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Coastal Cells in Scotland:
Cell 7 – Mull of Galloway to the Inner Solway Firth

D L Ramsay & A H Brampton

2000

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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 7 between the Mull of Galloway and the Inner Solway Firth on the south west coast of Scotland. It describes the various coastal characteristics and processes which affect the regime of this particular stretch of shoreline. The report includes 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 7 between the Mull of Galloway and the Inner Solway Firth, 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 the cell to allow as full an appreciation as is presently 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 as follows, 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 of Scotland in the context of coastal cells. Chapter 4 provides reference to data sources of relevance to coastal management in Cell 7. Chapter 5 forms the main body of the report. A brief description of Cell 7 detailing the cell boundaries, a description of its character and the processes occurring there is given. An assessment of climatic change, sea level rise, and the likely effects on the coastline of Cell 7 is given in Chapter 6, with Chapter 7 listing the references used. A listing of Sites of Special Scientific Interest, the locations of noted historical and archaeological sites, useful addresses and a glossary 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 eleven 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, such as those in the west of this region 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 alongshore transport of beach material are used to define cells in these situations. These include general orientation of the coastline and its hydraulic environment. Cell 7 has been defined in this manner.

Bearing the above description of cell boundaries in mind, the coast of Scotland has been divided up into eleven 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.

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 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). In consequence, although this report focuses on the Scottish (northern) coastline of the Solway Firth, in practice the coastal cell embraces also those shores on its southern coastline in England. These are described in HR Wallingford (1993).

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 Guideline (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 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, 1995a).

2.3 Coast protection legislation in Scotland

The new Unitary Authorities with a coastline are 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 5 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 1,000 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 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 an annual variation of tidal effects. The solar tidal components are also 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 inter-related 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:

Sites of Special Scientific Interest (SSSI) — Scottish Natural Heritage

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 byelaws. 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 byelaws. 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 *Cell 7 - 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 in Cell 7. Further, site specific information, particularly on littoral processes and coastal defences, is contained within Chapter 5.

Two general sources of coastal information on Cell 7 exist. The UK Digital Marine Atlas (UKDMAP) which was developed by the British Oceanographic Data Centre, Birkenhead, provides a reference database of 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 in the Solway Firth is provided in *Coasts and Seas of the United Kingdom: Region 13: Northern Irish Sea* (Barne et al, 1996).

Details of physical oceanographic and meteorological (metocean) data collected around the British Isles on behalf of the UK energy industry are 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 south west of Scotland has been studied in detail in several studies, for example *British Regional Geology: The South of Scotland* (Greig et al, 1971). This report references a large number of more detailed localised studies conducted within the region. The British Geological Survey have also produced a series of solid and drift geology maps, the availability of which is detailed in Table 2. A 1:625,000 scale Quaternary geology map, covering the area, is also available.

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 (1998).

Table 2 Available geological maps

Map No.	Map Name	Solid/Drift Geology	Scale
1	Kirkmaiden	Drift	1:50,000
3	Stranraer	Drift	1:50,000
4W	Kirkcowan	Solid & Drift	1:50,000
4E	Wigtown	Solid & Drift	1:50,000
2	Whithorn	Solid & Drift	1:50,000
5W	Kirkcudbright	Solid & Drift	1:50,000
5E	Dalbeattie	Solid & Drift	1:50,000
Special sheet	Rhinns of Galloway	Solid	1:50,000

The geomorphology of the Solway Firth is described in several studies, the main texts being *The coastline of Scotland* (Steers, 1973) and *The beaches of south west Scotland (Vol 1 & 2* (Mather, 1979). Other, more localised studies have also been conducted. These include a review and management recommendations for Luce Bay and Torrs Warren SSSI (Single & Hansom, 1994).

4.3 Bathymetry

The bathymetry of the Solway Firth is illustrated in detail on the following Admiralty Charts:

Table 3 Available Admiralty Charts

Chart No.	Location	Scale
1121	Irish Sea with St George's Channel & North Channel	1:500,000
1344	Kirkcudbright Bay	1:15,000
1346	Solway Firth & Approaches	1:100,000
1411	Irish Sea - Western Part	1:200,000
1826	Irish Sea - Eastern Part	1:200,000
2093	Southern approaches to North Channel	1:100,000
2094	Kirkcudbright to Mull of Galloway & Isle of Man	1:100,000

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.

A detailed bathymetric survey of the inner Firth was conducted as part of the Chapelcross nuclear generation Phase 2 siting studies (HR Wallingford, *pers comm*) with survey lines ranging from between 100m to 2000m. A large number of hydrographic studies were also conducted in conjunction with Phase 1 siting feasibility studies, but details of these studies could not be obtained.

4.4 Wind data

There are a number of anemometer stations where winds have been recorded and the information passed to the Met Office which could be useful in estimating wave conditions on the south west coastline of Scotland (Figure 6). At West Freugh, Dundrennan and Carlisle the recorders are equipped with Semi-Automatic Meteorological Observing Systems (SAMOS) which produce wind statistics continuously for immediate archiving. At Whithorn, Dumfries and Chapelcross, graphical recorders are used, which have to be hand-analysed to provide suitable data for archiving. The recorders at Point of Ayre on the Isle of Man and at St Bees Head may also be of use. A summary of the available wind data is provided in the following table:

Table 4 Cell 7 - Availability of wind data

Location	Period covered	Anemometer Type
Carlisle	01/70 - Present	Analysed anemograph from SAWS/SAMOS/CDL station
Chapelcross	01/79 - Present	Data on Metform 6910
Dumfries	01/72 - Present	Data on Metform 6910
Dundrennan	(unknown)	Analysed anemograph from SAWS/SAMOS/CDL station
Point of Ayre	01/70 - Present	Analysed anemograph from SAWS/SAMOS/CDL station
St Bees Head	(unknown)	Analysed anemograph from SAWS/SAMOS/CDL station
West Freugh	01/70 - Present	Analysed anemograph from SAWS/SAMOS/CDL station
Whithorn	05/83 - Present	Data on Metform 6910

4.5 Tidal data

There are no A-class tidal gauge installations within this Cell. A-class gauges are installed and maintained as part of a national network of tide-gauges organised by the Proudman Laboratory (POL) situated at Bidston, Merseyside. The closest A-class gauges are located at Portpatrick and Workington. Long term measurements from these gauges have been analysed to produce "harmonic constants" from which predictions of tidal levels can be made for any desired time. Harmonic constants have been calculated for a number of locations within Cell 7. These 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. A gauge was also installed for a short period of time at Garlieston Harbour by the Solway River Purification Board. Gauges have also been deployed for short periods of time within the Firth at four locations between July 1991 and November 1991 during a data collecting exercise associated with the feasibility of new nuclear power generation facilities at Chapelcross (HR Wallingford, *pers comm*).

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 a report *Data holdings of the PSMSL* (Spencer & Woodworth, 1993) which can be obtained from the Bidston Observatory. Within Cell 7 there are no locations where mean sea level is recorded, the closest being at Portpatrick.

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. To provide predictions at the coastline a more detailed numerical model would be required (discussed later in this section).

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). In practice, referring to these papers, or similar papers in the future, is likely to be the method used most often by coastal managers to determine extreme water levels in their area.

The Admiralty have 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.

Flow modelling of the entire Solway Firth has been conducted by HR Wallingford (1989 and subsequent unreported studies) in connection with the development of the Chapelcross Power Station. Details of this modelling are not available.

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 has a digital inventory of current meter data around the British Isles collected from a large number of both national and international organisations. The directory contains information up to 1991 and is available directly from BODC. A large amount of tidal current measurements have been recorded in the Solway Firth and are detailed in the Digital Inventory. A large amount of current data has also been recorded during feasibility studies into further nuclear power generation facilities at Chapelcross (HR Wallingford, 1989 and further unreported studies).

In addition the Admiralty also produce "Tidal stream atlases" with the offshore zone of Cell 7 covered in the Irish Sea Atlas (Hydrographer of the Navy, 1963). 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.

4.6 Wave data

Information on offshore wave conditions can be obtained 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 marine construction projects, e.g. harbour development. The only known deployment of wave recording equipment (Table 5) was in conjunction with the Chapelcross nuclear power generation phase 2 studies, (HR Wallingford, *pers comm*). It is likely that other wave recording was conducted during the phase 1 siting studies but no information could be obtained.

Table 5 Sources of measured wave data

Location	Lat/Long	Period covered	Mean Water Depth (m)	Contact
Mouth of the Solway Firth (10km south of the north coast)	54°41'31"N 34°8'5"W	10 Oct 1991 to 10 Oct 1992	20m CD	HR Wallingford

The records listed in Table 5 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 which can be used to predict wave climates and extremes.

Information on wave conditions can also be obtained from the VOS (Voluntary Observations from Ships) archives. The majority of 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), mean 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. 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 are permanently stored in an archive, whilst the data from T+0 hours to T+36 hours are 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, incorporating both wind-sea and swell. Figure 6 shows the grid point locations offshore of the Solway Firth coast. Further details are given in the table below. Modern numerical methods are also capable of accurate predictions of "wind-sea" for offshore areas, especially if there is good quality, sequential wind data available to provide the basic input conditions. There is only one known location where offshore wave conditions have been numerically modelled (HR Wallingford, *pers comm*) details of which are given in Table 6.

Table 6 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
Inner Solway Firth	Offshore: 54°41'31"N 3°48"5"W	01/79-06/91	20m CD	Climate and 0.1, 1, 10 & 100 year extremes	HR Wallingford
	Inshore: NY 178 640 NY 207 636 NY 192 645 NY 208 645		10m 7.5m 7.5m 7.5m	Climate and 0.1,1, 10 & 100 year extremes	HR Wallingford

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 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 (particularly important along the eastern frontage of this Cell) 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. The inshore wave climate at four locations have been derived, two in the main channel of the River Eden and two on the sandflats at Annan and Seafield (HR Wallingford, *pers comm*).

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.

Table 7 Natural heritage designations

Designation	Number	Designation	Number
SSSI	15	NSA	3
NNR	1	NHA	-
MNR	-	AGLV	-
LNR	1	ESA	1
SAC	2	MCA	-
SPA	1	RSPB	-
RAMSAR	-	LWT	

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.

A description of the various designations is given in Section 3.6. Within Cell 7 the number of designated natural heritage sites is given in Table 7. The locations of SSSIs are shown in Figure 7 with further information detailed in Appendix 1. The locations of 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 Table 8. 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 the RCAHMS in this study. However, the RCAHMS advised that to locate all coastal sites along the coastline 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 Cell 7. 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. There are also a large number of sites, e.g. Listed Buildings, which do not appear in the NMRS database. Appendix 2 details the actual locations of scheduled sites within 500m of the coastline obtained from the RCAHMS database.

Table 8 Cell 7 - 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.

5 Cell 7: Mull of Galloway to the Inner Solway Firth

5.1 General

Cell 7 has been defined, (HR Wallingford, 1997), as the coastline between the Mull of Galloway and the Inner Solway Firth, Figure 5. The cell encompasses all beaches on the northern coastline of the Solway Firth.

The Mull of Galloway and the Solway Firth both form major boundaries to wave induced longshore transport. The Mull of Galloway acts as a drift divide to any sediments being moved by wave action along the coast. However, it does not act as a divide to sediments moved by strong tidal currents. The Solway Firth is a sediment sink with material accreting in the inner part of the estuary. As such there is no definitive boundary. However for the purpose of this report the border between Scotland and England can be considered suitable. It was considered that there would be no advantage to shoreline management to divide this cell up into further sub-cells as the supply and movement of beach material is also heavily influenced by the tidal processes which occur within the Solway Firth. However, self-contained beach units can be identified. For example the Luce Bay system can be considered relatively self contained, with Burrow Head tending to act as a drift divide. The locations of these "semi-independent beach units" are shown on the relevant littoral process maps.

Section 5.2 describes the coastal regime occurring within Cell 7.

5.2 Cell 7: Physical characteristics

5.2.1 General

The characteristics and processes occurring within Cell 7 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 are shown in Figure 10.

Details of the dominant hydraulic processes, i.e. the tides, currents and waves, are described. Tidal elevations within this cell are described and, where known, details of any surge information. The direction of the main tidal currents and magnitude of tidal velocities are also detailed. Any areas where significant tidal flooding occurs are noted. 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 dominant nearshore processes which affect the transformation of offshore to inshore wave conditions are also described.

The next section describes the main littoral processes within the cell. 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. Where there are areas of long term nett erosion and accretion these 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 and the dominant littoral processes are shown in Figures 12 and 13 respectively. Locations where maintenance dredging is conducted listed and, where possible, any known dredging rates and the source of siltation are detailed.

The final section describes 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 beach monitoring or coastal surveys have been conducted are presented and, where possible, details of the length of such records and monitoring authorities given. Details of existing coastal defences and locations where regular monitoring is conducted are shown in Figure 14.

5.2.2 Geology

The solid geology of the north Solway Firth coastline is dominated by Silurian siltstones, shales and greywackes. These rocks make up much of the southern part of the Rhinns of Galloway and the coastline extending to Kirkcudbright Bay and have considerable impact on the scenic character of the coastline. These rock strata tend to have a dominant north-east to south-west strike which influences beach morphology at a number of locations, such as the western side of Fleet Bay, (Mather, 1979). Where such rock outcrops at the coast, the variability in erosion rates between the Silurian mud and sandstones as compared to the greywackes has resulted in an indented coastline. This is further influenced by thin (generally <2m wide) igneous dykes which also run in the same direction.

Carboniferous outcrops are evident at the coast at two main locations, between Abbey Head and Balcary Point and underlying Preston Merse and the outer western coast of the Nith Estuary. The Carboniferous rocks which outcrop in this narrow section along the coast are composed of sandstones and mudstones with limestone beds and basaltic lavas and are evident as intertidal outcrops or shore platforms. Landward of these Carboniferous deposits is a large mass of granite which outcrops at the coast around Auchencairn Bay and Rough Firth and is responsible for the rugged terrain of the area.

New Red Sandstone, of Permian age, underlies the isthmus between Luce Bay and Loch Ryan. These deposits consist of red sandstones and breccias dipping to the south and east. They are not evident at the coast within Luce Bay due to the thick drift deposits which overly the strata there. The eastern side of the River Nith is similarly underlain with New Red Sandstone measures which again do not outcrop at the coast.

Drift deposits within this cell are abundant, with much of the solid geology overlain by thick glacial and postglacial deposits. The region is characterised by glacial deposition and did not undergo, to the same extent, the scouring action of the ice sheets which affected areas further north. Vast quantities of glacial sediments not only cover the land but also floor much of the Solway Firth. It is these sediments which have provided the material for the beaches and sandflats which occur within this cell.

The effect of the abundance of sediments and the effects of varying sea-levels during, and since, the retreat of the last ice sheet has created an assemblage of raised beaches, relict clifflines and associated features. The most distinct raised beaches can be seen on the south west facing coastline at the eastern side of Luce Bay where, from Burrow Head to the inner part of Luce Bay, an almost continuous relict cliff line exists fronted by a raised beach of about 100m width upon which the A747 runs. Raised estuarine deposits are also extensive along the Inner Solway Firth coastline, especially east of the River Nith.

5.2.3 Hydraulic processes

The mean tidal ranges for the spring and neap tides are given in Table 9 (and Figure 11). The tidal elevations are expressed relative to land datum, i.e. metres Ordnance Datum Newlyn. The conversion factor between Ordnance Datum and local Chart Datum is detailed in the final column of Table 9. The spring tidal range increases towards the inner firth from about 5.3m at Drummore to 7.4m at Hestan Islet and to over 8m in the inner Firth. These high tidal ranges are due to the Irish Sea being close to its resonant frequency for the semi-diurnal tidal constituents. The high water tidal wave takes approximately 3½ hours to travel from the Mull of Galloway to the inner part of the Firth. The tidal cycle is semi-diurnal with a mean period of approximately 12.1 hours. In the Inner Solway Firth the tidal curves are highly distorted with a very rapid flood and longer, weaker ebb.

Table 9 Tidal levels and ranges for Cell 7

Location	MHWS (m OD)	MLWS (m OD)	Spring Range (m)	MHWN (m OD)	MLWN (m OD)	Neap Range (m)	ODN to CD (m)
Drummore	2.8	-2.5	5.3	1.8	-1.1	2.9	+3.1
Port William	2.8	-	-	1.6	-1.5	3.1	+3.6
Isle of Whithorn	3.1	-3.1	6.2	1.6	-1.7	3.3	+3.8
Garlieston	3.2	-	-	1.9	-1.4	3.3	+3.8
Kirkcudbright Bay	3.8	-2.9	6.7	2.2	-1.3	3.5	+3.7
Hestan Islet	4.29	-3.11	7.4	2.29	-1.61	3.9	+4.01
Annan Waterfoot	5.0	-	-	2.7	-1.9	4.6	+2.1

In Table 9 the tidal elevations are quoted relative to Ordnance Datum Newlyn (the standard land based datum). The conversion to the local Chart Datum (where known) is shown in the final column.

There is little information into extreme water levels within the Solway Firth. Recent research by Dixon & Tawn (1997) has provided a spatial analysis of extreme water levels at 20km intervals around the coastline of the UK mainland. Their predictions depend on the year of interest and also take into account trends in mean sea level. Surge elevations in the Irish Sea (presented in Carter, 1988; based on data from Heaps & Jones, 1975) due to strong westerly winds associated with a cyclone to the north west of Ireland in January 1975 resulted in a surge elevation of 1.25m at the Mull of Galloway and across the outer Solway Firth and over 2m in the inner Firth. This is calculated to be approximately the 1:50 year return period surge elevation (BODC, 1991).

Tidal streams off the entrance to the Solway Firth rotate anti-clockwise. The main flood tide travels through the North Channel, around the Mull of Galloway and east into the Solway Firth with peak spring currents of up to 2ms^{-1}. In Luce Bay the tidal stream rotates anti-clockwise with a peak spring rate of approximately 0.6ms^{-1}. During the flood stream an eddy runs west towards Cailiness Point and then south to the Mull of Galloway. On the eastern coastline the tidal stream follows the coastline on both flood and ebb between Burrow Head and the Point of Lag. Towards the head of the bay, currents are weak and irregular.

In the outer part of Wigtown Bay tidal streams run in an east north east and east direction on the flood and west turning south west on the ebb. The peak spring rate is approximately 2ms^{-1}. In the inner part of the bay, the tidal streams run in and out of the River Cree reaching up to 2.5ms^{-1} peak spring rate on both flood and ebb tide. This rate can also be affected by spate flows from the river. The main flood and ebb stream runs across the mouth of Kirkcudbright Bay with a peak rate of up to 2ms^{-1}. However, within the bay, the tidal streams can depend on the flow from the power station dam at Tongland. In general tidal streams are extremely weak.

In the inner part of the Solway Firth between Abbey Head and Hestan Islet the tidal stream runs parallel with the coast with a peak Spring rate of 1.5ms^{-1} on both flood and ebb and up to 2.5ms^{-1} off Southerness Point. In the channels between the sandbanks at the head of the Solway Firth tidal currents can also be significant.

The Solway Firth is open to the south westerly sector. Fetch lengths for wave generation are restricted due to the coastline of Ireland and England and the Isle of Man. Between the Mull of Galloway and Burrow Head the coast is exposed to a very narrow wave window where fetch lengths extend out past the west coast of the Isle of Man, through St George's Channel and into the Atlantic. A similar fetch extends from the Inner Solway Firth and past the eastern coast of the Isle of Man. From other directions the fetch length is restricted to less than 250km. The dominant wind direction, and hence wave direction, is from the south west resulting in the Firth being exposed to onshore wave conditions for a high percentage of the time.

At the outer boundary of the Solway Firth wave heights over 1.5m are experienced for 10% of the time, with a corresponding wave height of 1.0m within Luce and Wigtown Bay and the Inner Solway Firth (BODC, 1991). Within the western part of the Cell, in the Luce Bay area, there is no known information on wave conditions. The bay is directly exposed to the south east where fetch lengths extend approximately 200km to the Lancashire coast, but will be dominated by the larger wave conditions generated from the south west which refract/diffract into the bay.

The offshore wave climate has been derived on the 20m CD contour in the outer Solway Firth to the south east of Dundrennan (HR Wallingford, *pers comm*) using 12½ years of wind data from Chapelcross and calibrated against wave measurements at the same location. The wave climate is dominated by wave conditions from 210°N to 250°N (40% of the time) with extreme conditions dominated by storms from between 190°N and 230°N.

The coastline of the Solway Firth can experience swell wave conditions dominantly from the south west in the Irish Sea (HR Wallingford, 1995). The maximum swell significant wave heights have been calculated as 2.3m, 3.2m, and 4.1m for the 1, 10 and 100 year return periods respectively. This is likely to be a conservative overestimate of swell conditions in the Solway Firth due to shallow water effects and energy dissipation resulting from the shape of the coastline and the influence of the Isle of Man.

Nearshore wave conditions have been derived at four locations in the Inner Solway Firth. This showed that penetration of wave conditions generated offshore into the Solway Firth was extremely low, due to the effects of the extensive sandflats, and that locally generated wave conditions were dominant (wave conditions refracted from offshore will be limited to a significant wave height of less than 1m). Maximum wave conditions are experienced from the south west but the severity of wave conditions inshore of a line between Abbey Head and Workington will be very sensitive to water level. Wave refraction numerical modelling at a water level of MHWS indicates that the maximum depth limited wave height in the channel of the River Eden would be 2.8m and 1.4m closer inshore. However, it is unlikely that the most extreme wave conditions will exceed 2m in height (a 2m wave height is considered to have a return period of between 100 to 150 years in the channel to the south of Annan).

5.2.4 Littoral processes

There is an abundance of sediments (sands and gravels) within the Solway Firth system but only at a few locations can the beach areas be described as well nourished. Figure 12 details the dominant foreshore and hinterland characteristics. Virtually all material within this cell is derived from glacial sources both from the seabed of the Solway Firth and from terrestrial deposits which have been reworked. Rivers entering the Solway Firth do not bring any appreciable amounts of fresh sediment. Present day reworking of hinterland deposits provides a low input of fresh sediment but tends to be fairly localised with large scale coastal edge erosion not appearing to pose a significant threat to infrastructure, Figure 13.

Much of the coastline is sheltered and longshore processes are generally restricted to the outer sections of the firth, e.g. around Luce Bay. However, due to the shallow and sandy nature of the seabed, nearshore sediment processes are highly dynamic. The general trend is for sediment movement in the nearshore zone into the Inner Solway Firth and also into the heads of the major bays which occur along the north coast.

Shingle fringe beaches occur along much of the eastern coastline of the Rhinns of Galloway with sand occurring over the lower foreshore. The dominant nett drift is to the north and the lack of sand on the upper beaches is due to much of this material having been transported into the inner part of Luce Bay. The less mobile shingle does move northwards but at a much lower rate. The small bays which have formed along this coast demonstrate this with much healthier shingle beaches at their northern end than to the south. Where sufficient volumes of shingle have accumulated some impressive shingle ridge beaches have formed, such as is found at Terally Bay. The northward drift of material has caused problems with siltation at Drummore Harbour with groynes situated immediately to the south to attempt to reduce this movement.

Single and Hansom (1994) have summarised the present knowledge on sediment transport patterns within Luce Bay. As on the western side, the dominant nett drift of beach material along the eastern coast is to the inner part of the bay. Again much of the upper beach is of shingle and any rate is extremely low and dependent upon the magnitude and direction of storm conditions. The movement of sand sized material on the lower foreshore and immediate nearshore zone into the inner bay is considerably greater with accretion tending to be most evident at the eastern end of Luce Sands. Four factors have been identified which act to accrete sand in the inner bay:

- the indented nature of the bay constrains waves propagating into the bay to a unidirectional nature,
- water depths in Luce Bay are shallow allowing sediment to be easily suspended due to wave action and transported by either waves or currents,
- unconsolidated glacial sands and gravels, which are easily suspended by wave action, form a thick covering over the seabed in the bay,
- there is evidence that Luce Bay forms a major sediment trap for material transported south along the outer Rhinns of Galloway coast and then moved northwards along a major flood channel on the west side of the bay.

Erosional problems are most evident on the western side of Luce Bay and a number of coastal protection schemes are in place mainly protecting the A716. However, any present problems appear to be extremely localised. Along the eastern flanks a healthy shingle beach on the upper foreshore provides adequate protection. Despite the Luce Sands area being generally one of accretion, erosion of the frontal dunes is evident. Single and Hansom (1994) state that the base of the dune scarp is at an elevation of 4.2m OD with MHWS at an elevation of 4.3m OD. However, erosion of the frontal dunes tend to be restricted to storm wave conditions at high water levels. The orientation of the beach to the south is conducive to dune formation with embryo dunes evident at the eastern end of the Luce Sands where the intertidal zone tends to be wider.

Burrow Head acts as a drift divide for wave induced sediment transport along the coastline in the intertidal zone (but not to sediments moved in the nearshore zone). However, despite the potential for wave induced transport along the western side of the outer part of Wigtown Bay the lack of sediments and rocky nature of the coast result in minimal transport. Beach areas are thin and tend to be located in indented bays, e.g. Isle of Whithorn, Rig Bay and Garlieston. Due to the orientation of the beaches, erosion is minimal and restricted to small localised areas. As in Luce Bay the movement of fine sediments in the nearshore zone is more significant with the inner part of Wigtown Bay tending to accrete. The sand banks of the inner bay will be dominated by tidal current actions, although wave action when the sand banks are covered at high tide will aid suspension of sediments. The wide intertidal zone due to these sand banks is extremely effective in dissipating wave energy and little erosion of the coastal edge occurs.

Fleet Bay, Kirkcudbright Bay, Auchencairn Bay and Rough Firth similarly act as traps to sediment moved by tidal action in the nearshore zone with little longshore processes evident. The shallow water depths within these bays limits wave action, and hence erosion of the coastal edge. Due to the rocky nature of much of this coast any minor areas of erosion are extremely localised. Towards Southerness Point the coastline becomes more exposed to the south west and larger fetch lengths in the direction of the prevailing wind. The coastline is afforded much protection from waves propagating into the firth by the extensive intertidal sand banks of Mersehead Sands and Barnhourie but, despite this, significant erosion of the coastal edge between Southwick and Southerness occurs. This appears to be a long term process with wave induced transport of sand to the east towards Southerness Point (where the rate of erosion tends to be least). Attempts to stabilise the dunes have been conducted at Southerness Golf Course. The rate of erosion tends to be variable along the frontage (Mather, 1979) and may perhaps be linked to shifting sand banks in the immediate intertidal and nearshore zone. Erosion is also noted in the Inner Solway Firth at Powfoot, Newbie, Annan, Redkirk and Gretna.

There is no record of any dredging conducted in Cell 7 in the UK Dredged Material Licence database (MAFF, 1995b). However, dredging has occasionally been conducted at Drummore Harbour by the Ministry of Defence (MoD) and the material placed on the beach to the north.

Summary of erosion and accretion

The Solway Firth is a sediment sink with material accreting on the sand banks within the estuary. However, there is considerable erosion of the coastal edge, notably within Luce Bay, between Southwick and Southerness, and along the Inner Solway Firth at Powfoot, Newbie, Annan, Redkirk and Gretna.

5.2.5 Coastal defences

The location and type of existing coastal defences occurring in Cell 7 are shown in Figure 14. Given the lack of development, particularly along the more exposed sections of the coast, defences tend to be small and on a localised scale with the exception of a number of sections protecting stretches of road, particularly the A716. An assessment of the defence requirements of the Dumfries and Galloway Region was undertaken by Babtie, Shaw & Morton (1989).

To the south of the harbour at Drummore a low concrete wall protects the road leading to Cairngarroch Bay. Shingle and cobbles form the upper beach immediately in front of the wall around the area known as Black Bore. The beach does not appear to be particularly dynamic, given the type of material and the limitations in severe wave conditions due to its orientation to the east, with the seawall having little effect upon the beach. Between this area and the harbour five gabion groynes extend across the sand beach to control the northward drift of beach material. These structures are in a relatively sound condition with little evidence of severe wave damage, but are probably too low in elevation to have a significant impact in arresting the drift of sand material to the north. A short section of masonry seawall, in need of maintenance, occurs to the north of the harbour.

The longest section of coastal defence works in cell 7 occurs to the north of Drummore. A study of the requirements of coastal defences in this area was conducted by HR Wallingford in 1987. A low concrete seawall, of relatively recent construction, to the north of Drummore runs continuously for approximately 1.5km along Kilstay Bay protecting the A716 which runs immediately behind the coastal edge. Shingle material has built up against the wall except at the southern end where the beach in front of the wall is denuded of such material due to the low northward drift. Overtopping of the wall and overwashing of shingle will occur when waves from the easterly sector combine with high tidal levels. Shingle will tend to build up against the wall allowing waves to ramp up and over.

At the southern end of Terally Bay a short stretch of older vertical concrete seawall again protects the A716. This is in a much poorer condition and the foundations at the southern end have become exposed due to lowering beach levels likely to have been caused as a result of wave reflection from the wall. There is also some evidence of outflanking of the wall at the southern end with some rock having been tipped to prevent this.

A concrete wall, in need of repair, protects private property at Chapel Rossan. Undermining of the wall has resulted in some rock being placed at the toe. At the head of Luce Bay, concrete blocks and concreted in stone provide protection to the coastal edge just to the west of the outlet of the Sandmill Burn at the caravan park. The construction of these defences, and the training of the stream which flows through the dunes, will have some impact on the immediate area. However, other anthropogenic activities, such as the flattening of dunes and spoil tipping have destroyed many of the natural features.

North of the harbour at Port William a masonry revetment and low upstand protect the A742. Repairs to the revetment have been conducted with an asphalt coating applied and it is in reasonable condition. Overtopping of the structure when onshore winds combine with high tides will affect the road. Rock protects the northern harbour breakwater. To the south a number of masonry walls occur, all requiring maintenance.

At Isle of Whithorn masonry walls form the small harbour and front the village. Given the age of these walls repairs, particularly on the intertidal low sections, are required. To the north a short stretch of concrete wall, in good repair, protects the B7063. At Garlieston and Rigg Bay a variety of masonry walls, all in various states of deterioration protect the coast. Frequent monitoring and maintenance is required given that there are numerous properties, a caravan park, corn mill and access road being protected by these structures. Rock rip-rap protects the A75 at Skyreburn bridge and, given the sheltered nature, is adequate with no signs of wave damage.

Short lengths of privately constructed defences occur around Mill Hall. Some rock rip-rap protects housing at the southern end of Nun Mill Bay and a short masonry seawall fronts a property built close to the coastal edge at Seaward. A number of small sections of defence work occur on the eastern side of Kirkcudbright Bay protecting the unclassified road. Small sections of masonry seawall protect the road to Balcary along the western flank of Auchencairn Bay. These walls are in a satisfactory condition but are susceptible to damage due to wave attack. However, given the location and orientation, such events are rare.

Masonry walls and revetments protect the villages of Kippford and Rockcliffe. These defences are in good condition and are well maintained. Wave overtopping under high tides and onshore wind will occur but should not significantly affect property.

Wave overtopping under high tides and onshore winds can cause significant overtopping and flooding of properties in Dumfries and Glencaple. Farmland and coastal roads in the hinterland of the Inner Solway Firth also experience significant flooding.

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

5.3.1 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**.

5.3.2 Natural heritage sites

Figure 7 shows the location of coastal SSSIs within Cell 7, with a summary of their main characteristics provided in Appendix 1. There are 15 coastal SSSIs within Cell 7 many of which have been designated on account of geological or geomorphological features.

Present day influences of coastal processes on SSSIs are likely to be minimal. Many of the geological sites are for exposures on relict coastlines, which no longer experience wave action, such as at Back Bay. Where designated geological sites are presently exposed to wave action, for instance Shoulder O'Craig, the igneous rocks are extremely resilient to marine action.

Many of the site designations are of coastal habitats or landforms and are much more sensitive to changes or extremes in coastal processes. Within the Solway Firth two factors reduce the impact of coastal processes which may be detrimental to such sites on more open coasts. Firstly, there is an abundance of sediments within the system resulting in a high degree of stability (i.e. there is little nett loss of sediment) at many such sites, e.g. Torrs Warren. Secondly, much of the wave action experienced on this coastline tends to be unidirectional, i.e. from the south west, and approaches the coastline at low angles of incidence due to the shallow offshore bathymetry. Slight changes in offshore wave direction are likely to have much less influence at the coastline than they would have on, say, a more exposed coastline.

In the inner bays of the Solway Firth the large sandflats and saltmarshes, many of which are designated SSSIs, are sheltered from the most detrimental wave action (largely due to the dissipative effects of the shallow water depths over these sandflats). However, the channels within the sandflats can be particularly dynamic depending on the interaction between river flows, tidal conditions and wave conditions and are not well understood. Given the lack of human intervention in this region (with the exception of the flood embankments at the outlets of the main rivers), sandflat and saltmarsh development is likely to continue in a natural manner.

5.3.3 Cultural heritage sites

The density of archaeological sites from the NMRS database is shown in Figure 9 with further details of the locations of such sites provided in Appendix 2. Little survey work appears to have been conducted along the coastline of Cell 7 to establish the present threat of coastal erosion to sites of cultural heritage (Ashmore, 1994)

A large number of sites are present along the flanks of Luce Bay. The shingle fringe beaches which occur along both the east and west coastline of the bay provide adequate protection and retreat rates of the coastal edge are low, other than at a few localised positions. Given the lack of severe wave conditions experienced upon this coastline there are unlikely to be many "high priority" sites.

To the east of Burrow Point, in the inner part of the Solway Firth, the coastal edge is protected by either relatively resilient rock or tends to be accreting. Erosion of the coastline is not likely to be as significant a problem as on more open coasts with much protection and dissipation of wave energy afforded by the shallow bathymetry and large sand banks. The only exception to this is Preston Merse which has experienced long term frontal dune erosion. However, no sites along this stretch of coastline have been noted in the NMRS database. Sites on low lying land will experience occasional tidal and river flooding.

6 Climate change and its effect on coastal management

6.1 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 6.2 is taken from Brampton (1996).

6.2 Evidence of climatic change

6.2.1 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.

6.2.2 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 fall 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 mean 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.

6.2.3 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 and 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 and 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.

6.3 Effects on coastal management

6.3.1 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 the beaches in Cell 7

In terms of the beaches and "soft" coastlines of Cell 7 it is extremely difficult to postulate what the responses to any climatic changes are likely to be. The situation is probably clearest along the Luce Bay coastline where shingle fringe beaches protect the immediate coastal edge. The movement of shingle on the upper beaches will only occur at high tide and given that wave conditions within Luce Bay are restricted, movement of shingle is only likely to occur during storm events. Wave conditions also tend to be strongly unidirectional, i.e. in a northward direction. Hence, there are unlikely to be any significant effects on the shingle beaches due to minor changes in wave directions, with increases in storminess also likely to have less of an effect than on an open coastline. At the head of Luce Bay, increases in extreme sea levels or frequency of storm conditions (and to a lesser extent mean sea levels) will result in increased frontal dune and upper beach erosion (with potentially less time for dune recovery) with this material being redistributed over the seabed within the nearshore zone. Much of this sand will remain in the Luce Bay beach system as nett longshore transport (in the wave breaking zone) is minimal.

The situation in the inner parts of the Solway Firth is much more complex. Little is understood of the morphological interaction between river flows, tidal currents and waves and the impact these processes have on the formation of the sand banks, flats and marshes. Increases in mean water level may well increase the length of time during the tidal cycle that both wave and tidal currents flow over these sand banks leading to increased sediment transport over them. What effect this will have on the surrounding coastline is unquantifiable with our present knowledge. The effect on the saltmarshes which occur along much of the coastline of the inner firth depends heavily on the rate of sea level rise and on sediment availability. For instance there appears to be a threshold value, where for rates below the threshold the saltmarsh surface is able to accrete and keep pace with the change. Above this threshold the marsh becomes submerged and is lost. Given that there is an abundance of sediment in the Solway Firth system and that there is a high tidal range, on the face of it significant saltmarsh loss would not be expected. There is also evidence to suggest that erosion and loss of saltmarsh is linked to increases in wave energy which may be more of a problem in this region if increased water levels result in marginally larger waves interacting with the marsh for a longer period of the tidal cycle. Of greater threat are changes in river flows which can effect the location of the river channels.

Any increases in extreme water level may have substantial impact on flooding at the heads of the main bays in the region. Much of the land at the outlet of the rivers is low lying with flood embankments providing much protection. Marginal increases in extreme tidal levels may not cause significant flooding upon the immediate estuarine hinterland, but the backwater effects could cause an increase in the severity of flooding further up river as presently occurs on the River Nith and Annan.

6.3.2 Impacts on man-made defences

General

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 man-made defences in Cell 7

There are a large number of coastal defence works in Cell 7. Most of these works are relatively minor, protecting short stretches of coastline. The major impacts of sea level rise or increase in storminess on coastal defences will occur on defences where there is a low margin of safety. The two main problems likely to be experienced on coastal structures within this cell due to increases in either storminess or water levels are:

- an increase in the frequency and magnitude of wave overtopping of defences
- an increase in damage and hence maintenance requirements.

Many of the defences in this cell are relatively low in elevation, possibly reflecting the low wave heights experienced on this coastline due to restricted fetch lengths. However, overtopping of defences at a number of locations is an existing problem during high tides and onshore winds (albeit given the sheltered location of many of these sites the occurrence is relatively infrequent). It is likely that an increase in the frequency of storm events will have a much greater impact than an increase in the magnitude of storm conditions as storm waves experienced upon most of this coast are limited by the effects of the shallow nearshore bathymetry. Of greater impact may be an increase in extreme water levels which both reduces the freeboard (i.e. the height of the crest of the defence above that of the still water level) and decreases the effects of the nearshore seabed in dissipating wave energy.

The same climatic changes which increase either the frequency or magnitude of overtopping may also cause an increase in the magnitude or frequency of damage to coastal defences. Given the wave conditions likely to be experienced in this cell it is unlikely that there will be any noticeable increase in the magnitude or frequency of damage to coastal defences. Many of the old masonry defences are in a relatively poor state and will suffer damage during direct onshore storms. However, many of these defences, particularly in the inner parts of the Firth, are sheltered experiencing waves from a narrow wave window. As such it is highly unlikely there will be any noticeable increase in damage to defences other than that occurring at present.

6.3.3 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 they are of significance in managing the coast.

Rainfall

There is a known past variation in the rainfall occurring in the UK. In the south of England an oscillation of about 40 years period has been observed. A similar oscillation has apparently been recorded by Stirling University when investigating River Tay flooding. 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 of 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. Most of the cliffs in cell 7 are relatively resilient to marine erosion and this is unlikely to be a significant problem.

- 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 that discharge into the Solway Firth have a low sediment suspension capacity which is unlikely to cause any significant change in the supply of fluvial sediments to the coastal zone. However, changes in river flows will have an influence in the movements of channels over the sand and mudflats in the inner parts of the main bays.

- 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 influence 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 in Luce Bay are likely to suffer 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.

It is difficult to comment on the impact of climatic change on the coastline of Cell 7. In some respects, given that much of the coastline is relatively sheltered, with short fetch lengths, this coast may not be as affected as other parts of Scotland. However, there are large areas of sand and mud flats and saltmarsh, which are particularly sensitive to changes in the natural hydraulic and sedimentary regime. Whether there will be large scale detrimental changes to such features, or whether the abundance of sediments within the Solway Firth allows these marshes and sandflats to respond to any such climatic changes remains to be seen.

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. This is particularly true of the Inner Solway Firth which is an extremely complex estuarine system evolving due to a large number of inter-relating natural influences 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 1-14

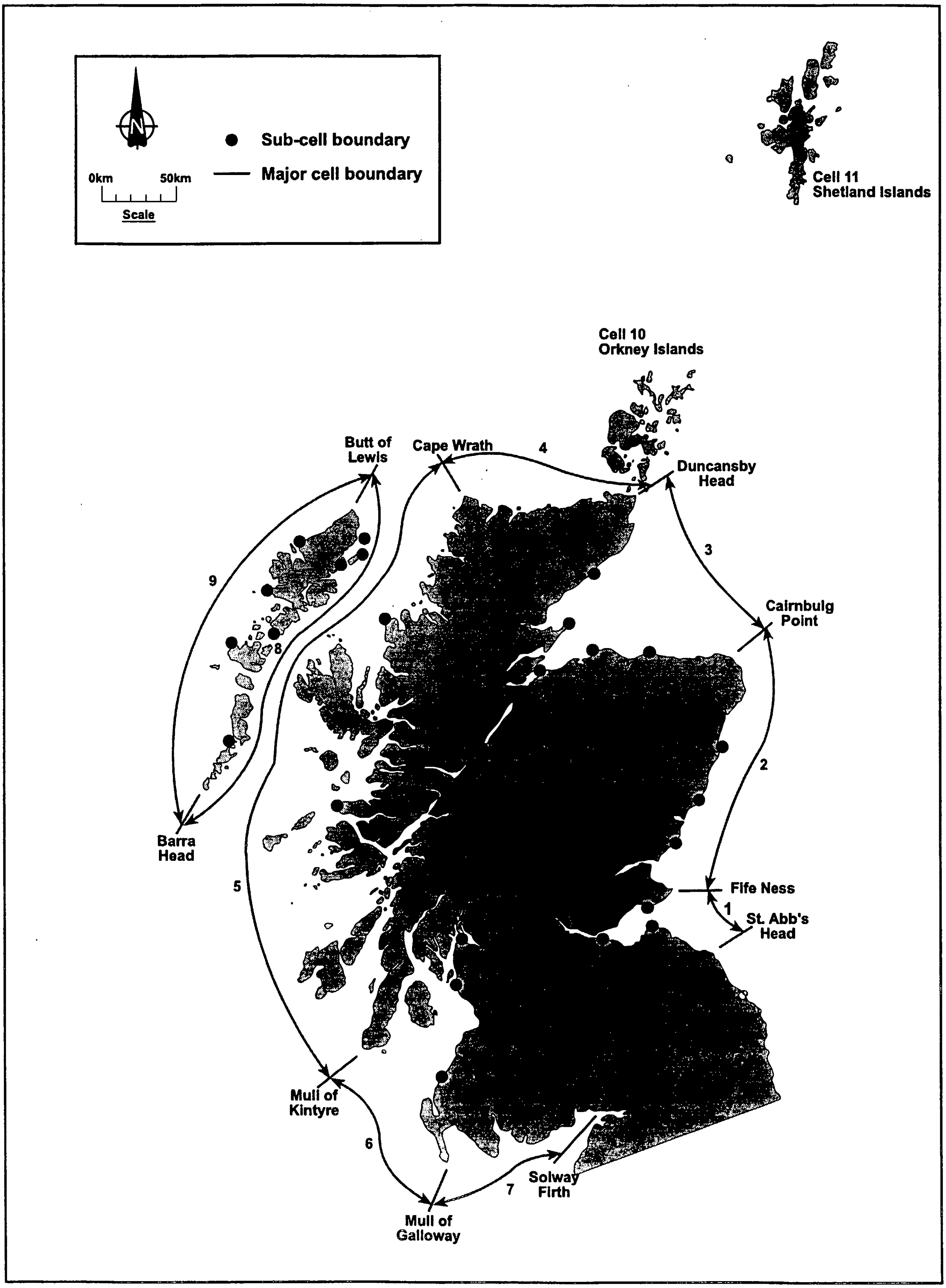

Figure 1 Coastal Cells in Scotland

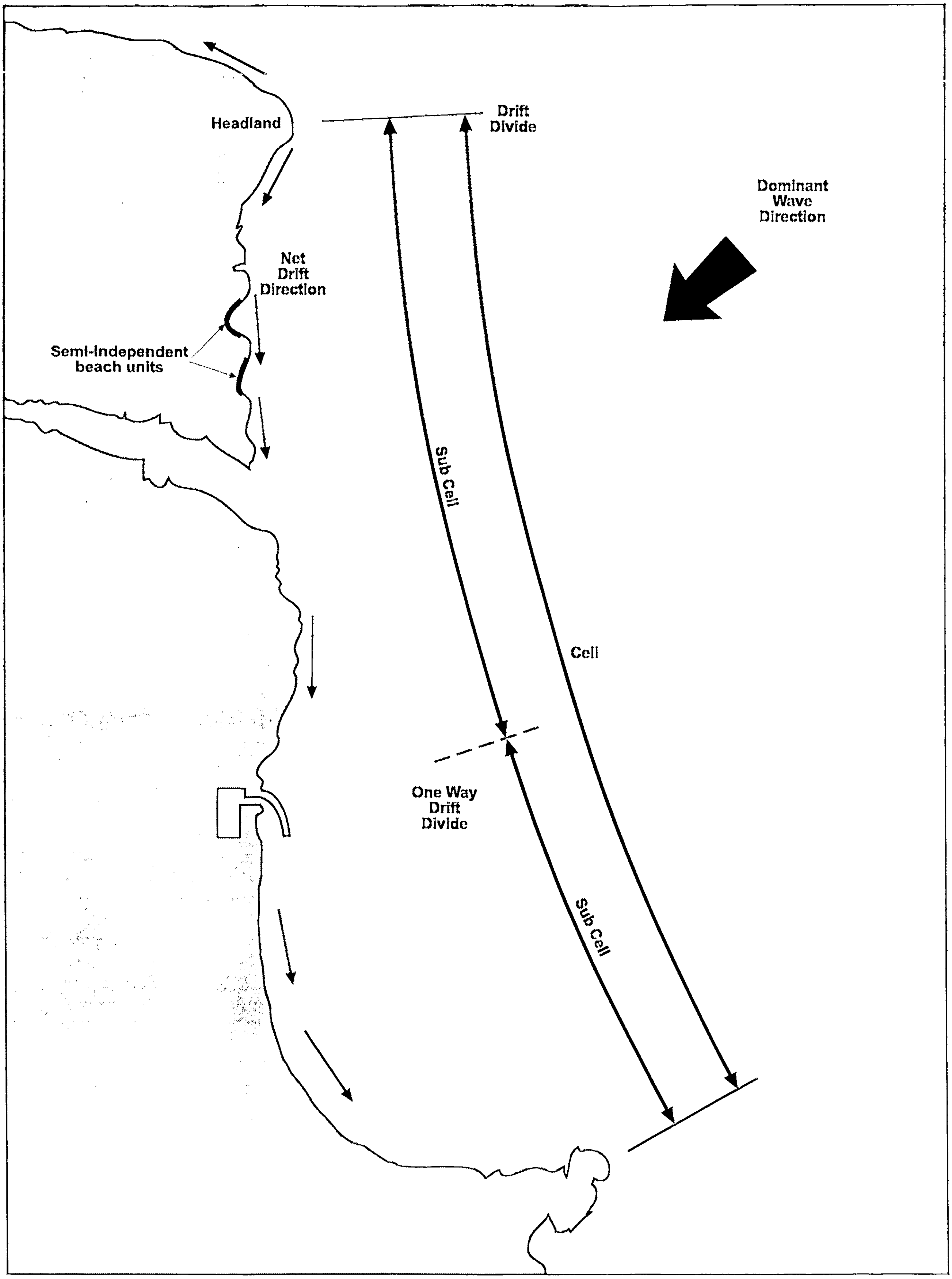

Figure 2 Idealised coastal cell

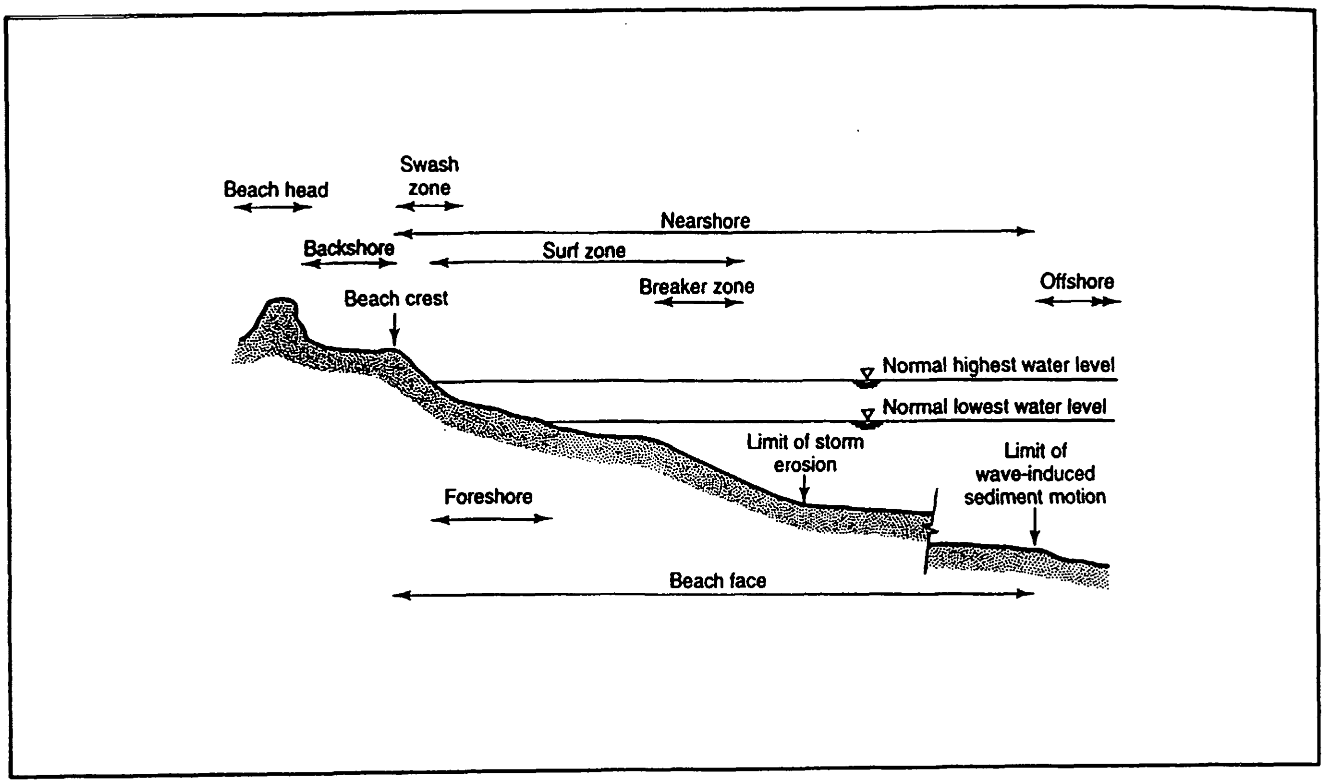

Figure 3 General beach profile and littoral zone

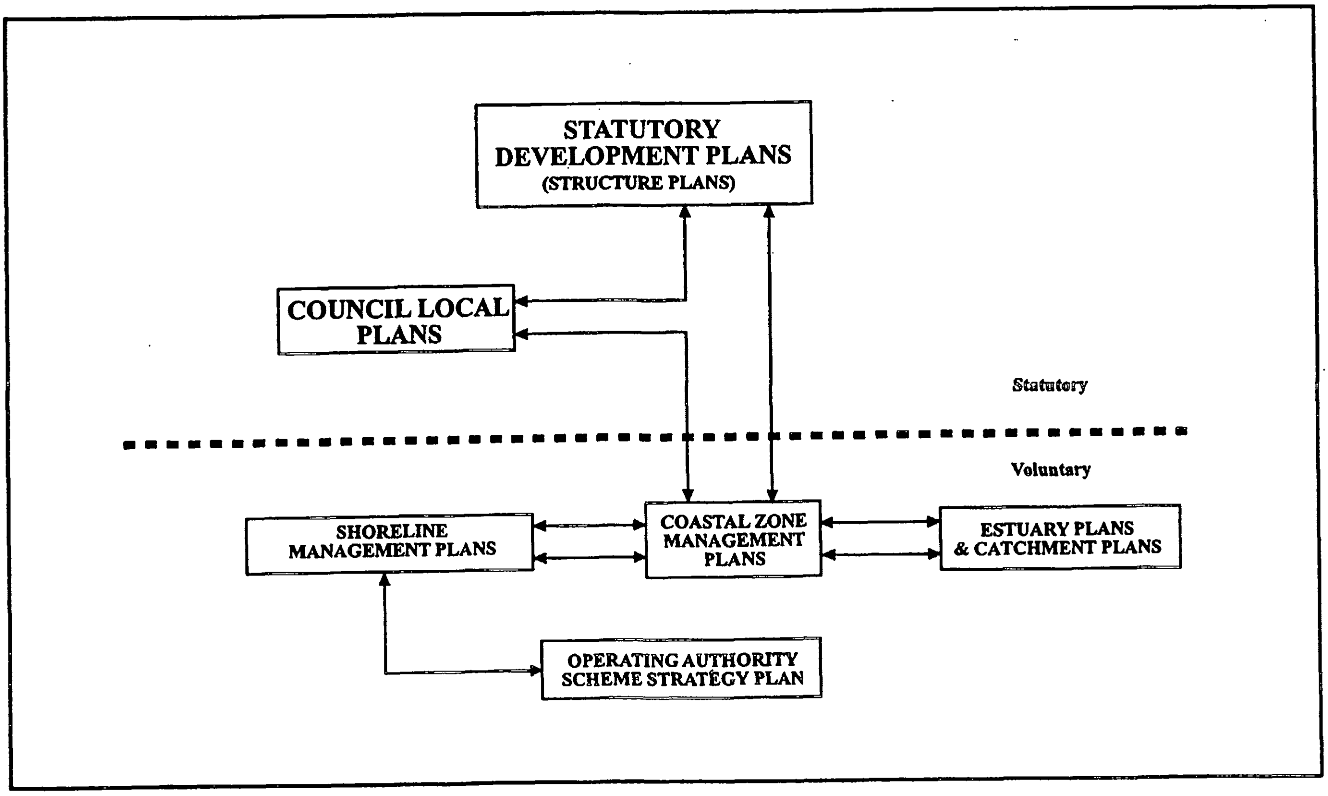

Figure 4 Relationship between coastal initiatives

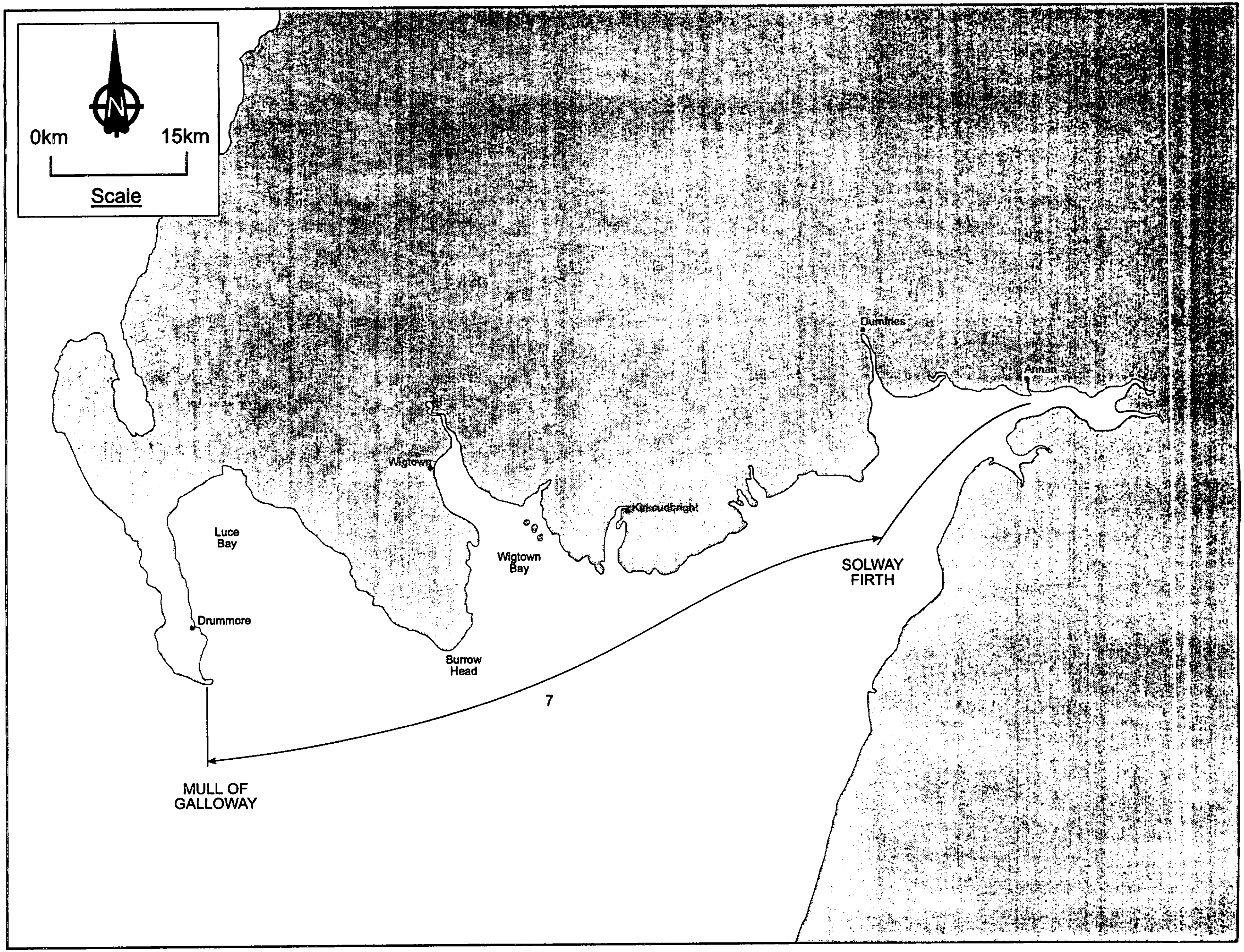

Figure 5 Cell 7 - Mull of Galloway to the Solway Firth

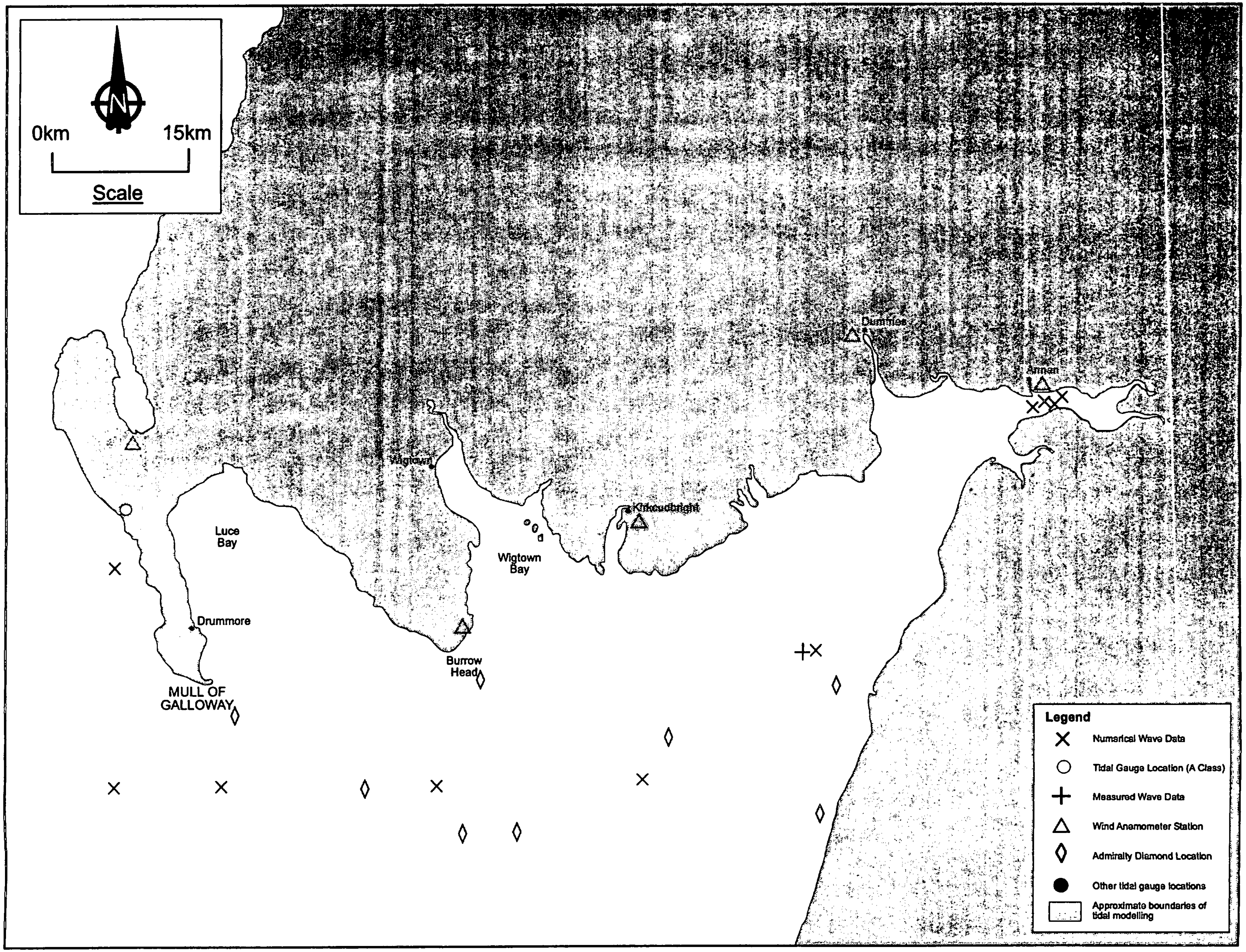

Figure 6 Cell 7 - Location of wind, tidal and wave data

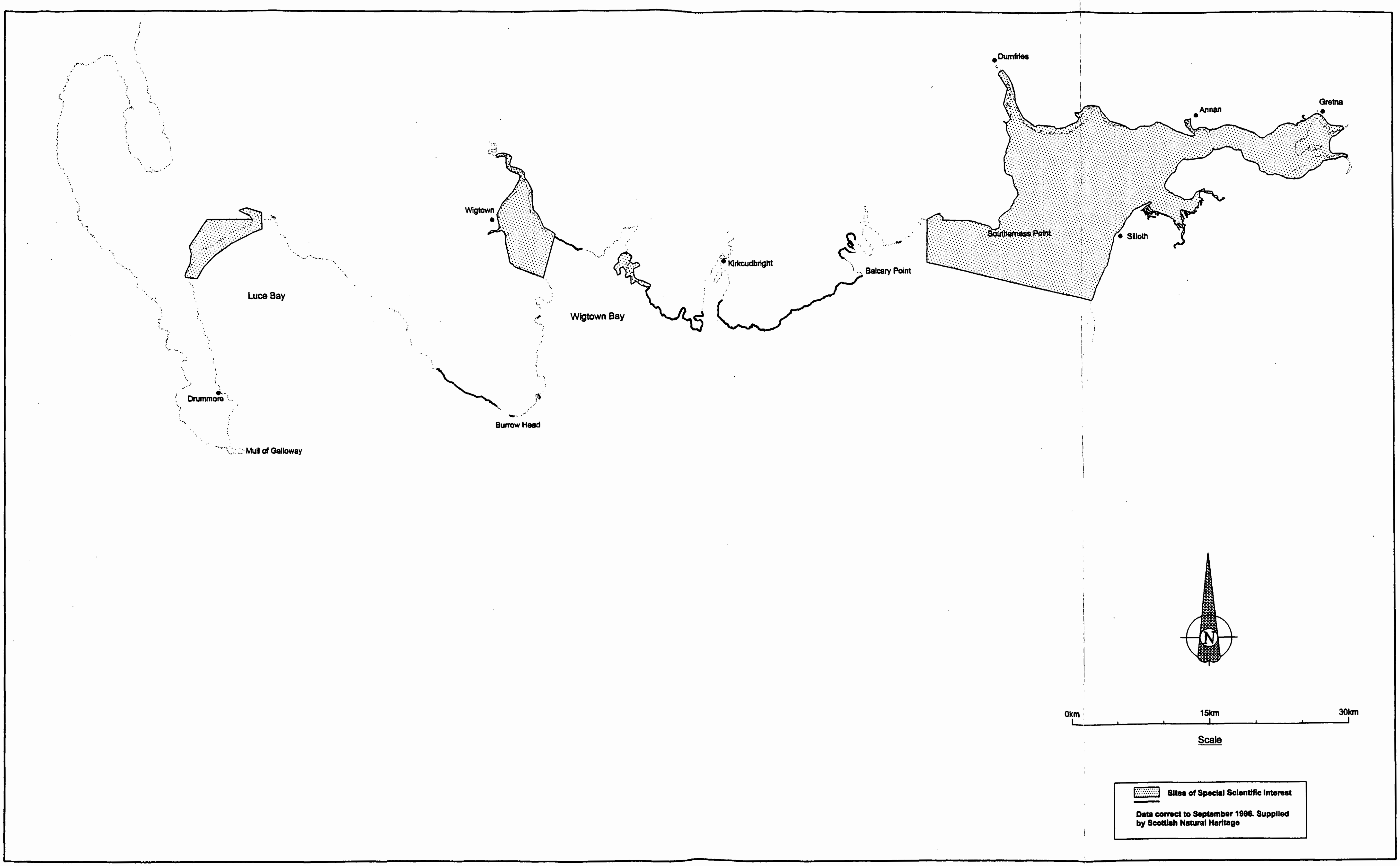

Figure 7 Cell 7 - Location of Sites of Special Scientific Interest

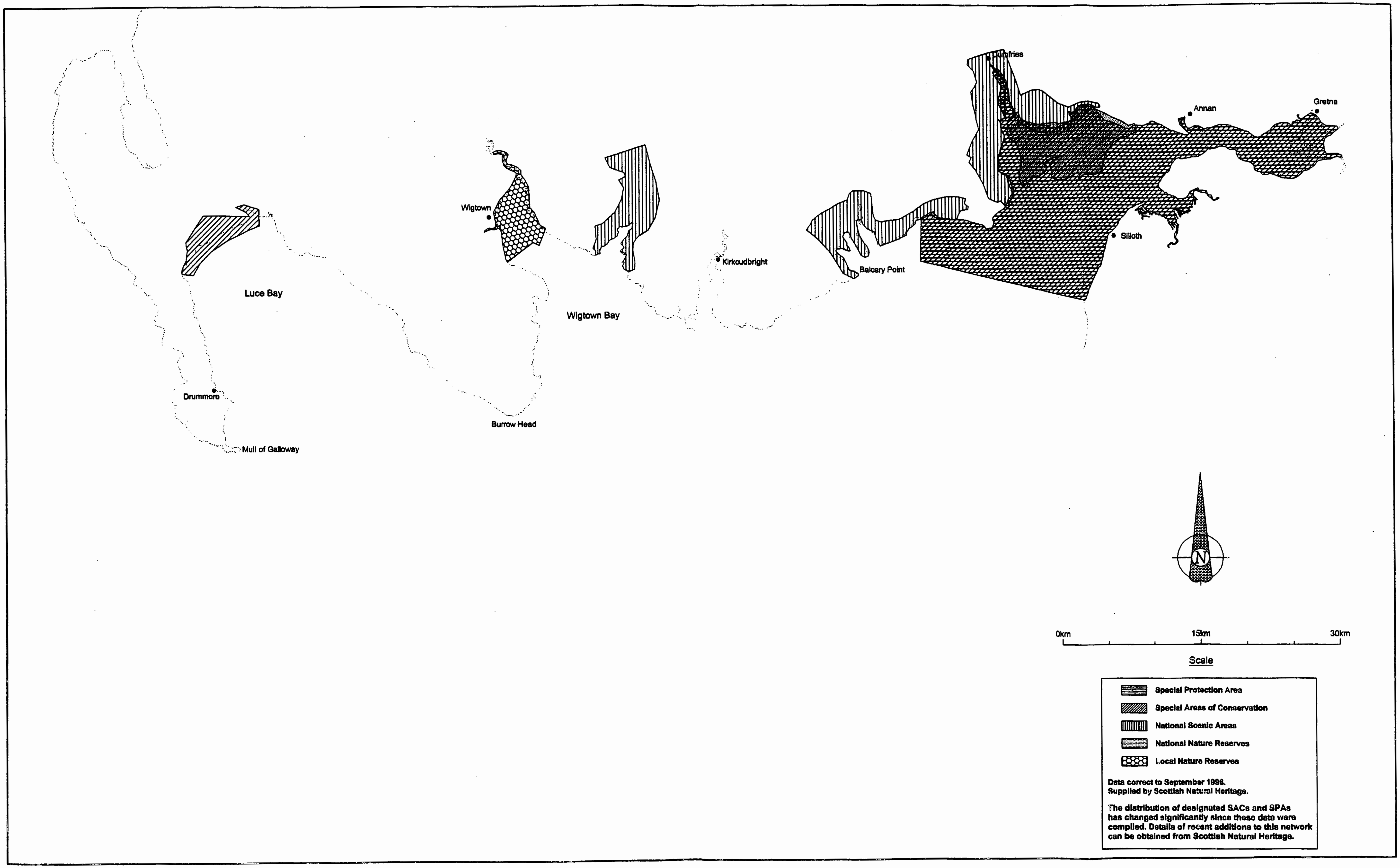

Figure 8 Cell 7 - Location of sites of natural heritage importance (other than SSSIs)

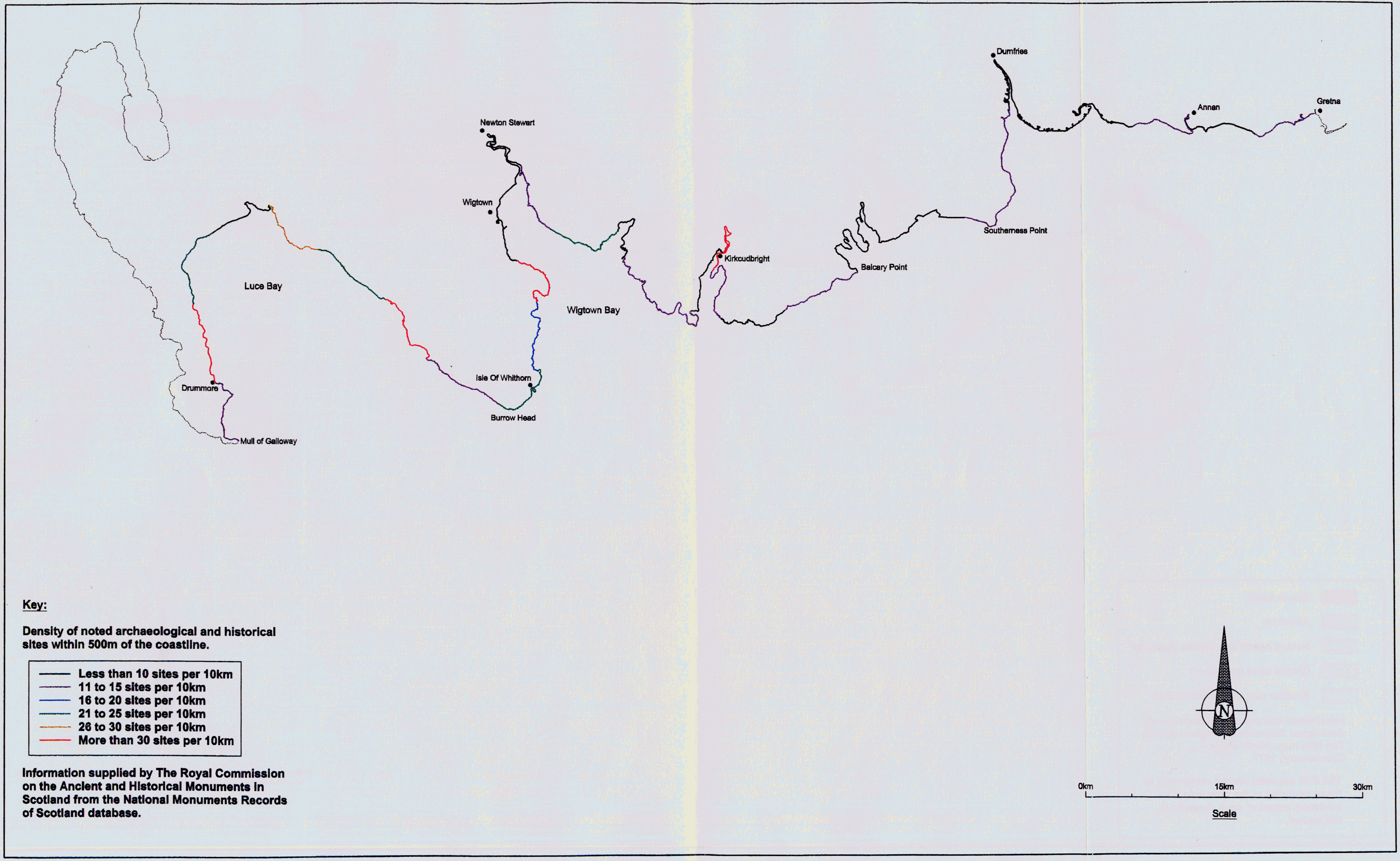

Figure 9 Cell 7 - Density of noted archaeological and historical sites

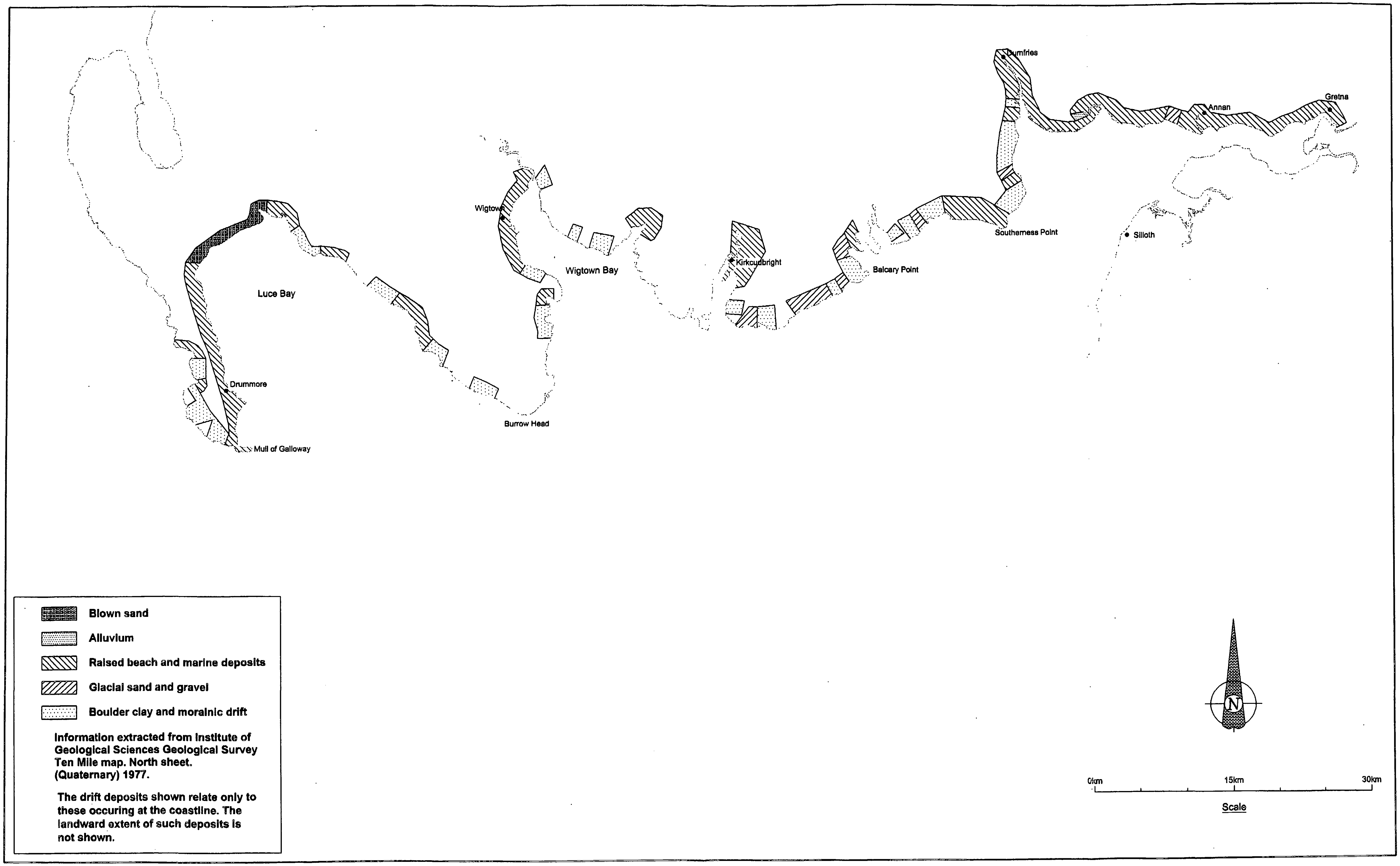

Figure 10 Cell 7 - Drift deposits

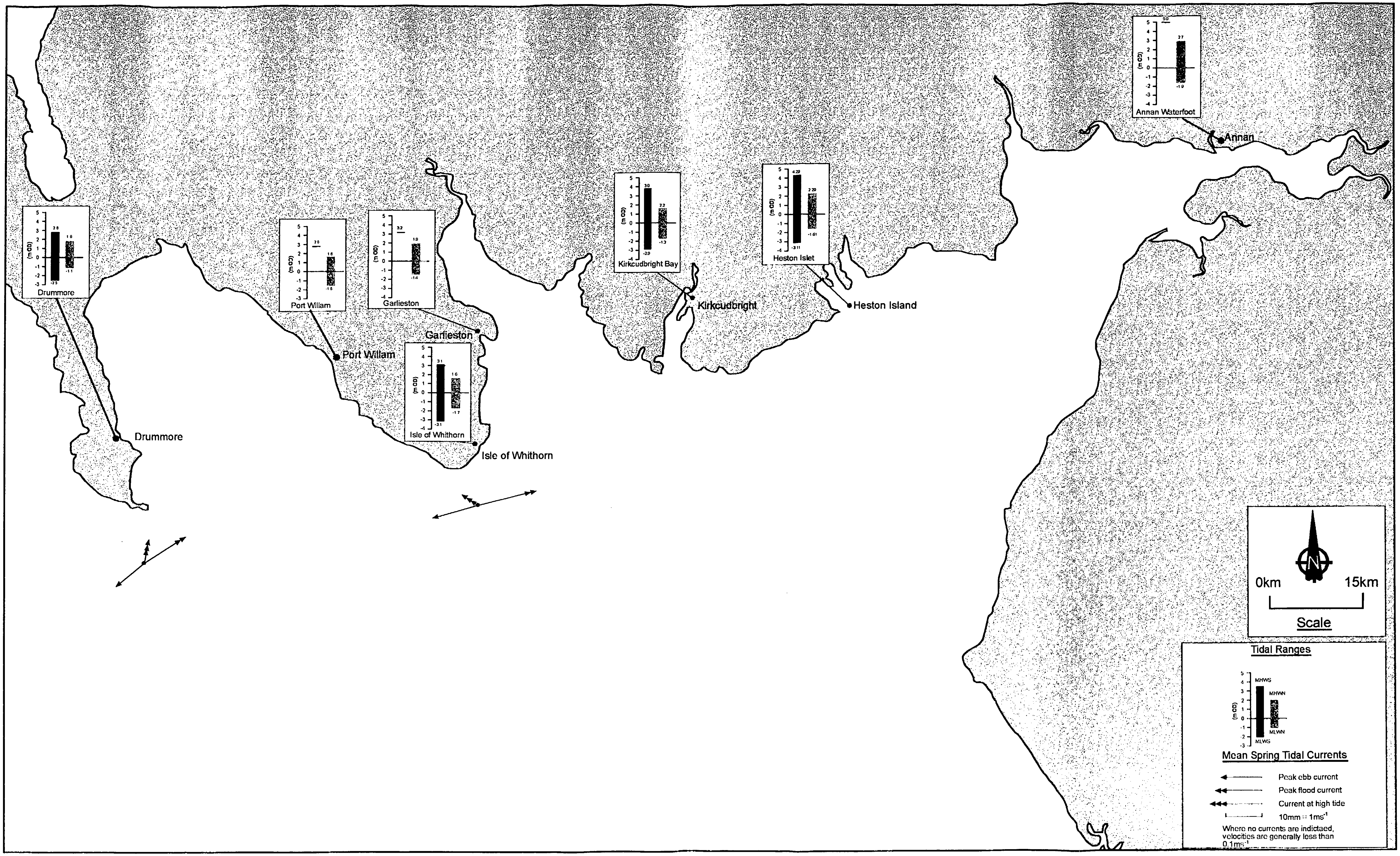

Figure 11 Cell 7 - Tidal levels and current information

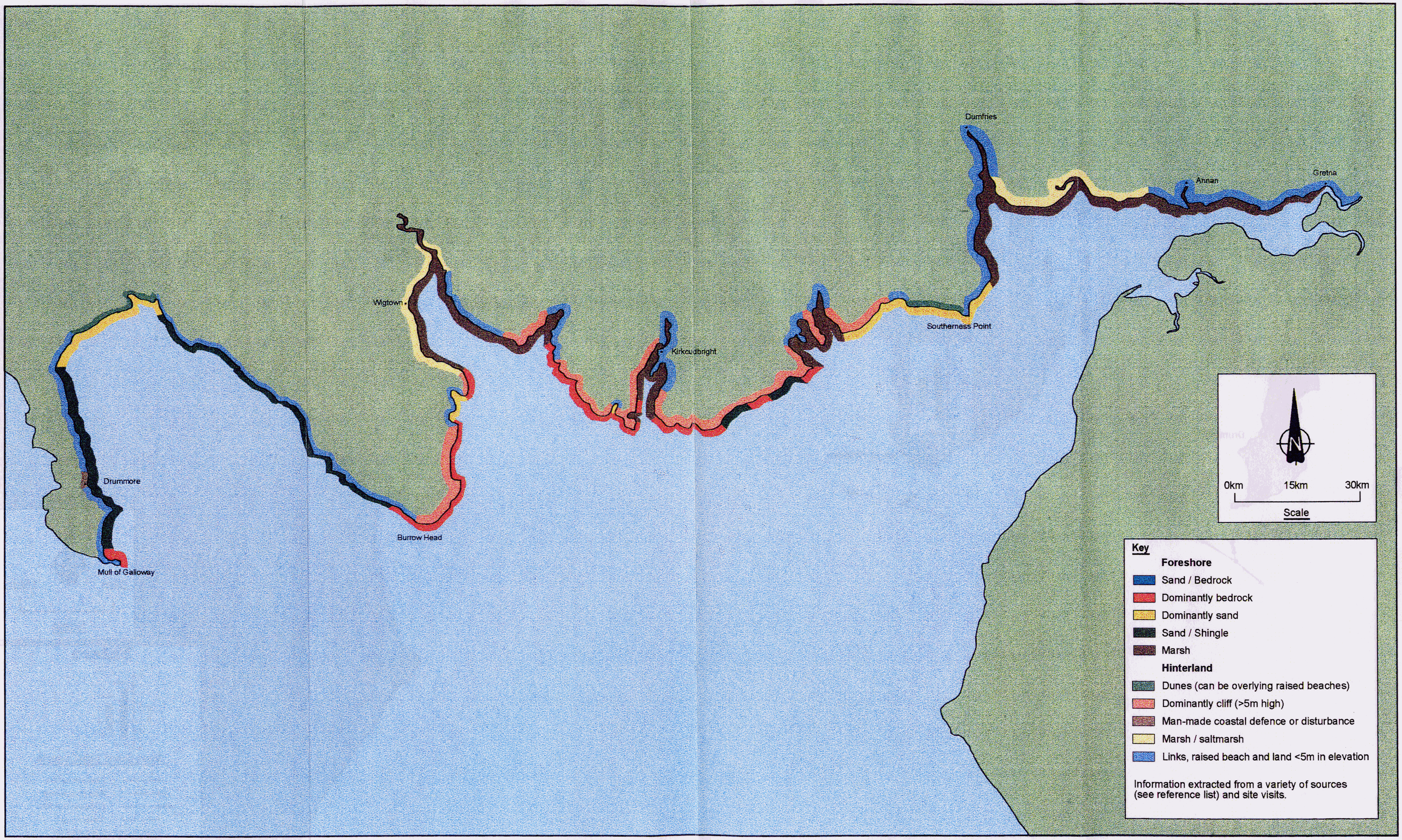

Figure 12 Cell 7 - Foreshore and hinterland characteristics

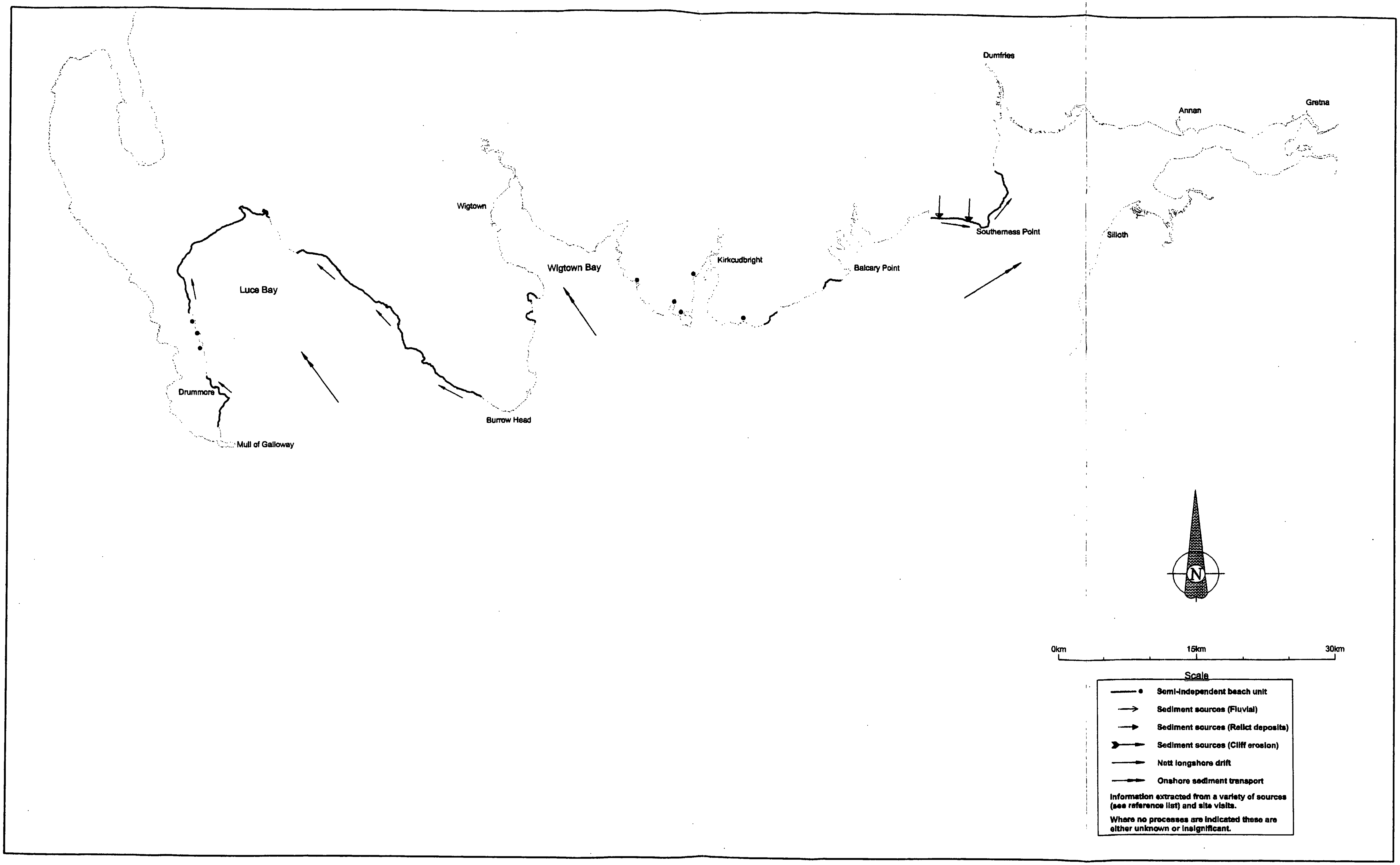

Figure 13 Cell 7 - Dominant littoral processes

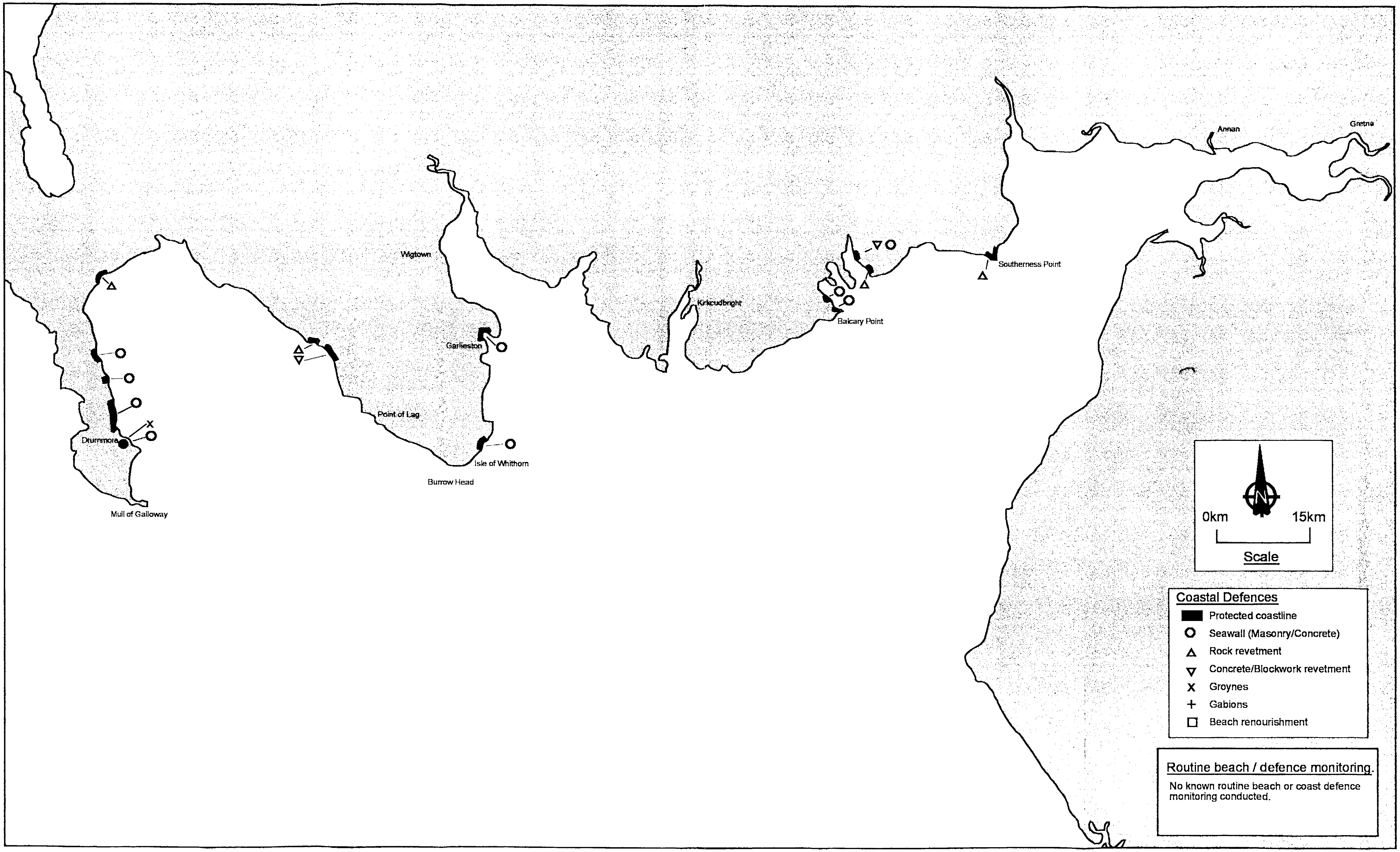

Figure 14 Cell 7 - Coastal defence and monitoring

Appendix 1 Cell 7 - 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
Royal Ordnance, Powfoot	NY165657	37	1994	No site designation noted
Port O'Warren	NX876534	5.9	1990	Sea cliff(hard rock) Dry grassland Maritime heath Scrub Seabirds breeding Comments: Largest cormorant colony in district, 2% of UK population.
Auchencairn & Orchardton Bays	NX809517	178.7	1988	Saltmarsh Site used for wintering wildfowl. Locally important
Abbey Burn Foot to Balcary Point	NX790469	186	1988	Vegetated shingle Sea cliff(hard rock) Dry grassland Maritime heath Scarce or rare plants Terrestrial invertebrates Seabirds breeding Comments: Breeding fulmar, gulls, black guillemot, rock pipit & cormorant.
Torrs to Mason's Walk	NX710437	168	1987	Geological interest Saltmarsh Sea cliff(hard rock) Dry grassland Maritime heath Flush or seepage line Scrub Scarce or rare plants Terrestrial invertebrates Comments: Oyster plant (*Mertensia maritima*).
Shoulder O'Craig	NX663491	0.5	1988	Geological interest
Borgue Coast	NX610457	749.1	1988	Geological interest Sand dunes Sea cliff(hard rock) Machair Dry grassland Maritime heath Peatland Fen Terrestrial invertebrates Seabirds breeding Site used for wintering wildfowl. Locally important.

Cree Estuary	NX465545	3456.5	1987	Tidal flats Saltmarsh Terrestrial invertebrates Fish noted Site used for wintering wildfowl. Internationally important. Comments: Pink footed geese; smelt (*Osmerus eperlanus*)
Cruggleton Bay	NX477448	1.3	1989	Geological interest Rocky shore
Isle of Whithorn Bay	NX476363	3.7	1990	Geological interest
West Burrow Head	NX452341	2.3	1989	Geological interest
Back Bay to Carghidown	NX400367	237.4	1988	Geological interest Saltmarsh Vegetated shingle Sea cliff(hard rock) Machair Maritime heath Scrub Scarce or rare plants Terrestrial invertebrates Waders breeding Seabirds breeding
Scare Rocks	NX258333	1.9	1986	Mammals noted Seabirds breeding Comments: Grey seal haulout; gannet, shag, guillemot, razorbill, kittiwakes.
Torrs Warren - Luce Sands	NX140545	2409	1985	Geomorphological interest Sand dunes Maritime heath Fen Terrestrial invertebrates Site used for wintering wildfowl. Locally important. Comments: >220 plant species
Mull of Galloway	NX115315	104.4	1987	Sea cliff(hard rock) Dry grassland Flush or seepage line Mammals noted Seabirds breeding Comments: Grey seal haulout; fulmar, shag, kittiwake, guillemot.

Appendix 2 Cell 7 - 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.