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Coastal Cells in Scotland:
Cell 6 – Mull of Kintyre to the Mull of Galloway

D L Ramsay & A H Brampton

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CONTENTS

Summary

This report reviews the mainland coastline of Cell 6 between the Mull of Kintyre and the Mull of Galloway 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 mainland coastline of Cell 6 between the Mull of Kintyre and the Mull of Galloway, is one of a series of 11 reports covering the entire coastline of mainland Scotland, the Western Isles, Orkney and Shetland. The study concentrates on identifying and describing the various natural and man-made characteristics and processes which affect the behaviour of this particular stretch of coastline. The report includes a description of the dominant hydraulic processes, areas of erosion and accretion, coastal defences and various other aspects of the coastal regime. The aim of the report is to provide an overall understanding of the character and processes occurring within each sub-cell to allow as full an appreciation as 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 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 some general background information on the marine environment in the context of coastal cells. Chapter 4 details available information of relevance to shoreline management in the Firth of Clyde. Chapter 5 forms the main body of the report. A brief description of Cell 6 detailing the cell and sub-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 6 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, 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" in this report. 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.

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

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

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

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

2.2 Coastal planning and development

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

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

2.3 Coast protection legislation in Scotland

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

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

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

Table 1 Required consents for proposed coast protection works

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

Notes

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

Abbreviations used:

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

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

3 The marine environment

3.1 Introduction

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

3.2 Geology and geomorphology

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

In geological terms, Scotland can be considered as being formed of 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 1000 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. 26,000-10,000yrs) and in the post-glacial 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 Post-glacial 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 also 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 in 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 waves are 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, ?.

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:

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

National Nature Reserves (NNR) — Scottish Natural Heritage

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

Marine Nature Reserves (MNR) — Scottish Natural Heritage

Provision is made in the Wildlife and Countryside Act 1981 Sections 36 and 37 to designate marine areas to conserve their marine flora and fauna. This is the only statutory designation which specifically relates to marine areas below the low water mark. Designation procedures involve extensive consultation and protection is by 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 6 - Information sources

4.1 General

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

Two general sources of information exists, for Cell 6. 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 south-west Scotland are detailed in *Coasts and Seas of the United Kingdom: Region 13: Northern Irish Sea* and *Region 14: South-west Scotland: Ballantrae to Mull* (Barne et al, 1996, 1997)
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 of 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, 1971), *The Midland Valley,* (Cameron & Stephenson 1985), and *The Grampian Highlands* (Stephenson & Gould, 1995). These reports reference a large number of more detailed localised studies conducted within the region. The British Geological Survey has 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.

Table 2 Available geological maps

Map No.	Map Name	Solid/Drift Geology	Scale
12	Campbeltown	Solid & Drift	1:50,000
29	Rothesay	Solid & Drift	1:63,360
30W	Greenock	Solid & Drift	1:50,000
22W	Irvine	Solid	1:50,000
14W	Ayr	Solid & Drift	1:50,000
7	Girvan	Solid & Drift	1:50,000
3	Stranraer	Drift	1:50,000
1	Kirkmaiden	Drift	1:50,000
Spec Sheet	Rhinns of Galloway	Solid	1:50,000

The geomorphology of the south-west coast of Scotland is described in several studies, the main texts being *The coastline of Scotland* (Steers, 1973); *The beaches of south west Scotland (Vol 1 & 2)* (Mather, 1979); *The beaches of Cowal, Bute and Arran*, (Ritchie, 1975); and *The beaches of mainland Argyll* (Crofts & Ritchie, 1973). Other, more localised, studies have also been conducted. These include a Shoreline Management Plan for the coastline between Saltcoats and Troon (HR Wallingford, 1996) and a similar management plan for the coast between Ayr and Troon (Carter & Scott, 1992).

4.3 Bathymetry

The bathymetry within the Firth of Clyde and just offshore is illustrated in detail on the following Admiralty Charts:

Table 3 Available Admiralty Charts

Chart No.	Location	Scale
1403	Loch Ryan	1:25,000& 1:10,000
1864	Harbours & anchorages in the Firth of Clyde	Various
1866	Ports in the Firth of Clyde	Various
1867	Plans in the Firth of Clyde	Various
1906	Kyles of Bute	Various
1994	Approaches to the River Clyde	1:15,000& 1:5,000
2000	Gareloch	Various
2126	Approaches to the Firth of Clyde	1:75,000
2131	Firth of Clyde & Loch Fyne	1:75,000
2198	North Channel - Southern part	1:75,000
2199	North Channel - Northern part	1:75,000
2220	Firth of Clyde: Pladda to Inchmarnock - South sheet	1:36,000
2221	Firth of Clyde: Pladda to Inchmarnock - Northern sheet	1:36,000
2381	Lower Loch Fyne	Various
2382	Upper Loch Fyne	1:25,000
2383	Inchmarnock Water	1:25,000
2491	Ardrossan to Largs	1:25,000
2724	North Channel to the Firth of Lorne	1:200,000
2798	Loch Foyle to Sanda Island including Rathlin Island	1:75,000
3746	Loch Long and Loch Goil	1:25,000& 1:12,500

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

4.4 Wind data

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 (Table 4 and Figure 6). At West Freugh and Machrihanish the recorders are equipped with Semi-Automatic Meteorological Observing Systems (SAMOS) which produce wind statistics continuously for immediate archiving. The Met Office also holds wind data recorded at Ardrossan and Prestwick but the wind recording facilities have now closed. In the Inner Firth of Clyde, winds are also recorded at Greenock Port and Abbotsinch. Winds have also been recorded at Hunterston and Faslane but the data have not been passed to the Met Office. A summary of the available wind data is provided in the following table:

Table 4 Cell 6 - Availability of wind data

Location	Period covered	Anemometer Type
Abbotsinch	01/70 - Present	Digital Anemograph Logging Equipment (DALE)
Ardrossan	01/70 - 1994	Digital Anemograph Logging Equipment (DALE)
Faslane	unknown	unknown
Greenock Port	01/76 - Present	Data on Metform 6910
Hunterston	unknown	unknown
Machrihanish	01/70 - Present	Analysed anemograph from SAWS/SAMOS/CDL station
Prestwick	01/70 - 1994	Digital Anemograph Logging Equipment (DALE)
West Freugh	01/70 - Present	Analysed anemograph from SAWS/SAMOS/CDL station

4.5 Tidal data

A-class tidal gauges within this cell are located at Millport and Portpatrick, Figure 6. A-class gauges are installed and maintained as part of a national network of tide-gauges organised by the Proudman Oceanographical Laboratory (POL) situated at Bidston, Merseyside. 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 6. 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 tide gauge is also located at Greenock, but is not part of the A-class network.

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 dataset are described in the report *Data holdings of the PSMSL* (Spencer & Woodworth, 1993) which can be obtained from the Bidston Observatory. Within Cell 6 the A-class gauges at Millport and Portpatrick are used to record mean sea levels for the PSMSL service.

Actual tidal levels, however, can and often do vary significantly from those predicted using harmonic analysis due to meteorological effects (surges) (see Section 3.3). The UK Met Office Storm Warning Service operate 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 from the A-class tide gauge network 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 coast of the UK mainland (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.

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 from 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.

Secondly, general details of tidal current patterns within and around the Firth of Clyde are provided in *The Tidal Stream Atlas: Irish Sea* (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 two sources, either from measured wave data or from synthetic wave data generated using numerical models. The only detailed record of instrumentally recorded wave data in Scotland is the MIAS catalogue (MIAS, 1982) which was compiled in 1982 and a catalogue compiled by Metocean (1994). An updated digital version of the MIAS catalogue is presently being developed. Other wave recording has been conducted by commercial organisations normally in connection with marine construction projects, e.g. harbour development. The only known deployment of wave recording equipment in Cell 6 was at Ardrossan (Table 5).

Table 5 Sources of measured wave data

Location	Lat/Long	Period covered	Mean Water Depth (m)	Contact
1800m south of Ardrossan Harbour	55°37'43"N 04°49'32"W	31 Oct 1978-01 Nov 1979	20m	MIAS Catalogue

The record in Table 5 contains 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 numerical wave 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 wave period (T_m). Although not scientifically measured, VOS records have been found to be a useful source of data where there have been a large number of records spanning over many years, e.g. major shipping lanes. VOS data are 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 offshore locations, 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 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. However, the resolution of the model is insufficient to correctly predict wave conditions in the North Channel and outer Firth of Clyde area. Modern numerical methods are also capable of accurate predictions of "wind-sea" for offshore areas, especially if there are good quality, sequential wind data available to provide the basic input conditions. There are a number of sites where offshore wave conditions have been numerically modelled, the locations of which are shown in Figure 6, with further details given in Table 6.

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. Table 6 details the locations where inshore wave conditions have been assessed, namely at Girvan, between Troon and Saltcoats, Fairlie and at Faslane.

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
Offshore of Girvan NW of Girvan Harbour	 55°14'14"N 4°52'W	1976-1985 1976-1985	>50m -5m CD	Climate & extremes to 1:100 Climate & extremes to 1:100	HR Wallingford
Offshore of Troon Barassie Irvine Beach Ardeer Beach	 55°33'45"N 4°40'24"W 55°35'18"N 4°41'18"W 55°37'00"N 4°44'06"W	1976-1985 1976 -1985 1976 -1985 1976 -1985	>39m -5m CD -5m CD -5m CD	Climate Climate Climate Climate	HR Wallingford
NATO Pier, Fairlie	-	-	-	Extremes to 1:100	HR Wallingford
Rhu Narrows	NS 259 837 NS 268 836 NS 273 833	-	20m 5m 7m	Extremes	HR Wallingford
Faslane	56°4.1°N 4°49.6'W	-	-20m CD	Climate & extremes to 1:1000	HR Wallingford

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.

Within Cell 6 the number of designated natural heritage sites is given in Table 7. The location of Sites of Special Scientific Interest is shown in Figure 7 with further information on these detailed in Appendix 1. Other natural heritage designations are shown in Figure 8.

Advice on historical or archaeological sites within the coastal hinterland of the south west coast of Scotland, can be obtained from Historic Scotland. A description of the various designations is given in Section 3.6.

Table 7 Natural heritage designations

Designation	Number	Designation	Number
SSSI	30	NSA	2
NNR	1	NHA	-
MNR	-	AGLV	-
LNR	-	ESA	-
SAC	-	MCA	-
SPA	-	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.

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) maintains a GIS database (National Monuments Records of Scotland, NMRS) with the locations of scheduled archaeological and historical sites. The locations of such sites were obtained from the RCAHMS. Only the locations of sites within 50m of the coastline were requested. However, the RCAHMS advised that to locate all 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 long strips along the coastline of Cell 6. 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, such as Listed Buildings, which do not appear in the NMRS database.

Table 8 Cell 6 - 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 6: Mull of Kintyre to Mull of Galloway

5.1 General

Cell 6 has been defined, (HR Wallingford, 1997), as the coastline between the Mull of Kintyre and the Mull of Galloway, Figure 5. The cell encompasses all beaches on the mainland surrounding the Firth of Clyde but excludes all the islands within the Firth of Clyde. Accordingly, island coastlines are not described in the following sections.

The Mull of Kintyre and Mull of Galloway both form major boundaries to wave induced longshore transport. Both act as a drift divide to any sediments being moved by wave action along the coast. However, neither will act as a drift divide to sediments transported on the seabed by strong tidal currents offshore. The cell is further sub-divided into four sub-cells. These are also shown in Figure 5. Sub-cell 6a has been defined as the coastline between the Mull of Kintyre and the Inner Firth of Clyde. There is no physical boundary in terms of littoral transport in the Inner Firth of Clyde but for the purpose of this report a line running north-south at Dumbarton is defined as the inner boundary as wave induced longshore transport is unlikely to be significant further upstream. Only on the eastern frontage of the Kintyre peninsula do significant littoral processes occur within this sub-cell. Along the edges of the large sea lochs, such as Loch Fyne and Loch Striven, beaches are virtually non-existent with the foreshore covered by unsorted shingle, cobbles and boulders. As such these areas will not be discussed as the concept of coastal cells is not applicable for the reasons outlined in Chapter 2. Sub-cell 6b is defined as the southern coastline of the Inner Firth of Clyde and extends from there to Farland Head. There are only a few minor beach areas in this region. Sub-cell 6c extends from Farland Head to Bennane Head. Much of this coastline is fronted by beach areas with most of the sand beaches within Cell 6 occurring within this sub-cell. Sub-cell 6d is specified as extending from Bennane Head to the Mull of Galloway. Beach areas along much of this coastline are in the form of pocket beaches with little sediment movement to or from these units, so the sub-cell has not been divided further. Within each sub-cell relatively self contained beach units can also be identified. For example there is unlikely to be significant interchange of beach material between the individual beach areas in sub-cell 6a. The locations of these "semi-independent beach units" are shown on the relevant littoral process maps.

Sections 5.3 to 5.6 describe the coastal regime occurring within Cell 6.

5.2 Cell 6: Physical characteristics

5.2.1 General

The characteristics of Cell 6 and processes occurring within it are described under the headings of Geology and geomorphology, Hydraulic processes, Littoral processes and Coastal defences and monitoring.

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

Details of the dominant hydraulic processes, i.e. the tides, currents and waves, are described. Tidal elevations within each sub-cell are described, Figure 11, 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 is known to occur is noted. The dominant nearshore processes which affect the transformation of offshore to inshore wave conditions are also described.

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

The final section details the location, type and influences of coastal protection work occurring in Cell 6. 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. The 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 the relevant figures for each sub-cell.

5.3 Sub-cell 6a: Mull of Kintyre to the Inner Firth of Clyde

5.3.1 Geology

Much of the coastal edge of Cell 6 is dominated by the solid geology, particularly in Sub-cell 6a where there is little "soft" coastline. There is considerable variability in the solid geology particularly around the Highland Boundary Fault which splits the sub-cell just to the north of Helensburgh.

Much of the basement rock of the Kintyre and Cowal peninsulas is composed of metamorphic rocks. Known as the Dalradian Supergroup, these are the oldest rocks within Cell 6, having been formed during the Pre-Cambrian (>544Ma). Of these, the oldest rocks are the Argyll Group which occur around the coastline of Loch Fyne and consist mainly of quartzite and schistose grits. The younger Southern Highland Group outcrop at the coastline mainly between Campbeltown and East Loch Tarbert and around most of the Cowal peninsula. These rocks consist of a variety of metamorphic rock types. All of the metamorphic rocks are extremely resilient to marine erosion resulting in much of the coastline where they outcrop being in a neutral state.

Around the south-eastern tip of the Kintyre peninsula cliffs of Old Red Sandstone are evident in the hinterland. At present these are not being worked by marine action, but during periods of previous higher sea levels they will have contributed a supply of material to the beach systems in this area.

To the south of the Highland Boundary Fault the character and lithology of the rock changes somewhat. The underlying bedrock to the south of Helensburgh is mainly Old Red Sandstone though exposures on the coast are scarce.

The Ice Age had a significant influence upon this area, the general feature being one of erosion with the formation of the long, glaciated sea lochs. There is a general lack of glacial deposits, reflected in the lack of material for the development of beach areas within this sub-cell. Most of the glacial deposits tend to consist of boulder clay with few fluvio-glacial sands and gravels evident. Reworking of some of these boulder clay deposits has produced raised beach features which contain deposits of sands and gravels. However, such areas are not extensive and tend to be restricted to the hinterland of the pocket beaches found in Cowal and in a narrow strip along the Helensburgh and Dumbarton coastline.

5.3.2 Hydraulic processes

The tidal cycle experienced within this cell is semi-diurnal with a period of approximately 12.4 hours in the Inner Firth of Clyde (Greenock). In the inner Firth, on average, the spring flood tide runs for a longer period than the ebb (approximately 6 hours 40min and 5 hours 35 minutes respectively) whereas the opposite occurs on the neap with a flood tide period of 5 hours 55 minutes and ebb tide period of 6 hours 30 minutes. The tidal wave passes into the Firth around the Mull of Kintyre taking over 3 hours to reach Glasgow. Tidal ranges on both spring and neap increase towards the inner Firth and sea lochs with a mean spring range of 2.0m at the Mull of Kintyre and a corresponding range of 4.0m at Glasgow, Table 9.

At the head of the sea lochs water elevations are affected by strong winds. Winds blowing in the direction of the head of the loch will delay low water and cause an increase in water levels whereas winds blowing away from the head of the lochs will tend to hasten and decrease low water. High waters will be similarly affected.

Table 9 Sub-cell 6a - Predicted tidal levels and ranges

Location	MHWS (m OD)	MLWS (m OD)	Spring Range (m)	MHWN (m OD)	MLWN (m OD)	Neap Range (m)	ODN to CD (m)
Southend, Kintyre	1.22	-0.78	2.0	0.72	-0.38	1.1	+0.88
Campbeltown	1.51	-0.89	2.4	1.11	-0.29	1.4	+1.39
Carradale	1.48	-1.22	2.7	0.98	-0.52	1.5	+1.62
Lochranza	-	-	2.7	-	-	1.6	-
East Loch Tarbert	1.78	-1.42	3.2	1.18	-0.52	1.7	+1.62
Inveraray	1.68	-1.52	3.2	1.28	-1.12	2.4	+1.62
Rubha Bodach	1.58	-1.12	2.7	1.08	-0.42	1.5	+1.62
Tighnabruaich	1.78	-0.82	2.6	1.38	-0.22	1.6	+1.62
Rothesay Bay	1.98	-1.12	3.1	1.38	-0.42	1.8	+1.62
Coulport	1.78	-1.32	3.1	1.18	-0.62	1.8	+1.62
Lochgoilhead	1.58	-1.62	3.2	0.88	-0.92	1.8	+1.62
Arrochar	1.78	-1.42	3.2	1.18	-0.72	1.9	+1.62
Rosneath	1.78	-1.32	3.1	1.08	-0.62	1.7	+1.62
Faslane	1.78	-1.52	3.3	1.18	-0.72	1.9	+1.62
Garelochhead	1.78	-1.42	3.2	1.18	-0.62	1.8	+1.62
Helensburgh	1.78	-1.32	3.1	1.18	-0.62	1.8	+1.62
Bowling	2.38	-1.22	3.6	1.68	-0.32	2.0	+2.00

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.

The most commonly referred to research on extreme water levels in the UK is that conducted by Graff (1981) and Coles & Tawn (1990). This analysis was based on tidal records from the A-class tide gauge network. In these publications the only location in sub-cell 6a where predictions of extreme water levels have been made is Glasgow. However, within the Firth of Clyde predictions have also been made at Ardrossan and Gourock. The predictions are detailed in the table below:

Table 10 Extreme water level predictions in the Firth of Clyde

Graff (1981):

Location	Return period levels (height above ODN (m))						
	1	5	10	20	50	100	250
Glasgow	3.47	3.92	4.06	4.26	4.46	4.56	4.75
Gourock	2.78	3.05	3.18	3.27	3.37	3.45	3.52
Ardrossan	2.49	2.88	3.03	3.20	3.40	3.52	3.72

Coles & Tawn (1990):

Location	Probability of annual maximum tidal levels (m ODN)		
	10%	1%	0.1%
Gourock	3.01	3.26	3.43
Ardrossan	2.78	3.44	4.21

The latest research into trends of extreme water levels (Dixon & Tawn, 1997) provides a spatial analysis at any location around the coastline of the UK mainland. In this study the predicted extreme water levels depend on the year of interest allowing for trends in mean sea level rise and hence have not been reproduced in this report. This research is likely to provide the most up-to-date and comprehensive analysis of extreme water levels available.

There is little other information on extreme water levels within this sub-cell. The 1:50 year return period surge (BODC, 1992) is calculated to be about 1.25m at the Mull of Kintyre increasing to over 1.75m in the Firth of Clyde to the north of Arran. Towards the inner Firth and in the sea lochs there is likely to be further amplification of surge levels.

The main flood tidal stream runs through the North Channel between the Mull of Kintyre and the coastline of Ireland, across the mouth of the Firth of Clyde, and southwards along the western coastline of the Rhinns of Galloway into the Irish Sea, with the ebb following the same path in reverse. Within the Firth of Clyde, along the coastline of Sub-cell 6a, the flood stream flows around the Mull of Kintyre and north through the Kilbrannan Sound, into Loch Fyne and through the Kyles of Bute. Along the eastern coastline of the Mull of Kintyre, peak spring rates can reach $0.75ms^{-1}$ off the headlands but are much lower close inshore. The flood stream also flows northwards in the Outer Firth of Clyde to the east of Arran and up into the Clyde Estuary and also into the Kyles of Bute. The two north going streams meet in the vicinity of the Burnt Islands. In the Kyles of Bute, peak Spring rates can reach 1 to $1.5ms^{-1}$ in the narrows.

In the Clyde Estuary the main stream generally follows that of the main channel. At the entrance to Gare Loch the stream divides with part running into Gare Loch and part running to the south east, past Ardmore Point and into the Inner Firth of Clyde. Rates are dependant on both river flows and meteorological conditions. Close inshore it is unlikely that tidal currents will be significant. Tidal current rates are, in general, insignificant in the sea lochs with the exception of a few localised areas. The most notable areas are in Loch Fyne where the loch narrows at the Otter Ferry and in the Rhu Narrows in Gare Loch where peak rates are between $0.5ms^{-1}$ and $1ms^{?1}$. During peak flows through the Rhu Narrows eddies occur in the lee of the promontories.

Waves occurring in the Firth of Clyde can arise from three different sources: Atlantic swell which propagates through the North Channel and into the outer Firth, waves generated within the Irish Sea and from locally generated wave conditions in the Firth. The influence of waves from the Irish Sea is likely to be least important apart from along the Rhinns of Galloway coastline and at the southern end of the Mull of Kintyre. Atlantic swell will affect the eastern coastline of the Outer Firth of Clyde and the Galloway coastline. The eastern coastline of the Mull of Kintyre and Inner Firth of Clyde will tend to be sheltered from Atlantic swell. Hence, locally generated wave energy will be the dominant wave mechanism affecting the coastline of Sub-Cell 6a.

Wave conditions experienced at the coastline of Sub-cell 6a will be highly variable due to varying degrees of exposure. Hence any assessment of wave conditions will be site specific as exposure and wave severity can change significantly over relatively short lengths of frontage. For instance, wave conditions at the Mull of Kintyre will be relatively more severe than those experienced within the sea lochs to the north of the sub-cell.

There is little quantitative information on wave conditions experienced upon this coastline. The prevailing wind direction is from the south westerly quadrant resulting in the eastern coastline of the Mull of Kintyre being sheltered from direct wave attack for a large percentage of the time. The southern section of the Mull of Kintyre is exposed to fetch lengths which extend to the east and south east as far as the Ayrshire and Galloway coastlines and to waves from a narrow wave window to the south where fetches extend through the North Channel and into the Irish Sea.

Within the sea lochs, and Inner Firth of Clyde, wave conditions will be most severe when winds are blowing parallel to the major axes of the lochs. For instance the longest fetch length in Loch Fyne is orientated to the south west resulting in winds being channelled up the loch. The importance of the fetch length for wave generation can be seen at Faslane where an assessment of wave conditions has been conducted (HR Wallingford, 1986). For waves from the longest fetch (i.e. to the south) the most severe wave heights are double those experienced from other directions.

5.3.3 Littoral processes

Beaches in sub-cell 6a are generally located along the eastern coastline of the Kintyre peninsula with a few small beaches occurring on the Cowal peninsula. Elsewhere along the edges of the large sea lochs beaches and beach processes are minimal. In general most of the beach areas in Sub-Cell 6a are either in a relatively stable state or are suffering erosion. There is little nett accretion of beach sediments and little fresh input of sediment into the present sediment budget of this coastline. The character of the foreshore and hinterland is summarised in Figure 12 with the dominant littoral processes shown in Figure 13.

On the Kintyre peninsula the main beach areas occur along the southern coastline around Southend and between Campbeltown and Skipness Point. At the southern tip of the Kintyre peninsula there are three main sandy beach areas, Carskley Bay, Dunaverty Bay and Brunerican Bay. Beach material is dominantly of fluvio-glacial origin and has been reworked during periods of, formerly, higher sea levels. All three beaches are dominantly sandy, backed by a frontal dune ridge and undulating machair surface. At Carskley there is a nett longshore transport westwards. Rates are not high but this is causing some erosion of the frontal dunes at the eastern end of the bay. The other two bays appear to be relatively stable with little frontal dune erosion due to wave action except at the eastern end of Brunerican Bay. Some wind erosion of the frontal dunes is also occurring at Brunerican Bay resulting in blown sand being deposited onto the golf course. There are a number of other thin sand and shingle beaches on the south east coastline of the Kintyre peninsula mostly backed by a narrow section of raised beach and fossil cliffs, most notably at Macharioch and Polliwilline.

Between Campbeltown and Skipness Point the potential for nett longshore drift is strongly to the north. However, there is no discernible longshore transport of material along this coastline (and there is unlikely to have been any significant movements during present sea levels due to the rocky nature of the coastline and the low volume of available beach material). The largest beach systems are those which face the south, such as at Saddell and Carradale where beach sediments have previously accreted. Rock reefs and a low rocky edge occur along much of the coastal edge limiting erosion with the main beaches forming between these outcrops.

From Macringans Point to Saddell Bay the coastline is characterised by thin sand and shingle beaches between, or resting on top of, rock outcrops. Most of these small beach systems are relatively stable with little input or output of material and only minor localised erosion of the coastal edge. The largest of these systems is at Ardnacross Bay where a wide sandy beach has formed. Longshore drift will, formerly, have been to the north, but the situation at present is relatively stable. Some storm erosion of the low coastal edge is evident.

The shingle beach at Saddell faces to the south. There is an abundance of shingle and the entire system is in an extremely stable condition and is likely to remain so. The sand/shingle beaches at Torrisdale and Dippen are well sheltered and, despite there being a low volume of beach material, they are both relatively stable with little erosion noted. As at Saddle, the beach system at Carradale faces due south and is well nourished with sand and fine gravel. There is little present day erosion evident except at the mouth of the stream at the eastern end of the beach where there is some undercutting of the dune face. There is little loss of material from the bay and with the large supply of sand and gravel stored in the backshore and lack of human intrusion this beach system is likely to cope with minor changes in incident hydraulic conditions.

There are a number of small shingle pocket beaches to the north of Carradale. The most notable of these is Claonaig where there is undercutting of the coastal edge. However, this erosion is not too serious given the thickness of the glacial gravel deposits backing the beach. The long, mixed sand and shingle beach at Skipness is at present in a stable condition with little evidence of any significant littoral processes causing erosion.

There are few beach systems in the remainder of this sub-cell. Shingle fringe beaches are a common feature around the coastline of many of the sea lochs with there being a number of interesting landforms, notably Otter Ferry. However, none of these are dynamically active at present sea levels. There are a number of pocket beach systems on the Loch Fyne coastline of the Cowal Peninsula of which Kilbride Bay, Auchalick Bay and Kilfinan Bay are among the largest. In terms of beach planshape these bays are stable units and are independent sediment cells with little input or output of beach sediments. Erosion of the coastal edges will occur, but there are sufficient stores of fluvio-glacial sediments in the hinterlands of each system to accommodate this minor erosion. Many of the systems have a range of complex geomorphological features which have been little affected by human activities making them worthy of further study.

The UK Dredged Material Database (MAFF, 1995b) indicates that maintenance dredging has been conducted at Campbeltown in 1990. Dredging is also conducted in the River Clyde. However, much of the siltation is due to fluvial material brought down the Clyde. This dredging is unlikely to have any influence on beach units within this sub-cell.

<u>Summary of erosion and accretion</u>
There are no areas of significant erosion or accretion within this sub-cell.

5.3.4 Coastal defences

Coastal defence work within this sub-cell is restricted to the main town and village frontages and in front of coastal roads. The principal coastal defence works are shown in Figure 14. Note that there are many short stretches protecting roads within the sea lochs not included on this figure. There are few stretches of coastal defence along this coastline which have a significant beach fronting them. There are no locations where coastal defence work is exacerbating erosion.

Coastal defences have recently been constructed at Southend where a rock revetment and sloping gabions protect the edge of the road with minimal impact on the thin sand beach which fronts these works. The only other recent work is at Port Righ where slight erosion of the till cliff backing the beach (upon which a property is situated) has resulted in a small rock revetment being constructed.

Most other defences are low masonry or concrete seawalls, many of which are performing adequately but, given the age of many of these structures, are likely to suffer damage if exposed to storm waves. A new rock revetment is planned to protect the railway line at Cardross.

5.4 Sub-cell 6b: Inner Firth of Clyde to Farland Head

5.4.1 Geology

Much of the solid geology along the southern coastline of the Inner Firth of Clyde is of Devonian and Carboniferous age. The oldest rocks occur at the coastline between Inverkip and Farland Head. These are of Upper Devonian age and consist of fine and medium grained red sandstones, siltstones and mudstones. Carboniferous sandstones and limestones of the Dinantian succession (360Ma to 330Ma) conformably overly the Devonian strata and occupy a thin strip along the coastline between Gourock and Port Glasgow. Volcanic activity affected this area during the Devonian Period resulting in a number of intrusive igneous dykes and sills outcropping at the coast most notably around Inverkip and Farland Head.

Glacial deposits are not as apparent along this part of the Clyde coastline as in other areas, such as the sub-cell immediately to the south. However, such deposits do provide virtually all the sand and gravel material occurring on the present day beaches. Similarly, changes in previous sea levels are not as apparent along this coastline as on other parts of the Ayrshire coast, but do occur. A shore platform and thin raised beach backs the present coastline from Farland Head to around Inverkip, backed in some sections by a relict cliffline. However, little of the beach material stored as raised beach deposits along this coastline provides a fresh input of sediment to the present day beaches because of the many coastal defences protecting this coastline.

5.4.2 Hydraulic processes

The tidal cycle experienced within this cell has a period of approximately 12.4 hours in the Inner Firth of Clyde (Greenock). In the inner Firth, on average, the spring flood tide runs for a longer period than the ebb (approximately 6 hours 40min and 5 hours 35 minutes respectively) whereas the opposite occurs on the neap with a flood tide period of 5 hours 55 minutes and ebb tide period of 6 hours 30 minutes. The mean tidal range is detailed in Table 11 with a mean spring range of 4m at Glasgow reducing to 2.8m at Wemyss Bay.

Table 11 Sub-cell 6b - Predicted tidal levels and ranges

Location	MHWS (m OD)	MLWS (m OD)	Spring Range (m)	MHWN (m OD)	MLWN (m OD)	Neap Range (m)	ODN to CD (m)
Glasgow	2.20	-1.80	4.0	1.50	-0.90	2.4	+2.50
Renfrew	2.05	-1.75	3.8	1.35	-0.75	2.1	+2.25
Port Glasgow	1.98	-1.32	3.3	1.28	-0.62	1.9	+1.62
Greenock	1.78	-1.32	3.1	1.18	-0.62	1.8	+1.62
Millport	1.78	-1.22	3.0	1.08	-0.62	1.7	+1.62
Wemyss Bay	1.78	-1.22	3.0	1.18	-0.52	1.7	+1.62

In Table 11 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.

The most commonly referred to research on extreme water levels in the UK is that conducted by Graff (1981) and Coles & Tawn (1990). This analysis was based on tidal records from the A-class tide gauge network. In these publications the only locations in sub-cell 6b where predictions of extreme water levels have been made is Glasgow. However, within the Firth of Clyde predictions have also been made at Ardrossan and Gourock (see Table 10).

The latest research into trends of extreme water levels (Dixon & Tawn, 1997) provides a spatial analysis at any location around the coastline of the UK mainland. In this study the predicted extreme water levels depend on the year of interest and also include allowances for trends in mean sea level rise (and hence have not been reproduced in this report). This research is likely to provide the most up-to-date and comprehensive analysis of extreme water levels available.

Sea levels are also significantly affected by wind conditions. Strong winds from the south and west result in an increase in sea levels in the Firth of Clyde. At Gourock this has on occasion resulted in an increase of up to 1.2m and in Rothesay Bay as much as 1.5m. Conversely north and east winds tend to cause a decrease in water levels with reductions of 0.9m and 0.5m having been noted at Gourock and Rothesay Bay respectively.

In the Inner Firth of Clyde tidal streams are dependent on river flows with the main stream following the main river channel. Towards Glasgow the duration of the outgoing stream increases in relation to the ingoing stream as flows from the River Clyde become more influential. In general, tidal streams are relatively weak in the main channel and barely perceptible at the coastline. During heavy river flows and during periods with winds from the north and east the rate and duration of the outgoing streams are much increased. Similarly during dry weather with winds from the south and west the rate and duration of the ingoing streams increase.

Between Cloch Point and Wemyss Bay, peak tidal currents are approximately 0.5ms^{-1} in the main channel and slightly greater over Skelmorlie Bank and along the coastline to the north of Wemyss Bay. The main stream flows in a regular pattern parallel to the channel. In the channel between the mainland coastline and the Cumbrae Islands tidal streams rarely exceed 0.4ms^{-1}

In the Inner Firth of Clyde all wave energy will be locally generated. Fetch lengths are also restricted in all directions resulting in limited wave heights. An assessment of wave conditions at Greenock, (HR Wallingford, 1990) indicated that the most severe wave conditions would be experienced from between 300°N and 330°N with a 1:50 year significant wave height of 1.16m. It is unlikely that wave conditions experienced on the north facing coastline of the Firth of Clyde will greatly exceed this value.

To the south of Cloch Point the coastline will be influenced by waves generated further downstream in the outer Firth of Clyde. However, such conditions are restricted to a narrow wave window which extends to the Isle of Arran between Bute and Great Cumbrae Island. For all other directions between Cloch Point and Farland Head fetch lengths are short resulting in relatively mild wave conditions. The only known location on the western facing coastline of this sub-cell where an assessment of wave conditions has been conducted is at Fairlie (HR Wallingford, 1980). Maximum fetch length is about 8.4km in the direction of 210°N with a maximum significant wave height of approximately 1.5m under a Force 9 gale from this direction.

5.4.3 Littoral processes

Between the Inner Firth of Clyde and Farland Head there are few beach areas, Figure 12. Much of the coastline along this frontage is low and rocky with a mixture of muds, sands, gravels and boulders occurring over the flat foreshore. Only at Largs, Wemyss and Lunderston Bays are there beaches of any significance. There is little evidence of any significant beach movements occurring on this coastline, mainly due to the restriction in wave heights due to short fetch lengths, Figure 13. Although there is evidence of a dominant northwards movement of beach material in the past, there is unlikely to be any present day longshore sediment movements due to a lack of sediment. There is also limited fresh erosion given the rocky nature of the coastline and the lengths of frontage with hard defences.

The beach to the south of the ferry terminal at Largs is split into two sections by a slipway. At the southern end (the Bowen Craigs coast) the beach is a mixture of coarse sands and gravel generally resting on a rock platform with there being little evidence of any significant dynamic movement of beach material. Much of this beach is backed by a low seawall protecting a footpath. Between the slipway and the ferry terminal there is a shingle upper beach which has suffered some beach lowering at the seawall immediately to the north of the slipway but is generally stable. The main beach at Largs is to the north of the ferry terminal where a well sorted shingle beach fronts a low esplanade. Beach lowering is occurring at the centre of the bay with the seawall foundations exposed. Remains of old groynes are evident at this section (now badly deteriorated and serving little purpose) with this localised section evidently being a problem. There is probably insufficient shingle within the bay to be redistributed into this area to provide a sufficient standard of protection to this section of wall. Under direct onshore storm conditions, overwashing of shingle onto the esplanade occurs.

The beaches at Wemyss and Lunderston Bays are both a mixture of sand and fine shingle. The beaches are stable with little evidence of littoral processes and no noted erosion of the low coastal edge.

The UK Dredged Material Database (MAFF, 1995b) indicates that maintenance dredging has been conducted at the following locations:

Location	Year	Authority	Dumping Site Name
Greenock	Annually	Clyde Harbour Authority	Cloch Point
Greenock	1990	Clyde Harbour Authority	Cloch Point
Greenock	1992	Clyde Harbour Authority	Cloch Point
Hunterston	1988-1990	Clyde Harbour Authority	Cloch Point
Hunterston	1992	Clyde Harbour Authority	Clock Point

Dredging is also conducted in the River Clyde. However, much of the siltation is due to fluvial material brought down the Clyde. It is unlikely that present dredging practices will have any detrimental effect on the coastline. Material at the dredged spoil dump sites (off Cloch Point) will not contribute any sediment to the beaches in the Firth of Clyde.

Summary of erosion and accretion

There is little significant erosion or accretion within this sub-cell due to the dominantly rocky nature of the coastline. There are a few minor localised spots where erosion is a problem such as at Largs to the north of the ferry terminal.

5.4.4 Coastal defences

A high percentage of this coastline is protected by some form of coastal defence works reflecting the highly developed nature of the coastal zone. In general, given the lack of beach sediments, and due to many of these coastal defences having been in place for a long period of time, there is little present day influence on beach sediments along this coast. Problem areas tend to be localised and are discussed below. The location and type of the main defences occurring within sub-cell 6b are shown in Figure 14.

Between Port Glasgow and Gourock there is little natural coastline remaining with mainly vertical seawalls fronting the developed areas. A short length of low concrete seawall is located to the north of Lunderston Bay presumably protecting a small localised area of erosion on an otherwise neutral coastline. Around the Marina and Power station at Inverkip, rock revetments provide adequate protection with little noticeable wave damage. At the southern end of Wemyss Bay a short section of low concrete seawall protects the road. There is some evidence of slight lowering of the shingle beach in front of this structure.

The entire frontage at Skelmorlie is protected by a vertical concrete seawall which supports the A78. There was evidence (June 1996) of overwashing of beach material at the side of the road, and under storm conditions particularly at high tides, wave overtopping is likely to be a problem. During the summer of 1996 a rock revetment was constructed along the front face, and up to the full height of the wall, which will not only provide protection to the wall but reduce the frequency and rate of overtopping considerably.

Between Skelmorlie and Largs, sections of the A78 have required protection (none recent) with concrete and masonry seawalls, rock and concrete revetments all present. At the northern end of Largs there a number of ad hoc masonry and concrete seawalls protecting individual properties, all in a generally poor state and unlikely to withstand a serious storm. Much of the Largs frontage is developed with low concrete seawalls protecting the coastal edge. There are a number of localised areas requiring attention, notably at the centre of the bay to the north of the ferry terminal where shingle levels are seriously low over a short section.

Between Largs and Fairlie a large marina is protected by rock breakwaters and revetments, all in good condition. At Fairlie the frontage is protected by numerous vertical masonry seawalls (virtually a different sea wall for each property). Most of these are in a very poor condition and will suffer damage under storm waves at high tides. Given the nature of the immediate foreshore and defences, overtopping may be significant.

There is an urgent need for a detailed assessment of the structural condition of all the sea defences in sub-cell 6b

5.5 Sub-cell 6c: Farland Head to Bennane Head

5.5.1 Geology

The coastline of Sub-cell 6c is situated within the Midland Valley of Scotland. The coastline is composed predominantly of sedimentary rocks of Devonian and Carboniferous age. Old Red Sandstone occurs between Farland Head and Ardrossan, at the Heads of Ayr and between Culzean Bay and Girvan. These outcrops form the cliffed coastline just south of the Heads of Ayr and along the Culzean coast. Much of the Ayr to Saltcoats frontage is underlain by Coal Measures of the Westphalian succession, which are slightly younger than the Old Red Sandstones, being laid down 315Ma to 296Ma.

Igneous activity has had a considerable influence on the coastline and outcrops of igneous rock are evident along the entire length of this sub-cell. Around Troon, volcanic activity around 315Ma produced a series of intrusions of dykes and sills. Dolerite sills form the headlands at Troon and Saltcoats and a number of other rock reefs which are exposed in the intertidal zones along this frontage. These outcrops play an important part in the planshape development of the "soft" coastline along this frontage. To the south of Ayr outcrops of basalt lavas form the rugged coastal scenery. A complex series of igneous outcrops comprising ultrabasic rocks, basalts and tuffs form the hard rocky coastline and high coastal relief to the south of Girvan.

The south west of Scotland is generally an area of glacial deposition, with thick layers of till and other deposits overlying the basement geology. The erosional and depositional sequences linked to glacial and post-glacial times have had a significant influence on the morphology of the present coastline. Glacial deposits will have provided virtually all the beach sediments within this sub-cell. These deposits have been reworked by waves and tides and sea level changes to form the present coastline. The importance of sea level changes on coastal landforms and evolution is particularly clear within this sub-cell. Raised shore platform and beach features extend virtually along the entire length of the coastline backed in many places by distinct relict clifflines. Around Irvine such features extend over 4km inland.

5.5.2 Hydraulic processes

The tidal range is relatively uniform along the Ayrshire coast with a mean Spring range of approximately 2.8m and mean Neap tide range of 1.5 to 1.6m (Table 12). Strong south westerly winds can cause an increase in tidal levels along the coastline of this sub-cell with winds from the north and east generally causing a decrease in levels.

Table 12 Sub-cell 6c - Predicted tidal levels and ranges

Location	MHWS (m OD)	MLWS (m OD)	Spring Range (m)	MHWN (m OD)	MLWN (m OD)	Neap Range (m)	ODN to CD (m)
Ardrossn	1.8	-1.2	2.	0.9	-0.5	1.	+162
Irvine	1.48	-1.32	2.8	0.88	-0.72	1.6	+1.62
Troon	1.58	-1.32	2.9	0.98	-0.62	1.6	+1.62
Ayr	1.38	-1.22	2.6	0.88	-0.52	1.4	+1.62
Girvan	1.48	-1.32	2.8	0.88	-0.72	1.6	+1.62

In Table 12 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.

The most commonly referred to research on extreme water levels in the UK is that conducted by Graff (1981) and Coles & Tawn (1990). This analysis was based on tidal records from the A-class tide gauge network. In these publications the only location in sub-cell 6c where predictions of extreme water levels have been made is Ardrossan (see Table 10).

The latest research into trends of extreme water levels (Dixon & Tawn, 1997) provides a spatial analysis at any location around the coastline of the UK mainland. In this study the predicted extreme water levels depend on the year of interest allowing for trends in mean sea level rise and hence have not been reproduced in this report. This research is likely to provide the most up-to-date and comprehensive analysis of extreme water levels available.

The main flood stream enters through North Channel and flows across the mouth of the Firth of Clyde dividing around Bennane Head with one part flowing to the north and the other to the south. The main flood direction is to the north along the Ayrshire coast with the northward flow continuing for approximately one hour after the main ebb stream further offshore of the coast has started. Tidal current speeds are low in the outer Firth with a peak Spring rate of less than $0.5ms^{-1}$. Closer inshore, in the surf zone, current speeds are likely to be significantly less. Due to the low tidal current speeds, wind induced currents may have a noticeable effect on both current velocity and pattern close inshore. As a general rule the depth averaged current is approximately 2% of the wind speed.

Offshore wave conditions in the outer Firth of Clyde have been assessed to the west of Troon (HR Wallingford, 1996) and Girvan (HR Wallingford, 1987). The wave climate offshore of Troon is shown in Figure 15. The prevailing wave direction, and the direction from where the largest waves come from, is between 210°N and 250°N corresponding to the longest fetch lengths which extend to the coastline of Ireland and the prevailing wind direction. At this location significant wave heights of 1m, 1.6m, 2m and 2.6m are predicted to occur approximately 11%, 1.4%, 0.21% and 0.013% of the time respectively. Further to the south, there is little difference in the wave climate with a slight increase in the number of events occurring from the north west quadrant. Extreme significant wave heights of 2.6m, 3.0m and 3.3m with return periods of 1:1 years, 1:10 years and 1:100 years respectively have been calculated. Due to the restriction in fetch lengths (the maximum fetch is less than 100km) wave conditions are unlikely to exceed 3.3m.

Swell wave conditions will be experienced within the outer Firth of Clyde. Swell experienced within the Firth will have been generated both in the North Atlantic and in the Irish sea.

However, due to the damping effects of the narrow and deep North Channel, swell conditions experienced in the Firth will be relatively mild compared to other, more exposed, areas of the UK coast.

Inshore wave conditions have also been calculated between Saltcoats and Troon and at Girvan. Along the south west facing coastline to the north of Ayr, the dominant wave direction is from between 220°N and 280°N with waves occurring from this sector for over 60% of the time. Headlands, such as at Troon, have a significant effect on the wave conditions experienced at the coastline. For instance the most frequent wave direction just to the north of Troon is that centred on 240°N whereas further north along the Ardeer frontage which is more exposed to the south the most frequent wave direction is from 220°N. Further south along the Girvan coastline, which is orientated to the north west, the dominant wave sector is from between 230°N and 310°N with waves from this sector occurring for almost 80% of the time. Inshore extreme wave conditions were calculated at Girvan at the -5m CD contour at MHWS. This estimated a 1:1, 1:10 and 1:100 year significant wave height of 2.3m, 2.6m and 2.9m respectively. These predictions are likely to be fairly representative of extreme wave conditions experienced along most of this sub-cell.

At the southern end of the sub-cell the severity of wave conditions experienced at the coastline will increase due to waves from the north Atlantic propagating through North Channel. However, there is no known quantitative assessment of wave conditions south of Girvan.

5.5.3 Littoral processes

Much of the coastline in Sub-cell 6c is fronted by sandy beaches usually backed by dunes or links, particularly between Seamill and Ayr and notably at Turnberry. The dominant foreshore and hinterland characteristics are shown in Figure 16 with the dominant littoral processes indicated in Figure 17. The dominant source of coastal sediments within this sub-cell has been glacial deposits both from within the Firth and from reworking of boulder clay deposits during periods of higher sea levels. Much of this material is presently stored in the hinterland with wide links areas backing many of the beach systems. There is presently very little fresh input of sediment into the coastal system although frontal erosion of the dunes along most of this frontage will release some sediment into the beach system.

The planshape of the coastline is considerably affected by the solid geology, with headland dominated bays formed. The shape of many of these bays, for instance Irvine Bay, suggests a plan shape in near equilibrium with the wave climate. All along this coastline the influences of formerly higher sea levels are obvious with wide raised beach areas evident for up to 4km inland.

The coastline between Seamill and Ardrossan is characterised by a thin sandy beach which rests between intertidal rock reefs. This is backed by a raised beach and relict cliff line. Much of the immediate coastal edge has been modified by human activities, such as spoil tipping and levelling of the coastal edge. Backshore erosion is a problem along the entire length of this coastline, particularly around Seamill, where there are a variety of coastal defences protecting properties, and along the West Kilbride Golf Course. To the south of Seamill sections of the coastal edge appear stable, particularly where the foreshore is rocky, providing greater protection from wave action. Given the scarcity of beach material there is little longshore transport evident, probably due to much of the incident wave energy, during normal tidal and wave conditions, being dissipated over the rock reefs.

Both the north and south beaches at Ardrossan are relatively stable in part because they are extremely sheltered from wave attack by the rocky headland upon which Ardrossan and Saltcoats are situated. Little of the natural backshore remains, particularly at South Bay which is backed by a low vertical concrete seawall.

A detailed assessment of the coastline between Saltcoats and Troon was conducted by HR Wallingford (1996). To the north of the mouth of the River Irvine, much of the coastal edge has been modified by human influences, e.g. the slag tipping forming Stevenson Point and the hard defences along much of the Ardeer frontage. Beach levels fronting the wall immediately to the south of Saltcoats are extremely low with the wall likely to be at risk. Outflanking at the southern end of this wall has resulted in significant erosion of the hinterland dunes. Map analysis indicates that between Saltcoats and Troon the overall appearance is one of retreat since the turn of the century with a steepening of the intertidal beach. Numerical modelling of littoral transport along the Ardeer frontage indicates a nett southwards drift towards the outlet of the Rivers Garnock and Irvine. The drift rate was calculated to be approximately 100,000m^3/year at the northern end of the Ardeer frontage reducing towards the outlet of the two rivers. Accretion at the southern end of the Ardeer frontage is evident with embryo dunes forming. Along the Wester Gailes frontage between Troon and the River Irvine the nett longshore drift is to the north. The nett drift rate is about 75,000m^3/year just to the north of Barassie reducing to about 12,000m^3/year at Irvine beach park. It is likely that the influence of flows from the Rivers Garnock and Irvine will recirculate material back along both the frontage to the north and to the south.

As further north, there appears to have been a nett retreat of the natural coastline over the last century with frontal dune erosion evident after storm conditions. Erosion and retreat of these dunes will be episodic occurring during storm conditions. There is little dry sand on the beach to renourish the dunes and as a result the volume of sand within them is decreasing.

The frontage between Ayr and Troon was the subject of a detailed investigation by Carter and Scott (1992). The situation along this frontage is very similar to that to the north of Troon. The beach areas are dominantly sand back by dunes. In many places these dunes have been greatly modified or completely removed by human interference. The planshape of the beaches along this frontage is controlled by intertidal rock outcrops. The nett longshore transport direction is to the north and the rate is unlikely to be any greater than that calculated along the Troon to Saltcoats frontage. Map analysis again indicates a general long term coastal edge retreat which is likely to continue.

Ayr South Beach extends from the harbour to Doonfoot with shelter provided by the Heads of Ayr increasing to the south. At the northern end the beach is dominantly sandy with a wide flat intertidal zone. It is backed for much of the frontage by a vertical seawall. At the southern end of the bay a low dune fringe backs the beach. Nett drift appears to be to the north but appears to be extremely low. There is little erosion evident on the unprotected coastal edge at the southern end of the bay.

The only other major sand beach is at Turnberry where a healthy beach is backed by stable dunes. There is little erosion of the frontal dune face evident with the dunes well vegetated. Any nett drift (extremely low) is to the north.

A number of small shingle pocket beaches and shingle fringe beaches are found to the south of the Heads of Ayr. In general these do not appear to be particularly dynamic except at Croy, where erosion has occurred of the coastal edge in front of the Caravan Park requiring a rock revetment, and along the edge of the golf course to the north of Girvan. The beach to the south of Girvan is a mixture of sand and shingle backed by a seawall. Blown sand appears to be a particular problem in this area and there is evidence of some coastal edge erosion of the immediate hinterland, with a long stretch of sloping gabion mattress having been installed recently. Elsewhere beach units are sparse and evidence of erosion localised.

The UK Dredged Material Database (MAFF, 1995b) indicates that maintenance dredging has been conducted at the following locations:

Location	Year	Authority	Dumping Site Name
Ayr and Troon	Annually	Associated British Ports	Ayr Bay
Girvan	1986, 1988, 1989	Strathclyde Regional Council	Girvan

Consideration was given to the sources of dredging in the Shoreline Management Plan for the Saltcoats to Troon frontage (HR Wallingford, 1996). It is considered that siltation at Troon is due to sand and silt movements over the surrounding sea bed. The material dredged from Troon and Ayr Harbours is deposited in Ayr Bay but is unlikely to provide a source of beach material. Dredging of the sand bar, which forms at the mouth of the Rivers Garnock and Irvine, was also conducted up until 1982.

Summary of erosion and accretion

Most of the frontal dunes occurring along the coastline in sub-cell 6c are suffering episodic storm erosion resulting in a general long term retreat. The coastlines most affected are the Seamill to Ardrossan frontage, most of the Saltcoats to Ayr frontage (with the exception of a small accreting area to the north of the mouth of the Rivers Garnock and Irvine), and the Turnberry to Irvine frontage.

5.5.4 Coastal defences

Due to the relatively heavy urbanisation and industry along this coastline a wide range of coastal defence works exists, Figure 18. Along the West Kilbride Golf Course large sections of the coastal edge are protected by rock revetments. Given that the beach is not particularly dynamic along this frontage, those structures have minimal influence. These revetments appear to be of relatively recent construction and are in a reasonable condition with little evidence of damage. A range of masonry and concrete seawalls of various vintage and condition protect property at Seamill. There appears to be minimal wave interaction with these structures and minimal impact on the beach at present. Short sections of rock revetment protect parts of the A78 to the north of Ardrossan. Much of the Ardrossan and Saltcoats frontage is protected by vertical seawalls. In both North and South Bays this appears to have little effect on the beach, mainly due to the sheltered location. However, to the south of Stevenson, the seawall which protects the railway is in a very poor condition. Beach levels fronting the wall have been lowered due to wave reflection from the structure with the foundations now exposed. Under storm conditions this experiences considerable damage with a very real threat of collapse. Severe wave overtopping of the structure is also known to disrupt rail services. The structure has also had a detrimental effect on the dunes and coastal hinterland immediately to the south with outflanking causing considerable erosion.

A curved concrete seawall protects a large part of the Ardeer frontage. This consists of large pre-cast concrete units having been placed directly on the natural dune face. These units have cracked and split with the dunes being washed out underneath them leading to further structural damage. In places these units have been removed and short sections of over-designed rock revetment placed. Despite the nature of these defences, surprisingly they appear to cause minimal beach erosion even under severe storm conditions (HR Wallingford, 1996).

A short stretch of sloping gabions protects the dune face at the southern end of Irvine Beach Park with minimal detrimental effect. At the southern end of Barassie a short length of masonry seawall protects North Shore Road. Lowering of beach levels at the base of the seawall during onshore storms does occur along with overtopping of the defences.

A considerable part of the frontage at Troon, Prestwick and Ayr is protected, mainly by low vertical seawalls. Falling beach levels have resulted in rock armouring being placed along sections of the seawall on the North Beach at Ayr. The loss of volume from the North Beach at Ayr will be due to the lack of material bypassing the training walls of the River Ayr (i.e. there is a downdrift effect albeit extremely slight). This is further exacerbated by wave reflection from these hard linear structures. A similar low concrete wall backs the beach at the northern end of Ayr South Beach. Again beach levels are relatively low and, with the lack of fresh input of material, unlikely to improve.

Much more detail on the present condition and impact of the coastal defences between Saltcoats and Troon and between Troon and Ayr is provided by HR Wallingford (1996) and Carter and Scott (1992) respectively.

To the south of the Heads of Ayr, coastal defence work is more localised with old masonry walls in need of periodic repair protecting property and the hinterland at Dunure and Maidens. A short section of poorly constructed rock revetment protects the caravan park at Croy. This appears to have provided adequate protection thus far with minimal impact on the adjacent beach. A similar rock revetment fronts the chemical works at Dipple.

To the south of the harbour at Girvan, a low concrete wall protects much of the esplanade. The wall is in good condition and at the time of inspection, blown sand had built up against it and was ramping over the top of the wall. To the south of the wall a sloping gabion revetment is in good condition and appears to experience little wave action. To the south of this the A77 passes close to the recently levelled coastal edge with housing immediately landward of the road. Extensive rock armour revetments were constructed in the winter of 97/98 at Lendalfoot and immediately to the north to protect threatened sections of the A77. Further south still, where the A77 passes close to the coastal edges there are a number of other short stretches of rock revetment.

5.6 Sub-cell 6d: Bennane Head to the Mull of Galloway

5.6.1 Geology

The solid geological structure of Sub-cell 6d is split by the Southern Upland Fault which dissects the coast at the northern end of Loch Ryan, also crossing the northern tip of the

Rhinns of Galloway. The solid geology of Sub-cell 6d is dominated by sedimentary rocks of Ordovician age which were formed about 505Ma to 438Ma. The lithology of the rock is dominated by beds of siltstones, shales or greywackes. Younger, Silurian sediments, of similar lithology, occur over the southern half of the Rhinns of Galloway. Much of this rock is exposed at the coastline in the form of cliffs which are resilient to marine erosion resulting in a relatively neutral coast.

Intrusive igneous rocks, formed during the Ordovician and Silurian, outcrop to the north of the Southern Upland Fault with the area displaying a complex zone of igneous activity and rock type.

Younger rock types, mainly New Red Sandstone of Permian age (290Ma to 245Ma), are located within the isthmus between Luce Bay and Loch Ryan. These are composed of sandstones and red breccias and form cliffs up to 45m high along the Loch Ryan shore. However, much of this outcrop is obscured by glacial deposits. A similar outcrop of New Red Sandstone occurs between Bennane Head and Ballantrae.

Boulder clay caps much of the underlying solid geology of the area. However, this material is above the elevation of any previous sea levels and as such has supplied little of the beach material within this sub-cell. Where beaches have formed, the main source will have been glacial deposits which have experienced wave action during previously higher sea levels or have been deposited at the coastline by fluvial action. Only around Ballantrae and within the isthmus between Loch Ryan and Luce Bay are there any significant accumulations of glacial material which have been reworked to form raised beach deposits. Such raised beach features are less evident along this coastline, with the exception of the area around Ballantrae, than they are further north along the Ayrshire coast.

5.6.2 Hydraulic processes

The tidal range on a mean spring tide is 3.5m at Portpatrick and 2.9m at Stranraer with corresponding mean neap tidal ranges of 2.1m and 1.8m (Table 13). The tidal cycle has a period of approximately 12.4 hours. In general, the periods of the flood and ebb tides are equal.

Table 13 Sub-cell 6d - Predicted tidal levels and ranges

Location	MHWS (m OD)	MLWS (m OD)	Spring Range (m)	MHWN (m OD)	MLWN (m OD)	Neap Range (m)	ODN to CD (m)
Stranraer	1.38	-1.52	2.9	0.78	-1.02	1.8	+1.62
Portpatrick	2.18	-1.32	3.5	1.38	-0.72	2.1	+1.62

In Table 13 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.

The most commonly referred to research on extreme water levels in the UK is that conducted by Graff (1981) and Coles & Tawn (1990). This analysis was based on tidal records from the A-class tide gauge network. In these publications there are no locations in sub-cell 6d where predictions of extreme water level have been made, the closest being Ardrossan to the north (see Table 10).

sea level rise and hence have not been reproduced in this report. This research is likely to provide the most up-to-date and comprehensive analysis of extreme water levels available.

Tidal streams on both flood (south going) and ebb (north going) tides run parallel to the west coastline of the Rhinns of Galloway. Off Black Head, and to the south, the peak Spring rate on both flood and ebb is approximately $2.5ms^{-1}$. To the north this peak rate decreases to $2ms^{-1}$ off Craig Laggan and to less than $1.5ms^{-1}$ off Corsewall Point.

Tidal streams run around Corsewall Point, to the north on the ebb, and to the south on the flood, to and from Bennane Head. Peak spring rates across the mouth of Loch Ryan are approximately $1ms^{-1}$ and decrease to the north. Within Loch Ryan the main tidal stream flows inwards past Finnarts Point and along the eastern coastline with the outgoing stream tending to flow along the western side of the Loch. Current speeds are extremely low particularly towards the head of the loch.

There is no known information on wave conditions within this sub-cell. Fetch lengths in most directions are relatively short and in general less than 100km. However, there is a narrow wave window to the north west where fetches extend out through the North Channel and into the North Atlantic. Waves from the north west passing through the North Channel between the Mull of Kintyre and the coast of Ireland will experience heavy diffraction around the Mull of Kintyre (resulting in wave energy passing through North Channel spreading into the outer Firth of Clyde).

The Rhinns of Galloway coastline will also be exposed to wave conditions from the south generated within the Irish Sea. Again this wave window is narrow with waves experienced from approximately a 20° sector centred on due south.

5.6.3 Littoral processes

There are few large beach areas in Sub-cell 6d with much of the coastline dominated by outcrops of bedrock. The largest beach system occurs around Ballantrae and there are a number of pocket beach systems mainly on the western coastline of the Rhinns of Galloway. Figure 16 summarises the foreshore and hinterland characteristics in Sub-cell 6d with Figure 17 showing the dominant littoral processes.

The beach system at Ballantrae extends from the south of Bennane Head to just south of the mouth of the River Stinchar. It is interrupted by the rocky headland upon which the harbour and village of Ballantrae are situated. The northern beach is a mixture of sand and shingle at the northern end and shingle at the southern end. The occurrence of sand at the northern end has resulted in formation of a low frontal dune ridge. The presence of sand sized material at the northern end may be due to a very low northerly longshore drift due to both waves and, possibly more importantly, aeolian transport. The shingle appears to be relatively stable and there is little evidence of frontal dune erosion, although some overwashing of shingle occurs on the low edge at the southern end. Behind the present day beach is a raised beach about 150m wide backed by a relict cliffline.

To the south of Ballantrae is one of the most interesting beach areas in Cell 6. The morphology of the spit feature across the mouth of the River Stinchar appears to be the result of a southerly movement of shingle. Historical analysis by Ting (1937) indicated that there has been large changes in this landform and in the position of the river outlet since the start of the nineteenth century. It is possible that the spit is a result of cross-shore sediment

To the south of Ballantrae is one of the most interesting beach areas in Cell 6. The morphology of the spit feature across the mouth of the River Stinchar appears to be the result of a southerly movement of shingle. Historical analysis by Ting (1937) indicated that there has been large changes in this landform and in the position of the river outlet since the start of the nineteenth century. It is possible that the spit is a result of cross-shore sediment movement (rather than dominantly longshore). Thus shingle washed onto the foreshore by spate river flows is subsequently moved back onshore during storm wave conditions at a high tide forming a shingle ridge over the mouth of the river. Surprisingly, given the complexity of this system, there appears to have been little study of the area.

There are few beaches bordering Loch Ryan with coarse shingle and cobbles generally occurring over the upper foreshore. Short fetch lengths restrict wave conditions and there appears to be little dynamic response.

Along the western freeboard of the Rhinns of Galloway a number of pocket beach systems occur. These units are self contained in terms of the sediment budget and there are virtually no longshore losses of beach material. The largest beach systems, at Broadsea Bay, Knock Bay and Port Logan, are dominantly sandy although shingle occurs on the upper beach at Broadsea. Despite this coast being the most exposed to severe wave action there is little evidence of significant erosion. As at Port Logan the overall stability of the entire bay planshape may have been increased by the positioning of the harbour breakwater.

The UK Dredged Material Database (MAFF, 1995b) indicates that maintenance dredging has been conducted at the following locations:

Location	Year	Authority	Dumping Site Name
Cairnryan	1990	Cairnryan Port Authority	Stranraer
Portpatrick	1992	Portpatrick Harbour Authority	Portpatrick

Siltation within Portpatrick Harbour is considered to occur due to sand sized material on the sea bed being transported into the outer harbour. A small beach has formed in the outer harbour. Waves propagating through the harbour entrance result in a movement of this beach material towards the inner harbour and a gradual siltation at its entrance. The dredged material is unlikely to contribute any material to the beach units within this sub-cell.

<u>Summary of erosion and accretion</u>
There is little evidence of any significant erosion within this sub-cell and no locations where accretion of beach material occurs.

5.6.4 Coastal defences

The majority of the coastal defence works within this sub-cell are located around Loch Ryan and in particular around Stranraer (Figure 18). Various rock revetments are located around the ferry terminal at Cairnryan; all are in reasonable condition given the lack of wave activity experienced along this coast. Most of the Stranraer frontage is protected by a number of concrete and masonry seawalls. As there is minimal beach sediment in this area there is little impact due to these structures. Storm damage will occur as most of the walls are relatively old and periodic maintenance will be required. There are further short sections of masonry seawall protecting the A718 on the western side of Loch Ryan.

A stepped seawall protects part of the amenity land backing the harbour at Portpatrick. There is wide boulder beach fronting this wall and evidence of wave damage is minimal with the wall in a good condition.

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

5.7.1 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 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 one hundred years or indeed in the next ten 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.

5.7.2 Natural heritage sites

Figure 7 shows the location of coastal SSSIs within Cell 6, with a summary of their main characteristics provided in Appendix 1.

Many of the SSSIs within Cell 6 have been designated on account of solid geological features. The solid geology within Cell 6 is relatively resilient to marine processes with the rate of attrition low. Present day influences of coastal processes are unlikely to have any noticeable affect upon these designations.

It is designations on the "soft" coastlines of Cell 6 where the effects of the present day dominant coastal processes and the effects of future climatic changes will be most evident. On the more exposed coastline of the outer Firth of Clyde the dune and links systems at Wester Gailles, South Troon and Turnberry are all designated SSSIs. The systems at Wester Gailles and South Troon are the most unstable at present with frontal storm dune erosion occurring and evidence of wind erosion, particularly at Wester Gailles. The dune system at Turnberry appears (at present) to be in a period of relative stability. These systems, along the Ayrshire coast, are all experiencing a deficit in the sediment budget with a long term retreat of the coastal edge (frontal dune system) which is unlikely to reverse in the medium term.

There are a number of Quaternary deposits which have been designated within this cell, for example Rhu Point and Otter Ferry. These tend to be relict features and at present appear to be dynamically stable with little change occurring due to marine influences.

In the Inner Firth of Clyde there are a number of tidal flats and saltmarshes designated. At present these are in a relatively stable state with no large scale dynamic changes occurring. However, these systems, particularly saltmarsh areas, are extremely sensitive to changes in the hydraulic climate. This is discussed more fully in Chapter 6.

5.7.3 Cultural heritage sites

The location of archaeological sites from the NMRS database is shown in Figure 8. Little survey work appears to have been conducted along the coastline of Cell 6 to establish the present threat of coastal erosion to cultural heritage sites, Ashmore (1994).

The coastline of Cell 6 has a high density of noted historical and archaeological sites. Much of the coastline of Cell 6 is predominantly rocky and resilient to marine erosion leading to a neutral coastal edge. In other areas, particularly in sub-cell 6b and parts of 6c, much of the coastline is protected by linear coastal defences and little landward retreat will occur. As discussed in the previous sections, a number of these defences are now in a poor structural state with a significant threat of serious damage. However, it is assumed that remedial work will be conducted before the risk of failure of such a structure would put large areas of the hinterland under threat.

In general terms, cultural heritage sites at most risk are likely to occur along the Ayrshire coastline, particularly between Ayr and Troon along the "soft" unprotected links sections. However, there are fewer noted sites in the hinterland of these areas than occur in the developed areas which are generally protected by coastal defence works.

There are few sites within Cell 6 that are likely to be under serious threat due to large scale coastal erosion. However, localised sections of erosion do occur and it would be prudent to conduct a survey of all sites backing beach areas (or non rocky coastal edges) within this cell to prioritise any planned work within this region.

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

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

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

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 breaches in Cell 6

In terms of the beaches and "soft" coastlines of Cell 6 the largest impact of any climatic change is likely to be felt along the coastline between Ayr and Farland Head. In general terms such changes are well documented, (e.g. Carter, 1988). The response of the sand beaches and dune systems along this coastline is dependent upon the balance of the sediment budget, i.e. between sediment supply and loss. Along the unprotected sand beach frontages, coastal response will be the erosion of sediment supplies stored in the immediate dune systems or links areas. This erosion, induced by an increase in mean sea level, is a result of changes in wave refraction and a decrease in width of the breaker zone, due to deeper water. Waves and currents will also tend to act higher up the beach. The extent of coastal edge retreat will vary, but such changes will be gradual with no sudden change in sea level or the rate of coastal edge retreat.

Along much of the unprotected frontage the rate of landward retreat will not cause a serious problem to infrastructure as there is a wide buffer zone where there is a large supply of beach material (although with golf courses located on many of the links areas). It is those areas where human development has encroached close to any unprotected coastal edge which will be most vulnerable to the risk of landward retreat. The direct effects on coastal structures are discussed in the next section, but increased water levels or wave conditions may also have an indirect effect on beach areas fronting defences. Where there are linear defences protecting the coastline and restricting landward recession, beach profile levels will drop as the mean low and high water levels attempt to migrate landwards. This can lead to a steepening of the intertidal beach, as the high water level is restricted by hard defences from moving further landward, leading to the process known as "coastal squeeze". This in turn could lead to less wave energy dissipation over the intertidal beach resulting in larger wave conditions propagating further inshore. Once beach levels adjacent to the structure are low enough to allow prolonged wave interaction with the structure, wave reflection exacerbates the rate of beach lowering and beaches do not often recover from this situation naturally. The beaches fronting the linear seawalls along much of the Ayr, Prestwick and Troon frontages are where such effects are likely to be most noticeable.

Where shingle beaches occur (or are present on the upper foreshore), for instance at Ballantrae, the response to increased sea levels or wave severity will be one of roll-over where shingle is transferred from the front face of the beach onto the backshore resulting in a gradual retreat of the coastline. The rate of this process, in most places in Cell 6, will be low.

Along much of the eastern coastline of the Kintyre peninsula, the beaches in Cowal and along the western freeboard of the Rhinns of Galloway most of the beach areas are in the form of pocket beaches, e.g. Saddell Bay, Kilbride Bay, Port Logan. The planshape of such beaches does not change dramatically, even if the offshore wave direction changes, as wave conditions at the shoreline are dominated by wave diffraction around the headlands at either end of the bay. Similarly, because many of these pocket beaches have adjusted and reached a position of no nett drift, a change in wave heights will have no effect on the longshore transport. Research into the influence of mean sea level rise on pocket beaches (Diserens et al, 1992) also concluded that there was no clear linkage between mean sea level rise and the position of the high water line. Hence it is unlikely that mean sea level rise will have a significantly noticeable effect. Of greatest impact on these pocket beach areas is likely to be any increase in extreme tidal levels as this will cause an increase in dune or backshore erosion, particularly on the beach areas where there is little present day width between the high water mark and the frontal dunes/coastal edge or where streams run onto the middle of the beach causing beach levels to be lower. However, in general there will be little loss of beach sediments from within each beach unit, with any erosion normally redistributing sediments across the intertidal part of the beach.

Increases in extreme sea levels will also increase the risk of tidal flooding. At present there appear to be few properties or infrastructure which experience flooding or inundation due to high tides alone. Most flooding within this sub-cell will be due to wave overtopping which is discussed in the next section.

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.

Impacts on the man-made defences in Cell 6

The detrimental effects of an increase in the magnitude or frequency of storm conditions (from the westerly sector) on coastal defence structures could, potentially be the most severe in Cell 6, in relation to the rest of Scotland. Many of the present defences are extremely old and are in a badly deteriorated structural state, for example along much of the

Sub-cell 6b coastline between Fairlie and the Inner Firth of Clyde and along parts of the Saltcoats to Irvine frontage. Given the present state of many of these old defences substantial damage is likely to occur during the first serious onshore storm event (e.g. the damage which occurred to many of these defences during the storm of January 1996).

Many of these defences are poor performers, functionally, with overtopping, as occurs along the railway at the southern end of Saltcoats, a frequent problem. Under any scenario where either extreme water levels increase or the frequency of extreme water levels increase, or where either the severity or frequency of storm conditions increase, the problem of overtopping and hinterland flooding will increase. The most seriously affected frontages are likely to be those fronted by a vertical sea wall with minimal beach fronting the structure (which includes a large proportion of the defences in sub-cell 6b and a number in sub-cell 6c).

Conversely along many of the inner sea lochs, minor climatic changes are unlikely to have an noticeable effect on coastal defences along these shores.

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 these are of significance in managing the coast.

<u>Rainfall</u>
There is an observed variation in the rainfall pattern 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 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 6 are relatively resilient to marine erosion and this is, therefore, 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 to the coast in Cell 6 will bring little beach sediment and this is unlikely to change significantly.

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

- Impacts on dune building
  Wet sand on the foreshore will be much less easily transported by winds than if it is dry, reducing the supply to dunes. However, many dune binding grasses suffer in drought conditions, and are generally healthier in moister climates. This would help to increase

the trapping efficiency, and encourage them to colonise new areas more quickly. It is not clear, therefore, whether increased rainfall will assist dune growth or be detrimental to it.

Changes in wind

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

- Aeolian sand transport
  Strong winds are capable of transporting large quantities of sand, both along the coastline and perpendicular to it. The former effect can add to, or counteract wave induced longshore drift, but tends to take place at 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.

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.

The impact of climatic changes upon Cell 6 may be more apparent here than elsewhere in Scotland due to the highly developed nature of parts of this coastline, notably in Sub-cells 6b and 6c. The rate or magnitude of change of relatively "natural" beach systems may not be any greater than any other area of Scotland, but it is the impact on the present defences which occur along this frontage which is likely to be of greatest concern. Many of these defences protect substantial property and infrastructure and at present do not perform well in reducing wave overtopping and are at risk of sustaining substantial structural damage.

At present, the complexity of the coastal and nearshore zone makes it difficult to predict morphological changes due to the range of inter-relating parameters which affect this zone. To identify and quantify the effect on the coastline of changes to any one, or a number, of these parameters would require good quality, long-term data to validate predictive methods and to identify changes in the marine (i.e. hydraulic) climate.

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

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There are a number of other publications that are not referenced within this report that may be of use to shoreline management in Cell 6.

Curran J C (1981). A finite-element model of pollution in the Clyde estuary: formulation, validation and utilisation. Applied Mathematical Modelling, 5, No , 137-142.

Deegan C E (1973). The superficial deposits of the Firth of Clyde and its sea lochs. Natural Environment Research Council, Institute of Geological Sciences, 73/9. HMSO, Edinburgh.

Donald A S and Townson J M (1985). Numerical modelling of storm surges in the Clyde Sea area. Proceedings Institution of Civil Engineers MC 85, 79, Part 2: Research and Theory, 637-655.

Dooley H D (1979). Factors influencing water movements in the Firth of Clyde. Estuarine and Coastal Marine Science, 9, 631-641.

HR Wallingford, (1985). Dredging in Faslane bay, An assessment of the impact of the disposal of dredged spoil on water quality in Gareloch. HR Wallingford Report EX 1356. HR Wallingford, Wallingford.

HR Wallingford, (1988). Rhu Narrows further hydraulic study. HR Wallingford Report EX 1711. HR Wallingford, Wallingford.

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HR Wallingford, (1988). Environmental conditions for Barrow-in-Furness and for Gareloch. HR Wallingford Report EX 1721. HR Wallingford, Wallingford.

HR Wallingford, (1990). Sea bed burial in the approaches to the Clyde, Development Phase. HR Wallingford Report EX 2094. HR Wallingford, Wallingford.

HR Wallingford, (1991). Prediction of seabed burial in Clyde Approaches. HR Wallingford Report EX 2280. HR Wallingford, Wallingford.

HR Wallingford (1991). Girvan Sewerage Scheme - Mathematical modelling investigation, Hydrographic surveys, Volume 1, Text, Tables and Figures. HR Wallingford Report EX 2327. HR Wallingford, Wallingford.

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HR Wallingford (1991). Girvan sewerage scheme - Mathematical modelling investigation, Bacterial loading surveys, HR Wallingford Report EX 2471. HR Wallingford, Wallingford.

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HR Wallingford, (1993). Environmental Data for the Clyde, HR Wallingford Report EX 2725. HR Wallingford, Wallingford.

Hunter, J C, (1991). Greenock/Gourock. Port Glasgow drainage scheme and long sea outfall design. Water and Environmental Management, **5**, 259.

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Figures 1-18

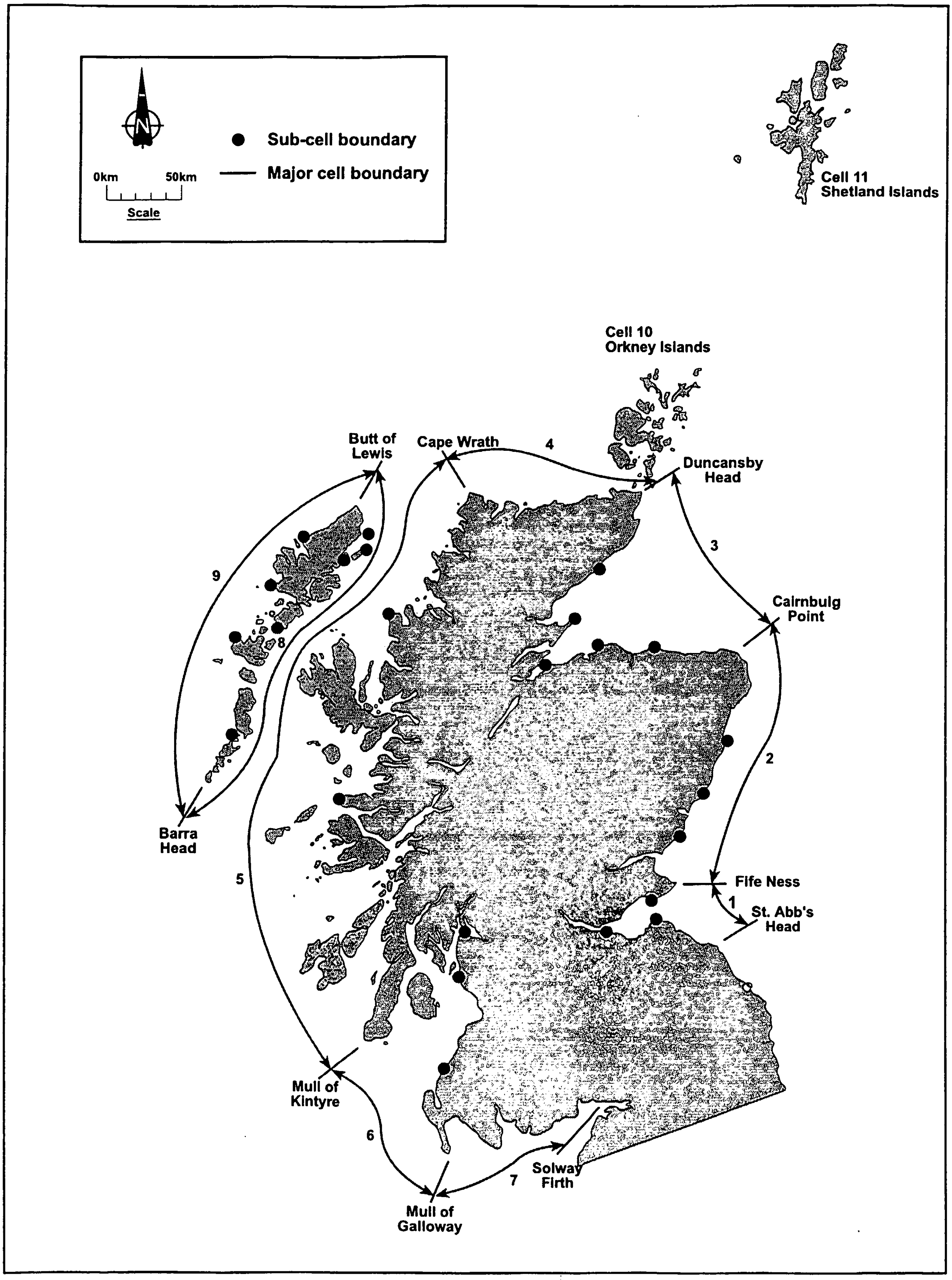


Figure 1 Coastal Cells in Scotland

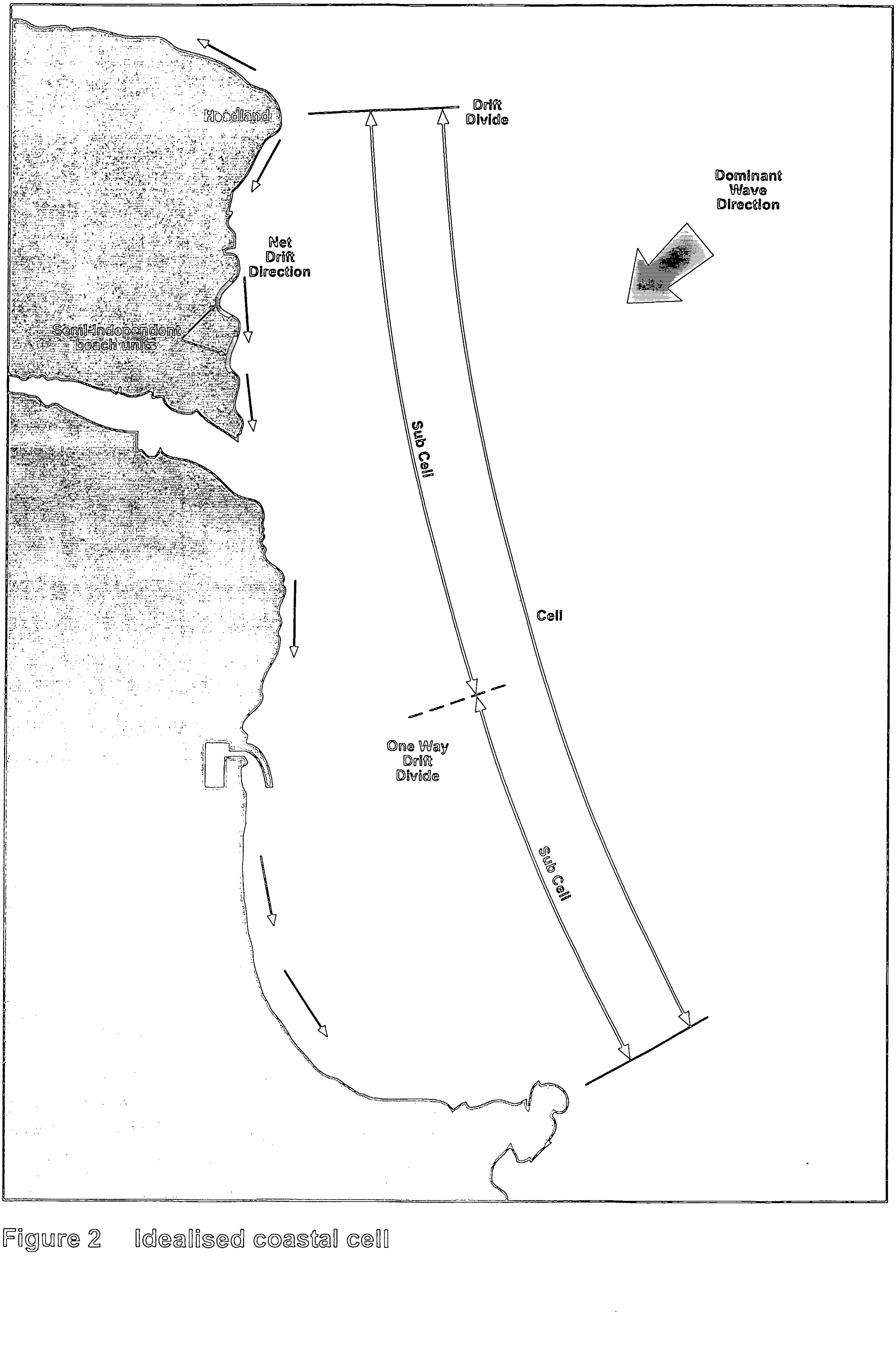


Figure 2 Idealised coastal cell

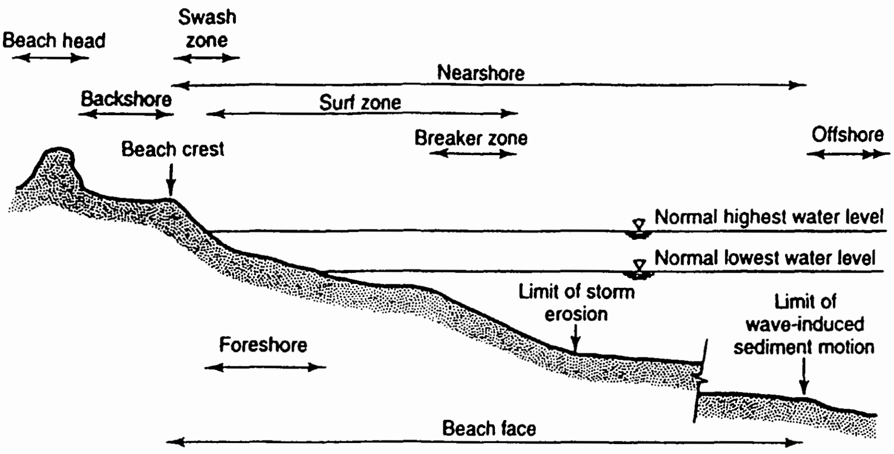


Figure 3 General beach profile and littoral zone

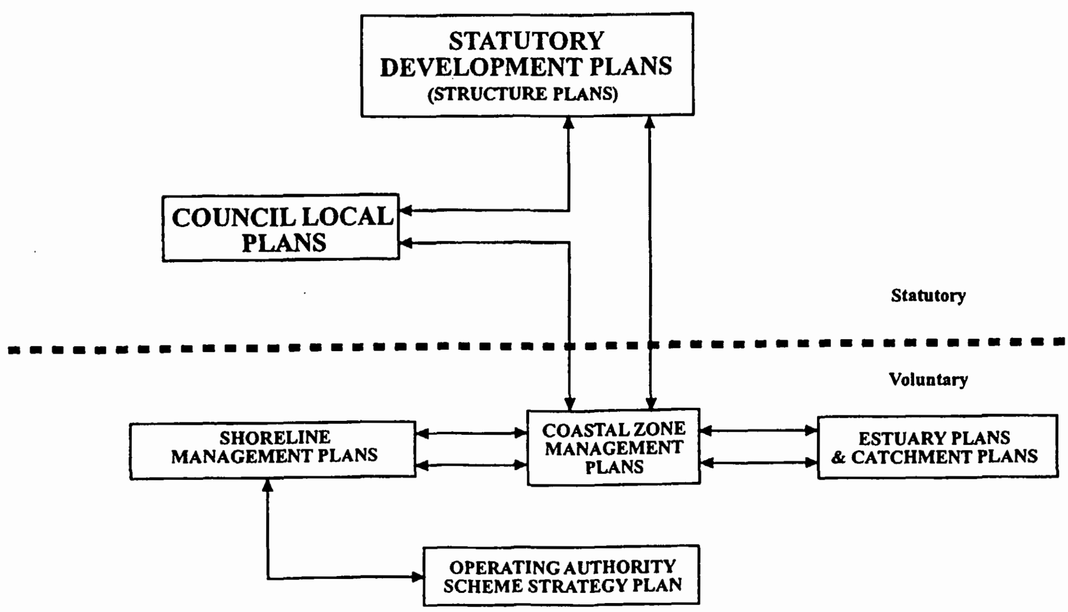


Figure 4 Relationship between coastal initiatives

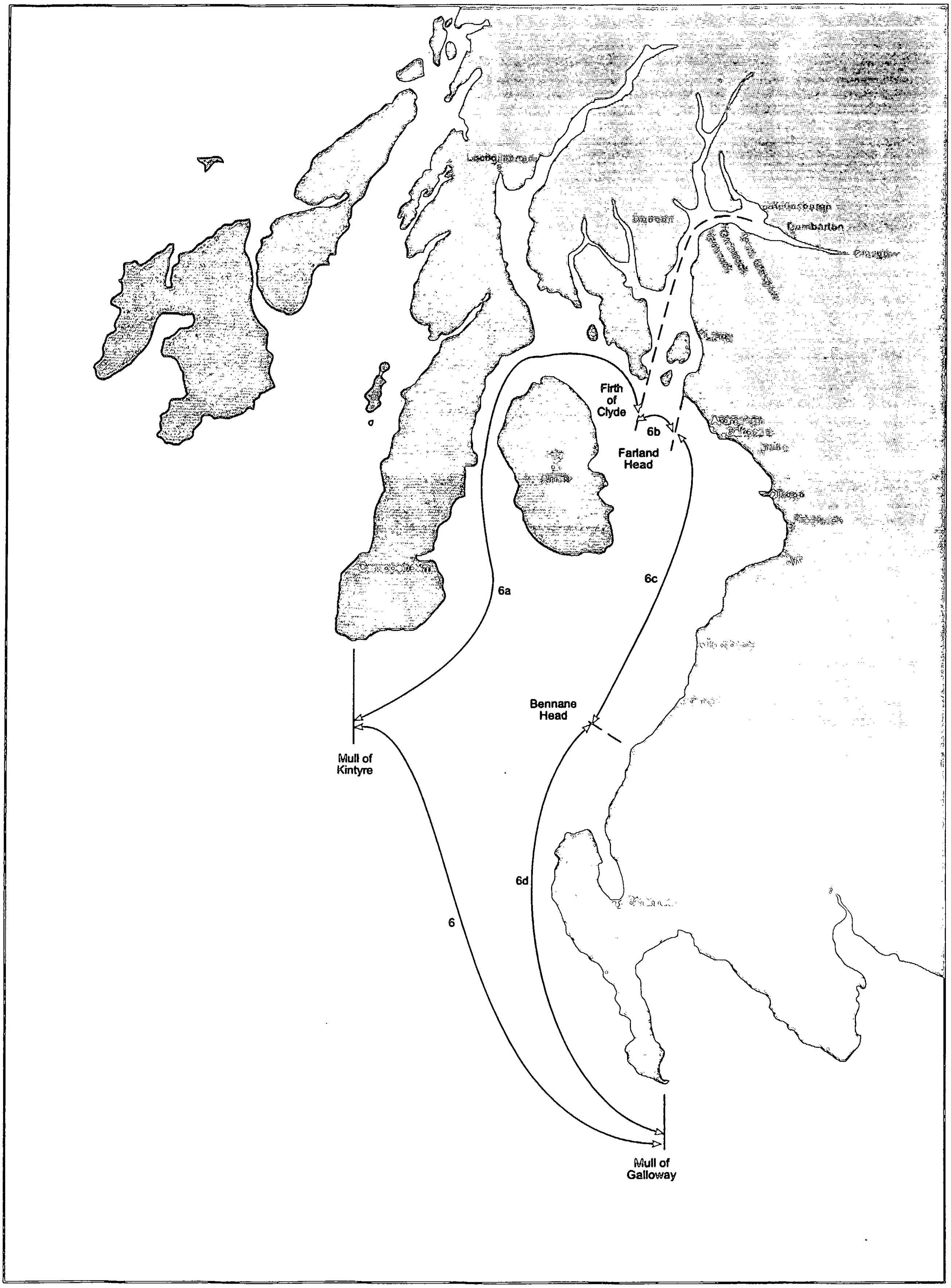


Figure 5 Cell 6 - Mull of Kintyre to the Mull of Galloway

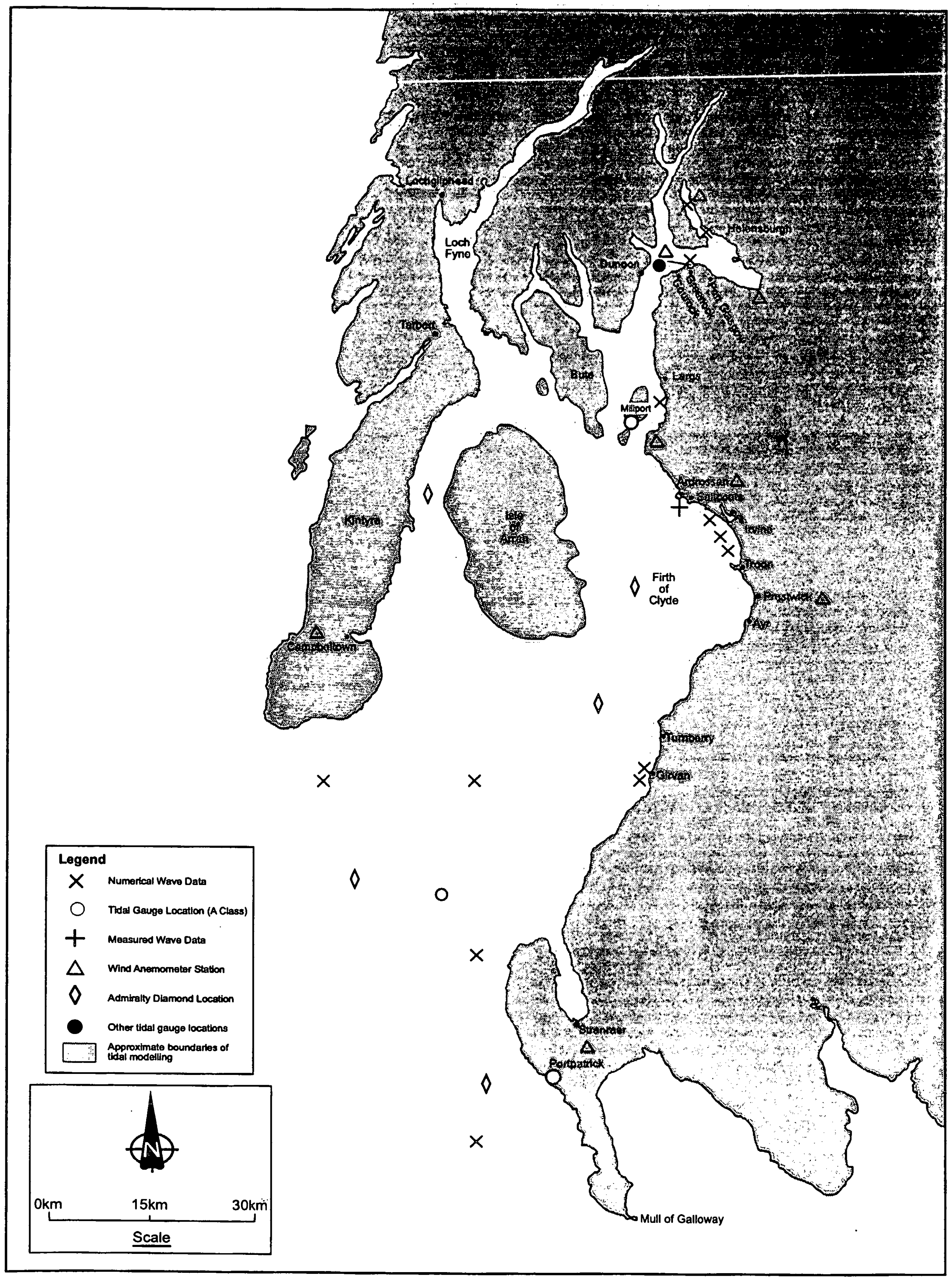


Figure 6 Cell 6 - Location of wind, tidal and wave data

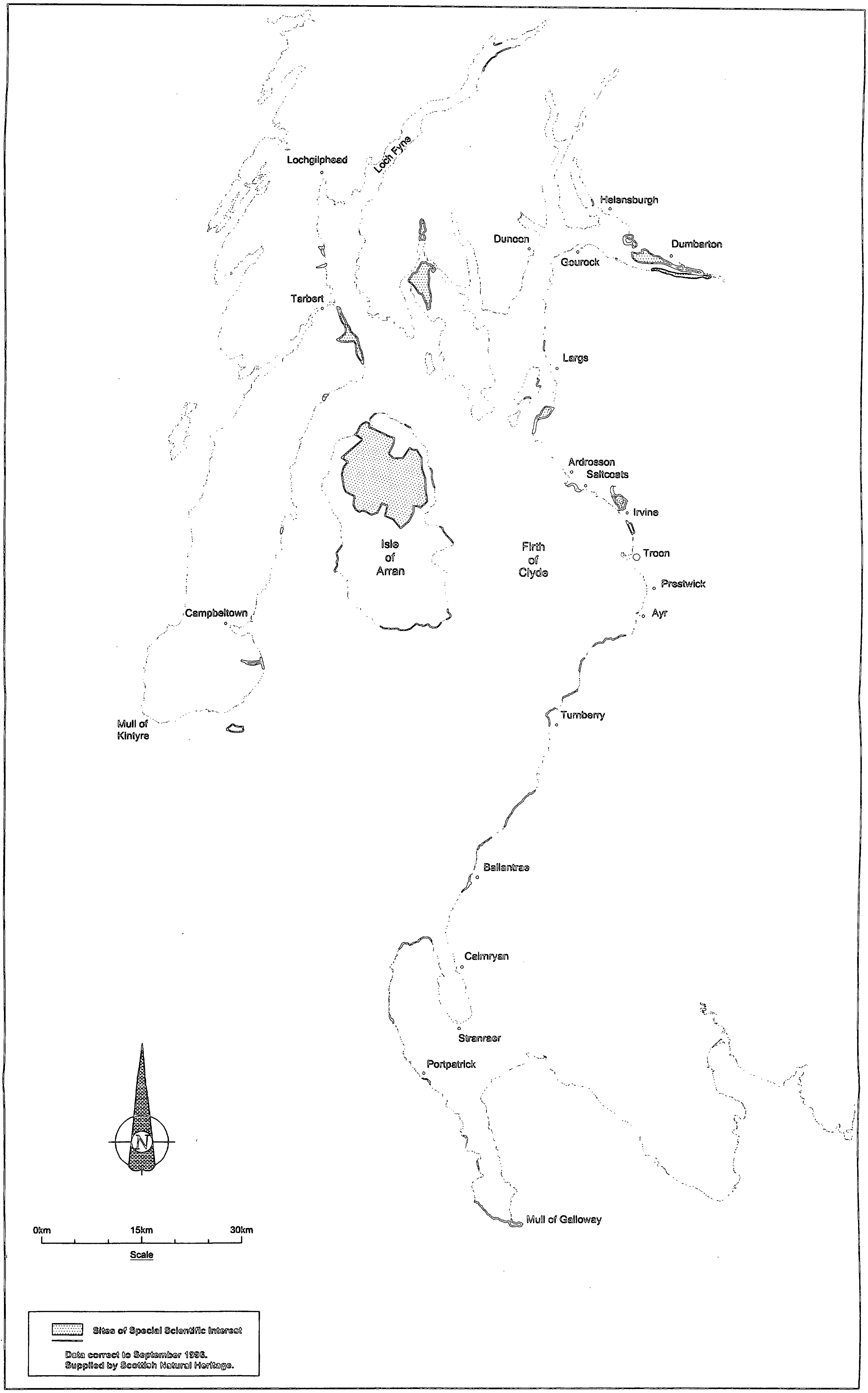
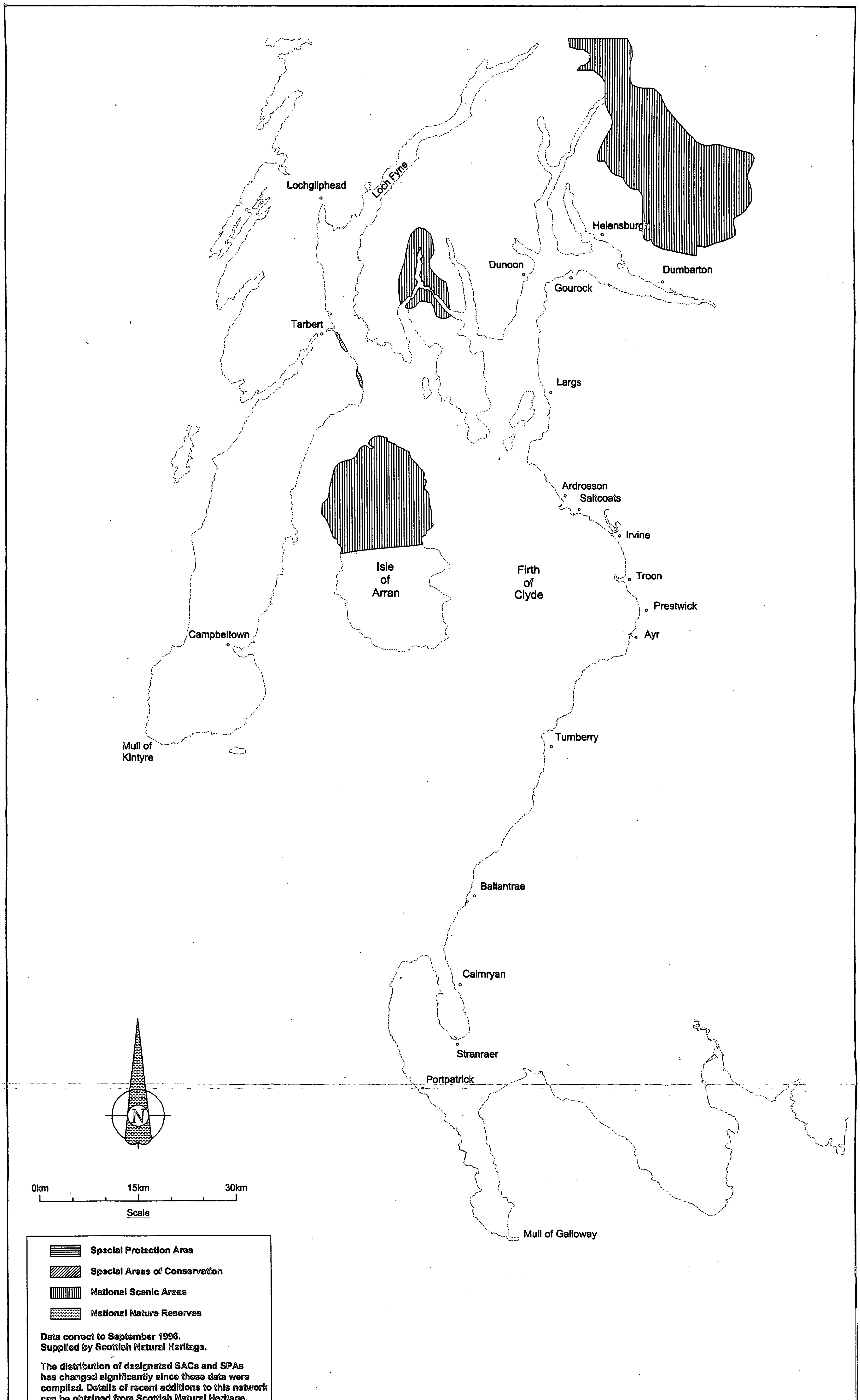


Figure 7 Cell 6 – Location of Sites of Special Scientific Interest

Figure 8 Cell 6 - Location of sites of natural heritage importance (other than SSSIs)



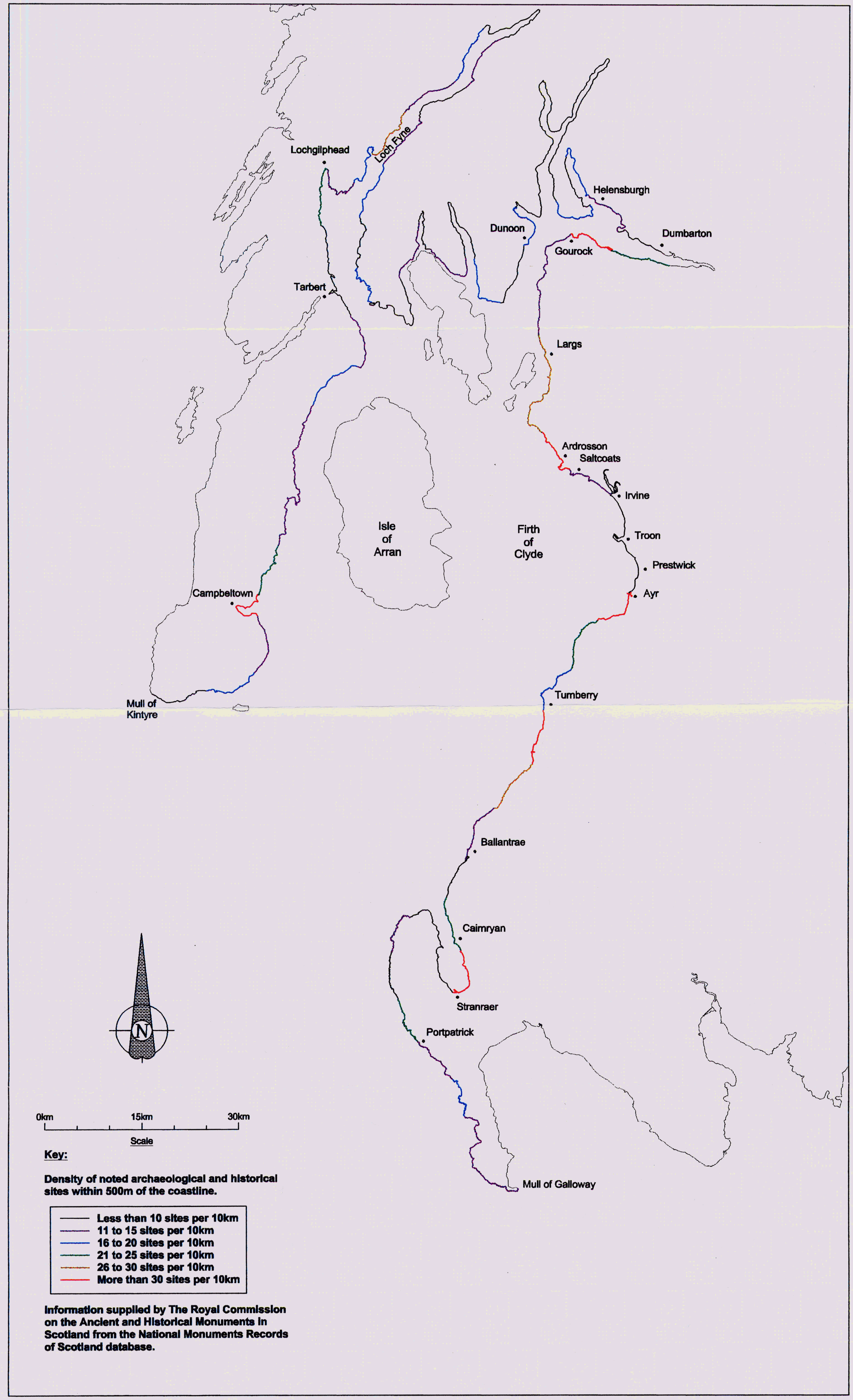


Figure 9 Cell 6 - Density of noted archaeological and historical sites

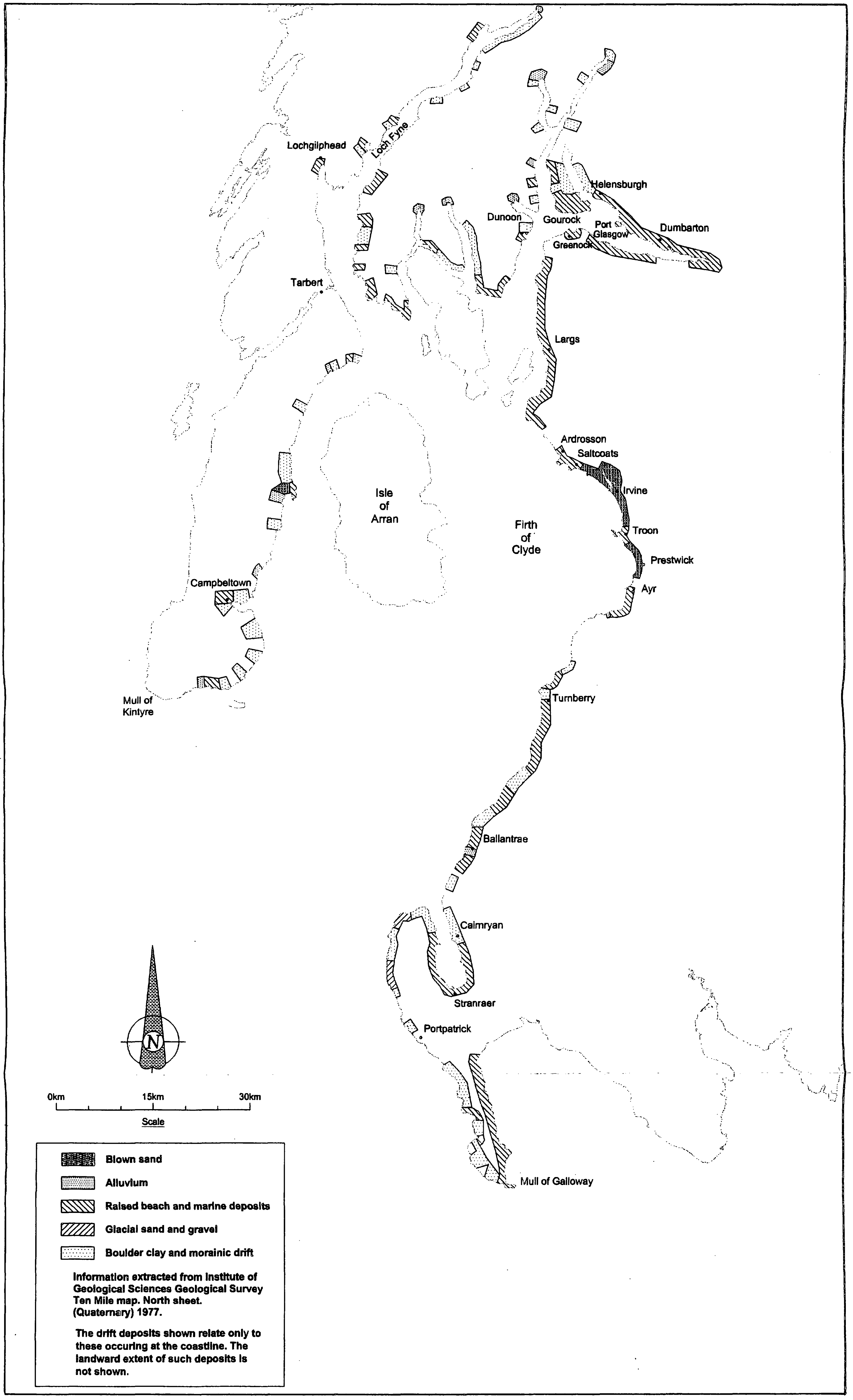
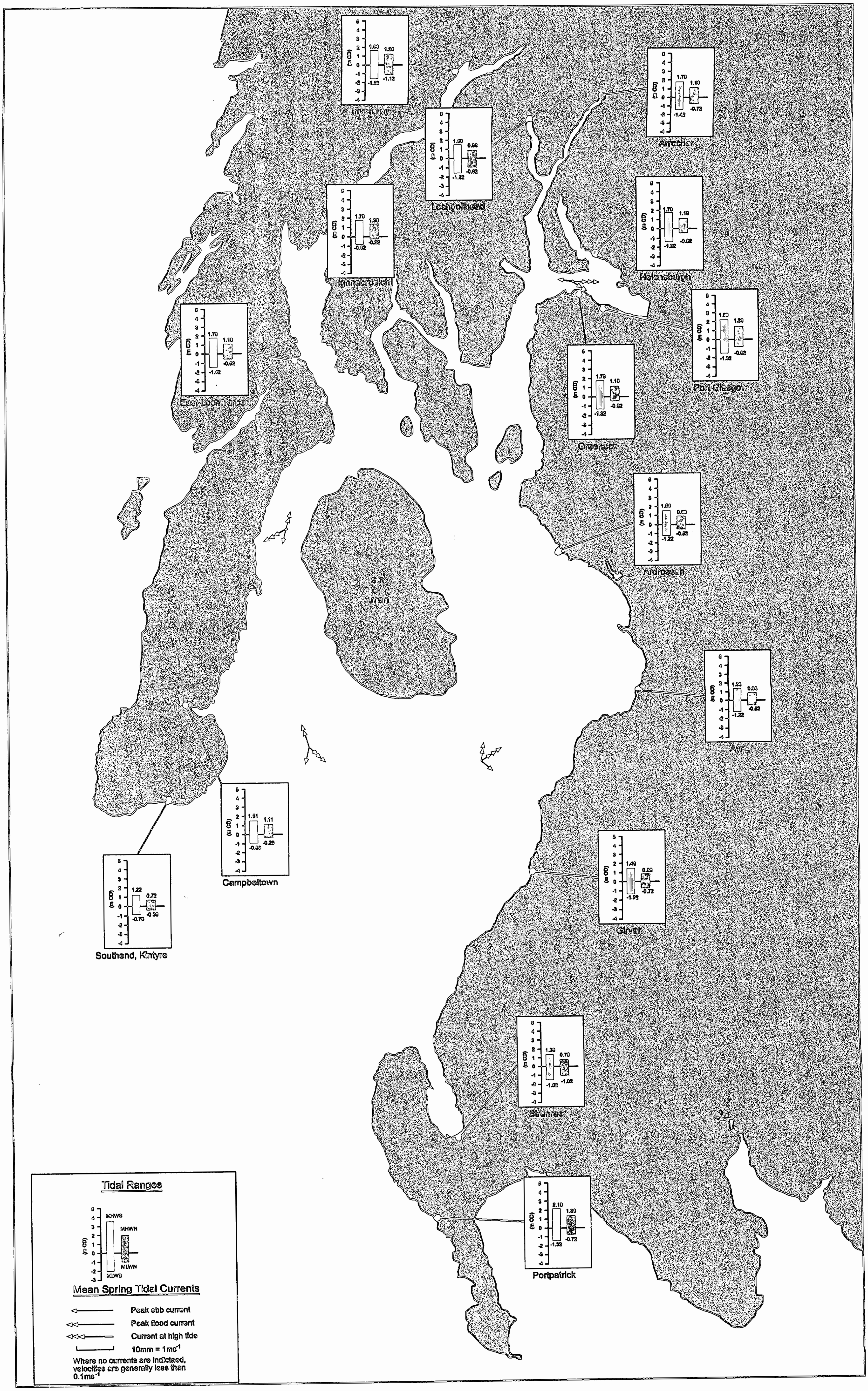


Figure 10 Cell 6 - Drift deposits

Figure 11 Cell 6 - Tidal levels and current information



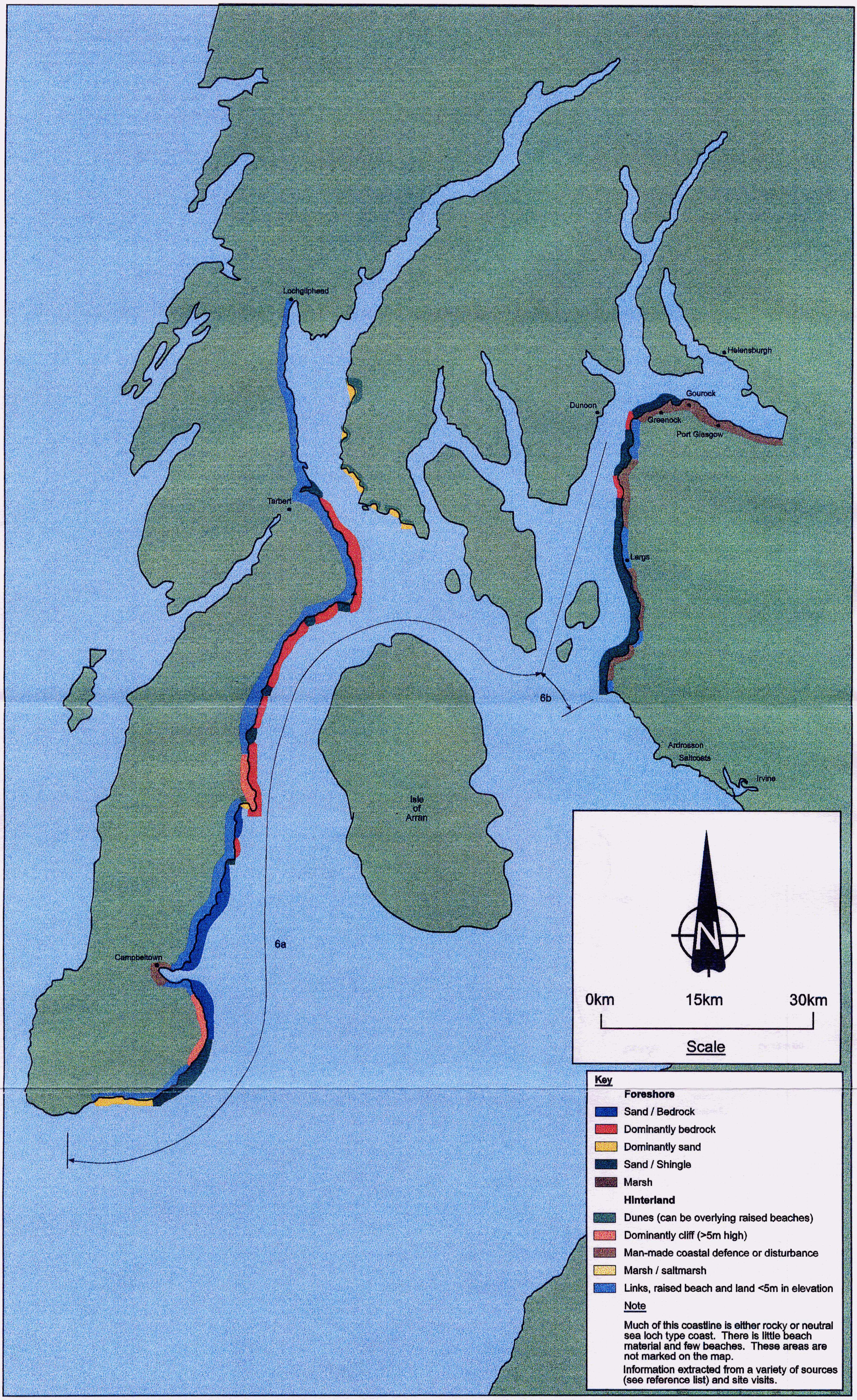


Figure 12 Sub-cells 6a & 6b - Foreshore and hinterland characteristics

Figure 13 Sub-cells 6a & 6b - Dominant littoral processes

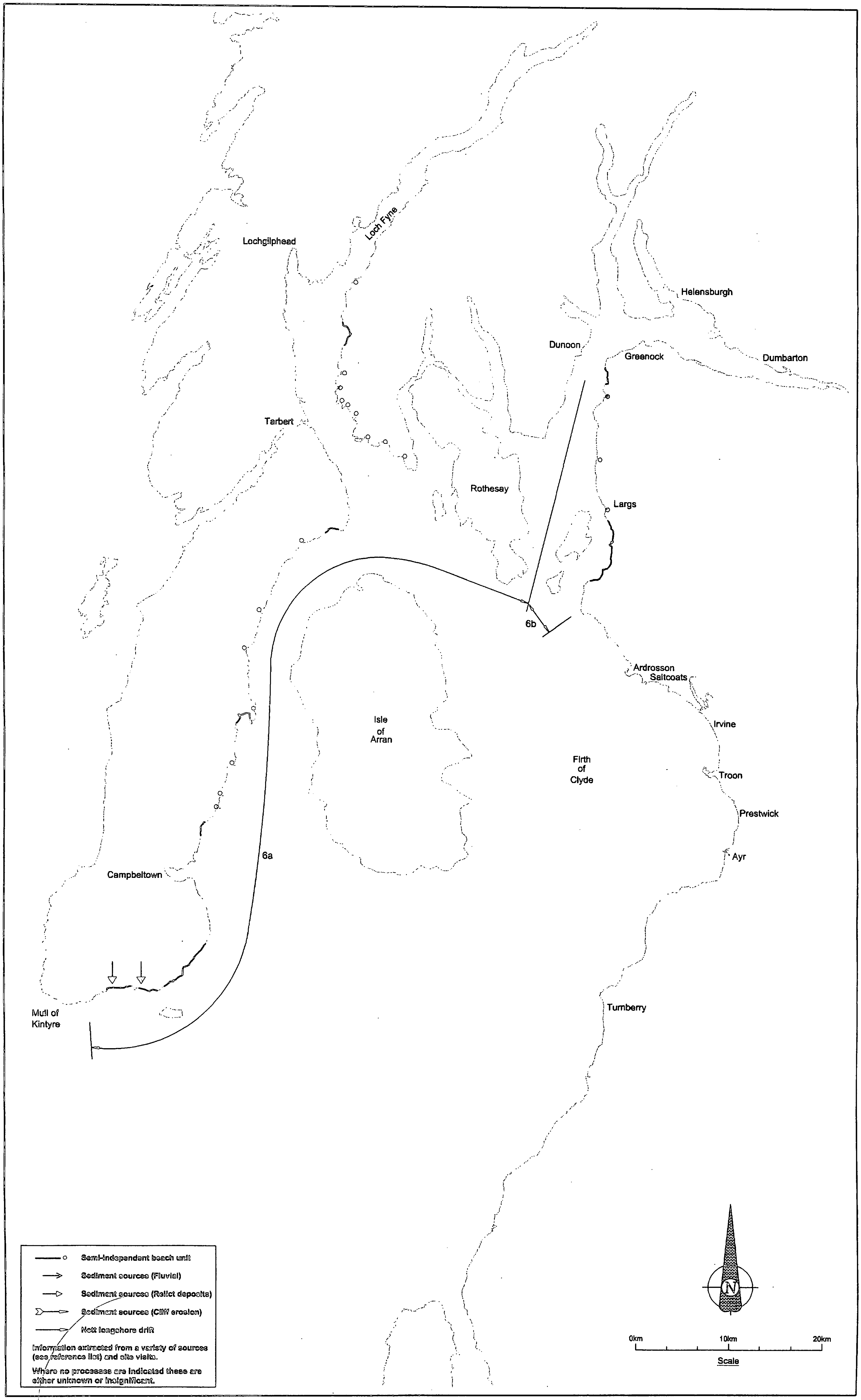
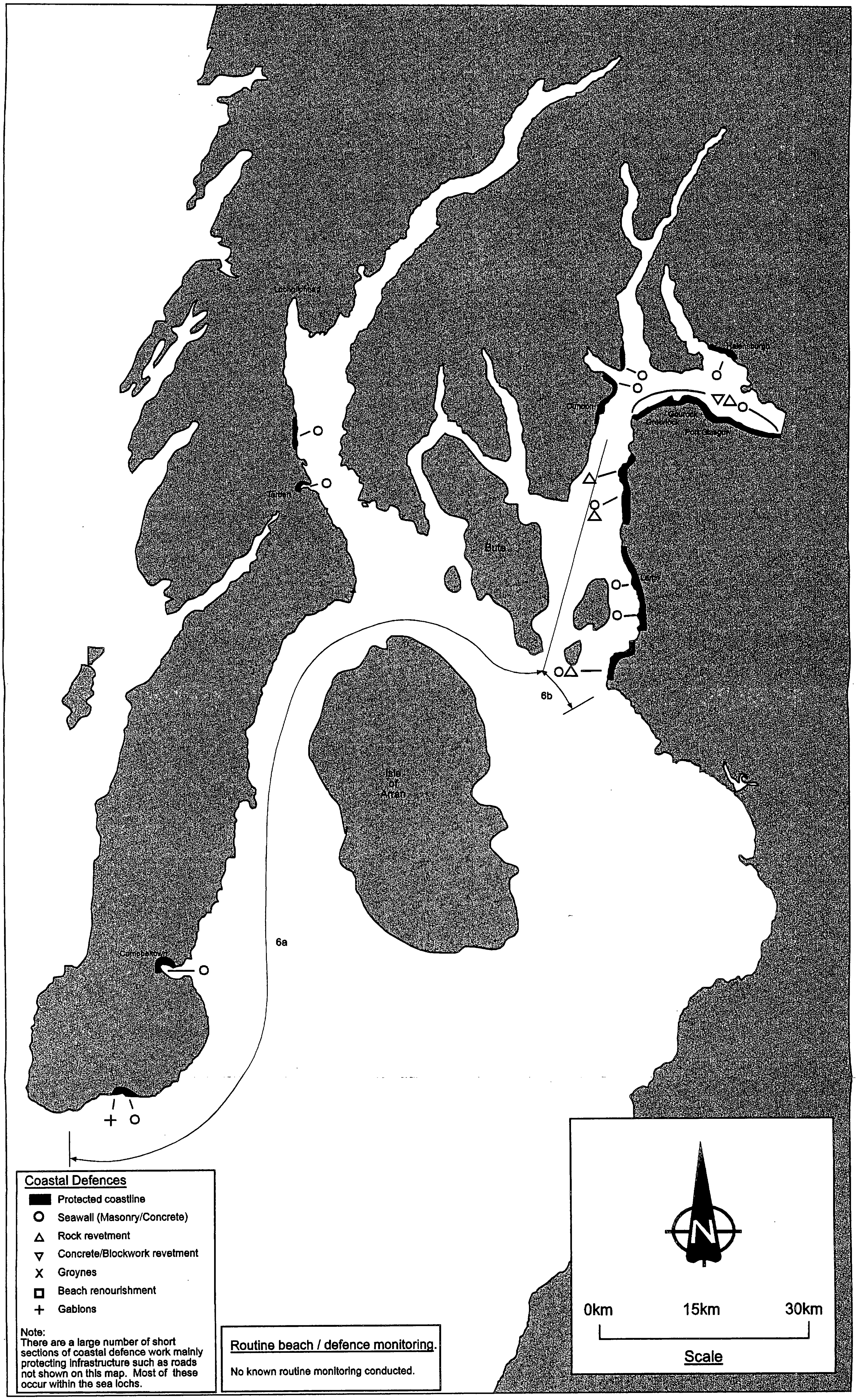


Figure 14 Sub-cells 6a & 6b - Coastal defences and monitoring



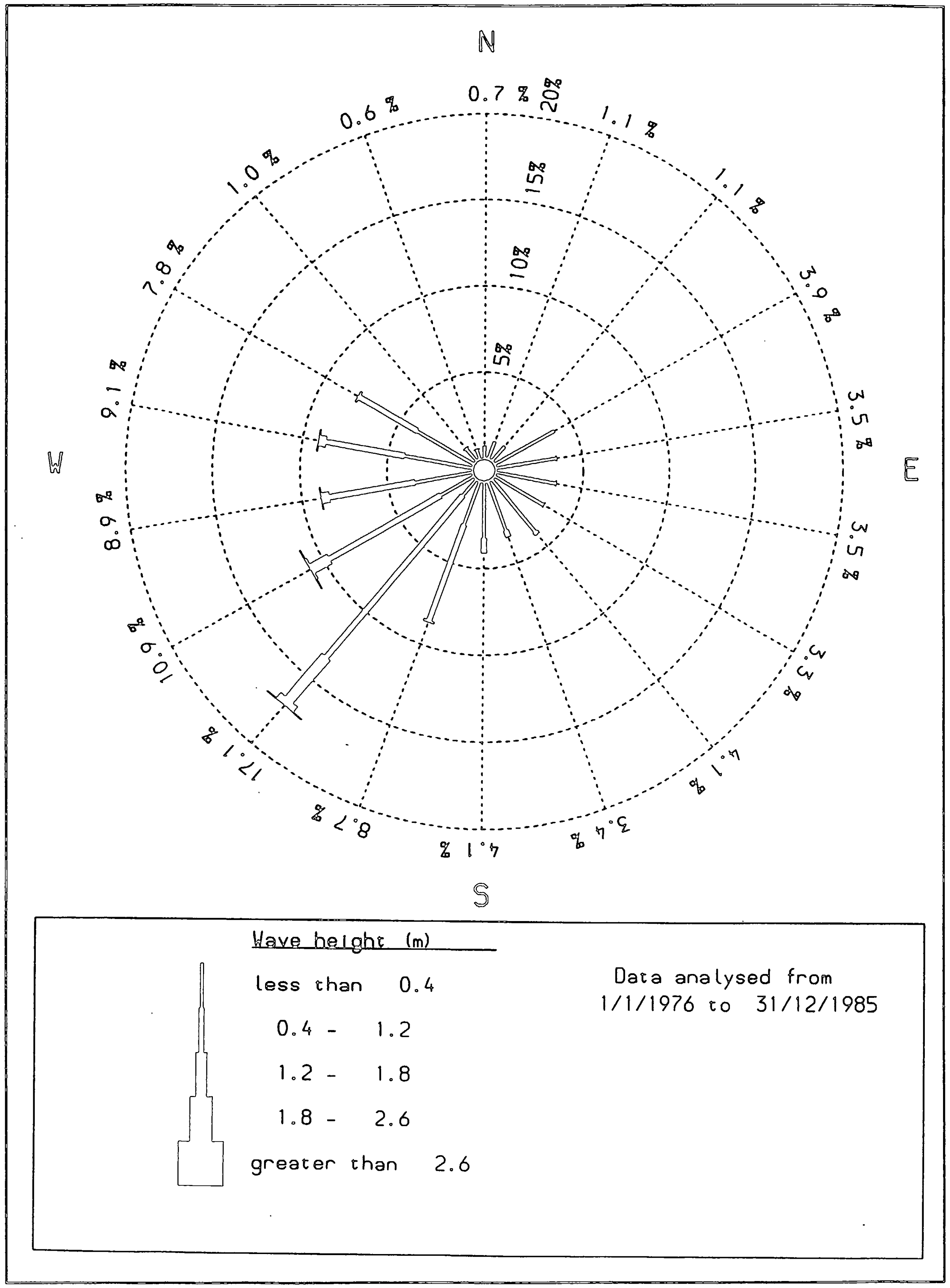


Figure 15 Wave climate offshore of Troon

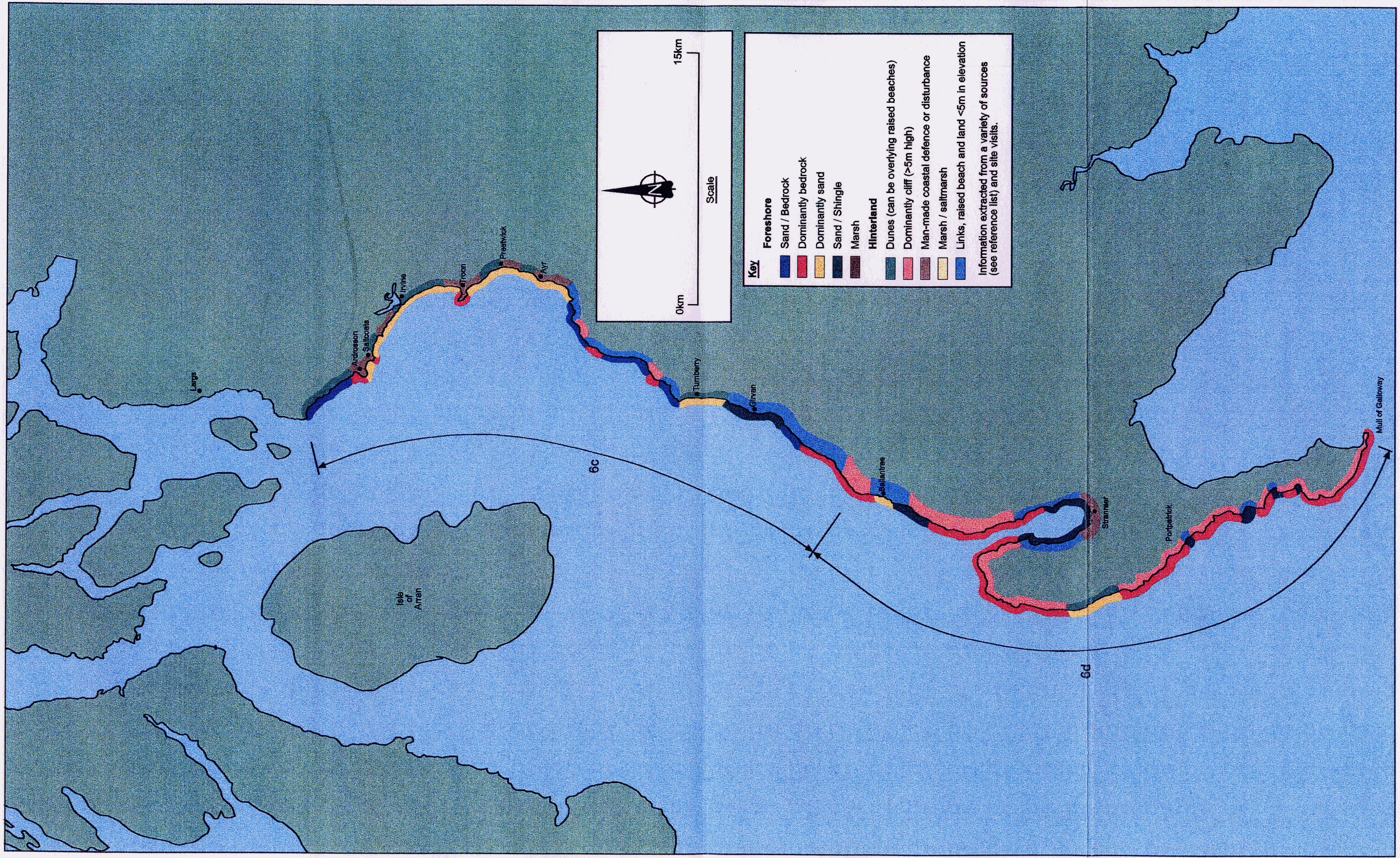


Figure 16 Sub-cells 6c & 6d - Foreshore and hinterland characteristics

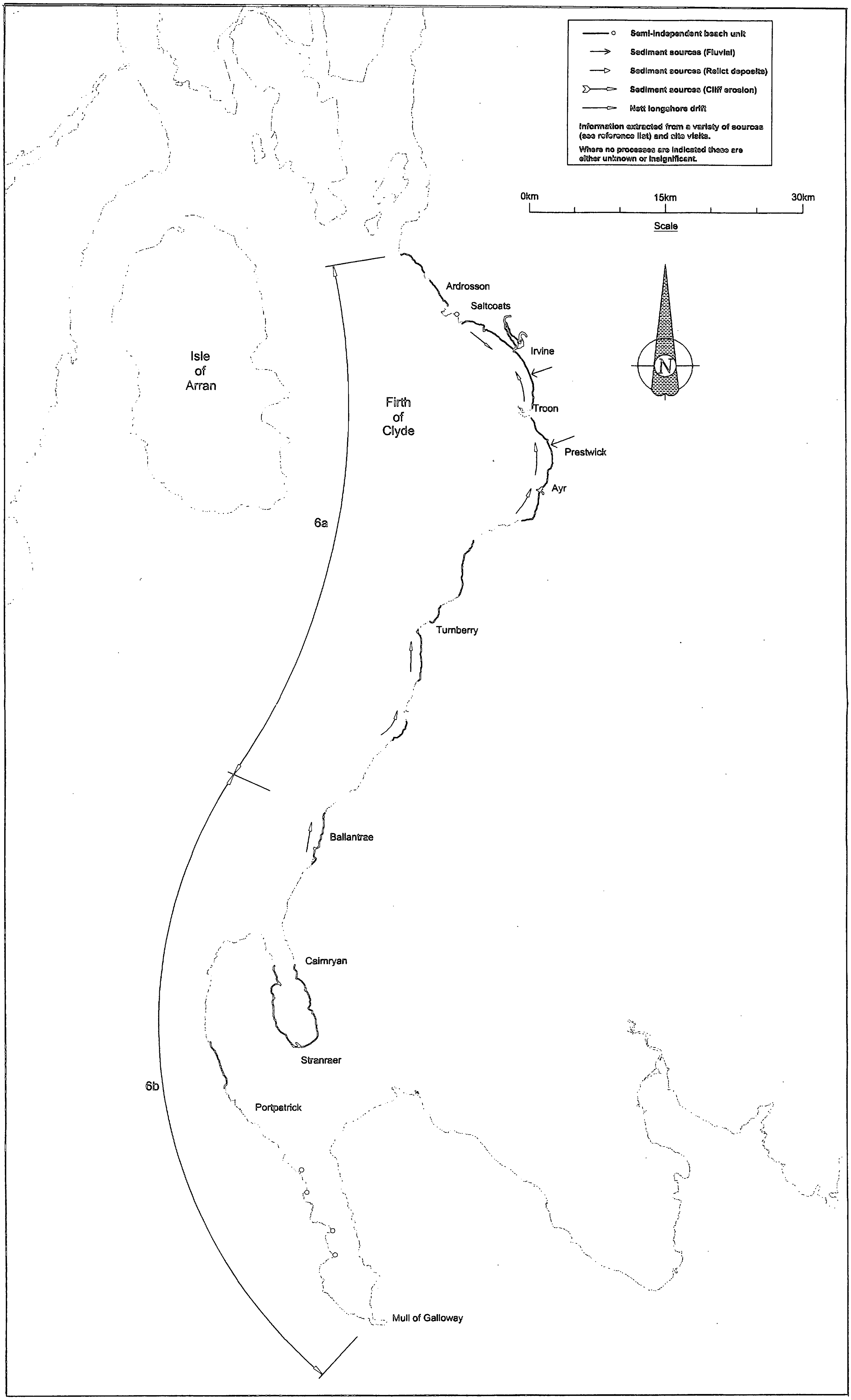
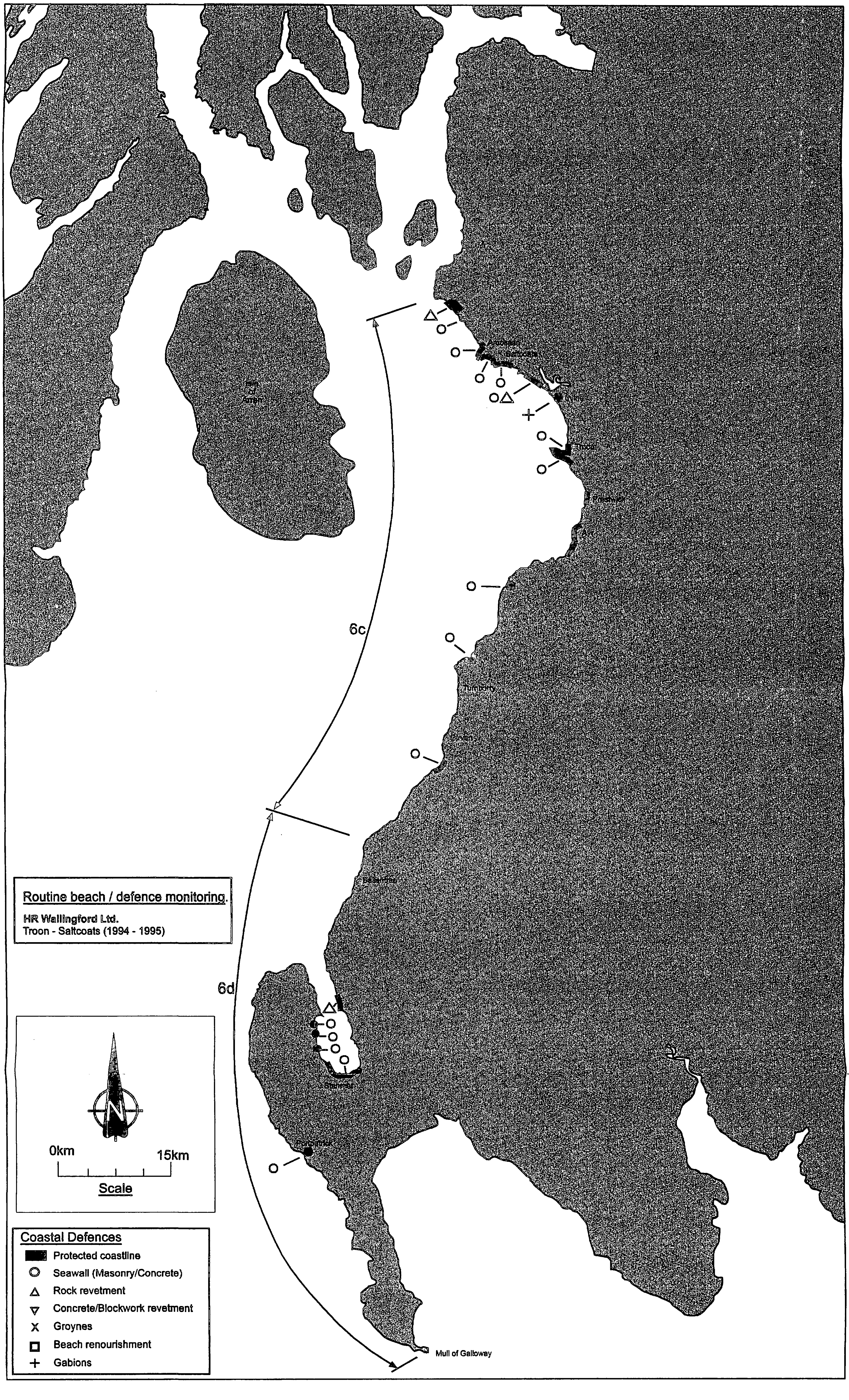


Figure 17 Sub-cells 6c & 6d - Dominant littoral processes

Figure 18 Sub-cells 6c & 6d - Coastal defences and monitoring



Appendix 1 Cells 6 - 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
Balnabraid Glen	NR760154	109.4	1985	Rocky shore Sea cliff(hard rock). Lower plants
Torrisdale Cliff	NR798348	27.8	1985	Sea cliff(hard rock) Woodland
Claonaig Wood	NR 864555	55.4		Biological Interest - Oak woodland
Tarbert - Skipness Coast	NR901640	592.3	1989	Sea cliff(hard rock) Woodland Peatland Lower plants Mammals noted Waders breeding Comments: Otters
Strone Point, North Loch Fyne	NN116087	4	1990	
Ruel Estuary	NS010800	341.7	1986	Tidal flats Saltmarsh Dry grassland Woodland Fen Lower plants
Rhu Point	NS264840	0.1	1984	Geological interest
Ardmore Point	NS314785	134.8	1983	Geological interest Saltmarsh Flush or seepage line Site used for wintering wildfowl. Nationally important.
Dumbuck Foreshore-Pillar Bank	NS350760	819.5	1983	Tidal flats Saltmarsh Marine biological interest Site used for wintering wildfowl. Internationally important.
Dumbarton Rock	NS400745	4.4	1986	Geological interest
Erskine to Langbank	NS395734	545.2	1984	Tidal flats Site used for wintering wildfowl. Internationally important. Comments: Internationally important for wintering redshank. Nationally important.
Largs Coast Section	NS192627	7.7	1990	Geological interest
Portencross Coast	NS190521	477.9	1971	Geological interest
Ardrossan - Saltcoats	NS240415	53.7	1987	Geological interest
Western Gailes	NS320358	93.7	1985	Saltmarsh Terrestrial invertebrates

Name	Grid Reference	Size (ha)	Date Notified	Site Designations
Troon Golf Links & Foreshore	NS335287	149.6	1985	Sand dunes Scrub Site used for wintering wildfowl. Locally important.
Maidens to Doonfoot	NS316194	224.5	1989	Geological interest Tidal flats Maritime heath Woodland Scrub Scarce or rare plants Terrestrial invertebrates Seabirds breeding
Turnberry Lighthouse -Port Murray	NS196072	24.4	1991	
Turnberry Dunes	NS199062	77.7	1985	Terrestrial invertebrates
Bennane Head Grasslands	NX110880	74.1	1992	Dry grassland Flush or seepage line Terrestrial invertebrates
Girvan-Ballantrae	NX095874	89.2	1989	Geological interest
Corsewall Point to Millevr Point	NX000729	60	1994	
Salt Pans Bay	NW966614	28.8	1988	Sea cliff(hard rock) Dry grassland Maritime heath Flush or seepage line Scarce or rare plants Seabirds breeding Site used for wintering wildfowl. Locally important.
Morroch Bay	NX017524	11.7	1990	Geological interest
Grennan Bay	NX074438	6.6	1989	Geological interest
Port Logan	NX092402	4.6	1988	Geological interest
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 6 - 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 — Tel: 0131-667 1000
EH9 3LA — Fax: 0131-668 2683

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

British Oceanographic Data Centre (BODC)
See Proudman Oceanographic Laboratory

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

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

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

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

Institute of Marine Studies
University of St Andrews
St Andrews
Fife — Tel: 01334 462886
KY16 9AJ — 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 — Tel: 0131-662 1456
EH8 9NX — Fax: 0131-662 1477

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

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

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

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

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

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

Scottish Tourist Board
23 Ravelston Terrace
Edinburgh — Tel: 0131-332 2433
EH4 3EU — 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.