastal zone due to the number of rock outcrops and offshore islands which occur and which control the planshape development of the beach areas. To the west of the sub-cell, beyond the Island of Vallay, the coastal edge becomes increasingly rocky with fewer beach areas reflecting the increase in exposure to the Atlantic. Where the bedrock is exposed, it is of considerable geological interest particularly at Udal and on the northern coast of Vallay. Both these areas are important in understanding the structural development of this basement rock with well-preserved dykes from the first major structural episode, the Scourian, which show little evidence of deformation from subsequent episodes. At Griminish Point a number of geos and arches have formed.

Quaternary deposits are limited to areas of blown sand. Much of the beach, dune and machair sediment will have derived from offshore glacial or glaciofluvial deposits. These have been extensively reworked by both marine and aeolian processes to form the complex range of landforms evident within this sub-cell at present. As in other parts of these islands there is little exposed evidence of raised beaches. However, peat deposits and a submerged forest between Pabbay and Berneray are indicative of postglacial periods of lower relative sea levels.

Much of the coastal zone is important from a geomorphological perspective due to the wide range of landforms occurring here. Machairs Robach and Newton have been designated a SSSI on account of the range of machair features and coastal geomorphology. Machair Leathann and the tidal strand at Vallaquie and Vallay also display a wide range of coastal landforms and processes.

6.6.2 Hydraulic processes

This sub-cell is subject to a semi-diurnal tidal regime and mesotidal range but no information is available on tidal ranges. The tidal ranges in surrounding cells are detailed in Figure 11. The main flood and ebb tidal streams occur well offshore and have little influence on this coastline. However, localised tidal flows between islands can be significant. At the east and west outlet of Vallay Strand the tidal streams can reach $1.5ms^{-1}$ on both spring flood and ebb tides with flows of up to $2ms^{-1}$ between North Uist and Berneray.

The offshore total and swell wave climates for the region to the west of the Uist are shown in Figures 22 and 23 respectively. The dominant wave conditions occur between 230° and 270°N. However, extreme wave conditions (significant wave heights of greater than 8m) are experienced from every direction apart from the south-easterly quartile. Extreme total sea offshore wave conditions have been predicted using the Met Office Wave Model and are detailed in Table 16.

Table 16 Total sea an swell extreme significant wave heights

Return Period (Years)	Total Sea Significant Wave Height (m)	Swell Significant Wave Height (m)
1	13.86	5.55
10	16.40	6.67
100	18.75	7.72

Swell wave conditions contribute a large proportion of the total wave energy experienced in this region. The dominant direction is from 250°N to 270°N although extreme swell wave conditions can occur from any westerly direction. Extreme swell wave heights for this offshore region are detailed in Table 16.

The inshore wave climate is extremely variable with many of the beaches being sheltered from the extreme conditions generated within the North Atlantic due to their orientation or by offshore islands and so may only be affected by locally generated wave conditions. Other beaches, such as on the west coast of Berneray, are directly exposed to swell and storm wave conditions generated over a long fetch. Rock reefs, shoals and outcrops are numerous in the nearshore zone and will have a significant influence in dissipating wave energy due to frictional effects. Wave diffraction around headlands and offshore islands of both storm and swell wave conditions will be significant.

6.6.3 *Littoral processes*

Details of the foreshore and hinterland characteristics are shown in Figure 14. The beach areas are headland dominated with swell wave conditions being the principal mechanism in their development. As such they are relatively stable, but may be sensitive to change, such as an increase in mean sea level, which may alter the shallow water transformation of swell waves. Offshore glacial deposits and biogenic material will have been the major beach material source. Other than reworking of existing wind blown deposits there is unlikely to be any significant fresh input of material to this sub-cell.

Nett sediment losses will be relatively minimal. Storm action will transport sediment offshore on the more exposed beaches along the western coastline of the island of Berneray and Machair Leathann. Elsewhere short fetch lengths and shallow water depths restrict the influence of wind generated waves within the tidal strands of Vallaquie and Vallay. However, erosion of the machair occurs when north easterly winds coincide with high tidal levels

Nett sediment movement by hydraulic processes is now limited, Figure 24. This can be seen in the development of the spit feature, Corran Aird a'Mhorain which is a good example of the latter development of a spit which has breached due to a reduction in the longshore supply of sediment. Even on the exposed coastline of Berneray there is unlikely to be any significant longshore drift due to substantial wave refraction and energy dissipation as a result of the shallow sloping and high friction nearshore seabed. As in other sub-cells along this western coastline the main frontal dune erosion due to wave attack will occur during storm conditions at high tidal elevations.

Localised tidal currents are sufficiently strong to suspend and transport sand-sized sediments. This is most evident between North Uist and Berneray where a current speed of over $0.5ms^{-1}$ occurs for over 50% of the time. Within the Sound of Berneray there are a number of sand banks and shoals which have formed due to tidal action. The construction of the causeway between the islands will cause changes to the tidal current patterns and the natural equilibrium of these sand banks. Within the tidal strands of Vallay and Vallaquie wind-induced currents may cause some redistribution of sediments, but there are unlikely to be any nett long term changes.

Aeolian transport of beach material is significant with a high volume of material moved from the foreshore of the west facing beaches into the dunes and machair. Transport by wind is probably the most dynamic erosive processes occurring at present and is probably responsible for the redistribution of the largest volume of sand sized material with large blowout features and deflation areas being actively worked.

Summary of erosion and accretion

Wave erosion of the frontal dunes is occurring along most of the western frontage of Berneray, the southern part of Machair Newton, much of Machair Robach, and Machair Leathann (although less so along the sheltered coastline of Traigh Ear).

6.6.4 *Coastal defences*

There are no known constructed coastal defences within this sub-cell.

6.7 Sub-cell 9e Griminish Point to Sound of Barra

6.7.1 Geology

The basement geology is dominantly Lewisian gneiss. Although much of the western coastline of the Uists and Benbecula is 'soft' these deposits, largely of blown sand, are relatively thin and the bedrock is found relatively close to the surface. The gneisses are most evident on the north west coast of North Uist where the coastal edge is predominantly rocky. However rock outcrops and headlands occur along all this frontage. As a result the planshape development of the beach areas is intrinsically linked to these 'hard' headlands. Offshore of the immediate nearshore zone, bedrock is exposed over much of the seabed with few drift deposits evident.

The exposed gneiss sections along the north west coastline of North Uist and at Garry-a-Siar on Benbecula are important due to the range of structural features exposed there which demonstrate the two principal deformation episodes experienced in this region. Some of the oldest rocks in Britain are exposed at Ardivachar Point.

Extensive blown sand deposits back the beach areas along the west facing coastline of both North and South Uist and for much of Benbecula. These deposits have been reworked from offshore glacial deposits which were moved onshore in post glacial times by fluctuating sea level. Due to the dynamic nature of the postglacial coastal processes which have shaped this coastline many of the landforms are geomorphologically important. The Loch Bee Machair is a designated SSSI on account of the range of beach, dune and machair features. Other landforms such as Kirkibost and Baleshare islands and Gualan spit have developed with virtually no human influences.

6.7.2 Hydraulic processes

The main flood and ebb tidal stream flows in a north-south direction parallel with the coastline. The tidal range is mesotidal with a spring range of approximately 3.2m, Table 17.

Table 17 Sub-cell 9e - Predicted tidal levels and ranges

Sub-cell	Location	MHWS (m CD)	MLWS (m CD)	Spring Range (m)	MHWN (m CD)	MLWN (m CD)	Neap Range (m)	CD to OD* (m)
9e	Scolpaig	3.8	0.7	3.1	2.8	1.5	1.3	-
9e	Balivanich	4.1	0.5	3.6	3.1	1.5	1.6	-
9e	Shillay	4.2	0.4	3.8	3.0	1.3	1.7	-

* Ordnance datum (local)

In Table 17 the tidal elevations are quoted relative to Chart Datum. Ordnance Datum in the Western Isles is relative to a local datum and not to Ordnance Datum Newlyn.

Offshore current velocities are generally low except directly offshore of the headland areas, e.g. Griminish Point and Rubha Ardvule, where peak Spring speeds of up to $1ms^{-1}$ can occur. However these currents have little influence on beach processes. Within the channels and tidal strands separating the main islands peak current speeds are greater. Wind-induced currents can also be significant at high tides over these sand flats. However, there is little information on current patterns or sediment movements within these areas.

The offshore total and swell wave climate for the region directly to the west of the Uists is shown in Figures 22 and 23 respectively. Almost 80% of wave conditions occur from between 210°N and 290°N although extreme wave heights can be experienced from any direction in the westerly sector. Swell wave activity is a large contributor to the total wave energy climate. Swell wave activity is dominated by Atlantic swell wave energy mainly from between 230°N and 290°N. Extreme wave heights for this offshore region are detailed in Table 16 in Section 6.6.2.

The shallow sloping, rocky and irregular bathymetry to the west of these islands provides a considerable amount of shelter to the predominantly sandy coastline. Wave energy dissipation effects due to seabed friction, refraction and offshore wave breaking all reduce the magnitude of the offshore wave energy before it reaches the coastline. The shallow sloping nearshore seabed also creates a wide breaker zone which further reduces wave energy levels. The extent of these wave energy dissipation processes depends heavily on tidal levels with high tidal levels reducing the sheltering effect provided by the seabed. Wave induced damage to this coastline will be greatest during spring tides, or when storm surges produce a large tidal residual. Such conditions occur when deep atmospheric depressions (anti-cyclones) move towards the Western Isles from the Atlantic. Hence, there will be a high correlation between the occurrence of such events and storm wave activity.

6.7.3 Littoral processes

Much of the western coastline of the Uists and Benbecula is characterised by long dominantly sandy beaches, Figure 14. These beaches are controlled by rock outcrops and headlands where the beach planshape has developed due to swell wave action. As such, each of these beach systems can be considered relatively stable as diffraction and refraction effects result in waves approaching the beach at a low angle of incidence. However, slight changes for instance in mean sea level, can cause considerable changes to the shallow water wave transformation processes and hence in the planshape of such bays.

Beach sediment sources are presently limited to the reworking of sand deposits of the machair land which back most of this coastline. Rock covers most of the offshore seabed and there is unlikely to be any input of beach sediment from offshore. Along much of the west Uist coastline sand beach levels fluctuate with an offshore/onshore transport of sediment. At present sand beach levels appear to be low, with all of the shingle upper beaches completely exposed, possibly indicating an increase in the number of recent storm events. The importance of these shingle upper beaches in providing protection from storm waves can not be understated. Extreme storm wave conditions may cause a nett offshore movement of sand sized sediment which may be trapped and prevented from moving back onshore by the irregular rocky seabed.

Nett longshore transport due to hydraulic effects is not significant and many of the bays can be considered as individual units, Figure 24. Only under severe storm conditions will there by any apparent longshore drift and movement of beach material between adjoining bays. Despite the offshore wave climate being the most severe around the British Isles, the shallow sloping offshore bathymetry results in waves approaching the shoreline at very low angles of incidence reducing the potential for longshore transport. Nearshore refraction and frictional effects also cause a large reduction in the offshore wave energy before it reaches the coastline. The occurrence of vast laminaria (i.e. kelp) beds off south Uist also assist in dissipating wave energy. The magnitude of the effect of these shallow water processes is extremely sensitive to tidal levels. Significant storm damage and gross longshore transport can occur if severe wave action corresponds with extreme surge and tidal levels. Such extreme tidal level/storm wave activity will cause the main erosive episodes on this coastline.

Within the tidal strands between the three main islands tidal and wind induced currents will result in redistribution of sediments. Without detailed mapping over a number of years no judgement can be made on erosion and depositional trends in these regions. However, an assessment by HR Wallingford (1988) estimated an erosion rate of approximately 0.5m per year along the RA Ranges frontage.

Summary of erosion and accretion
Long term wave erosion (mainly episodic storm erosion) is occurring along virtually the entire length of the exposed coastline of this sub-cell.

6.7.4 Coastal defences

A rock revetment and upstand protects the road to the north of Hougharry from wave attack and reduces the amount of shingle being deposited upon the road during storm conditions. The revetment is in good condition with no significant detrimental effects upon the coastline. Rock revetments also protect short stretches of the coastline at Balivanich, the edge of the road at Poll nan Crann and the north facing frontage at Balgarva. All defences are presently in good condition with little evidence of detrimental effects on the surrounding beach or coastal edge. The locations of constructed coastal defence work in Sub-cell 9e are shown in Figure 25.

Short lengths of gabion mattress protect the firing ranges at the RA Ranges on South Uist. The existence of vegetation which has established upon the mattress indicates that these structures are seldom affected by wave action.

At Pollachar a short length of rock wall protects the road to the inn. This rock wall is unlikely to withstand direct storm wave action. Short stretches of rock revetment also protect the road to East Kilbride. The size of rock used, and construction of these defences, is more suited to withstanding the hydraulic climate than the rock used at Pollachar. However, wave overtopping and the deposition of beach material onto the road occurs during storm conditions.

On Eriskay a low rock wall protects the machair edge at the townships of Rhuban and Balla. Storm damage is likely to occur due to the small diameter of the rock and the vertical construction.

A detailed topographic survey which included beach areas was conducted by the Property Services Agency in 1986 along the coastline fronting the RA Ranges on South Uist and at Rubha Ardvule. Other than this no routine coastal monitoring is conducted.

6.8 Sub-cell 9f Sound of Barra to Barra Head

6.8.1 Geology

The underlying geology of the islands to the south of the Sound of Barra is similar in lithogy to most of the other islands in the Western Isles being of Lewisian gneiss. The bedrock dominates both the topography and the coastal edge particularly on the western and southern freeboards where high rocky cliffs occur. A band of crushed gneiss, which occurs along much of the eastern coastline of the Uists, reaches the west coast of Barra at Greian

Head and at Ard na Gregaig. At Greian Head this exposure is geologically important as it displays some of the best examples of a fault-injected vein complex of breccia in Britain.

6.8.2 Hydraulic processes

The main flood and ebb tidal stream flows in a north-south direction parallel with the coastline. The tidal range is mesotidal with a Mean Spring range of approximately 3.2m, Table 18.

Table 18 Sub-cell 9f - Predicted tidal levels and ranges

Sub-cell	Location	MHWS (m CD)	MLWS (m CD)	Spring Range (m)	MHWN (m CD)	MLWN (m CD)	Neap Range (m)	CD to OD* (m)
9f	Barra Head	4.0	0.8	3.2	3.0	1.8	1.2	-
9f	Castle Bay	4.3	0.6	3.7	3.1	1.7	1.4	-2.25
9f	Barra (North Bay)	4.2	0.6	3.6	3.2	1.8	1.4	-

* Ordnance datum (local)

In Table 18 the tidal elevations are quoted relative to Chart Datum. Ordnance Datum in the Western Isles is relative to a local datum and not to Ordnance Datum Newlyn. The conversion factor from Chart Datum to Ordnance Datum (local) is provided in the final column (where known).

Offshore current velocities are generally low except directly offshore of the headland areas, e.g. Greian Head, where peak Spring speeds of up to $1ms^{-1}$ can occur. However these currents have little influence on beach processes.

The offshore total and swell wave climate for the region directly to the west of the Uists is shown in Figures 22 and 23 respectively. Almost 80% of wave conditions occur from between 210°N and 290°N although extreme wave heights can be experienced from any direction in the westerly sector. Swell wave activity is a large contributor to the total wave energy climate. Most of the swell wave activity is generated within the North Atlantic and occurs from a relatively narrow directional sector of between 230°N and 290°N. Extreme wave heights for this offshore region are detailed in Table 16 in Section 6.6.2.

The shallow sloping, rocky and irregular offshore bathymetry found along much of the west coast of the Uists continues along much of the frontage of this sub-cell. However, the nearshore seabed slope landward of the 20m CD contour is generally steeper and more variable. This is reflected in the character of the coastline with deeper water extending close inshore at rocky headlands, such as Greian Head, and a more gentle sloping bathymetry (1:150-1:300) occurring offshore of the main beach areas. The nearshore seabed provides a considerable amount of shelter to the beach areas due to seabed friction, refraction and offshore wave breaking which all reduce the magnitude of the offshore wave energy before it reaches the coastline. However, the degree of shelter provided by the nearshore bathymetry is unlikely to be as great as that experienced along the western Uist coastline with larger wave conditions experienced at the coastline. This also results in less dissipation of swell wave energy which tends to have a constructive effect in moving sand onto the beaches.

As to the north, wave induced damage to this coastline will be greatest during spring tides, or when storm surges produce a large tidal residual. Such conditions occur when deep atmospheric depressions (anti-cyclones) move towards the Western Isles from the Atlantic.

Hence, there will be a high correlation between the occurrence of such events and storm wave activity.

On the east facing beaches at Eoligarry the inshore wave climate is very much milder and dominated by wind waves. Fetch lengths in all directions are restricted by the numerous islands and rock outcrops which occur to the north east of Barra and hence severe wave conditions are extremely rare.

6.8.3 Littoral processes

The beach areas on the western coastline of Barra and Vatersay are dominantly sandy with a shingle storm beach protecting the dunes or coastal edge, Figure14. The two main features are the tombolos at Eoligarry and on Vatersay with a number of other smaller pocket beaches on the western coast of Barra. Rock platforms have a greater influence on the beach development, e.g. the tombolo features, than further north in South Uist.

As in most of the Western Isles, the beach material has been derived from the reworking of seabed glacial deposits moved onshore during times of rising sea levels. Due to the relative stability of sea levels during the last 3000 years (compared to the immediate Postglacial period) there is unlikely to be any present day supply of beach material from this source. The present day east-facing beaches, such as Traigh Scurrival and Traigh Mhor, were also initially formed from this supply of beach material.

The western facing beaches, due to their exposure to a much more extreme hydraulic climate, are much more dynamic than those facing east. Swell wave conditions (and the interaction between these swell waves and the solid geology, i.e. seabed and rock headlands) have dominated how the planshapes of these beaches have developed. Hence, due to the effect of swell waves, these west-facing beaches tend to have a relatively stable beach orientation, with there being little nett longshore transport of beach material.

The dominant littoral processes occur cross-shore, Figure 24. Storm wave conditions will tend to draw material offshore due to a flattening of the beach slope, whereas periods of swell waves will move this material back landward and cause the intertidal beach slope to steepen. The shingle upper beaches which occur along many of the west-facing beaches are a vital component in protecting the beach and dune systems from erosion. These shingle beaches are extremely effective in dissipating wave energy and without them, the frontal dune systems would quickly erode. The exception to this is at Halaman where there is sufficient width of beach to allow the beach slope to respond to storm conditions. Probably of greater threat to the overall stability of the coastal regime along this frontage is wind action on the high mature dunes with a number of large blowouts evident particularly at Traigh Eais and at Halaman. However, the movement of sand by wind action from the beach at Traigh Eais to Traigh Mhor provides an important feed of beach material for the eastern facing beaches. A detailed assessment of the beach system at Eoligarry was conducted by Hansom & Comber (1996).

On these eastern facing coastlines, the influence of storm waves is more damaging, but the extent of such damage is very dependent on water level due to the shallow sloping intertidal zone. There is no shingle upper beach and hence the coastal edge (i.e. the machair) is more susceptible to erosion during storm conditions (albeit that such events from the east are much rarer). Such erosion is extremely detrimental as there is no swell wave action upon these beaches to transport sand landward up the beach.

Summary of erosion and accretion
Storm erosion is most evident on the west facing beaches of sub-cell 9e, Traigh Eais, and Vatersay and along much of the coastline between the northern part of Traigh Mhor to Traigh Scurrival. There are no locations where long term accretion appears to be occurring.

6.8.4 Coastal defences

The only constructed coastal defences are a rock revetment at the northern end of the beach at Halaman protecting the hotel and a small section of rock rip-rap protecting the road at Traigh Tuath, Figure 25. Due to the small scale of these defences they do not have a significant detrimental effect on the coastal regime. Some dune stabilisation work has been attempted at Halaman using pallets and oil drums, the former being far more effective than the latter. Extensive marram grass planting has been conducted at Eoligarry.

The Western Isles Council conducts a yearly survey of Common Grazings Committees to identify areas which are being affected by coastal erosion. However no routine quantitative surveying or monitoring is conducted.

6.9 Summary of effects of coastal processes on natural and cultural heritage sites

6.9.1 Introduction

The natural and cultural heritage of the coastline of Scotland is rich and diverse. Much of the character and many of the features of natural heritage interest are due to the effects of the last Ice Age and subsequent post glacial climatic variations. It is since the last Ice Age that evidence of the first inhabitants of Scotland can be traced. Effects of coastal processes have been instrumental in developing both the natural and cultural heritage around the coast. For instance many important coastal geomorphological features evident are due to processes acting at previously much higher sea levels. Archaeological sites also demonstrate changes in these processes over the last 10,000 years or so. For example Skara Brae in Orkney, now requiring engineering protection from the sea, was once some considerable distance from the shoreline. Remains in Gleann Sheillach south of Oban indicate that 6000 years ago this site was at the head of a sea loch even though now it is 1.5km from the shoreline (Ashmore, 1994).

The present threat of erosion and the likelihood of future climatic changes considerably increases the risks of many of these sites being affected by erosion and/or flooding. However, as discussed in the next chapter, our present knowledge of either the patterns of future climatic change or how the coastline will respond to these changes is extremely limited. It is impossible at present to predict with any confidence what changes will occur in the coastline for example in the next 100 years or indeed in the next 10 years. However, the next sections attempt to present a broad based summary of the influences of present day and possible future coastal processes upon natural and culturally designated areas. **This report is concerned with the macro-scale processes occurring around the coastline. To generalise about the effects of coastal processes, particularly on individual cultural heritage sites, is extremely difficult, and many such sites require much more detailed, individual assessments to establish and prioritise the particular potential risks.**

6.9.2 *Natural heritage sites*

Figure 7 details the location of coastal SSSIs within Cells 8 and 9, with a summary of their main characteristics provided in Appendix 1. There are 22 SSSIs within Cells 8 and 9, many of which have been designated on account of geological or geomorphological features. A further 7 SSSIs exist on uninhabited, offshore islands not covered by this study.

There are a few sites in the Western Isles designated on account of the solid geology. Present day influences of coastal processes are unlikely to have any great detrimental effect on these sites. The majority of the coastal SSSIs designated in the Western Isles are due to (or partly due to) either important glacial features, post glacial geomorphology or present day coastal habitats. These sites are much more sensitive to changes in the naturally occurring processes.

At Port of Ness the exposed sediments which form the coastal cliffs which back the beach are important on account of the sequence of sands, gravels, and tills which were deposited as the Late Devensian ice-sheet melted. The sandy beach which fronts these cliffs has been supplied from marine erosion of these deposits with present day erosion of these cliffs the only fresh supply of sediment to the beach. Present erosion rates are low and limited to periods of extreme water levels or storm conditions when waves can reach the base of the cliff. However, any future increase in either extreme sea level, storminess or occurrence of storms from the north east will increase the rate of erosion.

The landforms and deposits on the north west coast of Lewis coast display important evidence of glaciation and sea level changes. These till cliffs rest on a shore platform with many of the sections only becoming exposed due to marine erosion (which is causing a long term retreat of the coastal edge along this frontage). At present the rate of retreat is relatively low, compared to previous times, with much protection afforded from wave attack by the wide shore platform. As at Port of Ness it is under extreme conditions that the main erosive events will occur with the magnitude of erosion sensitive to any increases in either sea level or the magnitude or occurrence of storm wave events.

The most sensitive coastal sites in the Western Isles are those designated on account of post glacial geomorphological features and habitats. These sites generally consist of important dunes and machair features. Perhaps the most sensitive are those occurring in South Harris and along the Western seaboard of the Uists, for example, Luskentyre and the South Harris beaches, and the machairs of the Uists and Barra. Potentially the most severe threat is from anthropogenic activities, such as livestock overgrazing and trampling and quarrying operations which initiate erosion which is then exacerbated by the severe physical conditions experienced along this coast. At certain locations, particularly in South Uist, the effects of rabbits have also resulted in severe erosion of the machair surface. Similarly the effects of tourism, such as caravanning at Traigh na Berie, have caused severe erosion at a number of locations. Not enough is known on how systems, such as the large erosion features in the dunes at Luskentyre, respond to changes in the physical climate to assess possible future scenarios. Only by limiting detrimental anthropogenic activities and monitoring of these systems can an understanding be gained of how such systems evolve.

On the east coast of Lewis a number of SSSIs are designated on account of saltmarsh habitat, such as at Graiss and Tong. These saltmarsh systems appear to be relatively stable at present, but are extremely sensitive to climatic changes, with mean sea level rise likely to be the greatest threat. This is discussed more fully in Section 7.

6.9.3 Cultural heritage sites

The density of archaeological sites from the NMRS database is shown in Figure 9. The coastal zone of the Western Isles is one of the most extensively archaeologically surveyed coastlines in Scotland (Ashmore, 1994).

There are probably two main factors affecting archaeological sites situated in the coastal hinterland in the Western Isles. Firstly, sites situated close to the coastal edge which could be lost due to continual coastal erosion. At present in these islands erosion and retreat of the coastal edge is a function of storm condition, i.e. although there may be a long term nett landward movement of the coast, it tends to be episodic. Hence, given the severity of storm conditions experienced, particularly on the exposed western seaboard of these islands, sites presently located close to the coastal edge have the potential to be lost in the space of one storm. This is most evident along much of the north west coastline of Lewis where eroding till cliffs form the coastal edge.

The second factor is the dynamic nature of much of the immediate coastal hinterland where large dune and machair systems exist. Many archaeological sites have been uncovered due to shifting sands, for example in dune systems, and it is likely that further sites will be discovered. However, this same dynamic response can cause submergence and loss of sites, albeit perhaps not permanently. This situation is more relevant to much of the "soft" western coastline of South Harris, the Uists and Barra where the influence of wind action can have a greater dynamic influence on the coastal zone than hydraulic processes. This is not to say that storm damage of archaeological sites will not occur. Given the severity of wave conditions experienced along this coastline archaeologically important sites within the frontal dunes or close to the machair edge can be considered at a high risk of being lost to coastal erosion, particularly where there is little shingle on the upper beaches providing protection against wave attack.

Given the scarcity of quantitative information on factors such as coastal retreat rates (as with much of the Scottish coast) it is not possible to prioritise the areas most at risk. However, given the severity of the coastal processes experienced upon this coastline sites within 5-10m of the present "soft" coastal edge should be considered high priority on a national scale.

7 Climate change and its effect on coastal management

7.1 Introduction

The importance of climate change in the context of coastal management has generally been equated to the problems caused by an increase in mean sea level. This remains an important issue, particularly for low-lying areas where economically important assets are situated close to, or below, extreme tide level. However, recent winters in the UK have indicated a number of other potential impacts affecting the management of the coastline and its defences which may be more important, at least in the short-term. Such factors include an increased frequency of storms. Increased erosion of the coast may therefore be a greater concern in much of Scotland than flooding due to sea level rise. Much of Section 7.2 is taken from Brampton (1996).

7.2 Evidence of climatic change

7.2.1 General

The Intergovernmental Panel on Climate Change (IPCC) concluded that 'The balance of evidence from changes in global mean surface air temperature and from changes in geographical, seasonal and vertical patterns of atmospheric temperature, suggests a discernible human influence on global climate' (Houghton *et al.*, 1996). The conclusion of the IPCC rests on: (i) the physical effect of greenhouse gases on the atmosphere; (ii) observed climatic trends; and (iii) projections from global climate models.

The greenhouse effect results from certain gases in the atmosphere retaining heat that would otherwise be radiated into space. These greenhouse gases are relatively transparent to sunlight but absorb thermal infrared radiation emitted by the Earth's surface. The natural greenhouse effect already keeps the Earth over 30°C warmer than it otherwise would be; increasing concentrations of greenhouse gases warm the Earth still further.

The main greenhouse gases are carbon dioxide, methane, nitrous oxide and some industrial chemicals such as chlorofluorocarbons (CFCs) but also include water vapour. Significant modification of the atmosphere by human activities has occurred since the industrial Revolution. However, the magnitude of greenhouse gas emissions has increased enormously in recent decades. Increased carbon dioxide is the most important driver of global change contributing about 64% of the radiative forcing that produces global warming (Houghton *et al.*, 1996).

Global average surface air temperatures can be computed back to 1856. The record shows warming of about 0.5°C over the 140-year period to 1997, with the warmest year occurring in 1997 and the warmest six years all recorded since 1983 (Parker & Folland, 1995). The decade 1987-1996 has been 0.25°C warmer than the 1961-90 average.

7.2.2 Tidal and sea level change

Geomorphological evidence shows a long-term pattern of sea level rise relative to the land around much of the UK coast, stretching back over 10,000 years to the end of the last Ice Age. Generally rates of sea level rise during this period have been higher than they are today although there have been several periods of "stands" in level, or even periods of falling levels. However, since the end of the last Ice Age, the isostatic uplift of the land mass due to post-glacial recovery (in mainland Scotland at least) has been occurring at a greater rate. The net result has been a <u>fall</u> in sea levels relative to the land level in most of Scotland, except for the Northern and Western Isles where gradual submergence has continued. Evidence for this is largely from geological features such as raised beaches which are a common occurrence around much of the Scottish coastline. The rate of isostatic uplift since the last Ice Age has been one of an exponential decrease and at present over much of Scotland the rate of increase in sea levels (eustatic increases) is now occurring at a slightly greater rate, i.e. sea levels are now increasing relative to land levels albeit at a very low rate (and certainly a much lower rate than say experienced on the south east coast of England). Whilst the Intergovernmental Panel on Climate Change (IPCC) (Houghton *et al.*, 1996) estimates a global <u>mean</u> sea level of 12-95cm higher than 1990 by the year 2100, the rise around the Scottish coast is expected to lie at the lower end of these values. Estimates by Hill *et al.*, (1999) indicate that the net mean rise in sea level around the Scottish coast by 2050 will be up to 30cm with nearly a third of the coastline only experiencing a rise up to 10cm, although the Shetland Isles may experience a net rise in sea level greater than 30 cm. These regional variations reflect differences in the rate of crustal uplift across the country which moderate or exacerbate, locally, the global rise in sea level. The term "net rise" means that land uplift rates are taken into account.

It is important to note that an increase in extreme tidal levels may not, in the short-term, be the same as an increase in mean sea levels. There is not only a long-term variation in the height and frequency of surges (as in wave heights, see Section 3.3), but also a change in the range of the astronomical tides. This latter aspect has been observed, for example in Newlyn, but not apparently explained. An increase in extreme tidal levels might be expected to increase the chances of wave overtopping of beaches and coastal defences or to increase dune erosion.

However, the evidence for this is far from conclusive. Recent research (Woodworth et al, 1991) carried out by the Proudman Oceanographic Laboratory analysed the long-term tide record from Newlyn in Cornwall. This has indicated the influence of the 18.6 year periodicity (caused by the precession of the plane of the Moon's orbit around the Earth, relative to the elliptical plane). During certain stages of this 19-year cycle, the mean tidal ranges increased by about 20mm/year, and it can be expected that the spring tidal ranges will increase by an even greater amount. This effect lasts for several consecutive years. During such periods, the effects on the upper parts of the beach would presumably be much the same as if mean sea level was rising by about half that amount, i.e. about 10mm/annum. Therefore it can be assumed that there would be periods of rapid beach erosion and landward recession during these times (presumably followed 9 years later by periods of beach accretion as high water levels decline). At present we are at the end of one of these rapid rise periods.

7.2.3 Wave climate change

Wave action around most of the coastline of the UK is the principal mechanism affecting evolution of the nearshore zone, i.e. the region where water depths are less than 5m at low tide. Hence changes in wave heights, either in terms of general trends or in severe storms, are of considerable importance. There is now no doubt that such increases in wave height do occur and may continue to do so for some considerable time. Bacon & Carter, (1991) have conducted the most comprehensive review available of wave climate changes in the North Atlantic and North Sea. Their data suggests that mean wave height increased from about 1960 to a peak around 1980, with a subsequent decline. Recent winters, (particularly 1988-1989 and 1993) have produced severe storms in the northern North Sea which may affect these trends. This agrees with more recent work (Leggett et al, 1996) which analysed wave climate data in the northern North Sea between 1973 and 1995 and concluded that:

- in the northern North Sea mean significant wave heights (H_s) have increased by approximately 0.2-0.3m (5-10%) since 1973. Wave conditions have been higher since 1988/89, with a secondary peak in 1982/83.

- Peak H_s values since 1988 have generally been significantly higher than those from the period 1973-1987. Recent years have seen storms with peak H_s of 12.5-14m, whereas peak values recorded before 1987 were around 11-12m.

- Since the 1980s wave conditions appear to have become a little calmer in autumn and more severe in late winter.

There is also some qualitative information to suggest that the increase in severity of the wave climate in the North East Atlantic has occurred in parallel with an increase in the frequency of very deep low pressure systems in the North East Atlantic (Lynagh, 1996). This report suggests that the latest peak in the frequency of occurrence of these low pressure systems may be over and that the next few years will see a decrease in such systems. However, there is insufficient evidence to confidently predict whether such a decrease will occur or indeed if these variations are linked to variations in storminess.

Wave direction can be almost as important as wave height in coastal management. Any changes in long term average wind directions can cause large morphological changes. There is not a sufficient length of time series of reliable directional wave data to assess any trends in direction. Analysis of wind climate data has revealed that there has been very little change in the wind climate and no proof that recent increases in storminess are statistically significant. Unpublished work by Jenkinson & Collison (1977) found no significant change in wind speeds over the Atlantic or North Sea occurred between 1881 and 1976. Historical evidence analysed by Lamb and Weiss (1979) detected a climatic cycle of about 200 years. Over the North Sea the change consisted mainly of changes in the relative proportions of northerly and westerly winds. At present, it was reported, we are experiencing an increase in the proportion of northerlies which may lead to an increase in mean wave heights affecting the east coast. It was forecast that this trend would continue for a further 70 to 100 years. However, there has been some concern that depressions from the Atlantic have been tracking further to the south than previously. This has increased the dominance of south easterly winds potentially affecting the rate (even the direction) of the nett alongshore drift at various locations. There is no available information to confirm whether this is a long term trend.

7.3 Effects on coastal management

7.3.1 Impact on beaches

General

One method for predicting shoreline erosion caused by sea level rise is known as the Bruun Rule (Bruun, 1983). This suggests that as sea levels rise, the beach will adjust to maintain a constant depth profile, i.e. the upper beach erodes, while the nearshore bed accretes. There is some evidence to suggest that this also happens in real life, but it should be realised that the method assumes a two-dimensional response when the development of a beach will almost always be three dimensional. The amount of sediment available is also a critical factor in the response of a beach to sea level rise, with those with a limited supply being more likely to retreat.

In the UK, the effect of sea level rise on beaches is probably not as great as those associated with changes in the wave climate, in the short term at least. An increase in the occurrence of very large waves will, for example, alter beach profiles or cause dune erosion which may take many months, or even years, to repair naturally. Conversely an increase in the occurrence of more modest waves, may be accompanied by a decrease in the largest wave heights. This would lead to a general steepening of the beach profile and a reduction in erosion. A change due to sea level rise may therefore go completely undetected.

Although a change in wave heights will cause changes to beach profiles, the long-term evolution of the shoreline is almost always linked to changes in the longshore transport of beach sediments or, more precisely, the changes in transport from point to point along the coast. The longshore transport does depend on wave height, but more crucially on wave direction. The former influence, in the long term, can only increase or decrease the rate at which the coastline is eroding or accreting. However, a change in the "average" wave direction will often cause a change in the present trends of erosion and accretion (affecting both rates and patterns). At some locations, it has been found that erosion problems have recently occurred on stretches of coastline which have been stable or accreting for many years.

Impact on beaches in Cells 8 and 9

Minor changes in sea levels or wave conditions will have very little effect on the hard coastline of Cell 8. The major impacts will occur around the surrounding coastline and isthmus connecting the Eye Peninsula to the Lewis mainland and along the northern coastline of Broad Bay. The extent of this impact will vary considerably, depending on the nature of the climate change and on the physical character of the coastline.

Where there is little human intervention, i.e. coastal defences, the most noticeable changes will occur on the sand beach frontages which are backed by sand dunes, for instance at Melbost, Traigh Chuil, Traigh Ghriais and at Traigh Mhor in Cell 8. Changes are likely to be episodic, being linked to storm activity, rather than any continuous evolution. The most damaging effect of climatic change on this frontage is likely to be due to either an increase in extreme water levels or an increase in the frequency of storm events which will cause an increase in dune erosion, i.e. erosion of the frontal dune face. As many of these beaches are contained between rock outcrops, which will restrict the littoral movement of sediment between beach units, the dominant loss of beach material will be offshore. However, given the shallow sloping nature of the seabed in Broad Bay it is unlikely that offshore losses will be significant and that beach material will be retained within, or just seaward, of the intertidal zone.

Most of the glacial deposits lie above harder gneiss which outcrops in the form of a wave abrasion platform in the intertidal zone. This platform protects these glacial cliffs from all but the most severe storm conditions, by dissipating much of the wave energy through frictional effects and wave breaking. A marginal increase in water level, particularly extreme water levels, will result in a reduction in the level of protection provided by this platform, allowing a greater percentage of the total wave energy to reach the frontal face of the cliff. This will increase marine erosion of these cliffs. Where there is no infrastructure at threat this may not be serious as it will provide a supply of fresh beach material. However, where infrastructure exists close to the cliff edge, such as Aiginis and Port of Ness, there is an increased risk of such infrastructure being affected by erosion.

Along the south facing coastline of the Eye Peninsula and Branahuie isthmus the volume of shingle on the beaches is low and provides little protection against storm wave attack. An increase in the number of storm events will result in overwashing of these shingle storm beaches and roll over with beach material progressively transferred from the front face onto the hinterland thereby causing a landward retreat. Where the shingle beach is prevented from moving landward, say due to a seawall, the beach will tend to be drawn down with shingle moved seaward again reducing the level of protection. To the south of the airport this shingle has been formed into a ridge. Any increase in either the magnitude and/or frequency of storm events will increase the frequency of breaching and the rate of retreat of this ridge, leading to more regular flooding of the hinterland.

The "soft" coastline of Cell 9 is likely to one of the most sensitive to climatic change in Scotland. The extent of this impact will vary considerably, depending on the nature of climatic change and on the physical character of the coastline; e.g. the climatic factors affecting, and response of, the long open coastline of South Uist will be different to that experienced in the pocket bay beaches such as at Dalmore Bay in Lewis.

Considering firstly the pocket bay type beaches, i.e. where a beach is constrained by two headlands, such as occur in Lewis, Harris and Barra and at a few locations in North Uist. The beach planshape on such beaches does not change dramatically, even if the offshore wave direction changes, as wave conditions at the shoreline are dominated by wave diffraction around the headlands at either end of the bay. Similarly many of these pocket beaches have already adjusted and reached a position of no nett drift. A change in wave heights will therefore have little effect on any longshore transport of beach material. Research into the influence of <u>mean</u> sea level rise on pocket beaches (Diserens et al, 1992) also concluded that there was no clear linkage between <u>mean</u> sea level rise and the position of the high water line. Hence it is unlikely that mean sea level rise will have a significant effect. Of greatest impact on these pocket beach areas is likely to be due to an increase in <u>extreme</u> tide levels which may result in an increase in dune or backshore erosion, particularly on the beach areas where there is little present day width between the high water mark and the frontal dunes/coastal edge or where streams run onto the middle of the beach causing beach levels to be lower.

On the more open, exposed coastlines, such as along the western seaboard of the Uists and the north west coast of Lewis, the effects of climatic change will be more serious. Swell wave conditions are likely to have had a dominating effect on the planshape formation of the soft coastline in this cell. Due to the nature of the seabed offshore of these islands, particularly off the Uists, it is unlikely that small changes in mean sea level will have a significant effect on swell conditions at the coastline (either in terms of wave height or wave direction). However, changes are likely to be episodic, being linked to storm activity, rather than any continuous evolution. The most damaging effect of climatic change on this frontage is likely to be due to either an increase in extreme water levels or an increase in the frequency of storm events.

The immediate sea bed to the west of the Uists protects the islands from the severe wave conditions in the North Atlantic (due to the shallow sloping, and frictional effects, of the offshore bathymetry). Hence, the severity of the wave conditions experienced at the shoreline is very sensitive to the water depth. Any slight increase in the magnitude of extreme water levels will have a significant effect on the severity of the wave conditions experienced at the coastline. Any increase in erosion will be most evident where there is no shingle upper beach

An increase in the number of storm events along the exposed coastline of the Uists will have two effects. Firstly it is during these events that the shingle upper beach is most dynamic. Overwashing of these shingle storm beaches is likely to increase causing roll over with beach material progressively transferred from the front face onto the machair hence causing a landward retreat. Where dunes restrict the retreat of the shingle ridge, the shingle is likely to be drawn down, i.e. the toe of the beach will move seaward as the slope of the shingle beach flattens. This will lead to increased dune erosion and hence retreat. Where there is no shingle protecting the machair or dune edge, the magnitude of erosion, i.e. coastal edge retreat, will be much greater.

The second effect is on the sand intertidal beaches which front the shingle upper beaches. The sand beach levels along the Uist coastline will fluctuate depending on preceding wave conditions. Storm conditions will tend to lower beach levels and move beach material seaward (i.e. as the beach slope flattens in response to these severe waves) and swell waves will tend to build the beach back up. Beach drawdown can occur in a matter of hours, i.e. during one storm, whereas the re-building of the beach occurs over a much longer period (often months). To a certain extent this process will occur on the majority of the sand beaches in Cell 9, but it is on the open, exposed frontages of the Uists, where wave conditions directly affect the beaches from a wide range of directions, i.e. almost the entire westerly sector, that any increase in storm events will be most noticeable. Hence, under such a scenario, the beach areas may not have a sufficient period to recover, resulting in low intertidal beach levels which could increase the severity of the wave conditions on the shingle upper beaches, machair or dune front and hence increase the rate of erosion, i.e. retreat. This process appears to be occurring at present with many of the shingle storm beaches along the Uist seaboard now appearing to be continually exposed (whereas previous photographs have shown much higher sand beach levels covering the shingle).

Along the coast of north Lewis, glacial cliffs are protected from continuous wave attack by a wide rock platform which dissipates much wave energy. Erosion of these cliffs occurs generally during severe storm events or during times of high water level. Any increase in the frequency of such events will lead to an increase in erosion of these cliffs. There are also a number of shingle ridges fronting the brackish lochs on the north west Lewis coastline and a notable ridge which protects low lying land at Stoneybridge on South Uist. These features will respond in a similar manner as described in the above paragraph by rolling backwards. Breaching of these ridges will become more frequent (and hence flooding of the hinterland more regular) with any increase in storminess.

Of greater uncertainty is the effect any change in the hydraulic climate will have on the intertidal sandflat areas between the Uists and Benbecula and along the north coast of North Uist. Certainly an increase in either mean or extreme water levels will increase the risk of flooding in the low lying areas adjacent to these sandflats. However it is difficult to assess the likely impact (if any) on the littoral regime of these areas. Where saltmarsh has developed there is some evidence to suggest that below a certain threshold rate of sea level rise, the saltmarsh is able to accrete and keep pace with the change. Above this threshold the marsh becomes submerged and is lost. There is also evidence to suggest that erosion and the loss of saltmarsh is linked to increases in wave energy. This may be the dominant threat on salt marsh areas which are moderately exposed to some wave activity, such as between Benbecula and the Uists and along the North Uist coastline, whereas in the more sheltered locations such as in Loch Paible, at Northton and Traigh Luskentyre on Harris, increases in sea level may be more important.

7.3.2 Impacts on man-made defences

<u>General</u>

A study into the effects of sea level rise on coastal structures was carried out by Townend (1994). This showed that the effect of sea level rise on design parameters such as armour weight and run-up depended very much upon the location of the structure in the surf zone and whether waves were breaking or non-breaking at the structure. For instance with breaking waves rock armour weight requires an increase of over 100% for an increase in water depth of only 10%. However, in shallow water where waves are not breaking there is a slight reduction in the required armour weight and in the level of run-up with increases in sea level due to reduced wave shoaling. The effect of sea level rise will always cause an increase in the overtopping of defences irrespective of wave condition.

Possibly of greater importance in the design of coastal structures such as breakwaters and seawalls is the impact of increased storm activity. For example, the size of stable rock armouring on a revetment or breakwater depends on the cube of the design wave height. An increase in extreme wave heights of only 1% each year could, in a decade, lead to a requirement for armour unit weights to be some 38% heavier to achieve the same degree of safety.

In most situations, defences first fail "functionally", allowing erosion or flooding of the land behind. Occasionally, however a defence will suddenly fail "structurally", leading to a much greater danger to life and property, for example the collapse of the seawall at Towyn in North Wales. In most cases, the failure of defences results from a combination of factors, e.g. low beach levels, a high tide and large waves from a limited directional sector. A gradual change in the probability of occurrence of just one of these parameters may therefore not be apparent for many years.

Impact on coastal defences in Cells 8 & 9

In Cell 8, coastal defences are located mainly along the isthmus to the Eye Peninsula. By the very nature of these defences, an increase in either sea level rise, or storminess will have an extremely detrimental effect on the beaches fronting them and in the longer term, without intervention, may eventually lead to their collapse. Both seawalls on the north and south coastline of the isthmus reflect a large amount of the incident wave energy. Any increase in this reflected energy, due either to an increase in sea levels or wave conditions, will reduce beach levels, leading to increased wave reflection and so on. Also a decrease in beach levels will lead to increased wave attack on the structure, and hence damage, and also the possibility of undermining of the foundations and, ultimately, collapse. Already beach levels at the eastern ends of both north and south walls are dangerously low.

The rock revetment protecting the northern end of the main runway at Stornoway Airport is in a good state of repair and shows little sign of existing wave damage. However, an increase in either sea levels (and hence nearshore wave conditions) and/or storminess may result in a slight reduction in the degree of safety provided by such structures. It can be assumed that both the frequency and extent of damage of these structures is likely to increase under an assumed increase in sea level (mean or extreme) or increase in storminess, i.e. for a storm of the same return period as the design return period there would be a gradual increase in the level of damage to the structures. The rock wall at Tong and the short stretches of revetment occurring elsewhere, e.g. to the south of the airport, are less likely to withstand any increase in the severity of the hydraulic conditions and an increase in the frequency of damage of these structures will be evident.

There are few coastal defences in Cell 9. An increase of either sea levels (and hence nearshore wave conditions) and/or storminess may result in a slight reduction in the degree of safety provided by the rock revetments and walls. The structures most at risk are the rock walls at Kneep, Northton and Balla which are likely to be susceptible to wave damage at present. Hence, both the frequency and extent of damage of these structures is likely to increase under an assumed increase in sea level (mean or extreme) or increase in storminess. The revetments at Hougharry, Balivanich, Poll nan Crann and Balgarva are possibly less at risk. However, for a storm of the same return period as the design return period there would be a gradual increase in the level of damage to these structures.

7.3.3 Other effects

There are a number of other climatic factors which may affect the coastline evolution and hence management techniques. Two of these are discussed below. In each case little is known of the extent of any variations in these climatic factors and whether these are of significance in managing the coast.

Rainfall

There is an observed variation in the rainfall occurring in the UK. In the south of England an oscillation of about 40 years period has been observed. There is anecdotal evidence that a 20-30% increase in rainfall has been recorded in central Scotland over the last 25-30 years. No similar studies on rainfall patterns are known of in the north west of Scotland. As rainfall increases, a number of effects are likely to occur at the coastline:

- De-stabilisation of soft cliffs

  Cliff falls are usually caused by a combination of marine erosion, e.g. undercutting their front face, and geotechnical problems, e.g. rotational slips. The latter effect is increased by greater rainfall and hence higher run-off, higher water tables etc. The most obvious location where this could be a problem is on the conglomerate cliffs around the isthmus to the Eye Peninsula, the cliffed sections of coastline along the northern side of Broad Bay, at Port of Ness, and along the north west coast of Lewis. An increase in cliff erosion could affect infrastructure at a number of locations. For instance the township and access road to Aiginis are presently at risk, mainly due to marine erosion. Similarly, housing on the cliff top at Port of Ness and to a lesser extent at Aird Thunga may also be at risk from any increase in cliff erosion.

  In the longer term such destabilisation could have the benefits of increasing the supply of sediment to the beach areas along these frontages. However, given the nature of the coastline and the severity of the wave conditions it is unlikely that any increase in sediment supply will be evident on the beach areas.

- Increased river flows

  In many parts of the world, rivers still bring large quantities of sand and gravel to the coast, providing fresh supply. Increased river flows would increase the capacity of the river to transport sediment. Most of the rivers in the Western Isles are short with relatively low flows. It is unlikely that increased river flows will have any noticeable effect on the littoral regime in this cell.

- Impacts on sand transport on beaches

  In locations where a beach is affected by surface water run-off from land, there are often localised erosion problems, e.g. around outfalls. The frictional resistance of sand is reduced by the water, making it easier to be mobilised by waves and currents. It is therefore likely that increased rainfall will tend to cause localised beach erosion.

- Impacts on dune building

  Wet sand on the foreshore will be much less easily transported by winds than if it is dry, reducing the supply to dunes. However, many dune binding grasses suffer in drought conditions, and are generally healthier in moister climates. This would help to increase the trapping efficiency, and encourage them to colonise new areas more quickly. It is not clear, therefore, whether increased rainfall will assist dune growth or be detrimental to it.

Changes in wind

As well as changes in wind conditions altering waves, discussed earlier, there are other direct effects which may affect the coastline:

- Aeolian sand transport

  Strong winds are capable of transporting large quantities of sand, both along the coastline and perpendicular to it. The former effect can add to, or counteract wave induced longshore drift, but tends to take place a higher levels on the beach profile. Onshore transport by wind typically dominates over offshore movement. This is partly because winds blowing over the sea are stronger (less affected by friction) than those blowing offshore.

  A change in wind strengths or directions may also alter existing patterns of sand transport. It is likely that this will be most noticeable in changes in dunes, rather than on the beaches themselves. Large dune complexes such as are found along much of the west Uist and Harris coastline are likely to be affected most from such changes.

Much of the above discussion on climatic change and its impact on coastal response is based on logical argument rather than well documented case histories.

Although the impact of climatic change on the coastline of Cell 8 is unlikely to be as significant as say in Cell 9 there are localised areas of concern, e.g. around the isthmus to the Eye Peninsula. The western coastline of the Uists is likely to be one of the most sensitive to any changes in the marine climate due to the "soft" character of the coastline. Given that there is minimal human interference with this coastline this would be an ideal location to attempt to quantify some of the effects on the coastline of a changing hydraulic climate. At present, the complexity of the coastal and nearshore zone makes it difficult to predict morphological changes due to the range of inter-relating parameters which affect this zone. To identify and quantify the effect on the coastline of changes to any one, or a number, of these parameters would require good quality, long-term data to validate predictive methods and to identify changes in the marine (i.e. hydraulic) climate.

Trying to separate longer-term climate change effects from those caused by "normal" fluctuations in weather is a major challenge. There is a clear need for monitoring of the coastline, not only to understand the processes, but to provide a long-term data-set for future generations trying to deal with the effects of potentially more dramatic climate changes.

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Figures 1-25

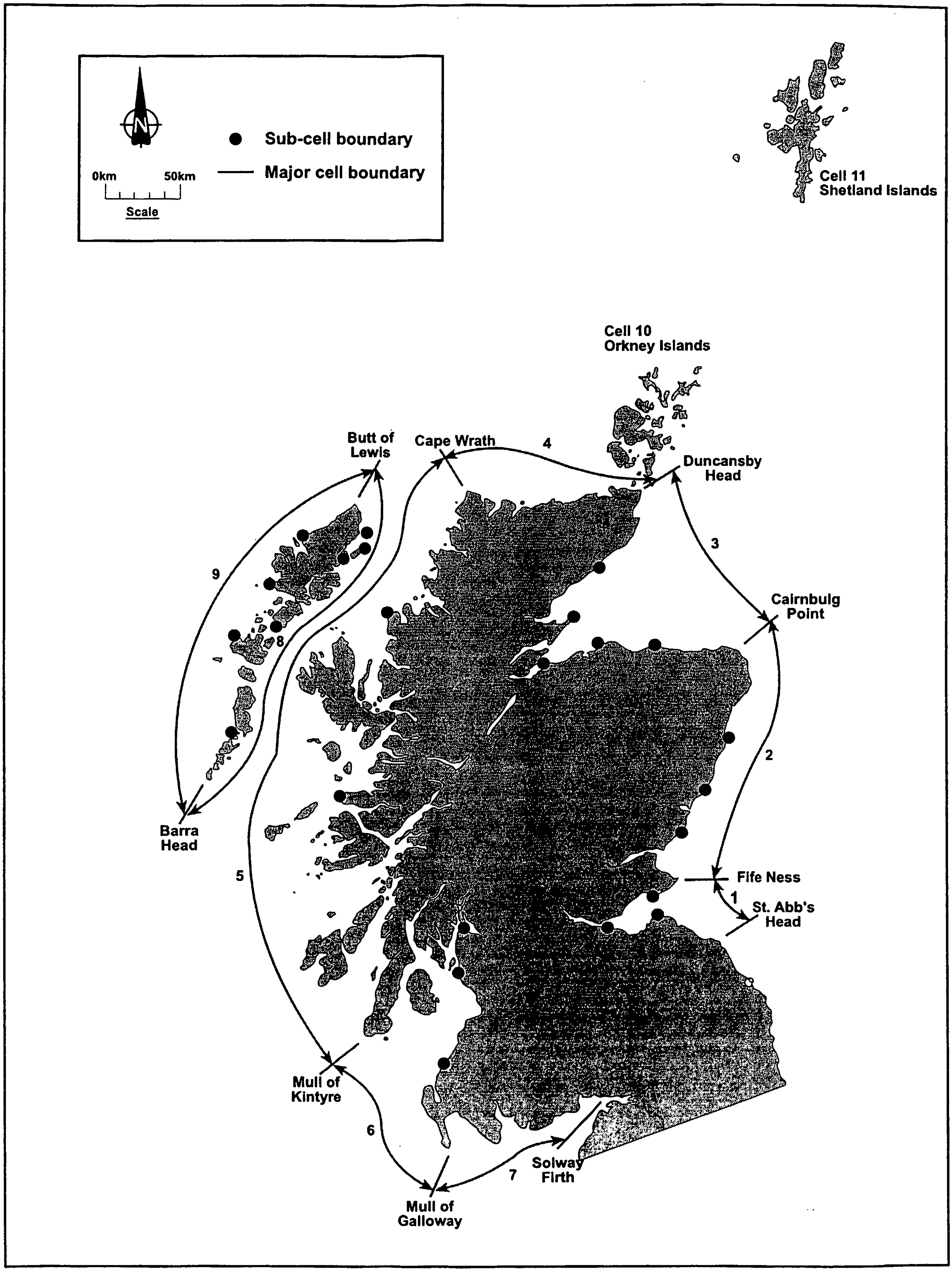


Figure 1 Coastal Cells in Scotland

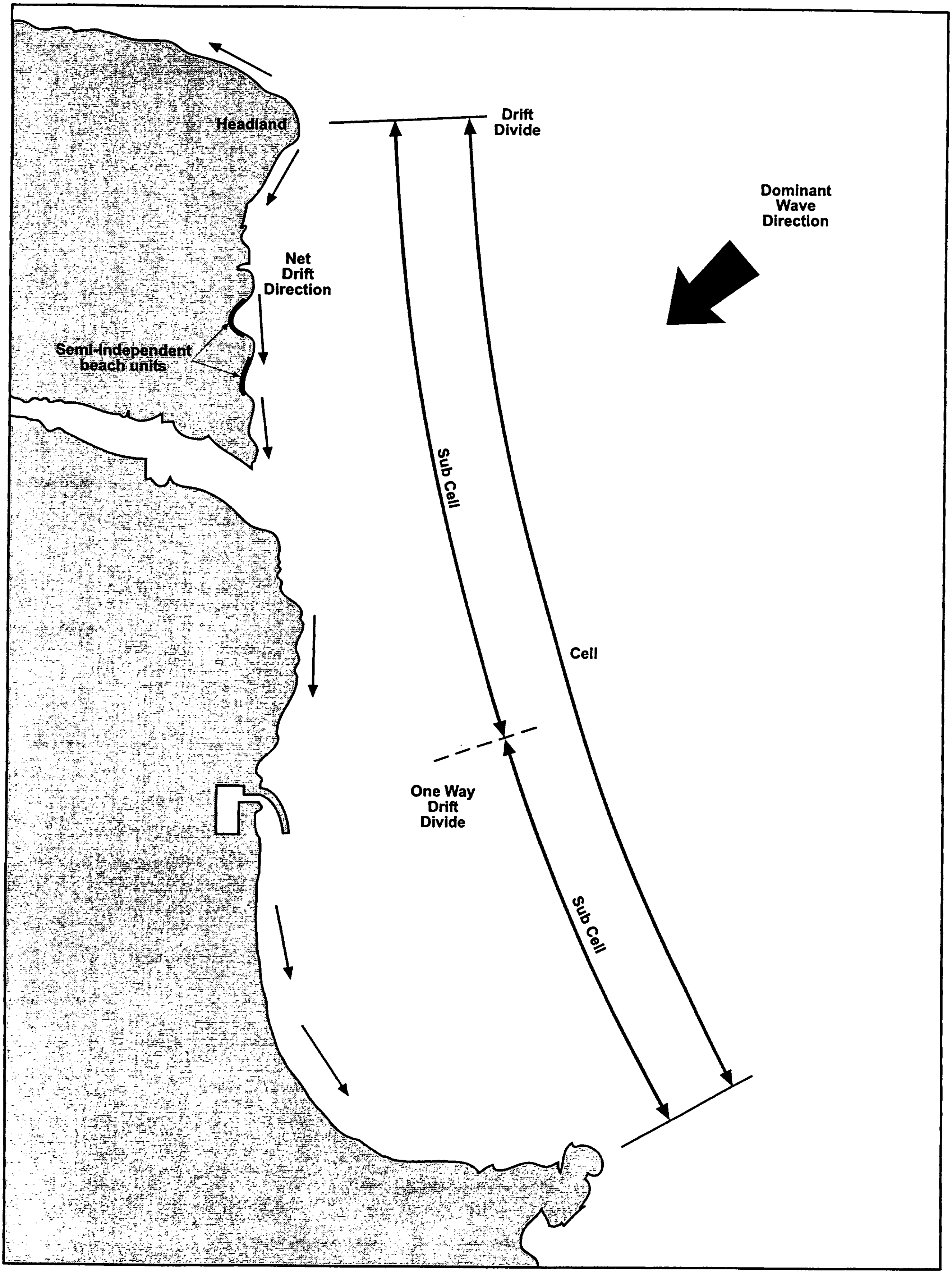


Figure 2 Idealised coastal cell

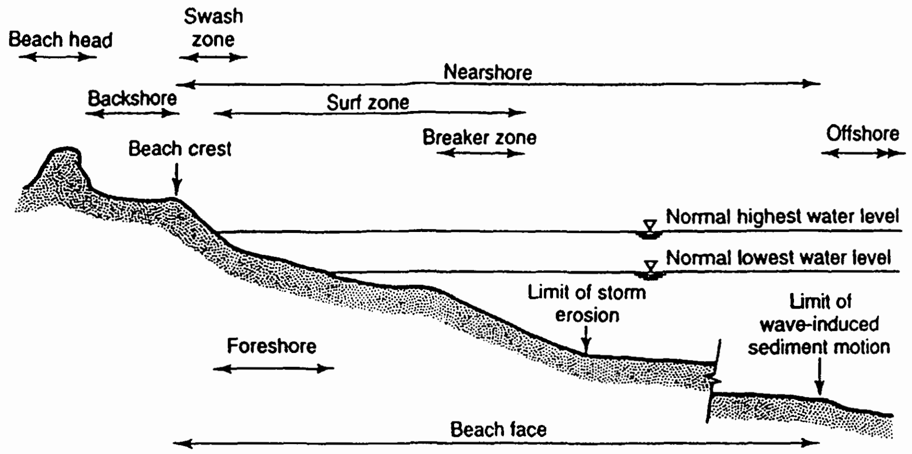


Figure 3 General beach profile and littoral zone

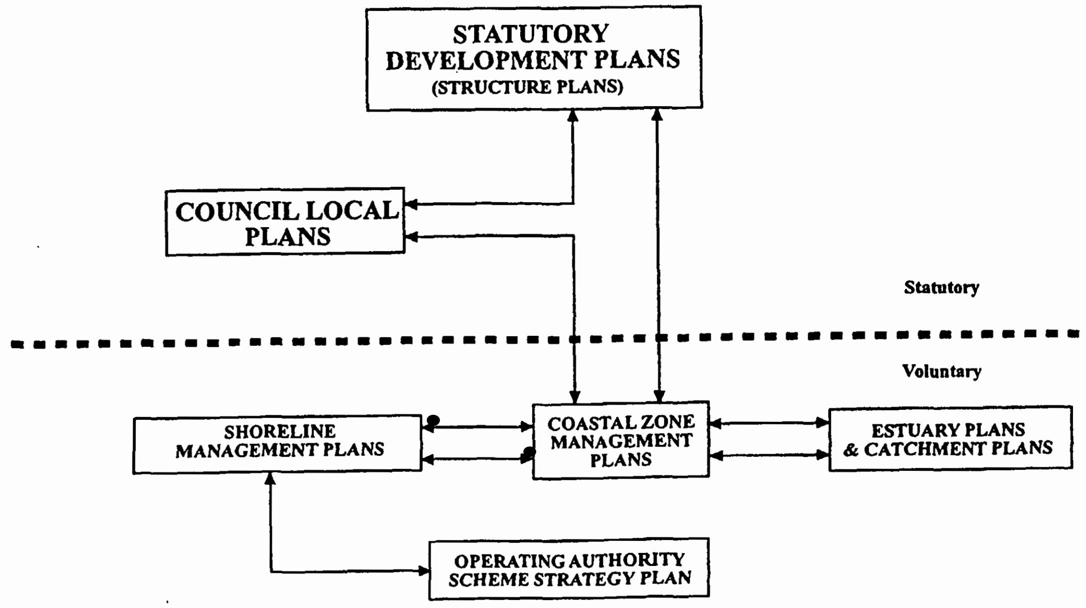


Figure 4 Relationship between coastal initiatives

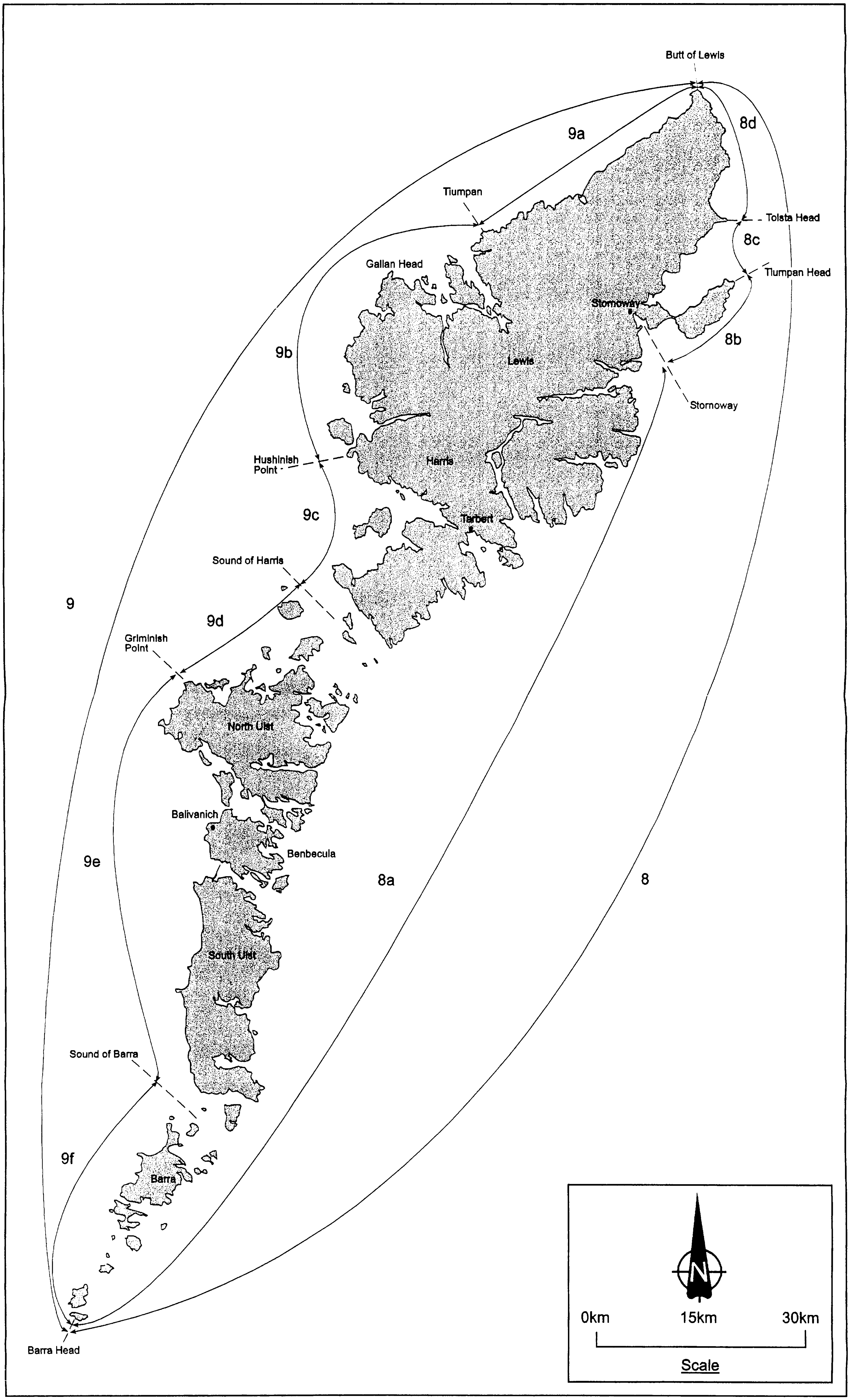


Figure 5 Cells 8 & 9 - The Western Isles

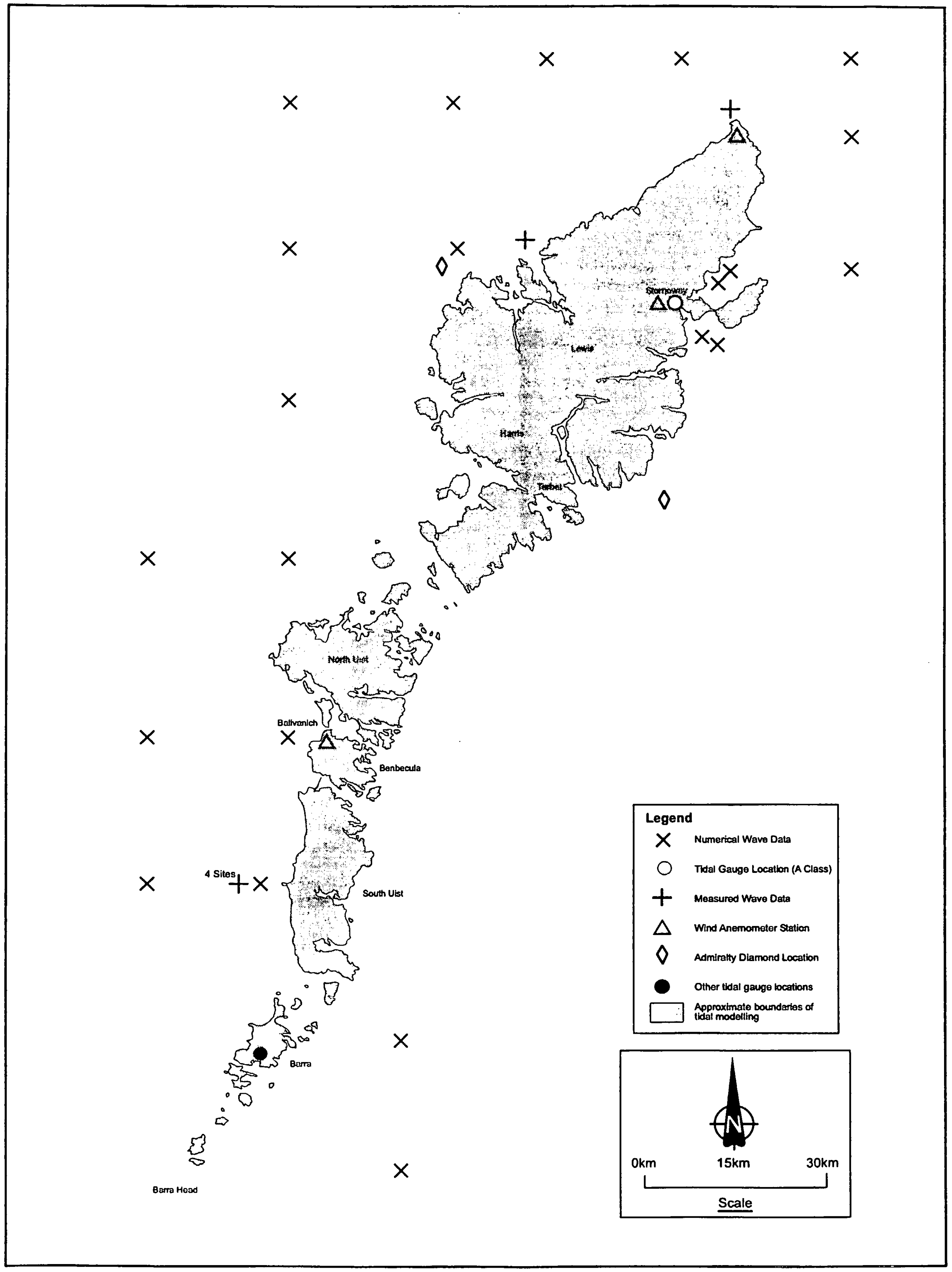


Figure 6 Cell 8 & 9 - Location of wind, tidal and wave data

Figure 7 Cells 8 & 9 - Location of Sites of Special Scientific Interest

Figure 8 Cells 8 & 9 - Location of sites of natural heritage importance (other than SSSIs)

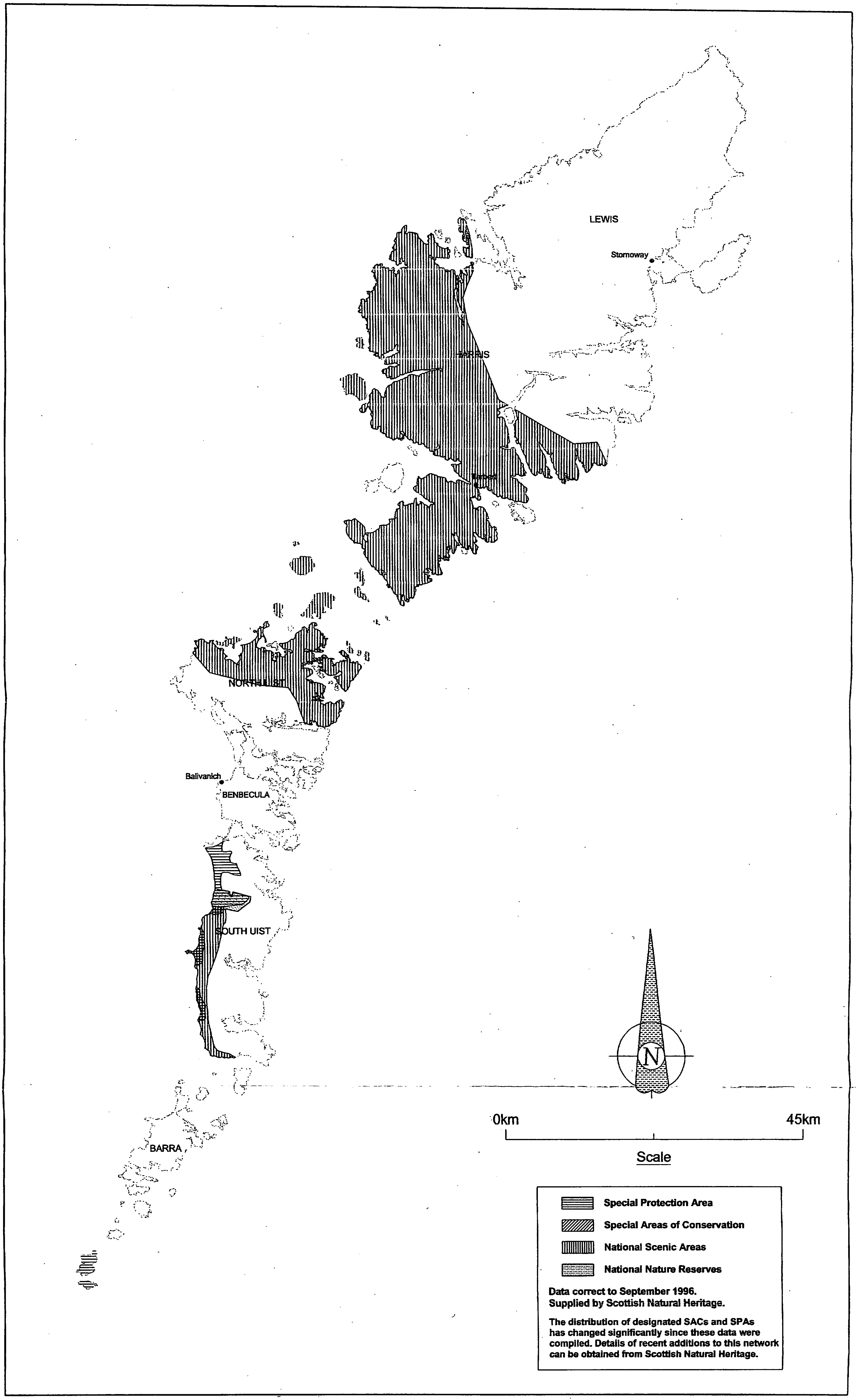


Figure 9 Cells 8 & 9 - Density of noted archaeological and historical sites

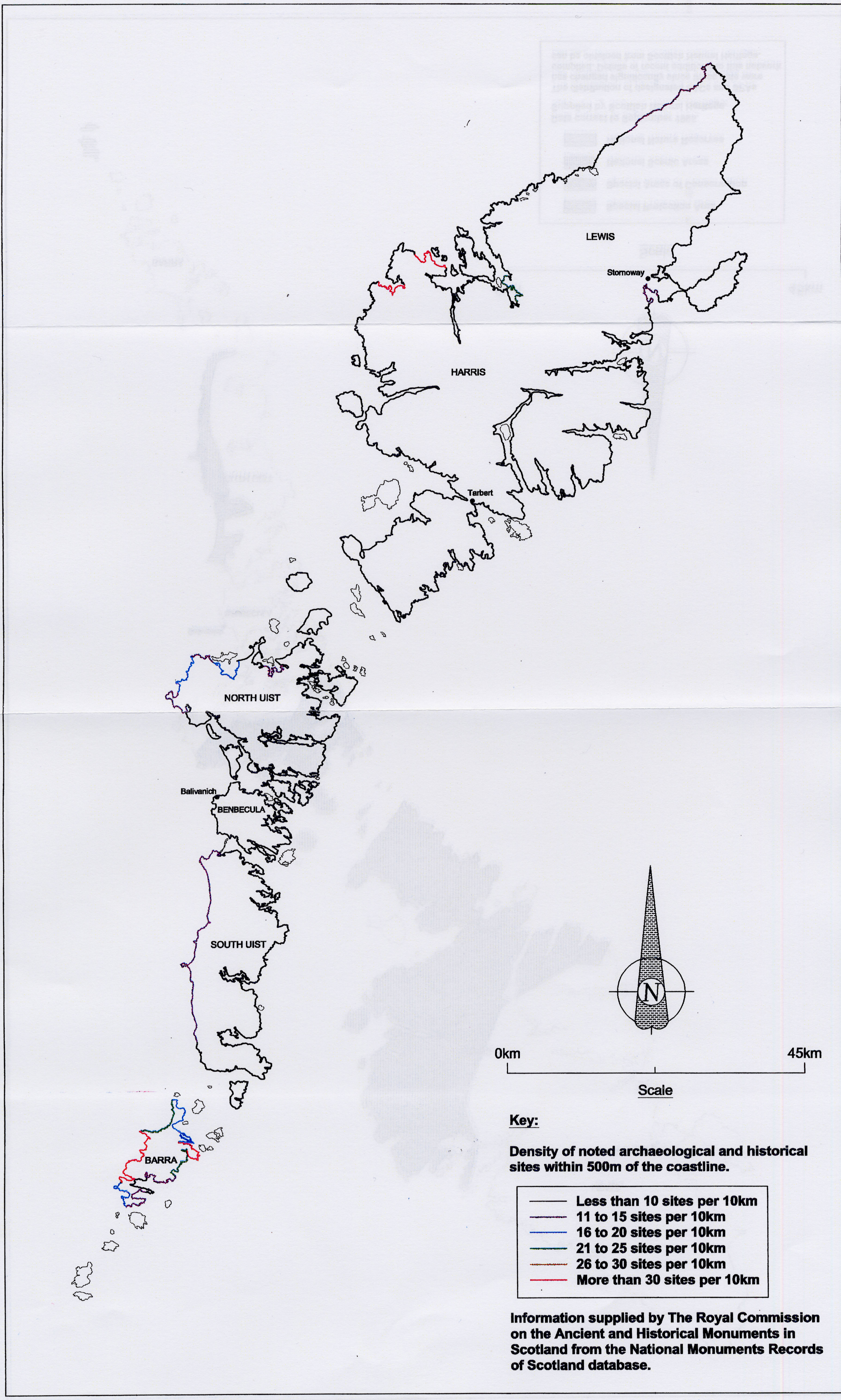
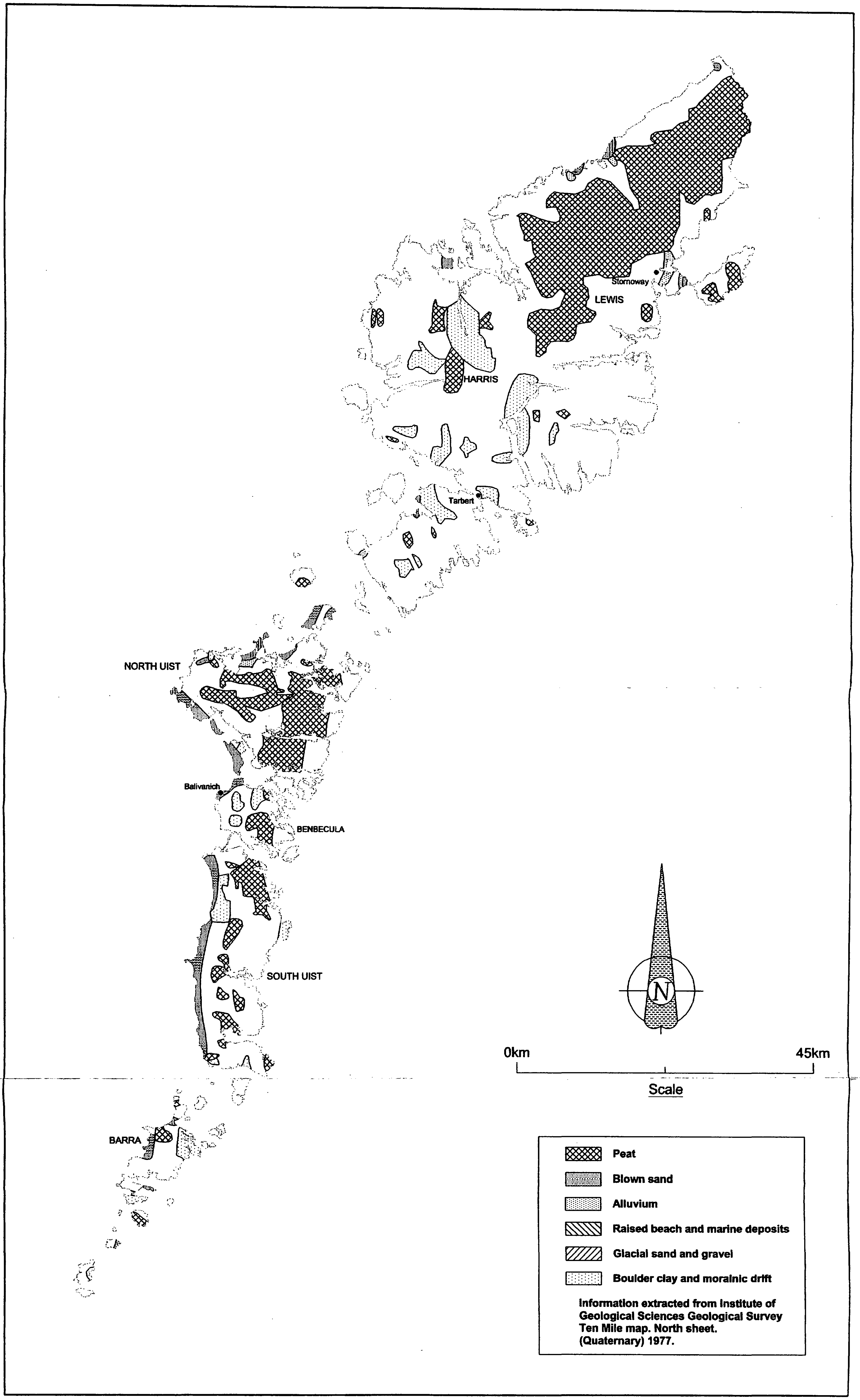


Figure 10 Cells 8 & 9 - Drift deposits



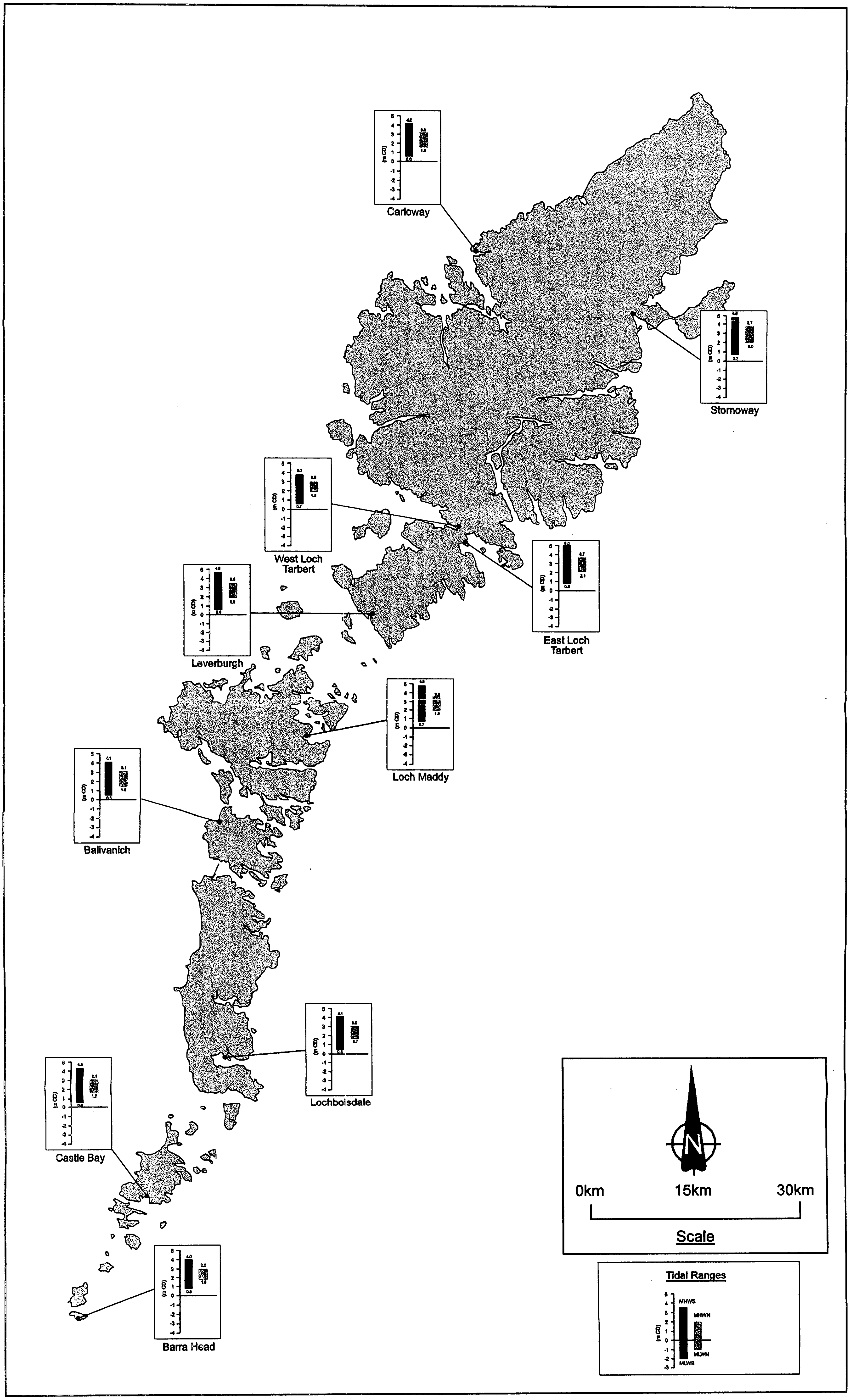


Figure 11 Cells 8 & 9 - Tidal levels

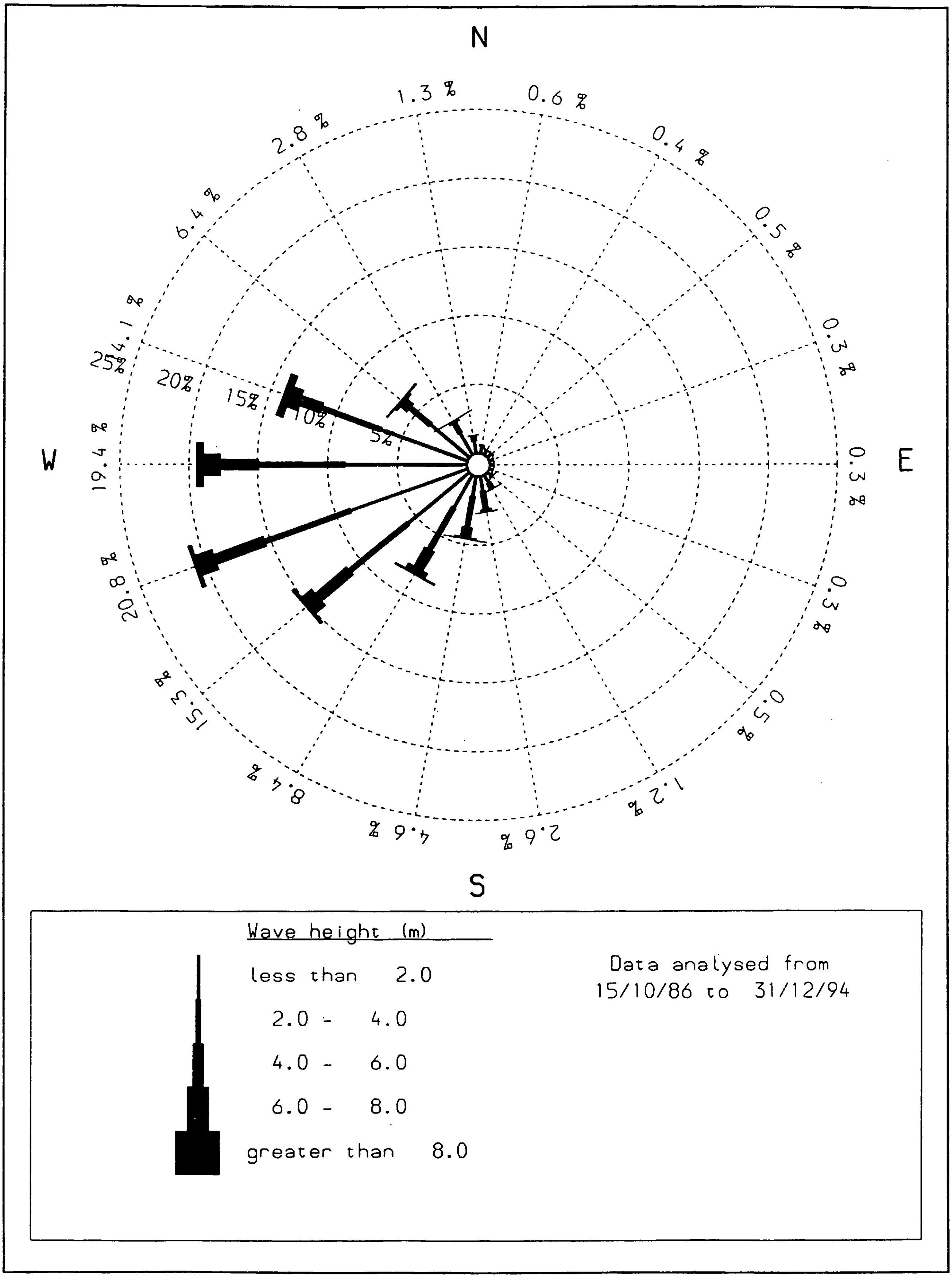


Figure 12 Offshore total wave climate to the SE of Barra

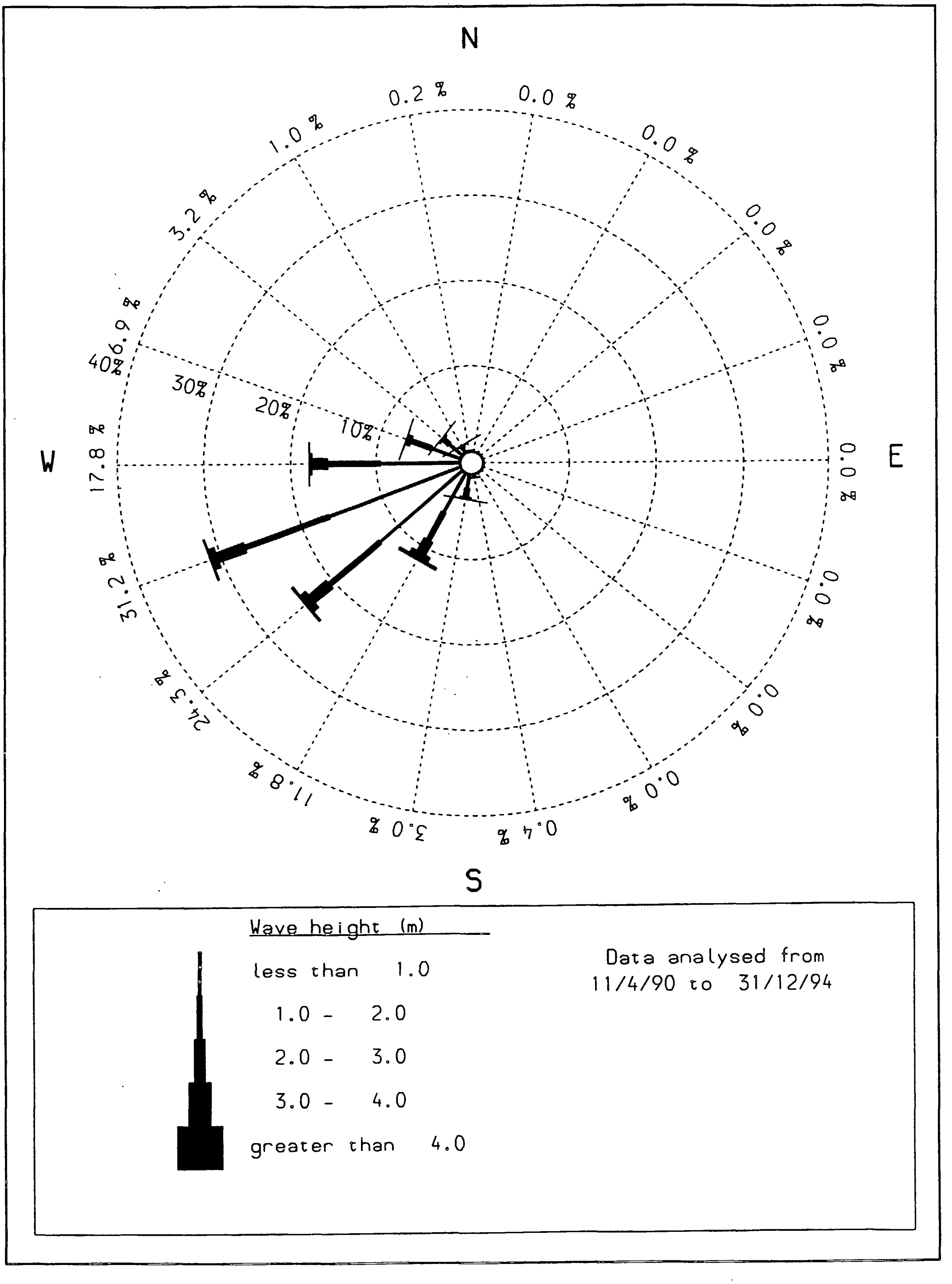


Figure 13 Offshore swell wave climate to the SE of Barra

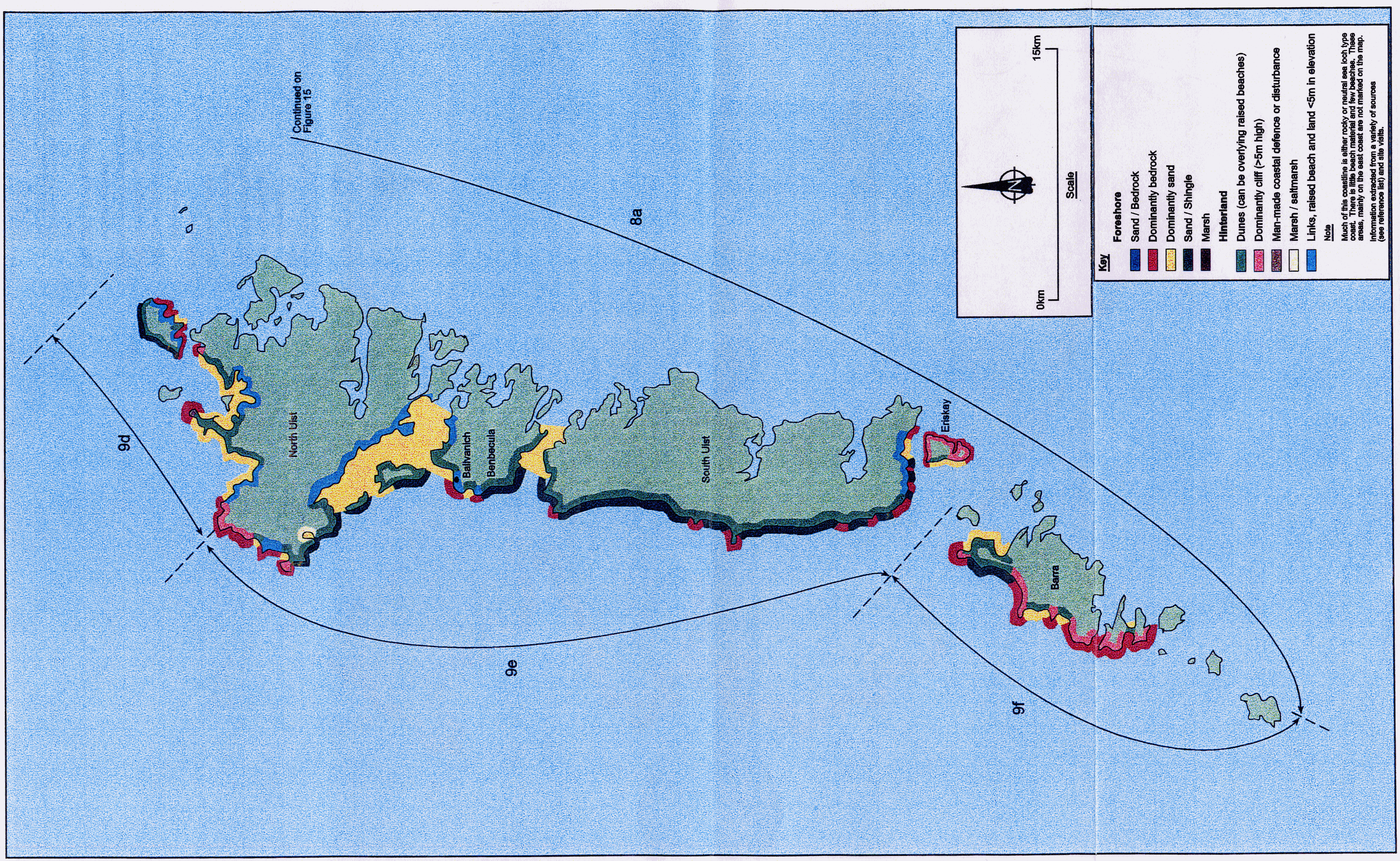


Figure 14 North Uist to Barra - Foreshore and hinterland characteristics

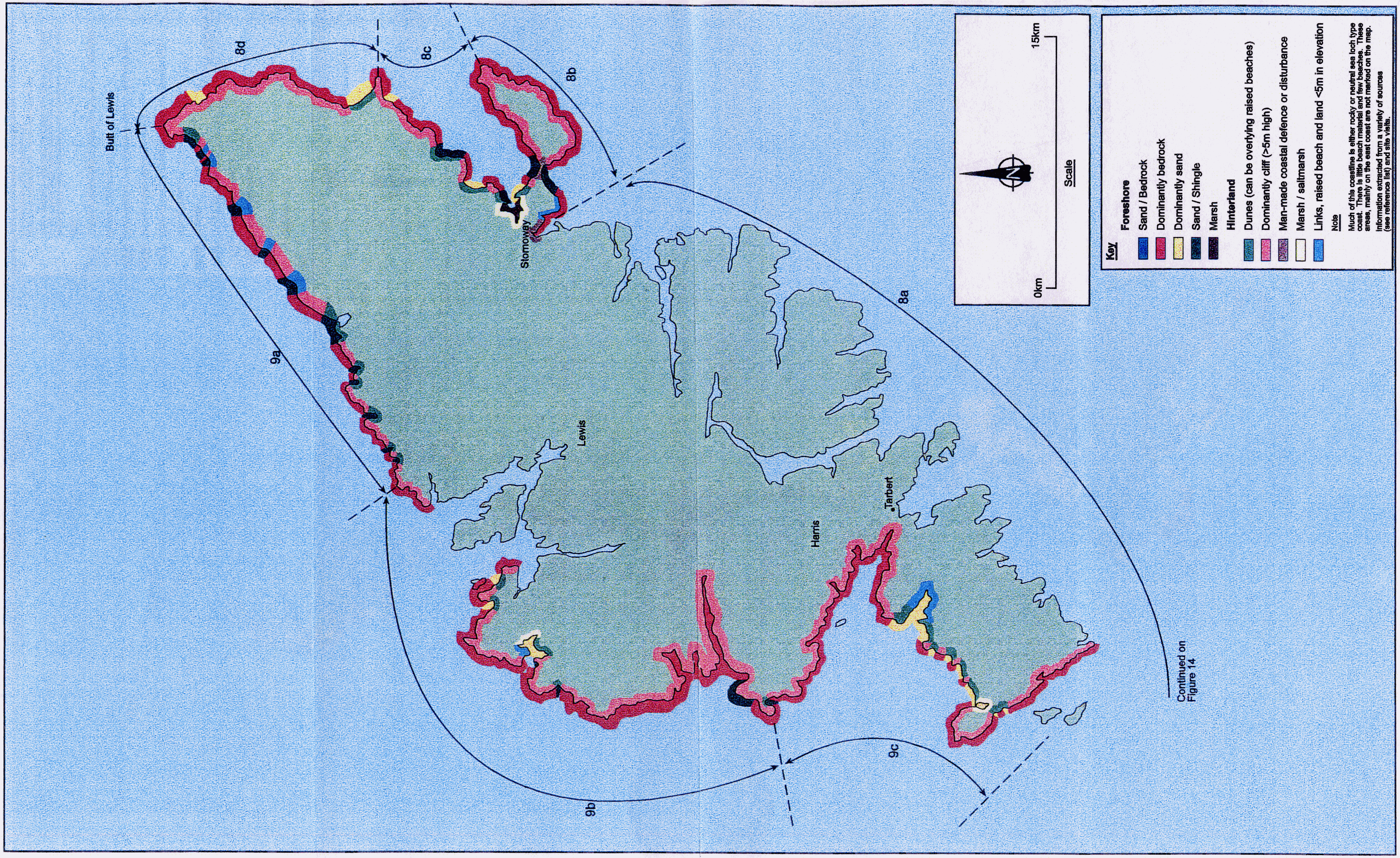


Figure 15 Lewis & Harris - Foreshore and hinterland characteristics

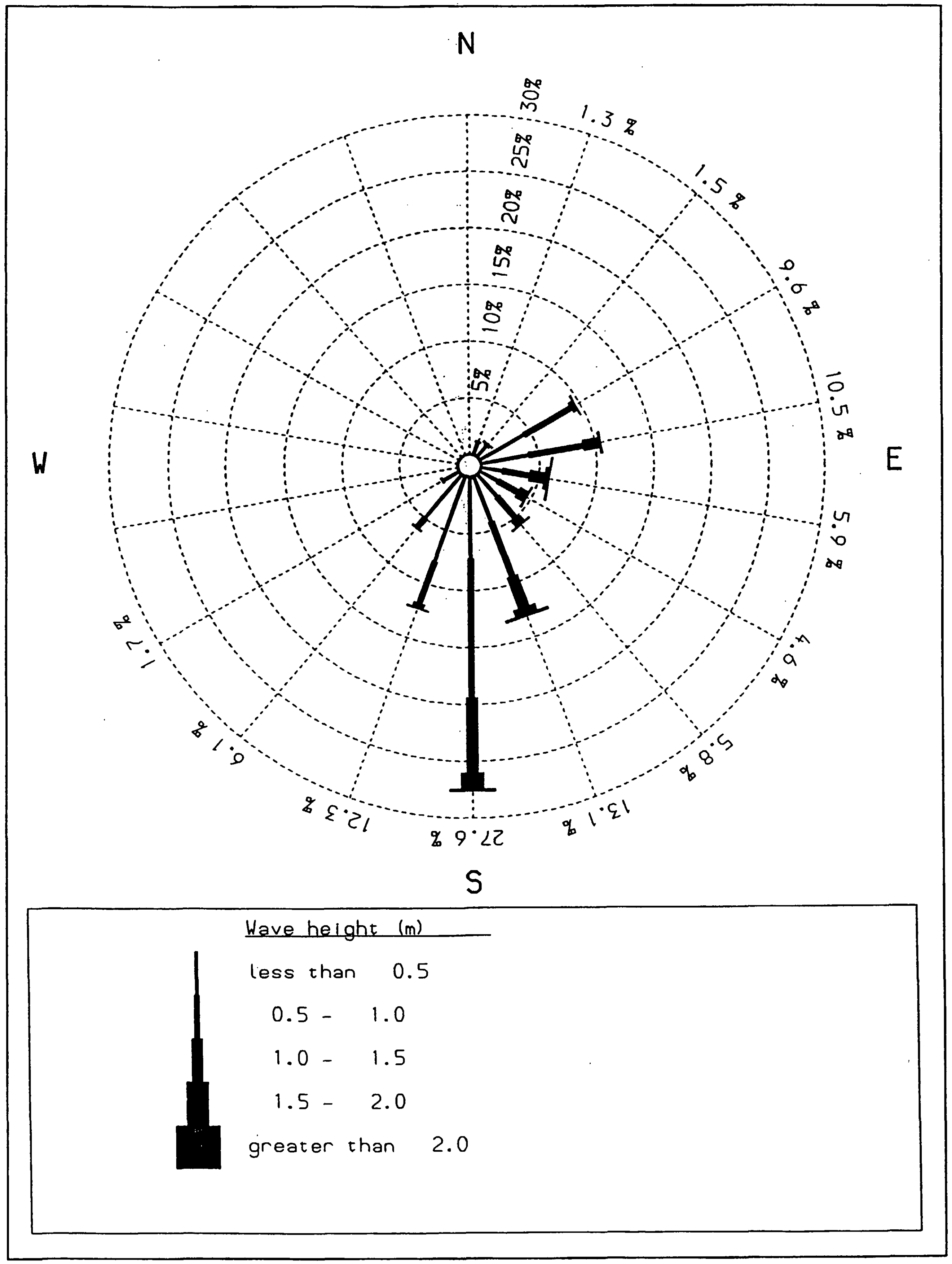


Figure 16 Wave climate offshore of Gob of Shilldinish

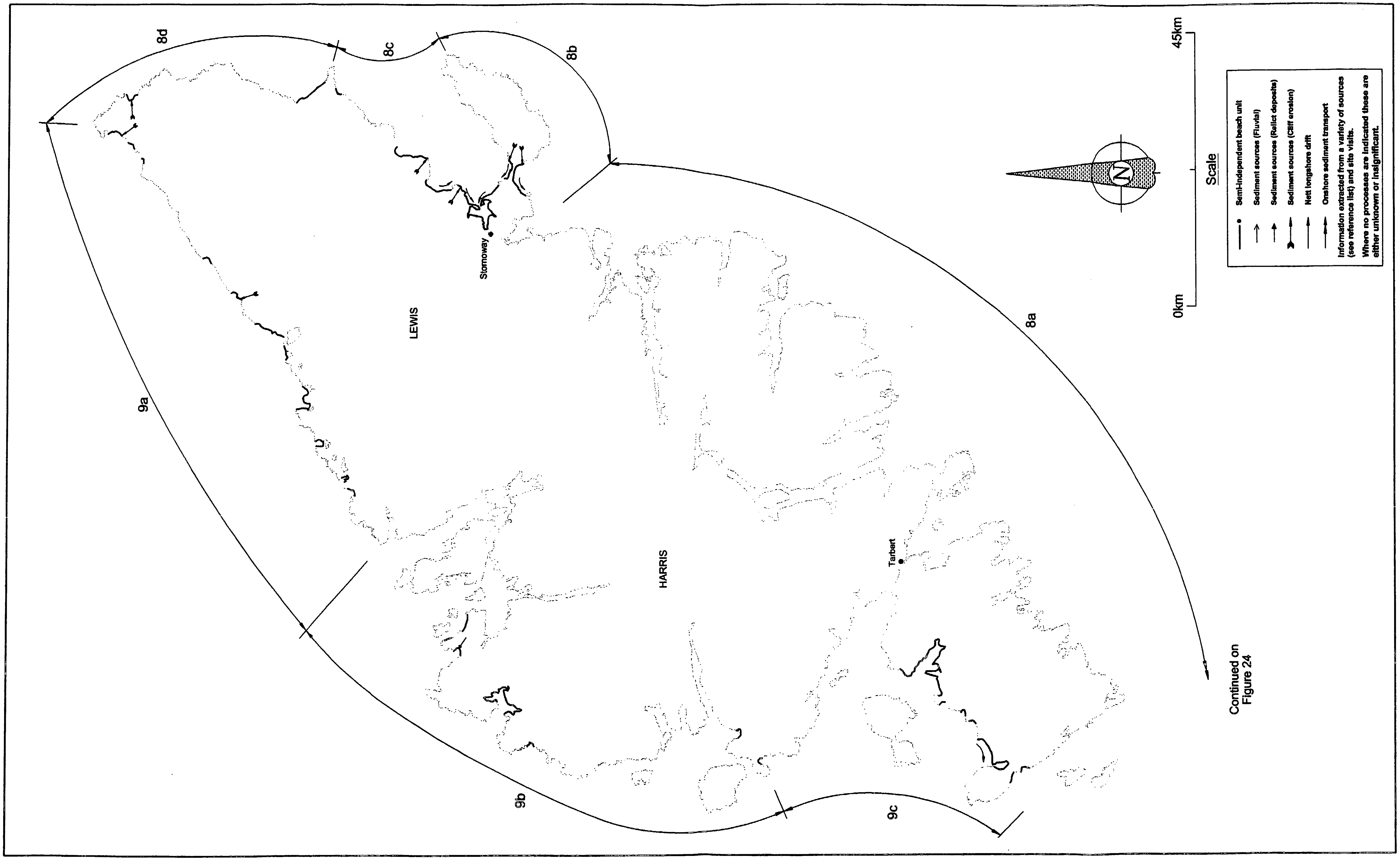
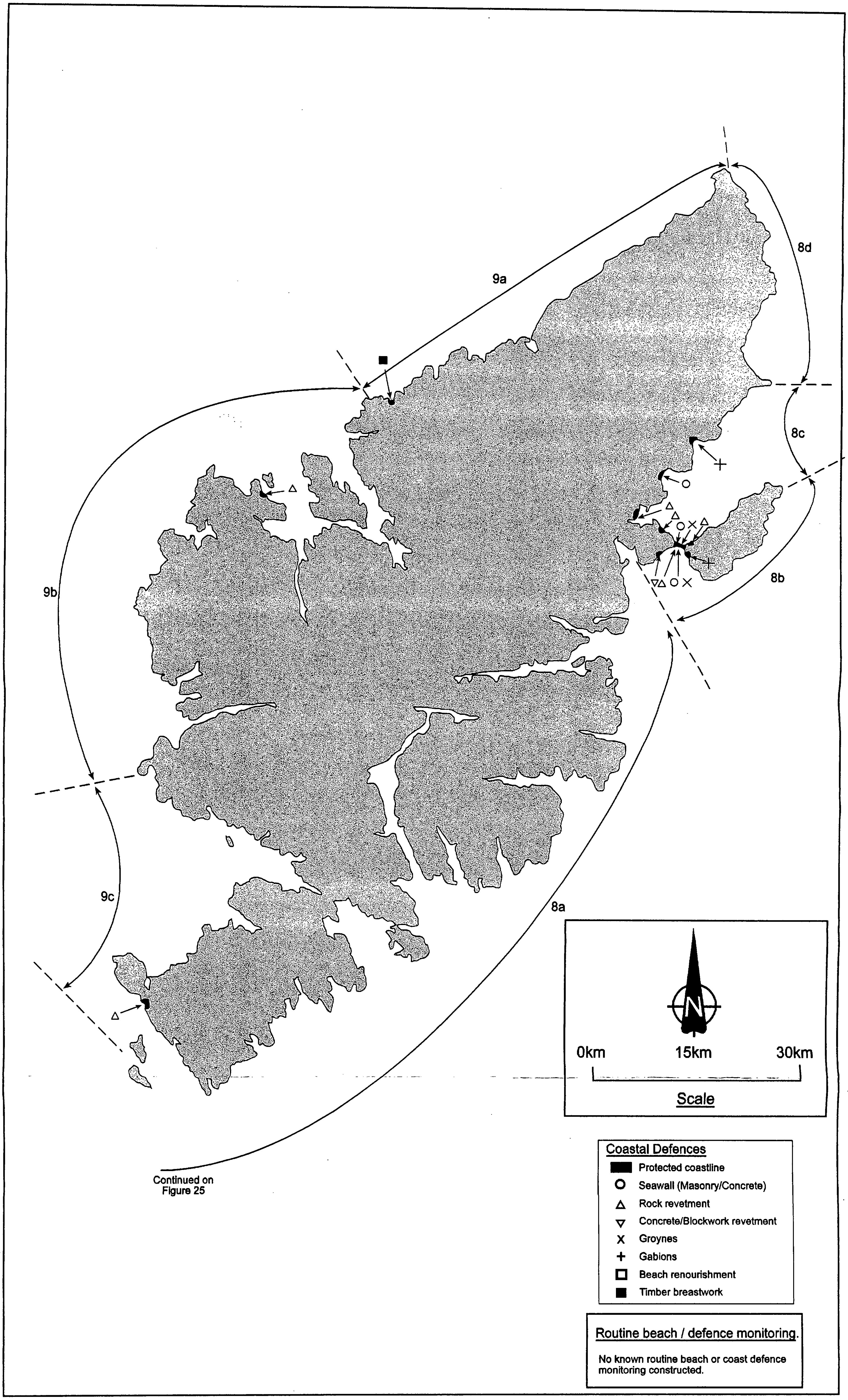


Figure 17 Lewis & Harris - Dominant littoral processes

Figure 18 Lewis & Harris - Coastal defences and monitoring



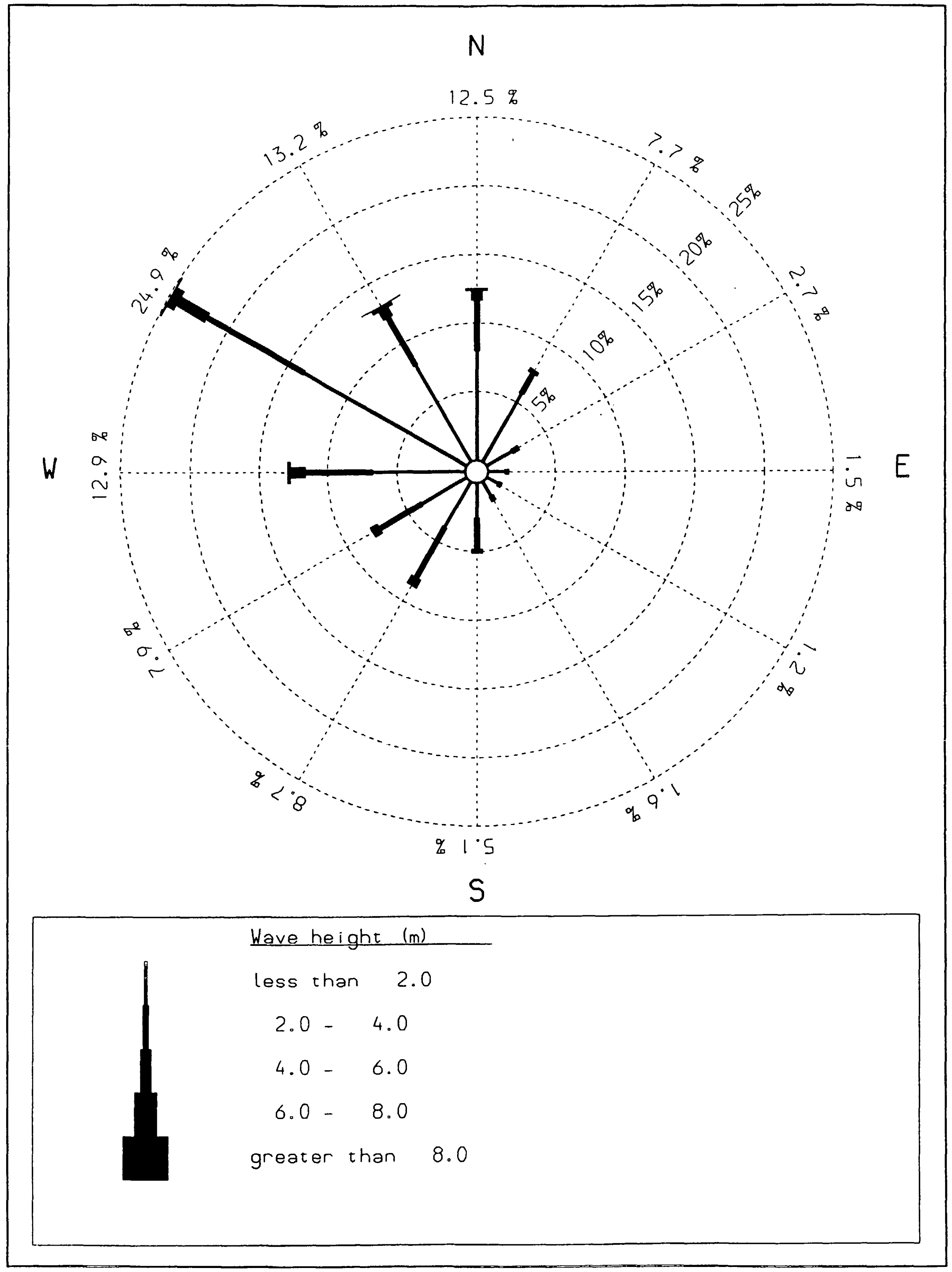


Figure 19 Wave climate to the NE of Lewis

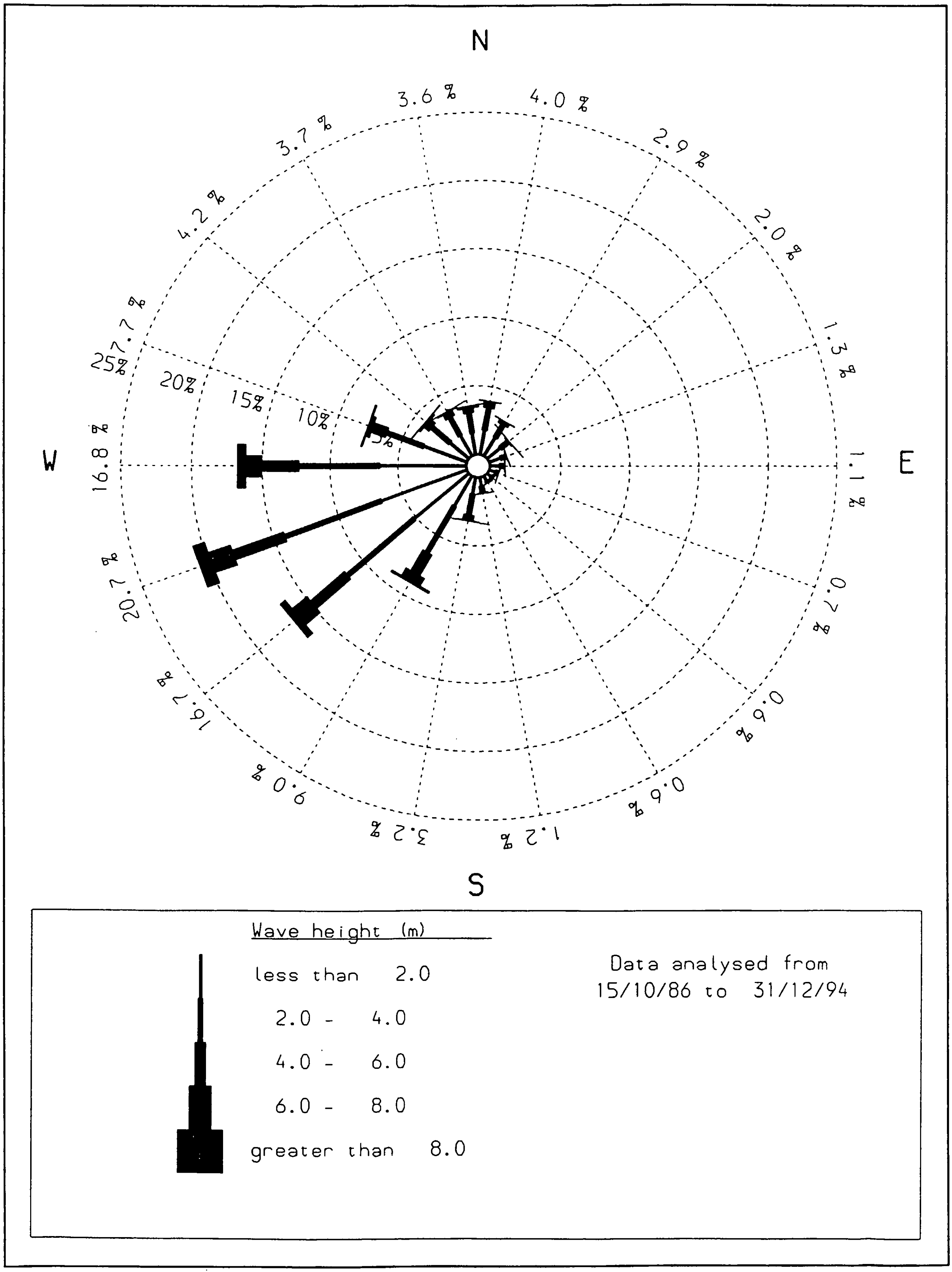


Figure 20 Offshore total wave climate NW of Lewis

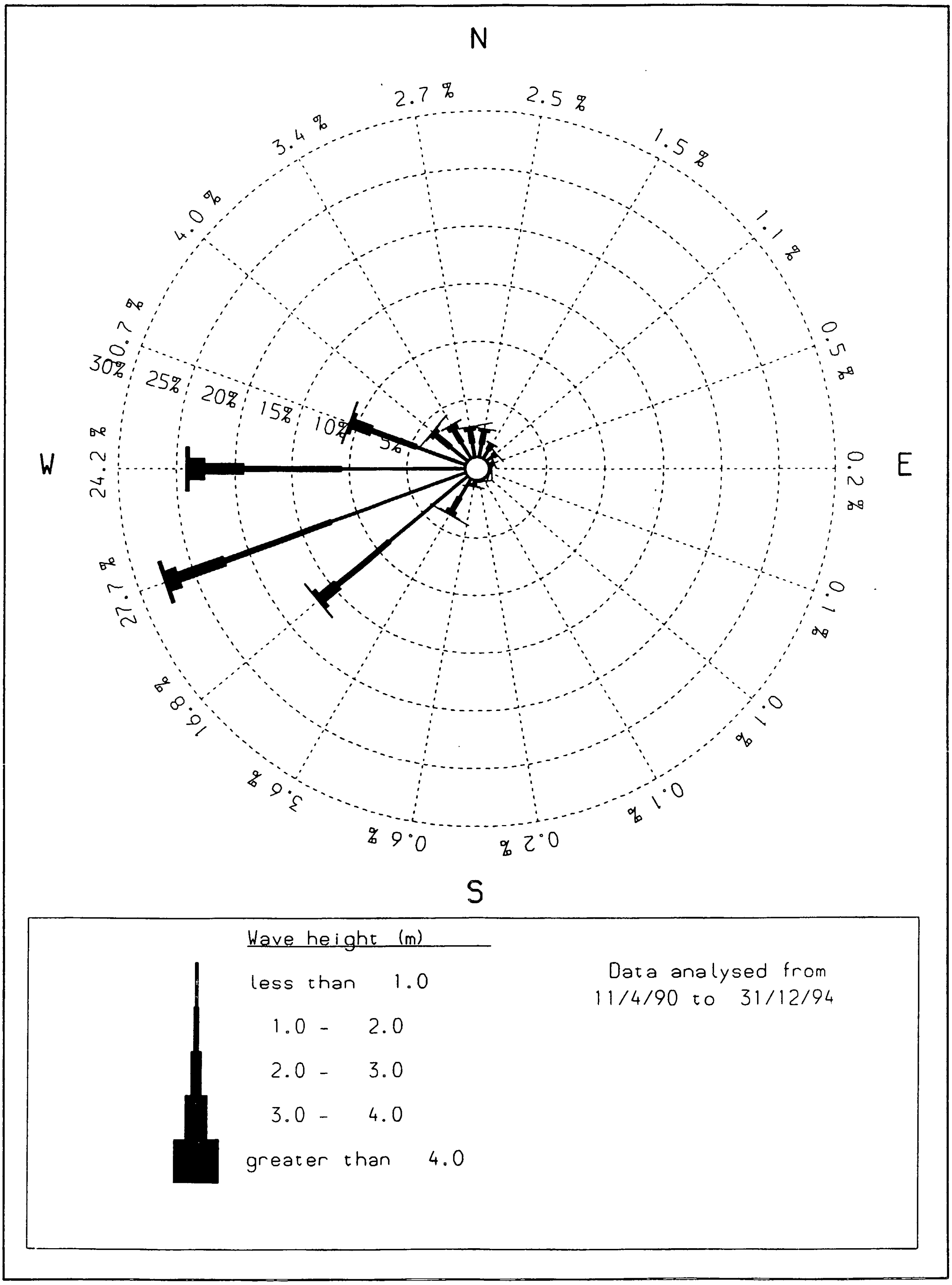


Figure 21 Offshore swell wave climate NW of Lewis

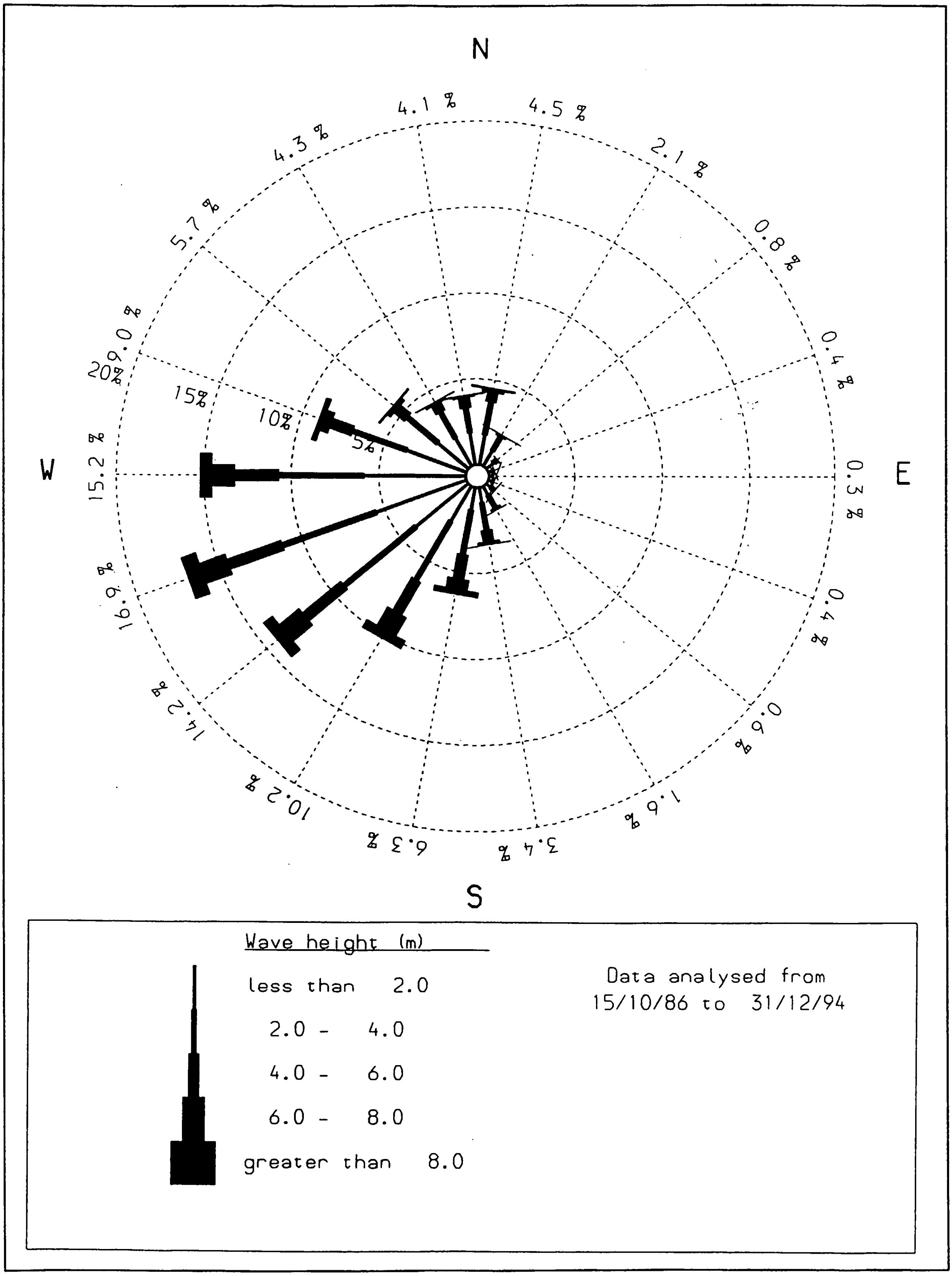


Figure 22 Offshore total wave climate west of the Uists

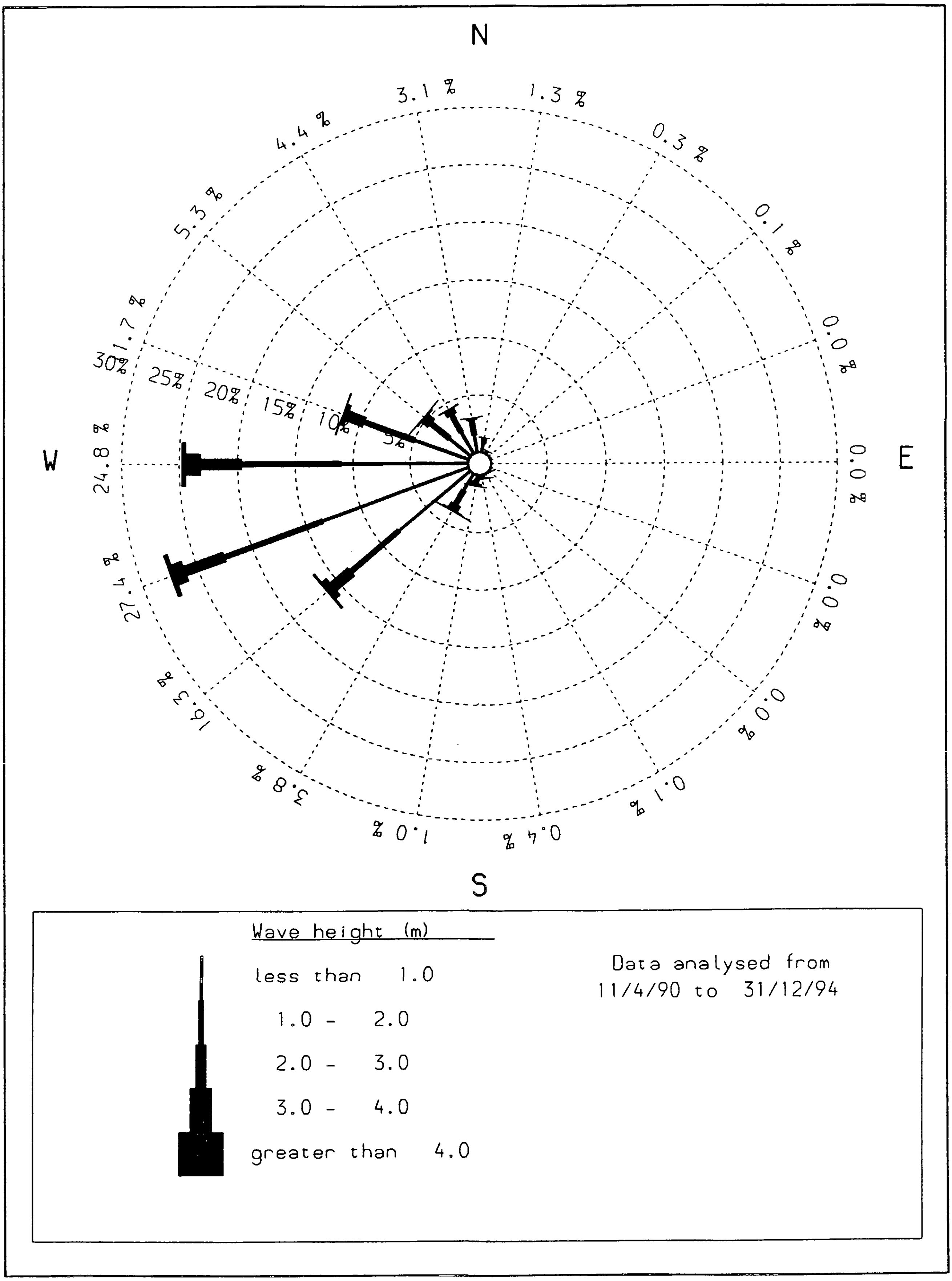


Figure 23 Offshore swell wave climate west of the Uists

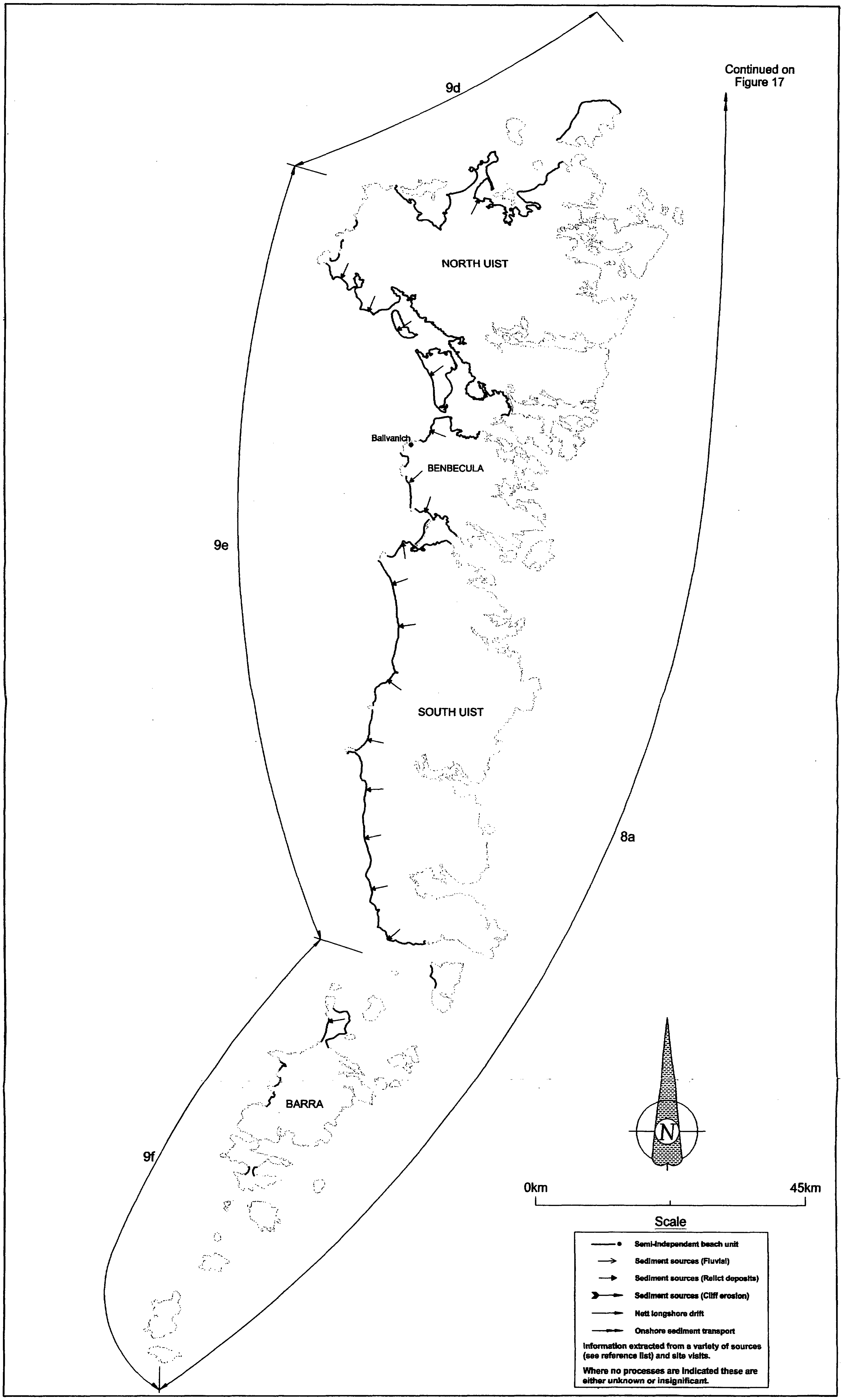


Figure 24 North Uist to Barra - Dominant littoral processes

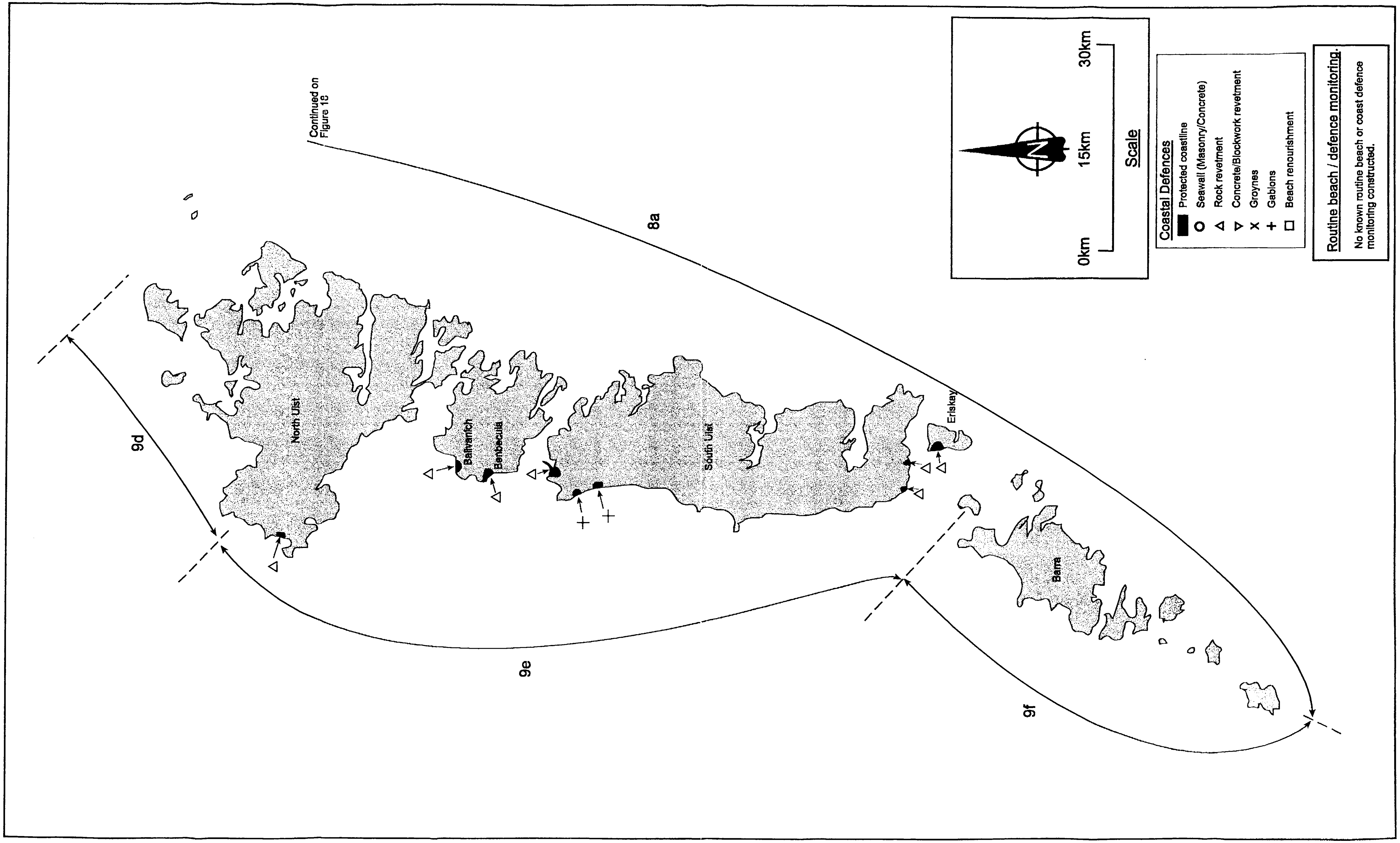


Figure 25 North Uist to Barra - Coastal defences and monitoring

Appendix 1 Cells 8 & 9 - Details of Sites of Special Scientific Interest

Extracted from the British Oceanographic Data Centre's UKDMAP. Data correct to 1996.

Name	Grid Reference	Size (ha)	Date Notified	Site Designations
Tong Saltings	NB440358	417.2	1984	Tidal flats Open water Saltmarsh Dry grassland Peatland Waders breeding Wildfowl breeding Seabirds breeding Site used for wintering wildfowl - Locally important
Gress Saltings	NB487414	86.5	1984	Saltmarsh Sand dunes Dry grassland Montane heath Seabirds wintering Site used for wintering wildfowl - Locally important
Tolsta Head	NB557468	3.9	1985	Geological interest
Loch na Cartach	NB534499	22.6	1984	Open water Sand dunes Machair Dry grassland Montane heath Scrub
Port of Ness	NB537636	4.8	1990	Geological interest
Loch Dalbeg	NB227457	4.4	1983	Open water Sand dunes Machair Dry grassland Peatland Fen
Mangersta Sands	NB009309	19.1	1985	Geological interest Machair Comments: Example of stripped machair
North Harris	NB065115	12921	1984	Open water Dry grassland Peatland
Luskentyre Banks & Saltings	NG080973	1172	1984	Tidal flats Open water Saltmarsh Sand dunes Machair Dry grassland Montane heath Peatland Waders breeding Wildfowl breeding Site used for wintering wildfowl - Locally important

Name	Grid Reference	Size (ha)	Date Notified	Site Designations
Northton Bay	NF990920	415	1984	Geological Interest Open water Saltmarsh Sand dunes Machair Dry grassland Montane heath Peatland Fen Wader & breeding site used for wintering Wildfowl - locally important
Machairs Robach and Newton	NF873763	758	1985	Sand dunes Machair
Vallay	NF775765	307	1990	Saltmarsh Sand dunes Machair Fen Site used for wintering bird species
Balranald Bog & Loch nam Feilhean	NF712705	838	1984	Tidal flats Open water Saltmarsh Sand dunes Machair Dry grassland Fen Wildfowl breeding Site used for wintering wildfowl - Locally important
Baleshare & Kirkibost	NF785623	1465.7	1985	Tidal flats Rocky shore Open water Sand dunes Machair Peatland Lower plants Waders breeding Wildfowl breeding Seabirds breeding
West Benbecula Lochs	NF771521	115.5	1985	Open water Machair Fen Waders breeding Wildfowl breeding Site used for wintering wildfowl - Locally important
Loch Bee	NF770430	1172.9	1984	Open water Saltmarsh Machair Dry grassland Montane heath Waders breeding Wildfowl breeding

Name	Grid Reference	Size (ha)	Date Notified	Site Designations
Loch Druidibeg	NF782378	1677	1987	Tidal flats Open water Machair Montane heath Woodland Peatland Marine biological interest Mammals noted Waders breeding Wildfowl breeding
Howmore Estuary & Lochs Roag Fada	NF756356	424.1	1985	Machair Montane heath Peatland Fen Marine biological interest Fish noted Waders breeding Wildfowl breeding Site used for wintering wildfowl - Locally important
Bornish & Ormiclate Machairs	NF753309	662.7	1988	Open water Machair Phragmites reedbed Waders breeding Wildfowl breeding Seabirds breeding Site used for wintering wildfowl - Locally important
Loch Hallan	NF738224	364.1	1988	Open water Machair Dry grassland Phragmites reedbed Lower plants Terrestrial invertebrates Waders breeding Wildfowl breeding
Eoligarry	NF700061	449.4	1990	Geological interest Saltmarsh Vegetated shingle Machair Fen Flush or seepage line Lower plants Site used for wintering wildfowl - Nationally important
Mingulay & Berneray	NL560830	819	1983	Open water Sea cliff (hard rock) Dry grassland Maritime heath Seabirds breeding
Monach Isles	NF626623	577	1983	Sand dunes Machair Dry grassland Wildfowl breeding Seabirds breeding

Appendix 2 Cells 8 & 9 - Location of known archaeological and historical sites within 500m of the coastline

Note: This map has not been published within the report but may be consulted (by prior arrangement) by contacting:

Earth Science Group
Advisory Services
Scottish Natural Heritage
2 Anderson Place
EDINBURGH
EH6 5NP

The underlying data are updated regularly by the National Monuments Record of Scotland and are available for inspection there, by prior arrangement.

Appendix 3 Useful addresses

Contact addresses for organisations referred to within the report and other useful contacts.

British Geological Survey (Scotland)
Murchison House
West Mains Road
Edinburgh
EH9 3LA
Tel: 0131-667 1000
Fax: 0131-668 2683

British Geological Survey (Coastal Geology Group)
Kingsley Dunham Centre
Keyworth
Nottingham
NG12 5GG
Tel: 0115 9363100
Fax: 0115 9363200

British Oceanographic Data Centre (BODC)
See Proudman Oceanographic Laboratory

Crown Estate Commission
10 Charlotte Square
Edinburgh
EH2 4DR
Tel: 0131 2267241
Fax: 0131 2201366

Historic Scotland
Longmore House
Salisbury Place
Edinburgh
EH9 1SH
Tel: 0131 6688600
Fax: 0131 6688789

HR Wallingford Ltd
Howbery Park
Wallingford
Oxon
OX10 8BA
Tel: 01491 835381
Fax: 01491 825539

Hydrographic Office (Taunton)
OCM (C)
Admiralty Way
Taunton
Somerset
TA1 2DN
Tel: 01823 337900
Fax: 01823 284077

Institute of Marine Studies
University of St Andrews
St Andrews
Fife
KY16 9AJ
Tel: 01334 462886
Fax: 01334 462921

Institute of Oceanographic Sciences
See Proudman Oceanographic Laboratory

Joint Nature Conservation Committee
Monkstone House
City Road
Peterborough
PE1 1JY

Tel: 01733 562626
Fax: 01733 555948

Macaulay Land Use Research Institute
Craigiebuckler
Aberdeen
AB9 2QL

Tel: 01224 318611
Fax: 01224 311556

Marine Information Advisory Service (MIAS)
See Proudman Oceanographic Laboratory

Metoc plc (Metocean)
Exchange House
Station Road
Liphook
Hampshire
GU30 7DW

Tel: 01428 727800
Fax: 01428 727122

Ministry of Agriculture, Fisheries and Food
(Flood and Coastal Defence Division)
Eastbury House
30-34 Albert Embankment
London
SE1 7TL

Tel: 0207 238 6742
Fax: 0207 238 6665

National Museums of Scotland
c/o Royal Museum of Scotland
Chambers Street
Edinburgh
EH1 1JF

Tel: 0131-225 7534
Fax: 0131-220 4819

Ordnance Survey (Scottish Region)
Grayfield House
5 Bankhead Avenue
Edinburgh
EH11 4AE

Tel: 0845 605 0505

Proudman Oceanographic Laboratory
(British Oceanographic Data Centre, MIAS & Permanent Service for Mean Sea Level)
Bidston Observatory
Birkenhead
Merseyside
L43 7RA

Tel: 0151-653 8633
Fax: 0151-653 6269

Permanent Service for Mean Sea Level (PSMSL)
See Proudman Oceanographic Laboratory

Royal Commission on the Ancient and Historical Monuments of Scotland (RCAHMS)
John Sinclair House
16 Bernard Terrace
Edinburgh
EH8 9NX
Tel: 0131-662 1456
Fax: 0131-662 1477

Scottish Environment Protection Agency
Erskine Court
The Castle Business Park
Stirling
FK9 4TR
Tel: 01786 457700
Fax: 01786 446885

Scottish Executive (re Coast Protection Act (CPA))
Rural Affairs Department
European Environment and Engineering Unit
Victoria Quay
Edinburgh
EH6 6QQ
Tel: 0131-556 8400

Scottish Executive (re Food and Environment Protection Act (FEPA))
Rural Affairs Department
Pentland House
47 Robbs Loan
Edinburgh
EH14 1TY
Tel: 0131-556 8400

Scottish Executive
Marine Laboratory
PO Box 101
Victoria Road
Torry
Aberdeen
Tel: 01224 876544
Fax: 01224 295511

Scottish Natural Heritage
12 Hope Terrace
Edinburgh
EH9 2AS
Tel: 0131-447 4784
Fax: 0131-446 2277

Scottish Trust for Underwater Archaeology
c/o Department of Archaeology
University of Edinburgh
16-20 George Square
Edinburgh
EH8 9JZ
Tel: 0131-650 2368
Fax: 0131-650 4094

Scottish Tourist Board
23 Ravelston Terrace
Edinburgh
EH4 3EU
Tel: 0131-332 2433
Fax: 0131-343 1513

UK Meteorological Office
Marine Consulting Service
Johnstone House
London Road
Bracknell
RG12 2UR

Tel: 01344 420242
Fax: 01344 854412

UK Offshore Operators Association Ltd (UKOOA)
30 Buckingham Gate
London
SW1E 6NN

Tel: 020 7802 2400
Fax: 020 7802 2401

Appendix 4 Glossary

Abrasion platform	A rock or clay platform which has been worn by the processes of abrasion (i.e. frictional erosion by material transported by wind and waves)
Accretion	The accumulation of (beach) sediment, deposited by natural fluid flow processes
A Class tide gauge	One of a UK network maintained to the highest and most consistent standards
Amplitude	Half of the peak-to-trough range (or height)
Apron	Layer of stone, concrete or other material to protect the toe of a seawall
Armour layer	Protective layer on a breakwater or seawall composed of **armour units**
Armour unit	Large quarried stone or specially shaped concrete block used as primary protection against wave action
Asperities	The three-dimensional irregularities forming the surface of an irregular stone (or rock) subject to wear and rounding during attraction
Astronomical tide	The tidal levels and character which would result from gravitational effects, e.g. of the Earth, Sun and Moon, without any atmospheric influences
Back-rush	The seaward return of water following the **up-rush** of a wave
Backshore	The upper part of the active beach above the normal reach of the tides (high water), but affected by large waves occurring during a high tide
Barrier beach	A sand or shingle bar above high tide, parallel to the coastline and separated from it by a lagoon
Bathymetry	Refers to the spatial variability of levels on the seabed
Beach	A deposit of non-cohesive material (e.g. sand, gravel) situated on the interface between dry land and the sea (or other large expanse of water) and actively "worked" by present-day hydrodynamic processes (i.e. waves, tides and currents) and sometimes by winds
Beach crest	The point representing the limit of high tide storm wave **run-up**
Beach face	From the **beach crest** out to the limit of sediment movement
Beach head	The cliff, dune or seawall forming the landward limit of the active beach
Beach plan shape	The shape of the beach in plan; usually shown as a contour line, combination of contour lines or recognizable features such as beach crest and/or still water line
Beach profile	A cross-section taken perpendicular to a given beach contour; the profile may include the face of a dune or seawall, extend over the **backshore**, across the **foreshore**, and seaward underwater into the **nearshore** zone
Beach recharge	Supplementing the natural volume of sediment on a beach, using material from elsewhere - also known as beach replenishment/nourishment/feeding

Bed forms — Features on a seabed (e.g. ripples and sand waves) resulting from the movement of sediment over it

Bed load — Sediment transport mode in which individual particles either roll or slide along the seabed as a shallow, mobile layer a few particle diameters deep

Bed shear stress — The way in which waves (or currents) transfer energy to the sea bed

Benefits — The economic value of a scheme, usually measured in terms of the cost of damages avoided by the scheme, or the valuation of perceived amenity or environmental improvements

Berm
(1) On a beach: a nearly horizontal plateau on the **beach face** or **backshore**, formed by the deposition of beach material by wave action or by means of a mechanical plant as part of a **beach recharge** scheme
(2) On a structure: a nearly horizontal area, often built to support or key-in an **armour layer**

Boulder — A rounded rock on a beach, greater than 250mm in diameter, larger than a **cobble** - see also **gravel, shingle**

Boundary conditions — Environmental conditions, e.g. waves, currents, drifts, etc. used as boundary input to physical or numerical models

Bound long wave — Long wave directly due to the variation in set-down at the breaker line due to wave groups

Breaching — Failure of the **beach head** allowing flooding by tidal action

Breaker depth — Depth of water, relative to **still water level** at which waves break; also known as **breaking depth** or limiting depth

Breaker index — Maximum ratio of **wave height** to water depth in the surf zone

Breaker zone — The zone within which waves approaching the coastline commence breaking, typically in water depths of between 5 and 10 metres

Breaking — Reduction in wave energy and height in the surf zone due to limited water depth

Breastwork — Vertically-faced or steeply inclined structure usually built with timber and parallel to the shoreline, at or near the **beach crest**, to resist erosion or mitigate against flooding

Bypassing — Moving beach material from the **updrift** to the **downdrift** side of an obstruction to **longshore-drift**

Chart datum — The level to which both tidal levels and water depths are reduced - on most UK charts, this level is that of the predicted lowest **astronomical tide** level (LAT)

Clay — A fine grained, plastic, sediment with a typical grain size less than 0.004mm. Possesses electro-magnetic properties which bind the grains together to give a bulk strength or cohesion

Climate change — Refers to any long-term trend in mean sea level, **wave height**, wind speed, drift rate etc.

Closure depth — The depth at the offshore limit of discernible bathymetric change between surveys.

Coastal cell — See Sediment cell

Coastal defence	General term used to encompass both coast protection against erosion and sea defence against flooding
Coastal forcing	The natural processes which drive coastal hydro- and morpho-dynamics (e.g. winds, waves, tides, etc)
Coastal processes	Collective term covering the action of natural forces on the shoreline, and nearshore seabed
Coastal zone	Some combination of land and sea area, delimited by taking account of one or more elements
Coast protection	Protection of the land from erosion and encroachment by the sea
Cobble	A rounded rock on a beach, with diameter ranging from about 75 to 250mm - see also **boulder, gravel, shingle**
Cohesive sediment	Sediment containing significant proportion of clays, the electromagnetic properties of which cause the sediment to bind together
Conservation	The protection of an area, or particular element within an area, whilst accepting the dynamic nature of the environment and therefore allowing change
Core	(1) A cylindrical sample extracted from a beach or seabed to investigate the types and depths of sediment layers (2) An inner, often much less permeable portion of a breakwater, or barrier beach
Coriolis	Force due to the Earth's rotation, capable of generating currents
Crest	Highest point on a beach face, breakwater or seawall
Cross-shore	Perpendicular to the shoreline
Current	Flow of water
Current-refraction	Process by which wave velocity is affected by a current
Cusp	Seaward bulge, approximately parabolic in shape, in the beach contours. May occur singly, in the lee of an offshore bulk or island, or as one of a number of similar, approximately regularly-spaced features on a long straight beach
Deep water	Water too deep for waves to be affected by the seabed; typically taken as half the **wavelength**, or greater
Deflation	Erosion of dunes by wind action
Depth-limited	Situation in which wave generation (or **wave height**) is limited by water depth
Design wave condition	Usually an extreme wave condition with a specified return period used in the design of coastal works
Detached breakwater	A breakwater without any constructed connection to the shore
Diffraction	Process affecting wave propagation, by which wave energy is radiated normal to the direction of wave propagation into the lee of an island or breakwater
Diffraction coefficient	Ratio of diffracted **wave height** to deep water **wave height**
Diurnal	Literally `of the day', but here meaning having a period of a `tidal day', i.e. about 24.8 hours

Downdrift	In the direction of the nett longshore transport of beach material
Drying beach	That part of the beach which is uncovered by water (e.g. at low tide). Sometimes referred to as `subaerial' beach
Dunes	(1) Accumulations of windblown sand on the **backshore**, usually in the form of small hills or ridges, stabilised by vegetation or control structures (2) A type of bed form indicating significant sediment transport over a sandy seabed
Duration	The length of time a wind blows at a particular speed and from the same direction during the generation of storm waves
Ebb	Period when tide level is falling; often taken to mean the **ebb current** which occurs during this period
Edge waves	Waves which mainly exist shoreward of the breaker line, and propagate along the shore. They are generated by the incident waves, their amplitude is a maximum at the shoreline and diminishes rapidly in a seaward direction
Epifauna	Animals living in the sediment surface or on the surface of other plants or animals
Event	An occurrence meeting specified conditions, e.g. damage, a threshold **wave height** or a threshold water level
Exponential distribution	A model probability distribution
Extreme	The value expected to be exceeded once, on average, in a given (long) period of time
Fetch	Distance over which a wind acts to produce waves - also termed **fetch length**.
Fetch-limited	Situation in which wave energy (or **wave height**) is limited by the size of the wave generation area (**fetch**)
Forecasting	Prediction of conditions expected to occur in the near future, up to about two days ahead
Foreshore	The intertidal area below highest tide level and above lowest tide level
Freeboard	The height of the crest of a structure above the **still water level**
Friction	Process by which energy is lost through shear stress
Friction factor	Factor used to represent the roughness of the sea bed
Frontager	Person or persons owning, and often living in, property immediately landward of the beach
Fully-developed sea	A wave condition which cannot grow further without an increase in wind speed - also fully-arisen sea
GIS	Geographical Information System. A database of information which is geographically orientated, usually with an associated visualization system
Gravel	Beach material, coarser than sand but finer than **pebbles** (2-4mm diameter)
Group velocity	The speed of wave energy propagation. Half the wave **phase velocity** in **deep water**, but virtually the same in **shallow water**

Groyne	Narrow, roughly shore-normal structure built to reduce longshore currents, and/ or to trap and retain beach material. Most groynes are of timber or rock, and extend from a seawall, or the **backshore**, well onto the **foreshore** and rarely even further offshore. In the USA and historically called a **groin**
Groyne bay	The beach compartment between two **groynes**
Gumbel distribution	A model probability distribution, commonly used in wind and water level analysis
Hard defences	General term applied to impermeable coastal defence structures of concrete, timber, steel, masonry etc, which reflect a high proportion of incident wave energy, cf **soft defences**
Hindcasting	In wave prediction, the retrospective forecasting of waves using measured wind information
Historic event analysis	Extreme analysis based on hindcasting typically ten events over a period of 100 years
Incident wave	Wave moving landward
Infauna	Animals living in the sediment
Infragravity waves	Waves with periods above about 30 seconds generated by wave groups breaking in the surf zone
Inshore	Areas where waves are transformed by interaction with the sea bed
Intertidal	The zone between the high and low water marks
Isobath	Line connecting points of equal depth, a seabed contour
Isopachyte	Line connecting points on the seabed with an equal depth of sediment
Joint probability	The probability of two (or more) things occurring together
Joint probability density	Function specifying the joint distribution of two (or more) variables
Joint return period	Average period of time between occurrences of a given joint probability event
JONSWAP spectrum	Wave spectrum typical of growing deep water waves
Limit of storm erosion	A position, typically a maximum water depth of 8 to 10 metres, often identifiable on surveys by a break (i.e. sudden change) in slope of the bed
Littoral	Of or pertaining to the shore
Littoral drift, Littoral transport	The movement of **beach material** in the **littoral zone** by waves and currents. Includes movement parallel (longshore drift) and perpendicular (cross-shore transport) to the shore
Locally generated waves	Waves generated within the immediate vicinity, say within 50km, of the point of interest
Log-normal distribution	A model probability distribution
Long-crested random waves	Random waves with variable heights and periods but a single direction
Longshore	Parallel and close to the coastline
Longshore bar	Bar running approximately parallel to the shoreline
Longshore drift	Movement of (beach) sediments approximately parallel to the coastline

Long waves	Waves with periods above about 30 seconds generated by wave groups breaking in the surf zone
Macro-tidal	Tidal range greater than 4m
Managed landward realignment	The deliberate setting back of the existing line of defence in order to obtain engineering and/or environmental advantages - also referred to as managed retreat
Marginal probability	The probability of a single variable in the context of a joint probability analysis
Marginal return period	The return period of a single variable in the context of a joint probability analysis
Meso-tidal	Tidal range between 2m and 4m
Micro-tidal	Tidal range less than 2m
Morphologically averaged wave condition	A single wave condition producing the same nett longshore drift as a given proportion of the annual wave climate
Mud flat	An area of fine silt usually exposed at low tide but covered at high tide, occurring in sheltered estuaries or behind shingle bars or sand spits
Nearshore	The zone which extends from the **swash zone** to the position marking the start of the **offshore zone**, typically at water depths of the order of 20m
Ness	Roughly triangular promontory of land jutting into the sea, often consisting of mobile material, i.e. a beach form
Numerical modelling	Refers to analysis of coastal processes using computational models
Offshore	The zone beyond the **nearshore zone** where sediment motion induced by waves alone effectively ceases and where the influence of the sea bed on wave action is small in comparison with the effect of wind
Operational	The construction, maintenance and day-to-day activities, associated with beach management
Overtopping	Water carried over the top of a **coastal defence** due to wave **run-up** exceeding the **crest** height
Overwash	The effect of waves **overtopping** a **coastal defence**, often carrying sediment landwards which is then lost to the beach system
Peaks over threshold (POT)	Refers to the maximum value of a variable during each excursion above a threshold value
Pebbles	Beach material usually well-rounded and between about 4mm to 75mm diameter
Persistence of storms	The duration of sea states above some severity threshold (e.g. **wave height**)
Phase velocity	The velocity at which a wave crest propagates, cf **group velocity**
Physical modelling	Refers to the investigation of coastal processes using a scaled model
Pierson-Moskowitz spectrum	Wave spectrum typical of fully-developed deep water waves

Piezometric surface	The level within (or above) a soil stratum at which the pore-pressure is zero
Pocket Beach	A beach, usually small, between two **headlands**
Preservation	Static protection of an area or element, attempting to perpetuate the existence of a given `state'
Probability density function	Function specifying the distribution of a variable
Profile of storms	Refers to the persistence of storms coupled with the rate of change of sea state (e.g. **wave height**) within the storms
Reef	A ridge of rock or other material lying just below the surface of the sea
Reflected wave	That part of an incident wave that is returned (reflected) seaward when a wave impinges on a **beach**, **seawall** or other reflecting surface
Refraction coefficient	Ratio of refracted **wave height** to deep water **wave height**
Refraction (of water waves)	The process by which the direction of a wave moving in **shallow water** at an angle to the contours is changed so that the wave crests tend to become more aligned with those contours
Regular waves	Waves with a single height, period and direction
Residual (water level)	The components of water level not attributable to astronomical effects
Return period	Average period of time between occurrences of a given event
Revetment	A sloping surface of stone, concrete or other material used to protect an embankment, natural coast or shoreline against erosion
Rip current	Jet-like seaward-going current normal to the shoreline associated with wave-induced longshore currents
Risk analysis	Assessment of the total risk due to all possible environmental inputs and all possible mechanisms
Runnel	Channels on a beach, usually running approximately shore-parallel and separated by beach ridges
Run-up, run-down	The upper and lower levels reached by a wave on a beach or coastal structure, relative to **still-water level**
Salient	Coastal formation of beach material developed by wave refraction and diffraction and longshore drift comprising of a bulge in the coastline towards an offshore island or breakwater, but not connected to it as in the case of a **tombolo** - see also **ness, cusp**
Sand	Sediment particles, mainly of quartz, with a diameter of between 0.062mm and 2mm, generally classified as fine, medium, coarse or very coarse
Scatter diagram	A two-dimensional histogram showing the joint probability density of two variables within a data sample
Sea defences	Works to alleviate flooding by the sea
Sea level rise	The long-term trend in mean sea level
Seawall	Solid coastal defence structure built parallel to the coastline

Sediment	Particulate matter derived from rock, minerals or bioclastic debris
Sediment cell	In the context of a strategic approach to coastal management, a length of coastline in which interruptions to the movement of sand or shingle along the beaches or nearshore sea bed do not significantly affect beaches in the adjacent lengths of coastline. Also referred to as a coastal cell
Sediment sink	Point or area at which beach material is irretrievably lost from a coastal cell, such as an estuary, or a deep channel in the seabed
Sediment source	Point or area on a coast from which beach material arises, such as an eroding cliff, or river mouth
Seiche	Standing wave oscillation in an effectively closed body of water
Semi-diurnal	Having a period of half a tidal day, i.e. 12.4 hours
Sequencing of storms	Refers to the temporal distribution of storms and therefore how they are grouped
Shallow water	Water of such depth that surface waves are noticeably affected by bottom topography. Typically this implies a water depth equivalent to less than half the **wave length**
Shingle	A loose term for coarse beach material, a mixture of gravel, pebbles and larger material, often well-rounded and of hard rock, e.g. chert, flint etc.
Shoaling	Decrease in water depth. The transformation of wave profile as they propagate inshore
Shoaling coefficient	Ratio of shoaled **wave height** to deep water **wave height**
Shoreline	One characteristic of the coast. Poorly defined but essentially the interface between land and sea
Shoreline management	The development of strategic, long-term and sustainable coastal defence policy within a **sediment cell**
Shore normal	A line at right-angles to the contours in the surf zone
Short-crested random waves	Random waves with variable heights, periods and directions
Significant wave height	The average height of the highest one third of the waves in a given sea state
Silt	Sediment particles with a grain size between 0.004mm and 0.062mm, i.e. coarser than **clay particles** but finer than **sand**
Soft defences	Usually refers to **beaches** (natural or designed) but may also relate to energy-absorbing beach-control structures, including those constructed of rock, where these are used to control or redirect **coastal processes** rather than opposing or preventing them
Spit	A long narrow accumulation of sand or shingle, lying generally in line with the coast, with one end attached to the land the other projecting into the sea or across the mouth of an estuary - see also **ness**

Standard of service	The adequacy of defence measured in terms of the return period (years) of the event which causes a critical condition (e.g. breaching, overtopping) to be reached
Still-water level (SWL)	Water level that would exist in the absence of waves
Strand line	An accumulation of debris (e.g. seaweed, driftwood and litter) cast up onto a beach, and lying along the limit of wave uprush
Sub-tidal beach	The part of the beach (where it exists) which extends from low water out to the approximate limit of storm erosion. The latter is typically located at a maximum water depth of 8 to 10 metres and is often identifiable on surveys by a break in the slope of the bed
Surf beat	Independent long wave caused by reflection of **bound long wave**
Surf zone	The zone of wave action extending from the water line (which varies with tide, surge, set-up, etc.) out to the most seaward point of the zone (**breaker zone**) at which waves approaching the coastline commence breaking, typically in water depths of between 5 to 10 metres
Surge	Changes in water level as a result of meteorological forcing (wind, high or low barometric pressure) causing a difference between the recorded water level and that predicted using harmonic analysis, may be positive or negative
Suspended load	A mode of sediment transport in which the particles are supported, and carried along by the fluid
Swash zone	The zone of wave action on the beach, which moves as water levels vary, extending from the limit of **run-down** to the limit of **run-up**
Swell (waves)	Remotely wind-generated waves. Swell characteristically exhibits a more regular and longer period and has longer crests than locally generated waves
Threshold of motion	The point at which the forces imposed on a sediment particle overcome its inertia and it starts to move
Tidal current	The movement of water associated with the rise and fall of the tides
Tidal range	Vertical difference in high and low water level once decoupled from the water level **residuals**
Tidal wave	The rise and fall in water level due to the passage of the tide
Tide	The periodic rise and fall in the level of the water in oceans and seas; the result of gravitational attraction of the sun and moon
Tides	(1) Highest astronomical tide (HAT), lowest astronomical tide (LAT): the highest and lowest levels, respectively, which can be predicted to occur under average meteorological conditions. These levels will not be reached every year. HAT and LAT are not the extreme levels which can be reached, as storm surges may cause considerably higher and lower levels to occur.

(2) Mean high water springs (MHWS), mean low water springs (MLWS): the height of mean high water springs is the average throughout a year of the heights of two successive high waters during those periods of 24 hours (approximately once a fortnight) when the range of the tide is greatest. The height of mean low water springs is the average height obtained by the two successive low waters during the same periods.

(3) Mean high water neaps (MHWN), mean low water neaps (MLWN): the height of mean high water neaps is the average of the heights throughout the year of two successive high waters during those periods of 24 hours (approximately once a fortnight) when the range of the tide is least. The height of mean low water neaps is the average height obtained by the two successive low waters during the same periods.

(4) Mean high water (MHW), mean low water (MLW): for the purpose of this manual, mean high/low water, as shown on Ordnance Survey Maps, is defined as the arithmetic mean of the published values of mean high/low water springs and mean high/low water neaps. This ruling applies to England and Wales. In Scotland the tidal marks shown on Ordnance Survey maps are those of mean high (or low) water springs (MH (or L) WS).

TMA spectrum — Wave spectrum typical of growing seas in limited water depths

Tombolo — Coastal formation of beach material developed by **refraction, diffraction** and **longshore drift** to form a `neck' connecting a coast to an offshore island or breakwater (see also **salient**)

Updrift — The direction opposite to that of the predominant longshore movement of beach material

Up-rush — The landward return of water following the **back-rush** of a wave

Water depth — Distance between the seabed and the **still water level**

Water level — Elevation of **still water level** relative to some datum

Wave celerity — The speed of wave propagation

Wave climate — The seasonal and annual distribution of **wave height, period** and **direction**

Wave climate atlas — Series of maps showing the variability of wave conditions over a long coastline

Wave direction — Mean direction of wave energy propagation relative to true North

Wave directional spectrum — Distribution of wave energy as a function of wave **frequency** and **direction**

Wave frequency — The inverse of **wave period**

Wave frequency spectrum — Distribution of wave energy as a function of frequency

Wave generation — Growth of wave energy by wind

Wave height	The vertical distance between the trough and the following crest
Wavelength	Straightline distance between two successive wave crests
Wave peak frequency	The inverse of wave peak period
Wave peak period	Wave period at which the spectral energy density is a maximum
Wave period	The time taken for two successive wave crests to pass the same point
Wave rose	Diagram showing the long-term distribution of **wave height** and direction
Wave set-up	Elevation of the water level at the coastline caused by radiation stress gradients in the surf zone
Wave steepness	The ratio of **wave height** to wavelength also known as **sea steepness**
Wave transformation	Change in wave energy due to the action of physical processes
Weibull distribution	A model probability distribution, commonly used in wave analysis
Wind rose	Diagram showing the long-term distribution of wind speed and direction
Wind sea	Wave conditions directly attributable to recent winds, as opposed to swell
Wind set-up	Elevation of the water level over an area directly caused by wind stress on the water surface
Wind stress	The way in which wind transfers energy to the sea surface

The Scottish Office

The Scottish Office commissions applied research to support the formulation, development and evaluation of its policies to improve the quality of the Scottish environment and the life of its people. Research also assists the Scottish Office in meeting its statutory responsibilities.

Historic Scotland

Historic Scotland is an Executive Agency within the Scottish Office. We discharge the Secretary of State for Scotland's functions in relation to the built heritage - that is, ancient monuments, archaeological sites and landscapes; historic buildings, parks and gardens; and designed landscapes.

We:

- promote the conservation of Scotland's historic buildings and monuments:
    - ∞ directly by looking after the buildings in our care, and
    - ∞ indirectly by compiling a schedule of ancient monuments and a list of historic buildings (both statutory), by providing advice and financial assistance to help conserve them, and, where they cannot be preserved and their recording is no one else's responsibility, by arranging for their survey or excavation;
- promote enjoyment of Scotland's built heritage, in particular by encouraging people to visit the properties in our care;
- advise and educate people on the rich heritage of Scotland's rural, urban and industrial landscape and its many ancient monuments and buildings.

Our aim is to protect Scotland's built heritage for the benefit of present and future generations, and to enhance its understanding and enjoyment.

Scottish Natural Heritage

Scottish Natural Heritage is an independent body established by Parliament in 1992, responsible to the Secretary of State for Scotland. Our task is to secure the conservation and enhancement of Scotland's unique and precious natural heritage - the wildlife, the habitats, the landscapes and the seascapes which has evolved through the long partnership between people and nature. We advise on policies and promote projects that aim to improve the natural heritage and support its sustainable use.

Our aim is to help people to enjoy Scotland's natural heritage responsibly, understand it more fully and use it wisely so that it can be sustained for future generations.