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Coastal Cells in Scotland: Cell 1 – St Abb's Head to Fife Ness

D L Ramsay & A H Brampton

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REPORT

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THE SCOTTISH OFFICE

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

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

Summary

This report reviews the coastline between St Abb's Head and Fife Ness on the south east coastline of mainland Scotland. It describes the various coastal characteristics and processes which affect the regime of this particular stretch of shoreline. The report includes a description of the major coastal features, processes, and defences along with other aspects of beach development. The stretches of coastline which, for coastal management purposes, can be treated as independent or semi-dependent cells, are also identified.

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

Note

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

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

1 *Introduction*

1.1 General

In January 1996, HR Wallingford was commissioned by Scottish Natural Heritage, (SNH), The Scottish Office Agriculture, Environment and Fisheries Department, (SOAEFD) and Historic Scotland (HS) to extend an existing study, (HR Wallingford, 1997) to define Coastal Cells and Sub-cells around the coastline of Scotland. This report, which reviews the coastline of Cell 1 between St Abb's Head and Fife Ness, 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 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 the Project Specification. The aims are to provide:

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

(ii) maps of the cell concerned 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 general direction(s) of littoral drift therein and known areas of erosion and accretion,

(iv) a map of each sub-cell identified 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 historical and archaeological sites to coastal erosion

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

1.3 Outline of report

A general introduction to the concept of coastal cells, and how the concept has been applied to the coastline of Scotland is provided in Chapter 2. Chapter 3 provides general background information on the coastal environment of Scotland in the context of coastal cells. Chapter 4 provides reference to data sources of relevance to coastal management in Cell 1. Chapter 5 forms the main body of the report. A brief description of Cell 1 detailing all the cell and sub-cell boundaries is given. For each sub-cell, a description of its character and the processes occurring there is detailed. An assessment of climatic change, sea level rise, and the likely effects on the coastline of in Cell 1 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 the 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, 1993a). 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, 1993a), resulted in its suggested division into 11 main cells, each of which was further divided into sub-cells. An ideal cell would be entirely self-contained from a sediment transport viewpoint, i.e. there would be no nett import or export of beach material. Then, although coastal defence works could affect the whole cell by interrupting the longshore drift, they cannot affect beaches in other cells. Once established, these cells (and sub-cells) have proved to be a useful basis for shoreline management purposes. In England, the Ministry of Agriculture, Fisheries and Food (MAFF) have introduced Shoreline Management Plans; these are drawn up to provide a strategic basis for planning future coastal defences. Apart from considering aspects such as waves, tidal levels and coastal erosion/accretion, these Plans consider wider issues. Typically these include land use, ecological and geological conservation, tourism and recreation etc. As a consequence, in England and Wales, these plans provide a useful input 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". Considerations other than just the longshore transport of beach material are used to define cells in these situations. These include general orientation of the coastline and its hydraulic environment.

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 five distinct units or divisions, each separated by a major fault or fracture in the Earth's crust:

- the north-west Highlands and Islands west of the Moine Thrust, composed of "ancient" Lewisian gneiss;
- the Northern Highlands between the Moine Thrust and the Great Glen Fault, composed of the eroded roots of the Caledonian Mountain Belt, consisting primarily of one thousand million year old metamorphosed sediments of the Moine;
- the Central Highlands between the Great Glen Fault and the Highland Boundary Fault, composed of 800Ma 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 three-hundred million years 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 100Ma, 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. 2,000,000 years (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 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 result 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 meterological 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, the small asymmetries can be fundamentally important in a large number of ways, particularly in the transport of fine-grained sediments (muds and clays), together with any adsorbed pollutants, for example heavy metals. In terms of sediment transport in the nearshore zone, the direction and velocity of currents acting at High Water Level may be more important than higher current velocities acting at mid tide. Similarly the tidal residual (vectorial displacement over the period of one tidal cycle) may also be important in the transport of nearshore sediments, particularly in estuaries.

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

Waves and swell

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

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

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

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

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

3.4 Littoral processes

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

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

Where waves break obliquely to 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, 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 where it is moved by wind action into a dune system, or whether it is accreting on the beach, is also important.

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

3.5 Coastal defence, monitoring and management

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

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

The standard of protection provided by a section of coastal defence depends on the margin of safety it provides against structural collapse or unacceptable high overtopping discharge, for example, both of which are highly influenced by the level and condition of the beach in front of the defence. Each of these criteria are interrelated with structural failure, a consequence of the hydraulic forces as well as structural and geotechnical aspects. Overtopping and flooding, as well as depending on the severity of storm conditions, is also a function of the crest level of the structure and its 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, hence allowing 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 a groyne system. The long-term effects of either reducing or stopping all drift along a coastline, can be an increase in coastal 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 designations which are used to protect terrestrial sites with natural and cultural heritage value. Statutory designations, or areas have some form of 'custodial' ownership, have mechanisms which protect them, to a limited extent, from certain development or harmful activities. There is also a wide range of conservation legislation protecting individual habitats and species which may affect future shoreline management. Further information on natural heritage sites can be obtained from Scottish Natural Heritage with information on cultural heritage sites from Historic Scotland.

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

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

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

National Nature Reserves (NNR) — Scottish Natural Heritage

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

Marine Nature Reserves (MNR) — Scottish Natural Heritage

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

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

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

Special Areas of Conservation (SAC) — Scottish Office

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

Special Protection Areas (SPA) — Scottish Office

The 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 SAC's.

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 the Countryside Commission for Scotland 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 have 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.

Area 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 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 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 one which the Secretary of State considers to be of national importance and is included in a set of records (known as the Schedule) maintained by him under the Ancient Monuments and Archaeological Areas Act 1979.

4 *Cell 1 - Sources of information*

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.

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 (BODC, 1991). 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 and species, and activities which have an effect on the North Sea, is detailed within *The Directory of the North Sea Coastal Margin* (Doody et al, 1991) and in *Coast and Seas of the United Kingdom. Region 4: South East Scotland: Montrose to Eyemouth* (Barne et al, 1997).

Details of physical oceanographic and meteorological (metocean) data collected around the British Isles on behalf of the UK energy industry is summarised in a report by Metocean (1994). This includes details 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.

4.2 Geology and geomorphology

The geology of the south east of Scotland has been studied in detail in several studies, the most comprehensive being *British Regional Geology: The South of Scotland* (Greig, 1971) and *The Midland Valley of Scotland* (Cameron & Stephenson, 1985). These reports reference a large number of more detailed localised studies conducted within the south east of Scotland. The British Geological Survey have also produced a series of solid and drift geology maps the availability of which is detailed below:

Table 2 Available geological maps

Map No.	Map Name	Solid/ Drift Geology	Scale
34	Eyemouth	Solid & Drift	1:50,000
33E	Dunbar	Solid & Drift	1:50,000
33W	Haddington	Solid & Drift	1:50,000
32E	Edinburgh	Solid	1:50,000
32W	Livingston	Solid	1:50,000
31E	Airdrie	Solid & Drift	1:63,360
39E	Alloa	Solid & Drift	1:50,000
40	Kinross	Solid & Drift	1:63,360
41	North Berwick	Solid & Drift	1:63,360

A 1:625,000 scale Quaternary geology map, covering the area is also available.

The Geological Conservation Review was a 12-year research programme initiated by the Nature Conservancy Council in 1977 to identify the key onshore earth science sites in Great Britain using available survey and research information. Site classification was completed in 1989 and the review is currently being published through a series of approximately 40 volumes, 14 of which are now available (1998).

The geomorphology of the coastline in this region of Scotland is described in several studies, the principal ones being *The coastline of Scotland* (Steers, 1973); *The geomorphology of the British Isles: Scotland* (Sissons, 1976); *The beaches of South East Scotland* (Rose, 1980) and *The beaches of Fife* (Ritchie, 1979). Information on the geomorphology of estuaries within Cell 1 can be found in the Estuaries Review carried out by the Joint Nature Conservation Committee (Buck, 1993). Other, more localised studies are detailed within the bibliography of this report.

4.3 Bathymetry

The bathymetry of the south east coast of Scotland is illustrated in detail on the following Admiralty Charts:

Table 3 Available admiralty charts in Cell 1

Chart No.	Location	Scale
175	Fife Ness to St Abb's Head	1:75,000
734	Firth of Forth: Isle of May to Inchkeith	1:50,000
735	Firth of Forth: North Craig to Oxcars	1:25,000 &1:10,000
736	Firth of Forth: Granton and Burntisland to Rosyth	1:15,000 &1:7,500
737	Firth of Forth: Rosyth to Grangemouth	1:15,000
738	Firth of Forth: Grangemouth to Stirling	1:20,000
739	Harbours in the Firth of Forth	1:200,000
1407	Montrose to Berwick	1:10,000 &1:7,500

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 (Figure 6), and the information passed to the Meteorological Office which could be useful in estimating wave conditions on the south east coastline of Scotland. At Turnhouse and Blackford Hill the recorders are equipped with Digital Anemograph Logging Equipment (DALE), which logs wind data onto magnetic tape, and which is sent to Bracknell for incorporation into the Climatological Data Bank. At Leith Harbour a graphical recorder is used, which has to be hand-analysed to provide suitable data for archiving. The recorders at Leuchars and Boulmer, despite being to the north and south respectively of this Cell, could be useful. These recorders are equipped with Semi-Automatic Meteorological Observing Systems (SAMOS) which produce wind statistics continuously for immediate archiving. A summary of the available wind data is provided in the following table:

Table 4 Available wind data in Cell 1

Location	Period covered	Anemometer Type
Blackford Hill	01/70 - Present	Digital Anemograph Logging Equipment (DALE)
Boulmer	01/70 - 12/91	Analysed anemograph from SAWS/SAMOS/CDL station
Leith Harbour	10/84 -Present	Data on Metform 6910
Leuchars	01/70 -Present	Analysed anemograph from SAWS/SAMOS/CDL station
Turnhouse	01/70 -Present	Digital Anemograph Logging Equipment (DALE)

4.5 Tidal data

The only A-class tidal gauge installation within this Cell is at Leith. 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 1 and 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 tidal predictions derived for these sites may not be as reliable as from an A-class gauge. Tidal gauges not part of the A-class network are also located at Dunbar and Rosyth, Figure 6.

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 1 the mean sea level is recorded at Dunbar, Leith and Rosyth.

Actual tidal levels, however, can and often do, vary significantly from those predicted using harmonic analysis due to the influence of meteorological effects (surges). The UK Meteorological Office Storm Tide 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 offshore. To provide predictions at the coastline a more detailed numerical model would be required. Details of such models are described later in this section.

A number of studies have been conducted into extreme (surge) water level predictions (e.g. Graff, 1981; Woodworth, 1987; Coles & Tawn, 1990). The latest research into trends of extreme sea levels (Dixon & Tawn, 1994) provides a site by site analysis of extremes around the coast of the UK. This research has been extended to produce a spatial analysis of extreme water levels every 20km around the coast (Dixon & Tawn, 1997).

Tidal flow modelling has been conducted for the entire Firth of Forth (HR Wallingford, 1993b, 1994a) to assess water movements, water quality and pollution movements within the Firth of Forth. A similar model covering the Firth has been developed at Strathclyde University.

Table 5 Tidal modelling studies within Cell 1

Cell	Location	Study	Contact
1a-1d	Firth of Forth	Tidal flow modelling Water quality modelling	HR Wallingford or SEPA (East)
1a-1d	Firth of Forth	Tidal flow modelling Water quality modelling	Strathclyde University

Tidal current measurements are normally made over relatively short periods of time, (usually less than 1 year), often in connection with a particular study. There are two main sources of such data. Firstly the British Oceanographic Data Centre have a digital inventory of current meter data around the British Isles collected from a large number of both national and international organisations. The directory contains information up to 1991 and is available directly from BODC. A large amount of tidal current measurements have been recorded within Cell 1 particularly in the Inner Firth of Forth. Other tidal current data is likely to be held by the new Unitary Councils and the East of Scotland Environment Protection Agency. General details of tidal current patterns within and around the Firth of Forth are provided in *The Tidal Stream Atlas: North Sea - Flamborough Head to the Pentland Firth* (Hydrographer of the Navy, 1963).

4.6 Wave data

Information on offshore wave conditions can be obtained from measured wave data or from synthetic wave data generated using numerical models. The only detailed record of instrumentally recorded wave data in Scotland is the Marine Information and Advisory Service (MIAS) catalogue (MIAS, 1982) which was compiled in 1982. An updated digital version is presently being developed. Wave recording is conducted occasionally by commercial organisations, normally in connection with marine construction projects, e.g. harbour developments. Waves have been instrumentally measured at several positions in Cell 1, notably at North Carr Lightvessel, at Methil and Pittenweem. Wave measurement locations are shown in Figure 6 with further details provided in Table 6.

Table 6 Sources of measured wave data

Location	Lat/Long	Period covered	Mean Water Depth (m)	Contact
North Carr Lightvessel	56°18'18"N 2°32'00"W	06/69 to 06/73	42m	MIAS
Methil	56°10'N 3°06'00"W	05/74 to 02/75	-	Redpath Dorman Long (MIAS Catalogue)
Pittenweem	56°11.4'N 2°42.0"W	10/86 to 1/87	30m	HR Wallingford Ltd

Information on wave conditions can also be obtained from the VOS (Voluntary Observations from Ships) archives. Many ships of passage make regular observations of wind and wave conditions as part of their routine duties. This information is collected worldwide and collated by the UK Meteorological Office. The records include date, time, location, wind speed and direction, significant wave height (H_s), zero-crossing period (T_m) and wave direction. Although not scientifically measured, VOS records have been found to be a useful source of data where there has been a large number of records spanning many years, e.g. major shipping lanes. VOS data is available in the form of monthly, seasonal and annual frequency tables of wave height and period in 300 sectors for sea areas specified in 10 latitude and longitude squares. Details of the density of VOS data can be obtained from the Meteorological Office.

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

In many locations offshore wave prediction using numerical modelling techniques is difficult. Around much of the UK coast it is necessary, as a minimum, to have a model which can predict the generation of waves over a substantial part of the sea or ocean, and then to "follow" those waves as they develop into swell. A number of such numerical models exist, all run by national meteorological offices, or other government 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 models are the result of an evolving series of such models, in use since 1976. They were designed primarily for offshore application, for example in ship routeing and operation of offshore structures. The model calculations are carried out on a polar stereographic grid, whose exact spacing varies from one latitude to another. The European Wave Model (grid spacing about 30km) is nested within the Global Model (grid spacing about 150km) from which it takes its boundary wave conditions. The 30km grid size means that shallow water effects are not well represented in the model, and grid points closest to the land are not used for prediction purposes. Before use, the model predictions therefore need to be transformed from 20-50km offshore to the shoreline (see below).

Both models are run twice daily, driven by wind fields extracted from operational global weather forecasting models. They produce wave forecasts from 12 hours prior to the run-time ("T") up to 36 hours ahead, at 3 hourly intervals. As well as noting the time, date, latitude and longitude, each forecast gives the wind speed and direction, and the significant wave height, mean wave period and wave direction for the separate wind-sea and swell components and overall. The data from T-12 hours to T+0 hours is permanently stored in an archive, whilst the data from T+0 hours to T+36 hours is immediately disseminated for forecasting purposes. Sea state observations from fixed buoys, oil platforms, Ocean Weather Ships, and more recently satellite wave measurements, are used for real-time "calibration" of the models, and also for periodic validation. The archived information provides a very useful "synthetic" offshore wave climate. Figure 6 shows the grid point locations offshore of the Firth of Forth.

Modern numerical methods are also capable of accurate predictions of "wind-sea" for offshore areas, especially if there is good quality, sequential wind data available to provide the basic input conditions. Cell 1, and particularly the Firth of Forth, is well served with numerical wave studies. The locations of these studies are detailed in Figure 6 with more information provided in Table 7.

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 the 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 estuarine 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. Locations where inshore wave conditions have been assessed in Cell 1 are shown in Figure 6 and detailed in Table 7.

Table 7 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: Closest point is normally less than 20km from the coast	1986 onwards	Variable	Wind, swell and total sea climate and extremes	UK Meteorological Office or HR Wallingford
Torness	Inshore wave prediction at various locations along Power Station seawall	-	Variable: -2.0m OD to 0.9m OD	Wave climate and extremes	HR Wallingford
Dysart & East Wemyss	Inshore wave prediction at each location	1976-1987	10m water depth at low tide	Wave climate & extremes	HR Wallingford
Pittenweem	Offshore: S E of Pittenweem Inshore 3 locations	-	Offshore: 30m CD contour Inshore: 10m CD & 5m CD contour	Extremes	HR Wallingford
Anstruther	Inshore: 2 locations	-	Approx. 10m CD & 5m CD contour	Extremes and joint probability analysis	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 1 the number of designated natural heritage sites is given in the table below:

Table 8 Cell 1 - Natural heritage designations

Designation	Number	Designation	Number
SSSI	19	NSA	-
NNR	2	NHA	-
MNR	-	AGLV	8
LNR	2	ESA	-
SAC	-	MCA	1
SPA	1	RSPB	2
RAMSAR	-		

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

The locations of Sites of Special Scientific Interest is shown in Figure 7 with further information detailed in Appendix 1. Other natural heritage designations are shown in Figure 8. These data are accurate to September 1996.

Advice on historical and archaeological matters are provided by a number of organisations which are detailed in Table 9. The Royal Commission on the Ancient and Historical Monuments in Scotland (RCAHMS) maintain a GIS database with the locations of scheduled archaeological and historical sites. Only the location of sites within 50m of the coastline was requested from RCAHMS in this study. However, the RCAHMS advised that to locate all coastal sites would require a resolution of 500m from the coastline. Figure 9 shows the relative density of scheduled archaeological and historical sites within 500m by 10km long strips along the coastline of Cell 1. 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 made. Along much of the coastline of Cell 1 such survey work has been completed (James, 1996; Robertson, 1996). Appendix 2 details the actual locations of scheduled sites within 500m of the coastline obtained from the RCAHMS GIS database.

Table 9 Information sources for cultural heritage sites

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 (Fife Council only)
Sites or monuments already known	Historic Scotland/Regional Archaeologist (Fife Council only)/RCAHMS
Archaeological remains discovered during development	Historic Scotland/Regional Archaeologist (Fife Council only)
The discovery of a site	Regional Archaeologist (Fife Council only)/RCAHMS
An isolated artefact find	Regional Archaeologist (Fife Council only)/National Museums of Scotland/Local Museum
Damage to a scheduled monument	Historic Scotland
Damage to an unscheduled monument	Regional Archaeologist (Fife Council only)

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

5 Cell 1 - St Abb's Head to Fife Ness

5.1 General

Cell 1 has been defined, as the coastline between St Abb's Head and Fife Ness and including all of the mainland coastline of the Firth of Forth up to the road bridge (HR Wallingford, 1997). Both boundaries have been defined on account of the change in orientation of the coastline, and hence wave climate experienced upon the coastline. As such both boundaries (in terms of littoral transport) can be considered as drift divides. For the purpose of this study the inner boundary of the cell has been defined as the Forth Road Bridge and island coastlines have been excluded. The sub-cell boundaries at North Berwick and Elie Ness have been defined on account of the wave climate and sediment transport considrations. Sub-cells 1a and 1d are more exposed to severe wave conditions generated within the North Sea than the relatively more sheltered sub-cells in the Forth estaury. There is unlikely to be any significant transport of beach material across both these boundaries. 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 1a. The locations of these "semi-independent beach units" are shown on the relevant littoral process maps.

5.2 Cell 1: Physical characteristics

5.2.1 General

The characteristics of Cell 1 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, and where known, details of any surge information. The direction of the main tidal currents and magnitude of tidal velocities is also detailed. Any areas where significant tidal flooding occurs are noted. The offshore wave climate (both total sea and swell) has been predicted from the Meteorological Office Wave Model along with a range of extreme offshore wave conditions. These wave climates are representative of the general offshore wave climate, i.e. they do not represent one particular location. 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. Any known locations where man-made development in the coastal zone has altered the littoral regime are also described. Details of the foreshore and hinterland characteristics are shown in the relevant figures for each sub-cell along with the dominant littoral processes. Locations where maintenance dredging is conducted are listed, and where possible, an indication of dredging rates and the source of siltation.

The final section details the location, type and influences of coastal protection work occurring at the coast. 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 is 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 1a - St Abb's Head to North Berwick

5.3.1 Geology

The north-east facing coastline of sub-cell 1a has a varied solid geology ranging in age from around 435Ma (Silurian) to 340Ma (Carboniferous). Much of this solid geology is overlain by more recent glacial and post-glacial deposits.

The sub-cell is dissected by the Southern Upland Fault which appears at the coastline just to the south of Dunbar. South of this fault the bedrock decreases in age from St Abb's Head towards Dunbar. For approximately 9km to the west of St Abb's Head the bedrock, known as the Queensberry Grits of Silurian age, is almost continually exposed. These consist of bands of greywackes, siltstones and shales, up to 6m thick in places. Around Siccar Point a band of Old Red Sandstone outcrops at the coastline resting unconformably on the underlying Silurian bedrock. Between Cockburnspath and the Southern Upland Fault younger Carboniferous sandstones and limestones outcrop.

North of the fault, the Carboniferous Limestone Series form the major outcrops at the coastline. Both extrusive and intrusive igneous rocks commonly outcrop, particularly around North Berwick. These igneous rocks, typically basalt and dolerite, are much more resilient to marine erosion than the relatively softer Carboniferous limestones, resulting in differential rates of erosion with headlands formed where igneous rocks outcrop. Shore cut platforms, where the less resilient Carboniferous rocks outcrop, are a common feature with most of the cliffs now fossil.

Glacial and post-glacial deposits are relatively thin along most of this sub-cell (Figure 10). However, extensive deposits do occur within Belhaven Bay, Ravenshaugh and Barns Ness where raised beaches occur. The deposits around Belhaven Bay and to the north at Ravenshaugh are generally post-glacial, derived from sand moved onshore by wave and wind action during periods of relatively lower sea levels. To the south of Dunbar along the Barns Ness coastline, sand and gravel deposits, generally of fluvio-glacial origin, have been reworked to form the beaches.

5.3.2 Hydraulic processes

The mean spring tidal range within this sub-cell is 4.5m at Dunbar with a mean neap range of 2.2m, as shown in Table 10 and Figure 11. The tidal cycle has a period of just over 12 hours and high tide occurs at approximately the same time along the length of this sub-cell.

Table 10 Sub-cell 1a - Predicted tidal levels and ranges

Location	MSL mODN	MHWS mODN	MLWS mODN	Spring Range (m)	MHWN mODN	MLWN mODN	Neap Range (m)	LAT mODN	HAT mODN	ODN to CD (m)
Dunbar	-	2.4	-2.1	4.5	1.4	-0.8	2.2	-	-	+2.80

In Table 10 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 is based on tidal records from the A-class tide gauge network. In these publications there are no locations in sub-cell 1a where predictions of extreme water levels have been made, the closest being North Shields to the south and Leith to the north (see Section 5.4.2). However, the latest research into trends of extreme water levels (Dixon & Tawn, 1997) provides a spatial analysis of extreme water levels at any coastal location around the UK, including sub-cell 1a. In this study the predicted extreme water levels depend on the particular year of interest, allowing for trends in mean sea level rise and hence values 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 have been a large number of studies into water circulation in the Firth of Forth (the main ones are detailed in the bibliography of this report). In sub-cell 1a, the flood tide travels south along the eastern coastline of Scotland and into the Firth of Forth around Fife Ness. Between St Abb's Head and Barns Ness the tidal streams run regularly ESE and WNW on the flood and ebb tide with a peak Spring rate of approximately $0.5ms^{-1}$ off the coast. To the north of St Abb's Head the WNW stream starts at around 5 hours after HW and continues until about 3 hours before the next HW. The corresponding ESE stream flows from 3 hours before HW until about 3 hours after with a lengthy period of slack water before the WNW stream begins. To the north of Barns Ness there is much irregularity in the direction of the streams due to tidal streams approaching (and diverging) to the north and south. Peak tidal streams rarely exceed $0.5ms^{-1}$.

Wave climate data from the archives of the UK Meteorological Office European Wave Forecasting Model are shown in Figures 12 and 13 for the total sea (i.e. wind & swell waves) and swell wave climate in the offshore region of Cell 1. Offshore wave conditions are experienced from between 340°N through to 200°N with, on average, approximately 35% of wave conditions occurring from between 20°N and 60°N. Significant wave heights over 4m can be experienced from any direction in the easterly sector but are most common from between 0°N and 120°N as there tend to be more extreme wind conditions from the north east than from the south east. Extreme total sea conditions derived from the archive are detailed in the table below:

Table 11 Offshore extreme total sea and swell conditions

Return Period (Years)	Total sea significant wave height (m)	Swell sea significant wave height (m)
1	6.23	3.56
10	7.62	4.49
100	8.95	5.36

Swell wave conditions are dominated by waves generated from between 20°N and 60°N, with approximately 60% of swell conditions experienced from this sector. Little swell is experienced from other directions due to either restricted fetch lengths or due to insufficient wind duration, for example from the south easterly sector. Extreme swell waves calculated from the Meteorological Office Wave Model data are detailed in Table 11 above.

For the region immediately offshore of Sub-cell 1a, the orientation of the coastline will limit offshore wave conditions to between 0°N through to 130°N. To the west of the sub-cell, the severity of wave conditions from directly north will decrease as fetch lengths (which are restricted by the Fife coastline) reduce.

The only information on nearshore wave conditions in this sub-cell is in connection with the construction of the seawall at Torness (HR Wallingford, 1976a). The largest wave heights occur from an offshore direction of 45°N to 90°N but refraction effects result in the inshore wave directions, at the seawall, being in the range 0°N to 45°N. Inshore wave heights can vary considerably along the coast due to the effects of the complex nearshore topography.

The nearshore seabed slope out to the -20m CD contour is relatively shallow from between approximately 1:60 offshore of North Berwick to 1:135 off the mouth of the River Tyne to 1:45 to the north of St Abb's Head. Much of the coastline is fronted by rock platforms which will dissipate wave energy in the nearshore region through wave breaking and bed friction. The severity of the wave conditions experienced at the coastline is also dependent on the water elevation.

5.3.3 Littoral processes

The coastline of sub-cell 1a faces north east and as a result can experience severe wave conditions generated in the North Sea. The main characteristics of the foreshore and immediate hinterland are illustrated in Figure 14. Beach sediments have come from two main sources. The thin beaches around Dunbar and the pocket beaches such as at Pease Bay, have developed from erosion of sandstone cliffs, whereas the Belhaven Bay, Barns Ness and Thorntonloch beach systems have formed from glacially derived sands and gravels. There is little fresh input of beach material into any of the beaches within this sub-cell, other than the reworking of hinterland glacial deposits.

In general most of the beach systems are largely self-contained in terms of sediment movements and there is little interaction or movement of beach sediment along this coast, Figure 15. Pease Bay is a small pocket beach. The beach material has been derived from erosion of the sandstone and till cliffs and from raised beach deposits which back the beach. Minor erosion of the coastal edge will occur under storm conditions, but on the whole the bay is relatively stable.

Between Cockburnspath and Dunbar the hinterland is overlain by fluvio-glacial sands and gravels. Much of the coastal edge is protected by rock reefs, but where there are breaks in these outcrops these glacial deposits have been reworked and beaches occur. The beach system at Thorntonloch is constrained between rock outcrops at either end (and the hard defences protecting Torness nuclear power station at the northern end). The beach is predominantly sandy but with a shingle storm ridge. There is little evidence of any nett longshore transport of beach material but the dune edge is actively being eroded, which has resulted in a rock wall being constructed to protect a caravan site.

Along the Barns Ness shoreline (between Chapel Point and Mill Stone Neuk) there are a number of small embayment beaches intersected by rock outcrops. The largest occurs to the south of Barns Ness lighthouse where the beach is dominantly sandy and low dunes have formed. Some undercuttting of the frontal dunes by wave action occurs under storm conditions. To the west of Barns Ness the sandy coves, such as White Sands, have a shingle storm beach which provides some protection to the low coastal edge. However, there is ample evidence of overwashing of this shingle by storm action, and erosion of the coastal edge does occur.

The River Tyne estuary is contained between the rocky outcrop upon which the town of Dunbar is situated and the rock headland of St Baldred's Cradle to the north. Sediments are likely to have been derived from glacial deposits moved onshore during periods of changing sea levels since the end of the last Ice Age. There is little fresh input of beach material. The bay is relatively stable at present with a wide sand beach fronting saltmarsh and the intertidal mudflats at the outlet of the River Tyne. The beach is orientated to face the dominant wave direction and as such there appears to be little nett sediment transport. Some wave erosion of the dune edge is evident but this is relatively minor. At the northern end the spit known as Sandy Hirst is in the later stages of its development. There is no fresh material to maintain this feature, and a breach may well occur at its proximal end if directly affected by an onshore storm during a high tide.

To the north of the headland of St Baldred's Cradle, Ravensheugh and Peffer Sands occur. These sand beaches are constrained between rock outcrops and are in a relatively stable condition with little nett longshore processes evident. Wave attack on the frontal dunes is evident but does not appear to be causing any significant long-term erosion.

The UK Dredge Material Licence Database (MAFF, 1995b) indicates that no dredging has occurred within this sub-cell since 1986 (up to 1993).

Summary of erosion and accretion

There is no significant present day longshore drift evident on the beach systems within this sub-cell and hence areas of long-term erosion or accretion are not all that apparent. Periodic storm damage will occur on most of the "soft" coastal edges but this sediment appears to be retained within the immediate beach system. Only at the northern end of Belhaven Bay, at the proximal end of the spit know as Sandy Hirst, may erosion cause significant change.

5.3.4 Coastal defences

There are few coastal defences within this sub-cell, Figure 16. To the east of the harbour at Dunbar a variety of masonry seawalls occur. These are in relatively poor condition, are suffering from wave damage and are frequently patched up. Wave reflections off these structures may well explain the lack of beach material fronting the walls.

The only other major coastal defences protect Torness Power Station, where a substantial rock revetment and seawall protect the installation. To the south of Torness, a rock wall placed in front of the dune face limits frontal dune erosion along the caravan park frontage at Thorntonloch. Gabions protect the edge of the caravan park at Pease Bay.

There is no known routine monitoring of the beaches or of the coastal defences along this coastline.

5.4 Sub-cell 1b - North Berwick to the Inner Firth of Forth

5.4.1 Geology

The underlying bedrock outcropping on this coastline is dominantly Carboniferous, ranging in age from the Dinantian to the Westphalian (360Ma to 300Ma). Extrusive and intrusive igneous outcrops, the remnants of sills or dykes, are a common feature within this sub-cell and form most of the small islands in the Firth of Forth.

The basement rock is low lying and dominantly composed of Calciferous Sandstone and Carboniferous Limestone Series. Younger rock of Namurian and Westphalian age occurs between Cockenzie and Joppa. The Namurian strata make up the Millstone Grit Series and generally consist of sandstones, siltstones, mudstones and coal measures, with limestones occurring in the upper measures. The younger Westphalian strata are rich with coal seams. Igneous rocks, which are more resilient to marine erosion outcrop all along this coastline. Around North Berwick mainly extrusive outcrops of basalt occur. Intrusive basalt outcrops form many of the shorecut platforms and headlands which control the development of the "softer" beach areas between.

Both glacial and postglacial deposits occur in substantial quantities within this sub-cell (Figure 10). Boulder Clay and glacial sands and gravels overlie the bedrock inland of the coastal zone. There are a number of raised beaches evident which have been extensively studied (e.g. Sissons, 1976). Raised beach deposits extend inland from Aberlady Bay and along most of the coastline between Cockenzie and Cramond. In the more sheltered north-west facing bays, such as at Seton Sands, Gullane Bay and Broad Sands, these deposits are overlain with extensive post-glacial blown sand accumulations. To the west of Cramond, boulder clay overlies the bedrock at the coastal edge. The shore platform is littered with glacial boulders suggesting at least some of this material is derived from erosion of till cover.

5.4.2 Hydraulic processes

The tidal cycle has a mean tidal period of 11.8 hours at Leith and 12.1 hours at Rosyth. The tidal range increases from a mean spring tidal range of 4.6m (and Neap of 2.3m) at Fidra at the mouth of the Firth, to 4.8m at Leith (2.1m) and 5.2m at Grangemouth (2.6m), as shown in Table 12 and Figure 11. At Leith, the flood and ebb durations on the spring tide are the same with a slightly longer flood duration (0.17hr) on the neap. Upstream at Rosyth, the flood duration is longer on the spring tide (0.42hr) but equal on the neap. In the vicinity of the Forth Road Bridge the longer duration flood is relatively unusual and is thought to be caused by the unique geometry of the estuary and the low level of energy dissipation in the relatively deep Firth of Forth and Lower Forth Estuary (HR Wallingford, 1993b, 1994a). There is also a tendency for there to be two high waters in this region due to the tide being reflected strongly from the sudden narrowing of the estuary at Queensferry and near Grangemouth. Due to the low rate of energy dissipation in the estuary the rate of damping of the reflected waves and the shape of the tides will vary with the tidal range.

Table 12 Tidal levels and ranges for Sub-Cell 1b

Location	MSL mODN	MHWS mODN	MLWS mODN	Spring Range (m)	MHWN mODN	MLWN mODN	Neap Range (m)	LAT mODN	HAT mODN	ODN to CD (m)
Leith	0.3	2.7	-2.1	4.8	1.6	-0.8	2.4	-2.9	3.2	+2.90
Granton	-	2.7	-2.1	4.8	1.6	-0.8	2.4	-	-	+2.90
Rosyth	0.25	2.85	-2.15	5.0	1.75	-0.75	2.5	-2.95	3.45	+2.95
Grangemouth	-	2.95	-2.25	5.2	1.75	-0.85	2.6	-	-	+2.75

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 is based on tidal records from the A-class tide gauge network. Predictions on the southern coastline of the Firth of Forth have been made at Leith and Grangemouth, and are detailed in the Table below.

Table 13 Sub-cell 1b - Extreme sea levels

Graff (1981):

Location	Return period levels (Height above ODN (m))					
	5	10	20	50	100	250
Leith	3.49	3.58	3.63	3.70	3.74	3.80
Grangemouth	4.02	4.17	4.27	4.44	4.56	4.68

Coles & Tawn (1990):

Location	Probability of annual maximum tidal levels (mODN)		
	10%	1%	0.1%
Leith	3.55	3.70	3.79
Grangemouth	4.02	4.38	4.66

The latest record into trends of extreme water levels (Dixon & Tawn, 1997) provides a spatial analysis of extreme water levels at any coastal location around the UK, including sub-cell 1b. In this study the predicted extreme water levels depend on the particular year of interest, allowing for trends in mean sea level rise hence values 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.

General tidal streams in the Firth of Forth are described in Section 5.3.2. Current velocities to the east of Leith are low with a peak Spring rate of $0.5ms^{-1}$ on the flood and $0.4ms^{-1}$ on the ebb (with a peak Neap rate of $0.25ms^{-1}$ and $0.2ms^{-1}$ respectively) in Narrow Deep to the north east of Leith. Closer inshore current velocities will be negligible particularly over the extensive sand flats between Eyebroughy and Leith and on Drum sands. In these shallow water areas the influence of wind induced currents will have a significant effect on both current magnitude and pattern. As a rough approximation the depth averaged wind induced current is approximately 2% of the wind speed.

Stronger currents are experienced in the main channel between North and South Queensferry with strong turbulence experienced and eddies forming, for instance in the lee of Port Edgar. The geometry of the narrows results in regions where either the flood or ebb currents dominate. Slightly stronger peak currents are experienced on the ebb (with a peak spring rate of approximately $0.9ms^{-1}$) than on the flood ($0.8ms^{-1}$). The shallow foreshore and number of piers which extend over the foreshore will restrict the magnitude of any currents close to the shoreline.

Wave conditions offshore of the Firth of Forth are described in Section 5.3.2. Considering the entire frontage of Sub-cell 1b wave conditions generated within the North Sea will only directly affect this coastline if generated from between approximately 30°N and 70°N. Towards the inner part of the Firth the angular spread of the wave-window to the North Sea will decrease further. The southern coastline of the Firth of Forth will also be influenced by locally generated wave conditions from within the Firth. Such wave conditions will be most severe from the north where the longest fetch lengths extend into Largo Bay.

The only known wave studies conducted on the southern coastline of the Firth of Forth have been within Aberlady Bay area (IMCOS, 1974; HR Wallingford, 1976b) and at the Forth Road Bridge (HR Wallingford, 1996b). Within Aberlady Bay wave heights of 1.4m, 2.0m, 2.5m and 3.3m are exceeded on average 2.5%, 1.5%, 0.8% and 0.4% of the time respectively.

An assessment of wave conditions on the -10m CD contour at the southern end of the Forth Road Bridge indicate that the majority of waves are experienced from between 270°N and 290°N (47% of the time) and from between 50°N and 90°N (32% of the time). More severe wave conditions will be experienced from the easterly sector due to much longer fetch lengths, giving a calculated 1:1 year return period significant wave height of 2.3m and a 1 in 100 year return period of 4.10m. From the westerly sector restricted fetch lengths limit the severity of the wave conditions to approximately 1m for the 1 in 100 year event.

5.4.3 Littoral processes

The coastline of sub-cell 1b is extremely varied from the relatively natural coastline between North Berwick and Port Seton and further west along the Dalmeny Estate to the heavily developed shoreline between Port Seton and Cramond. The dominant characteristics of the foreshore and immediate hinterland are shown in Figure 17.

Longshore transport of beach sediment is dominated by wave action from the North Sea which results in a nett westerly movement of beach material within this sub-cell. However, on the flat lower foreshore tidal currents will control the movement of fine sediments such as silt and sand. It is unlikely that tidal currents are a significant process closer to the shoreline as there are a number of features, e.g. Cramond Breakwater, Granton Harbour and Leith Docks, which tend to push the main currents further offshore. In terms of exposure to wave action the sub-cell can be divided into two. To the east of Leith Docks the coastline can experience considerable wave action whereas to the west of the docks the shoreline is more sheltered. The dominant littoral processes are shown in Figure 18.

At the eastern end of this sub-cell, between North Berwick and Port Seton, the solid geology has considerable influence on the development of the 'softer' shores. The beach material is dominantly sand with extensive dunes and links occurring in the hinterland. Outcrops of igneous rocks on the foreshore control the planshape development of these beach areas as they act as a focus point for wave energy, resulting in the embayment shaped beaches between them. Without these rock outcrops this coastline would suffer a much greater rate of erosion than is presently experienced. On the more exposed frontages the beaches are sensitive to seasonal changes, being drawn down in winter and building up in the summer months. Nett drift is wave induced and to the west, but the rate is moderate to low due to the influence of the numerous rock outcrops on the foreshore. Between North Berwick and Gullane Point the dune edge shows signs of undercutting. This will generally be limited to periods of storm conditions at higher water levels. However, the general trend along this frontage (at present) is of frontal dune erosion.

Aberlady Bay, by its shape and orientation, acts as a sediment sink for beach material with a history of prograding dunes on the eastern side of the bay due to the abundant supply of sand within the bay. North westerly storm conditions acting with a high tide will cause some erosion of the dune face but the effects are unlikely to be all that significant. To the south-west of Aberlady Bay lies Gosford Bay which in contrast appears to be poorly nourished with much less beach material over the foreshore. It is likely that any sediment bypassing Aberlady Bay in an east to west direction also bypasses Gosford Bay and arrives at the shoreline further to the west.

The alignment of the renourished beach at Portobello is almost perpendicular to the angle of predominant wave attack. At the southern end, the orientation of the coastline and the presence of rock reefs at Joppa indicate that this may be a sediment drift divide. Tidal modelling (HR Wallingford, 1994a) suggests that around the peak flood, currents diverge around this location with a westerly flow along the Portobello frontage and a weak east going eddy towards Fisherrow. Along the beach at Portobello bi-annual surveys suggest a westerly drift of material but the rate is low due to the orientation of the coast and the influence of wooden groynes. To the west of Portobello beach there is little beach sediment and the coastline has been completely modified by hard defences. The eastern breakwater of Granton Harbour acts as a terminal groyne, trapping any beach material which is being moved to the west along this section. The downdrift effects can be seen to the west of Granton Harbour where beach material is thin and erosion of the backshore would be prevalent if the coastal edge were not protected for most of its length. At Cramond, the breakwater acts as a groyne and there is considerable build up of sand and pebbles on the eastern side with embryo dunes formed on the backshore. The effects of tidal currents in moving sediments on the lower foreshore can be seen along the causeway linking Cramond Island to the mainland where minor scour holes are evident. The westerly wave induced drift of beach material continues along the Dalmeny Estate frontage where there are a number of rock outcrops and a couple of rock groynes which shown build up of their eastern flanks and display downdrift erosion effects to the west. The rate of movement of beach material is low.

Dredging (both maintenance and capital) is conducted at a number of ports and harbours in sub-cell 1b. The following information is extracted from the UK Dredged Material Database, (MAFF, 1995b), for the period between 1986 and 1993:

Location	Year	Authority	Dump Site Name
Port Seton	1987	Port Seton Harbour Authority	Port Seton Site
Port Edgar	1987	Lothian Regional Council	Port Edgar
Port Edgar	1992	Lothian Regional Council	Oxcars
Leith	Yearly	Forth Ports plc	Leith, Oxcars
Grangemouth	Yearly	Forth Ports plc	Leith, Oxcars
Granton	Yearly	Forth Ports plc	Leith, Oxcars

There is little information on sediment movement of dredged spoil. However, the dredging or disposal is unlikely to have any significant detrimental or beneficial influence on the beaches of this sub-cell.

Summary of erosion and accretion

Long-term erosion is occurring along much of the coastline of this sub-cell with many of the beaches experiencing a nett loss of material principally due to the nett westerly longshore drift. Of particular note are the frontages between North Berwick and Gullane Point, Portobello to Leith, and at various localised points west of Granton Harbour. Long-term accretion is most evident at Aberlady Bay, Dumbarnie Links and Fisherrow Sands.

5.4.4 Coastal defences

The coastline of sub-cell 1b is one of the most developed areas on the Scottish coast. As such, much of the coastline is protected by hard defences particularly to the west of Port Seton. A detailed assessment of the coastal defences within part of this cell (the City of Edinburgh Council frontage between the Dalmeny estate and Joppa) has recently been completed (HR Wallingford, 1996a).

Figure 19 details the length of frontage protected within sub-cell 1b and the main sea defence types. At the eastern end of the cell a vertical masonry seawall extends for approximately 200m along North Berwick Bay. Wave reflections from this wall at high tide appear to be causing a lowering of beach levels exposing a waste water pipe which runs along the beach in front of the seawall. The wall itself is in a relatively poor condition. Between North Berwick and Port Seton there are few other built coastal defences. A short stretch of masonry seawall, in need of maintenance, protects the A198 at the southern end of Gosford Bay and concrete anti-tank blocks provide a little protection to the north-facing coastline at Ferny Ness.

Along the coastline between Port Seton, Musselburgh and towards Fisherrow the coastline is defended by a number of concrete and masonry walls of varying age and condition. Most are founded on the rock outcrops which occur along much of this frontage. To the east of Fisherrow Harbour a wide beach is backed by a concrete seawall.

Between Fisherrow and Joppa there is a mixture of vertical masonry and concrete seawalls founded upon rock outcrops. Rock armouring at the toe of the wall is provided along much of the length of these walls. The masonry walls are generally in a poor condition, have been heavily patched, and require frequent maintenance. The rock armour at the toe of the walls dissipates much of the wave energy, increasing protection to the walls and minimising undermining.

The low lying frontage at Portobello is protected by a concrete seawall. Serious sand loss occurred from in front of the seawall up to the 1960s leading to continuous wave attack and serious overtopping. Much of this was attributed to losses due to sand mining for the glass industry. The beach was artificially renourished with coarse sand won offshore, in the 1970s and again in 1988. Wooden groynes were also constructed to control the predominant westerly drift. The beach provides adequate protection to the seawall and prevents any serious overtopping and flooding of the hinterland. Bi-annual surveys of beach levels have been conducted since the first renourishment. To the north-west of the renourished beach at Portobello various seawalls and sloping revetments, mainly of concrete, extend to East Sands of Leith. Most of these structures display extensive wave damage. Along much of the eastern breakwater at Leith Docks a vast quantity of builders' and other waste has been dumped. Although unsightly the rubble does provide an effective first line of defence. However this dumping has caused large scale despoliation of the foreshore. Much of the material is easily degradable (e.g. brick, earth) which may have considerable environmental impact on marine flora and fauna.

The seawalls and harbour walls along the Leith Docks to Granton Harbour frontage are mainly masonry walls. Between Leith Docks and Granton Harbour, local wall failure has occurred a number of times requiring frequent maintenance. Running directly behind the seawall is the A901 coast road which would be severely affected if a serious breach occurred. Granton Harbour interrupts the westerly drift of material along this whole coastline with build up of a beach against the eastern harbour wall and on the eastern side of the sewage outfall.

From Granton Harbour to Cramond there are a number of different coastal defences. The masonry seawall at West Shore Road is protected to some extent by waste tipping. Although unsightly this waste tipping does provide an input of sediment. If this were to cease, erosion would increase due to the nett loss of material caused by the nett westward drift (the dominance of the westerly drift is exacerbated by wave reflections off Granton Harbour breakwater). Immediately to the west of the masonry wall erosion of the unprotected reclaimed land is now threatening the road. Much of the recreational land from Muirhouse to Cramond is protected by revetments of varied construction. These structures are in a reasonable condition but show some signs of wave damage. Cramond Breakwater acts as a groyne trapping much sand material being transported in an east to west direction along the coastline. This structure is in a poor condition.

The only major stretch of coastal defences along the Dalmeny Estate frontage is around the promontory where a masonry wall protects approximately 800m of frontage. For most of this length rock armour protects the toe of the structure. There are a number of other localised stretches of protected coastline mainly old masonry walls or rock armour and a couple of rock groynes. At a number of locations localised downdrift erosion is evident on unprotected stretches of coastline to the west of these defences.

The frontage at South Queensferry is protected by masonry walls and revetments and rock armour. Again much of the masonry defences are prone to wave damage and require frequent patching.

5.5 Sub-cell 1c - Inner Firth of Forth to Elie Ness

5.5.1 Geology

The solid geology of the north coastline of the Inner Firth of Forth is very similar to that occurring on the southern coastline with sedimentary rocks of Carboniferous age prevalent. Calciferous Sandstone measures are present at the coastline between Rosyth and Burntisland but are generally overlain by glacial deposits and are not exposed. To the east of Kinghorn, younger sedimentary rocks of Namurian and Westphalian age and generally consisting of bands of Coal Measures, Millstone Grit and limestone occur.

As on the southern coastline of the Firth of Forth, igneous outcrops are a common feature evident on this coastline. A large outcrop of intrusive basalt forms the headland at North Queensferry. A similar large outcrop of basalt occurs at Kinghorn. At the eastern end of the sub-cell the headland of Ruddons Point is agglomerate. Both the Carboniferous sediments and the lavas and sills are exposed at the coastline as shore cut platforms and intertidal outcrops.

The solid geology along this coastline is generally low-lying and overlain with more recent glacial and post-glacial deposits, Figure 16. Boulder clay is the main glacial deposit evident today with fossil boulder clay cliffs extending from Kirkcaldy to Buckhaven. Previous marine erosion (during times of higher sea levels) will have provided much of the shingle beach material found overlying the bedrock platform along sections of this stretch of coastline. Elsewhere, particularly to the south of Kirkcaldy and to the north east of Buckhaven post-glacial marine deposits occur for some considerable distance inland. Evidence of a number of different raised marine platforms is widespread on this coastline, a classic example of which is at Kincraig.

5.5.2 Hydraulic processes

The tidal cycle within this sub-cell has a mean period of approximately 12.1 hours in the inner Firth. Between Elie Ness and the Forth Road Bridge the mean spring tidal cycle is between 4.7 and 4.8m with a mean neap range of 2.3m to 2.4m, Table 14 and Figure 11. Upstream of the Forth Road Bridge the tidal range on both spring and neap tides increases.

Table 14 Sub-cell 1c - Predicted tidal levels and ranges

Location	MSL mODN	MHWS mODN	MLWS mODN	Spring Range (m)	MHWN mODN	MLWN mODN	Neap Range (m)	LAT mODN	HAT mODN	ODN to CD (m)
Rosyth	0.25	2.85	-2.15	5.0	1.75	-0.75	2.5	-2.95	3.45	+2.95
Burntisland	-	2.75	-1.95	4.7	1.65	-0.65	2.3	-	-	+2.85
Methil	-	2.6	-2.2	4.8	1.5	-0.9	2.4	-	-	+2.90

In Table 14 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 is based on tidal records from the A-class tide gauge network. Predictions within sub-cell 1c have been made at Kirkcaldy and Methil (and Rosyth). The predictions are detailed in the table below:

Table 15 Sub-cell 1c - Extreme sea levels

Graff (1981):

Location	Return period levels (Height above ODN (m))					
	5	10	20	50	100	250
Rosyth	3.63	3.73	3.77	3.85	3.90	3.95
Kirkcaldy	3.37	3.42	3.52	3.62	3.67	3.73
Methil	3.72	3.79	3.86	3.94	3.99	4.06

Coles & Tawn (1990):

Location	Probability of annual maximum tidal levels (mODN)		
	10%	1%	0.1%
Rosyth	3.77	3.98	4.11
Kirkcaldy	3.42	3.65	3.83
Methil	3.82	4.05	4.26

The latest research into trends of extreme water levels (Dixon &Tawn, 1997) provides a spatial analysis of extreme water levels at any coastal location around the UK. In this study the predicted extreme water levels depend on the particular year of interest allowing for trends in mean sea level rise hence values 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.

Between Methil and Kirkcaldy the current direction changes on spring tides close to high water and 1 to 1.5 hours before low water with peak flows on the ebb predicted to occur 2.5 hours after high water and peak flood current about 3.5 hours before. Peak spring current speeds are generally less than $0.4ms^{-1}$ on the ebb and slightly less on the flood. Current speeds within Largo Bay are generally lower. To the west of Kinghorn, the main tidal flows within the Firth of Forth on both flood and ebb tend to flow along the northern coastline. Peak current speeds in the main channel exceed $1ms^{-1}$ on both flood and ebb and can be influenced by high river flows. Closer inshore, tidal eddies and slack zones form in the lee of headlands and islands. The formation of these features is dependent on the stage of the tidal cycle. Between the narrows at Queensferry there are distinct regions where either the flood or ebb currents dominate.

Wave conditions experienced offshore of the Firth of Forth are described in Section 5.3.2. Such conditions generated within the North Sea will only approach the coastline of this sub-cell from a very small angular sector to the east between Elie Ness and North Berwick. The exposure of the coastline of this sub-cell varies significantly between that at the eastern end of Largo Bay and the western boundary of the sub-cell. Wave conditions have been assessed at East Wemyss and Dysart (HR Wallingford, 1994b) and at the northern end of the Forth Road Bridge (HR Wallingford, 1996b). At East Wemyss and Dysart there are two distinct classes of waves. Locally generated waves approach from between 180°N and 210°N for approximately 34% of the time at Dysart and 43% of time at East Wemyss. At Dysart the maximum significant wave height is about 1.4m and about 1.8m at East Wemyss due to slightly longer fetch lengths.

Much larger wave conditions approach from the east due to waves generated in the North Sea. At Dysart these waves approach from between 70°N and 100°N and at East Wemyss from between 80°N and 110°N, with waves occurring at both locations for approximately 24% of the time. On the 10m CD contour the largest significant wave height will be approximately 3.75m with waves in excess of 2m significant wave height exceeded 1.7% of the time and waves greater than 3m approximately 0.3% of the time.

Further east, into Largo Bay, the percentage of wave conditions experienced from the easterly sector will reduce due to shelter provided by the coastline at Elie and because wave conditions from the south easterly sector are relatively infrequent. Consequently there will be an increase in both the relative frequency and magnitude of wave conditions from the south westerly sector.

To the west of Kinghorn, the width of the Firth reduces and fetch lengths are restricted in all directions apart from those to the east. Again waves are experienced upon the coastline from two main directions, namely between 240°N and 300°N (51% of the time) and from between 60°N and 100°N (27% of the time). Extreme wave conditions from the westerly sector will be fetch restricted with a calculated 1 in 100 year return period of only 1m. The longer fetch lengths to the east will result in more extreme conditions with a calculated 1 in 1 year return period significant wave height of 1.6m and a 1 in 100 year return period wave height of 2.85m.

5.5.3 Littoral processes

The source of beach material along the south Fife coast is generally glacial. However colliery waste from the numerous coal mines in south Fife has also contributed a large quantity of material to the beaches. Figure 20 displays the dominant foreshore and immediate hinterland characteristics occurring within this sub-cell and Figure 21 the main littoral processes.

Between the Forth Bridges and Kinghorn most of the beach units are self-contained bays. The beaches are mainly sandy but with some gravel and shell fragments usually also found. There is little interaction between beach units. The strong flood and ebb tidal currents tend to be deflected further offshore by the rocky headlands and have minimal influence on beach development. The main influence is wave activity from the east propagating into the Inner Firth of Forth. This has the potential for causing a east to west nett littoral drift but the beach areas have long since adapted to this influence. For instance most of the sediments at the coastline to the east of Silversands Bay have long since been transported into the bay where the beach is orientated to face the dominant wave direction. Much of the backshore along this coastline is protected, which cuts off the input of fresh material released to the system by wave erosion.

The coastline between Kinghorn and Ruddons Point at the eastern end of Largo Bay is extremely active in terms of littoral processes. In general terms there is a strong westerly nett drift of beach material along this coastline from around Lower Largo to Kirkcaldy whereupon the magnitude of this drift rate decreases as the orientation of the coastline sharply changes. At Lower Largo the occurrence of the shore rock platform at the centre of the bay suggests that this is a drift divide. To the west of the platform waves from the east and south east will tend to cause a nett movement of sediment to the west. To the east of this outcrop the headlands around Earlsferry will protect much of the eastern end of Largo Bay from waves from the east and south east. Hence it is the smaller, but more frequent, wave conditions from the south west which cause a nett sediment movement in a easterly direction along this coast.

Along the Kirkcaldy town frontage, bedrock is exposed. This is probably due to the high percentage of reflected waves off the vertical seawall and the effects of the harbour blocking drift from further east. To the south of the seawall at Kirkcaldy, the orientation of the coastline changes to face almost due east. This change significantly reduces the south westward nett drift rate and a mainly sandy beach overlies the rock platform. However this beach is directly exposed to severe wave conditions travelling into the Firth from the North Sea and erosion of the edge of the links is apparent. To the north of the harbour a mainly sandy beach is found, also suffering from backshore erosion.

A study of coastal erosion processes at Dysart and East Wemyss was conducted by HR Wallingford (1994b). Estimates of the longshore drift rate of colliery waste material along this coastline was of the order of about 70,000m^3/year at Dysart and slightly higher at East Wemyss. On this coastline the past (over the last century) and future evolution is dominated by the supply of heavy colliery waste which was tipped onto the beaches. This input of material has now stopped and rapid landward erosion is occurring along this coastline. Without intervention it is suspected that the beaches will attempt to revert to the position of about 1900, putting much of the development on the coastline since this time at risk. In addition to the longshore losses much of this colliery material is also being abraded by wave action and lost offshore. The rate of erosion along this frontage also appears to be exacerbated by the effects of subsidence due to the complex mine works which are collapsing. An assessment of OS benchmarks between Kinghorn and Methil has indicated significant subsidence at the coast (McManus, 1996)

Around Buckhaven and Methil much of the coastal edge has been reclaimed and protected by coastal defences. There is little beach material along this frontage as any material from further east along the Leven frontage will tend to move quickly along this frontage with little to hinder its progress. At Leven Links the beach is dominantly sandy with some small shingle around high water mark. The orientation is to the south east and although there is a nett movement of material to the west the rate is likely to be low to moderate on account of the fact that some protection is afforded by the coastline around Earlsferry from waves from an easterly direction and the shallow sloping nearshore bathymetry. The coastal edge appears to be relatively stable with little wave erosion. The eastern end of Largo Bay is generally an area of accretion (although the rate of this is presently low). The curvature of the coast is orientated to face the predominant wave direction from the south west.

At the eastern end of the sub-cell are a number of small pocket beaches, e.g. Shell Bay, the Earlsferry and Elie beaches. These can each be considered individual beach units with little exchange of sediments between them. The beaches are dominantly sand overlying rock outcrops. Dunes and links back the beach areas. Storm damage of the frontal dunes occurs on most of these frontages, particularly around Elie which is marginally more exposed to severe wave conditions.

Dredging (both maintenance and capital) is conducted at a number of ports and harbours in sub-cell 1c. The following information is extracted from the UK Dredged Material Database (MAFF, 1995b), for the period between 1986 and 1993:

Location	Year	Authority	Dump Site Name
Burntisland	1992	Forth Ports plc	Oxcars
Kirkcaldy	Yearly	Forth Ports plc	Narrow Deep
			Oxcars
Methil	Yearly	Forth Ports plc	Oxcars
			Methil
			Narrow Deep

There is little information on sediment movements of dredged spoil. However, the dredging or disposal is unlikely to have any detrimental or beneficial influence on the beaches of this sub-cell, as most of the fines remain offshore.

Summary of erosion and accretion

Long-term erosion is evident along much of the coastline of this sub-cell, particularly between Buckhaven and Dysart, where rapid erosion of the colliery spoil tips are occurring, and along much of the Kirkcaldy to Kinghorn frontage. There is little evidence of any significant accretion.

5.5.4 *Coastal defences*

There is a wide range of coastal defence works along this coastline on account of the relatively high density of human development and the nautical history of this region (Figure 22). Various lengths of seawall, wharfs and jetties occur along the developed sections of the coast between North Queensferry and Aberdour. A masonry seawall protects the railway track which skirts the coastal edge to the east of Silversands Bay and again to the east of Burntisland There are also a number of defences associated with the docks at Burntisland. Most of these defences have been in place for some considerable time and as such do not appear to have any significant present day adverse effects on coastal processes along this frontage.

Much of the Kirkcaldy frontage is protected by a high vertical masonry seawall. The lack of beach fronting the wall results in considerable wave action on it. It is highly unlikely that beach material will accrete along this frontage due to the large amount of wave reflection from the structure. The lack of beach also contributes directly to the severe overtopping which can be experienced during storm wave conditions at high tides which results in flooding of the immediate hinterland.

Older masonry walls east of Penhall Rocks at Dysart are now being exposed as mine waste erodes. Various stretches of old masonry seawall occur along the frontage at Chapel Wood just to the west of West Wemyss and a variety of walls protect individual properties at West Wemyss. At East Wemyss a recently constructed rock revetment (Cuthbertsons and Partners, 1996) protects much of the village and Wemyss caves to the north. Reclaimed land fronts most of Buckhaven and Methil. A large rock revetment protects much of the Buckhaven frontage and concrete seawalls protect much of Methil Docks. To the north a stepped concrete revetment protects the coastal edge along the Leven town frontage with minimal obvious impact on the beach fronting this structure. A variety of old, mainly masonry, seawalls occur along the Lundin Links and Largo frontages. At Elie a masonry seawall extends to the west from the harbour. Wave overtopping under storm conditions and damage to the wall is likely to occur if a south westerly storm coincides with a high tide. To the east of the harbour in Wood Haven, five different types of coastal defence each protect short stretches of the coastline. In order from the harbour: concrete seawall, steel sheet piling wall, some anti-tank blocks, a rock revetment, and some gabion baskets. It is suspected (Ritchie, 1979) that erosion at the back of this relatively sheltered bay was principally due to wave energy reflecting off the harbour wall.

5.6 Sub-cell 1d - Elie Ness to Fife Ness

5.6.1 *Geology*

The solid geology of sub-cell 1d is dominantly of Calciferous Sandstone Measures of Dinantian age. The strata consist of pale sandstones, grey mudstones and siltstones. Volcanic agglomerate outcrops around Elie Ness. The Ardross Fault runs parallel with the coastline for approximately 2 miles with a number of volcanic vents evident which are more resilient to marine erosion.

The effects of post-glacial sea level changes are very much in evidence with raised shore platforms cut into the relatively soft Carboniferous rocks occurring along the entire length of the sub-cell. This has resulted in thin layers of raised beach deposits overlying these platforms (Figure 10).

5.6.2 Hydraulic processes

The tidal cycle experienced within this sub-cell has a period of approximately 12 hours. At Anstruther the mean spring tidal range is 4.8m and the mean neap range 2.4m. The flood tide enters the Firth from the north around Fife Ness with high water occurring almost simultaneously along the length of this Sub-cell (Table 16 and Figure 11).

Table 16 Sub-cell 1d - Predicted tidal levels and ranges

Location	MSL mODN	MHWS mODN	MLWS mODN	Spring Range (m)	MHWN mODN	MLWN mODN	Neap Range (m)	LAT mODN	HAT mODN	ODN to CD (m)
Anstruther Easter	-	2.6	-2.2	4.8	1.5	-0.9	2.4	-	-	+2.90

In Table 16 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 is based on tidal records from the A-class tide gauge network. There are no locations in sub-cell 1d where predictions of extreme water levels have been made (the closest being Methil and Aberdeen). However, the latest research into trends of extreme water levels (Dixon & Tawn, 1997) provides a spatial analysis of extreme water levels at any coastal location around the UK. In this study, the predicted extreme water levels depend on the particular year of interest, allowing for trends in mean sea level rise hence values 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 currents along the length of this sub-cell are generally low with peak currents 4km to the south east of Anstruther less than $0.5ms^{-1}$ on both the Spring and Neap tides. Closer inshore these rates are likely to be less. Both the flood and the ebb currents flow roughly parallel to the coastline. Strong winds from the south west may act to increase ebb flows marginally.

Wave conditions experienced offshore of the Firth of Forth are described in Section 5.3.2. The orientation of the coastline of this sub-cell to the south east will result in waves from the most frequent offshore directional sector (i.e. between 20°N to 60°N) having little direct influence on this coastline. Assessment of the wave climate directly offshore of Pittenweem has been conducted on the -30m CD contour using wind records from Bell Rock (HR Wallingford, 1986). Considering all wave directions the maximum extreme significant wave height for the 1:1 year return period was calculated to be 5.6m, for the 1:10 year return period 7.0m and for the 1:50 year return period 7.9m. Restricted fetch lengths will limit the severity of wave conditions from the south-west, hence these will be limited to locally generated "wind-waves".

Closer inshore, wave conditions have been assessed at both Pittenweem (HR Wallingford, 1986, 1987, 1991) and Anstruther (HR Wallingford, 1988a, 1988b, 1990, 1995). At Pittenweem wave conditions were assessed on the -10m CD and -5m CD contour at a water level of +5m CD. For offshore waves from 70°N to 240°N refraction results in the wave window at the -5m CD contour being between approximately 130°N and 200°N. The maximum wave condition occurs from an offshore direction of 90°N, which results in significant wave heights of 2.9m, 3.8m and 4.3m at the -5m CD contour, with an angle of approach between 134°N and 137°N. A joint probability analysis of waves and water levels was conducted at Anstruther (HR Wallingford, 1995) in the design of rock protection for Cellardyke Pumping Station. The 1:100 year joint return period combination of waves and water levels was calculated. For lower water elevations, wave refraction will be greater resulting in a narrower wave window with the magnitude of these extreme wave conditions lower due to increased shallow water effects.

The approach bathymetry runs approximately parallel to the coastline, resulting in wave conditions in the nearshore region being similar along the coastline. However, rock platforms front much of this sub-cell resulting in much of the wave energy occurring on the -5M CD contour being dissipated due to wave breaking and bed friction effects, before reaching the coastline. Hence the severity of wave conditions at the coast will heavily depend on the depth of water over these rock outcrops

5.6.3 Littoral processes

There are few beach areas in this sub-cell as there is a rock platform running virtually continuously from Saucher Point at Elie to Fife Ness (Figures 20 & 21). Beach areas are generally small pocket bays with thin sand, shingle or cobble cover. Most of this material was derived from marine erosion of the Carboniferous Sandstone rocks which outcrop along this coast. Due to the soft nature of this rock there is a history of storm erosion of these cliffs. However, the width of the present wave cut platform will provide a certain degree of protection and it will only be when storm wave conditions coincide with extreme water levels that significant erosion of these cliffs will occur. Hence, fresh input from erosion of these rocks is likely to be extremely low.

Maintenance dredging has been conducted at Anstruther, Pittenweem and St Monance. Details extracted from the UK Dredged Material Database (MAFF, 1995b) for the period between 1986 and 1993 are shown below:

Location	Year	Authority	Dump Site Name
Anstruther	1986	FifeRegional Council	Firth of Forth
	1989		
Pittenweem	1988	Pittenweem Harbour	Firth of Forth
	1992	Authority	Pittenweem
St Monance	1986	Fife Regional	Firth of Forth
	1989	Council	

There is little information on the dispersion of dredged spoil. However, the dredging or disposal is considered unlikely to have any detrimental or beneficial influence on the beaches of this sub-cell.

<u>Summary of erosion and accretion</u>
Erosion of the soft cliffs occurs all along this coastline but actual retreat rates are low. Storm damage has previously caused erosion at Elie but much of the eroded frontage is now protected. No areas of significant accretion occur.

5.6.4 *Coastal defences*

The few coastal defences along this coastline are mainly masonry seawalls protecting the few fishing villages. Short stretches of a variety of masonry and concrete seawalls protect eroding sections of cliff at a number of locations. Most of these walls are founded upon the rock platform and given the scarcity of beach material have limited influence on the surrounding coast. However, due to the general lack of beach material to protect these structures, significant wave attack and damage is experienced.

5.7 Summary of the 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 100 years or indeed in the next 10 years. However, the next sections attempt to present a broad based summary of the influences of present day and possible future coastal processes upon natural and culturally designated areas. **This report is concerned with the macro-scale processes occurring around the coastline. To generalise about the effects of coastal processes, particularly on individual cultural heritage sites, is extremely difficult, and many such sites require much more detailed, individual assessments to establish and prioritise the particular potential risks.**

5.7.2 *Natural heritage sites*

Figure 7 details the locations of coastal SSSIs within Cell 1, with a summary of their main characteristics provided in Appendix 1. A high percentage of the coastline in Cell 1 lies within Sites of Special Scientific Interest, often designated on account of their geological and geomorphological interest. At many of these sites the geological designations represent either:

- fossil features which have been a product of previous higher sea levels and are generally above the present limits of wave action or

- geological exposures on the many rock platforms which outcrop along the coast of this cell where the rate of attrition is relatively low.

The effect of coastal processes upon the solid geology will depend on the character of each site. Many of the SSSIs have been designated on account of the volcanic vents of igneous rocks which outcrop at the coast. Due to the "hard" nature of these rocks, these outcrops experience an extremely low rate of attrition from marine processes. Conversely, the Calciferous Sandstone Measures, which form the majority of the bedrock exposed along the coastline of this cell are much less resilient to marine erosion. Many of these outcrops are generally above the present limits of marine influences (e.g. fossil cliffs), but where marine processes still interact with this strata, erosion will occur. The designations for many of these sites are partly for the rich measures of fossils within the rocks (e.g. the SSSIs at Pease Bay, Wardie Shore and the Burntisland to Kirkcaldy Shore). Erosion is likely to uncover further such fossils. Despite being more susceptible to erosion than the resilient igneous rocks, the rate of cliff retreat is still relatively low, with any erosion generally restricted to storm events. Such erosion maintains the exposure of the cliff and hence the conservation interest. Although an increase in the severity of frequency of storm conditions may marginally increase the rate of erosion the main threat in the future to the conservation interest of such rocks is the construction of coastal defences which obscure the outcrop.

Given the variability in dominant coastal processes (e.g. wave conditions) occurring around the Scottish coast, the influence of these processes is much more evident upon SSSIs in the Firth of Forth designated on account of either coastal habitat and/or geomorphological features (i.e. typically on "soft" coastlines) or those of importance to feeding and roosting wading birds, i.e. mudflats. There are six main SSSIs within Cell 1 where the coastline can be described as "soft", namely Barns Ness, Tyninghame Shore, Gullane to Broad Sands, Aberlady Bay, Forth Bridge to Granton Shore and Dumbarnie Links. The hydraulic and littoral processes which occur along these coastlines has been discussed in the preceding sections. As the littoral processes, particularly in the outer Firth of Forth, are wave dominated, it is the more exposed coastlines of Barns Ness and Gullane to Broad Sands which are most sensitive to the effects of, and indeed any changes in, the hydraulic regime. This is most apparent in the rate of frontal dune erosion along these shorelines.

At Belhaven Bay (Tyninghame Shore SSSI) the stability of the saltmarsh and mudflats is highly dependent on the protection afforded by the spit feature of Sandy Hirst. The littoral system in Belhaven Bay is self-contained, i.e. there is little input or loss of material and, as such, despite the complexity of the littoral regime of this estuary, the bay is reasonably stable. However, the spit feature is in the latter stages of its development, and the lack of a fresh source of material suggests that a breach at the proximal end may well occur, e.g. during storms at high tide. Any increase in wave activity behind the spit due to a breach could cause serious erosion and changes to occur particularly to the saltmarsh within the inner part of Belhaven Bay.

Aberlady Bay and Dumbarnie Links are both areas of accretion, although present day rates are likely to be low. The orientation of Aberlady Bay shelters it from severe wave conditions and the wide sand flats provide additional protection in dissipating wave energy. At Dumbarnie Links, the coastline faces the dominant wave direction, but short fetch lengths restrict significant wave attack. Present day coastal processes appear to have little detrimental effect on either of these two areas. However, given the maturity of the dune systems at both sites any initiation of erosion, e.g. by human activities, may well result in considerable erosion due to wind action.

The influences of coastal processes on intertidal habitats, such as mudflats within the Firth of Forth is more difficult to establish. At present most areas appear to be reasonably stable. A study by Jones (1995) on intertidal habitat gains and losses in the Inner Firth of Forth has indicated substantial intertidal gain at Drum Sands between 1947 and 1987. However such sites are extremely sensitive to any changes in waves, water levels and tidal current patterns, particularly those to the east, where the level of wave energy is greater. Such gains may therefore not be sustainable. Monitoring of these sites would therefore be well advised.

5.7.3 Cultural heritage sites

The coastline of Cell 1 is one of the most dense in terms of cultural heritage sites in Scotland, with many of these sites linked to the long maritime history of the Firth of Forth. It is one of the few coastlines where detailed surveying to locate sites of archaeological importance, and to monitor the threat from erosion has been conducted (James, 1996; Robertson, 1996). Along the south coastline of the Firth of Forth (Dunbar to the Border of Fife) 423 archaeological sites and 155 listed buildings were recorded within 50m of the shoreline (James, 1996) with a total of 724 sites on the north shoreline (Kincardine to Fife Ness) (Robertson, 1996).

Much of the coastline of Cell 1 is protected, particularly in Edinburgh and along the developed frontages in Fife. As most of these defences are constructed to protect property or infrastructure, it can be expected the defences will be maintained in a reasonable state, hence protecting any listed buildings and other sites located upon the immediate hinterland. Along the southern coastline of the Firth of Forth, it is the "softer" beach areas between North Berwick and Gullane Point which appear to be suffering the greatest rate of erosion, with frontal dune erosion and landward retreat of the dune face likely to continue. Further south, along much of sub-cell 1a, the beach areas tend to be self-contained with minimal loss of beach sediment from the system and rates of retreat at present appear to be low. However, all of these frontages are susceptible to storm damage resulting in dune and coastal edge erosion. As described in the preceding section, the loss of protection provided by the spit feature of Sandy Hirst is likely to cause erosion within the inner part of Belhaven Bay. To the west of Cramond, along the Dalmeny Estate frontage, the coastline is largely unprotected. Erosion of the coastal edge does occur but at a much lower rate than that experienced on the more exposed coastlines of the outer Firth.

At present the Methil to Kinghorn coastline is one of the most rapidly eroding coastlines in Scotland. The threat from erosion to Wemyss Caves has already been identified and steps taken to protect this site with rock armour. It is expected that further coastal protection works may well be required on this coastline to ensure other features are preserved. For instance many of the buildings of the small villages at East and West Wemyss are listed but are protected by masonry walls which are susceptible to damage (some of these are also listed). This erosion, particularly of the colliery waste, may well uncover further features of historical importance linked to the mining activities of the area, but in doing so may well ruin existing features from this age.

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

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

<u>Impact on the beaches in Cell 1</u>
Along the coastline of sub-cell 1a the beach units are largely self-contained and are afforded much protection by rock outcrops. Increased sea levels will result in less wave energy being dissipated by these rock outcrops (assuming there is no change in the wave conditions) leading to an increased rate of erosion experienced at the coastline as the beach attempts to naturally adjust to this increased wave energy (i.e. the steepness of the beach slope will decrease). This will lead to an increase in frontal dune erosion, but such erosion will be limited mainly to storm events rather than a continuous cutback of the dunes or links edge. As most of these beaches are relatively self-contained (in terms of longshore transport) much of the sediment will remain within the active beach system. A similar effect will occur if there is an increase in storminess. A greater impact will occur to the west of North Berwick where again the coastal edge is protected by numerous rock reefs and outcrops. However, there is greater potential for sediment to be transported alongshore to the west leading to a nett loss of material from each of the beach systems which in turn leads to further dune and links erosion. The effects are likely to be most obvious at the eastern end of the sub-cell, decreasing to the west as the orientation of the coastline changes after Gullane Point.

The Edinburgh coastline is protected, with few natural beach areas. It is difficult to assess whether there will be any significant impact on the renourished beach at Portobello as it is orientated to face the most severe wave direction and hence any nett drift rate is low. Increased storm activity may well pull beach material further offshore leading to a flatter beach. However, provided waves do not start to interact with the seawall backing the beach (hence causing wave reflections) and provided that beach material drawn down is not transported out of the area by tidal currents the problems should not be as serious as along other sections of this Cell. To the west, any increase in sea level rise may well increase the angle of incidence of approaching waves to the shoreline, leading to increased longshore drift. There is very little material on the beaches to the west of Granton Harbour and any increased loss of material may well substantially increase the risk of damage to the coastal defences.

As assessment of the effects of climate change on the coastline of Fife was conducted by McManus (1990). Along much of the Fife coastline of this cell, coastal erosion is already a serious concern particularly on the frontage between Methil and Kinghorn. Any increase in wave conditions at the shoreline (either due to sea level rise allowing larger waves to propagate further inshore or an increase in the frequency of storm events) will increase this rate of erosion. The cessation of tipping colliery waste onto the coastline has removed an important source of fresh (albeit foreign) material and already the coastline is eroding and adjusting back probably to its original position. However, given that sea levels are likely to rise and that there appears to be considerable subsidence along the Methil to Kinghorn frontage it can be expected, along unprotected sections of this frontage, that the coastline will retreat to beyond the position it had around the turn of the century.

There are a number of historical accounts of rapid erosion of the relatively soft sandstone rocks which outcrop along much of sub-cell 1d. A wide shore platform fronting the coastal edge provides much protection. However, any increase in sea levels, particularly extreme water levels, will lead to increased wave attack upon these rocks accelerating erosion. Any increase in storm frequency will have a similar effect. It is difficult to assess which of these changes would be the more serious.

Towards the Inner Firth of Forth there are extensive mudflats. If deposition of these mudflats occurs at the same pace as any sea level rise then there should be little noticeable difference in level. However, if sea level rise increases at a faster rate, allowing marginally larger wave conditions over the mudflats, this could lead to an increase in both the magnitude and percentage of time over a tidal cycle where wave activity stirs sediment into suspension. Increased concentrations of sediments in suspension may increase the volume of material being transported by tidal currents away from the mudflats and possibly further offshore, leading to a loss of mudflat habitat.

There are also a number of important areas of saltmarsh within this Cell, notably within Belhaven and Aberlady Bays. The development of saltmarsh is extremely sensitive to changes in sea levels. For instance there appears to be a threshold rate of increase, where below the threshold the saltmarsh surface is able to accrete and keep pace with the change. Above this threshold the marsh becomes submerged and is lost. There is also evidence to suggest that erosion and the loss of saltmarsh is linked to increases in wave energy. It is difficult to ascertain whether there is likely to be any significant increase in wave activity in the inner part of either of these bays. At Belhaven, the spit feature of Sandy Hirst provides much protection from the open sea. If this were to be breached then the increase in wave energy in the inner part of Belhaven Bay would result in erosion of the saltmarsh.

With any increase in sea level rise, there is also an increase in the frequency and extent of coastal flooding. There does not appear to be any significant flooding problem along the frontage of sub-cells 1a and 1b. The main locations appear to be at Kirkcaldy and a number of the small Fife villages mainly due to wave overtopping of sea defences. This is discussed in the next section.

6.3.2 Impacts on man-made defences

<u>General</u>

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

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

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

Impact on the man-made defences in Cell 1

Much of the coastline of Cell 1 is protected by coastal defences. It is unlikely that there will be any significant increase in the occurrence of damage to structures such as rock revetments in the short-term, due to the relatively small changes occurring. However, there are a large number of older masonry walls which account for a high percentage of the total coastal defences within this sub-cell. Many of these structures already have a high maintenance commitment, such as the seawalls between Joppa and Eastfield, and any slight increase in either wave intensity or storm frequency may cause a substantial increase in damage to such structures. Many of these structures are protecting either infrastructure or property, the main ones being found along much of the Edinburgh frontage from Port Seton to the west of Granton Harbour, stretches of rail line between Aberdour and Kinghorn, and the Kirkcaldy town frontage. There are a number of other short stretches of masonry seawall in a similar condition and vulnerability particularly along the south Fife coast.

An increase in the occurrence and volume of wave overtopping of present structures will increase and on most sites is likely to be more obvious than an increase in the occurrence of damage to structures. At present the most serious location is the flooding of the immediate hinterland due to wave overtopping of the seawall at Kirkcaldy which occurs when storm conditions occur with high tides. Many of the seafronts of the small fishing villages are also presently affected by wave overtopping.

6.3.3 Other effects

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

Rainfall

There is an observed variation in the rainfall patterns occurring in the UK. In the south of England an oscillation of about 40 years period has been observed. There is also anecdotal evidence that a 20-30% increase in rainfall has been recorded in central Scotland over the last 25-30 years. 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. It is not known whether the cliffs which occur mainly in sub-cells 1a and 1d experience seepage related slips and fails. However, there is unlikely to be any significant increase in the supply of beach sediment due to any increase in cliff slips so the impact of changed rainfall patterns may not be significant in terms of beach behaviour.

- 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. There are no rivers within this cell which supply an appreciable volume of sediment to the beach systems but any increased flow in the Forth may well increase the duration of the ebb flows which may have a considerable effect on the movement of finer sediments already within the system.

- 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 mpre moist 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. Large dune complexes such as are found between North Berwick and Aberlady are likely to be affected from such changes.

Much of the above discussion on climatic change and its impact on coastal response is based on logical argument rather than well documented case histories. The impact of climatic change on the coastline of Cell 1 is likely to be relatively more serious than in other cells given the nature of the coastline, the density of development along the coast and the present state of the many coastal defences which occur. At present it is difficult to make predictions, other than qualitative ones, on the impacts of climatic change and its effect on the morphology of a coast due to the range of interrelating 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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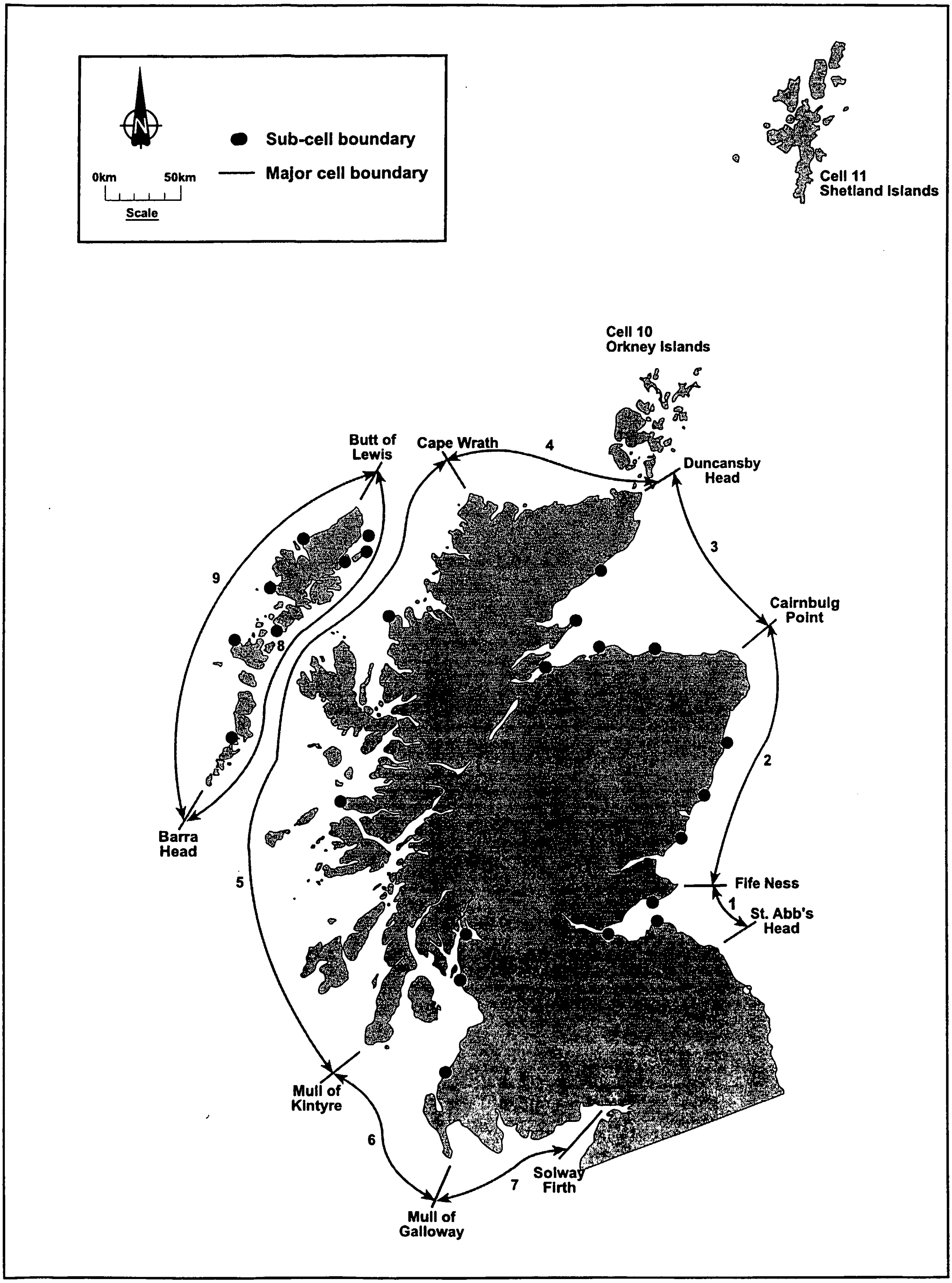


Figure 1 Coastal Cells in Scotland

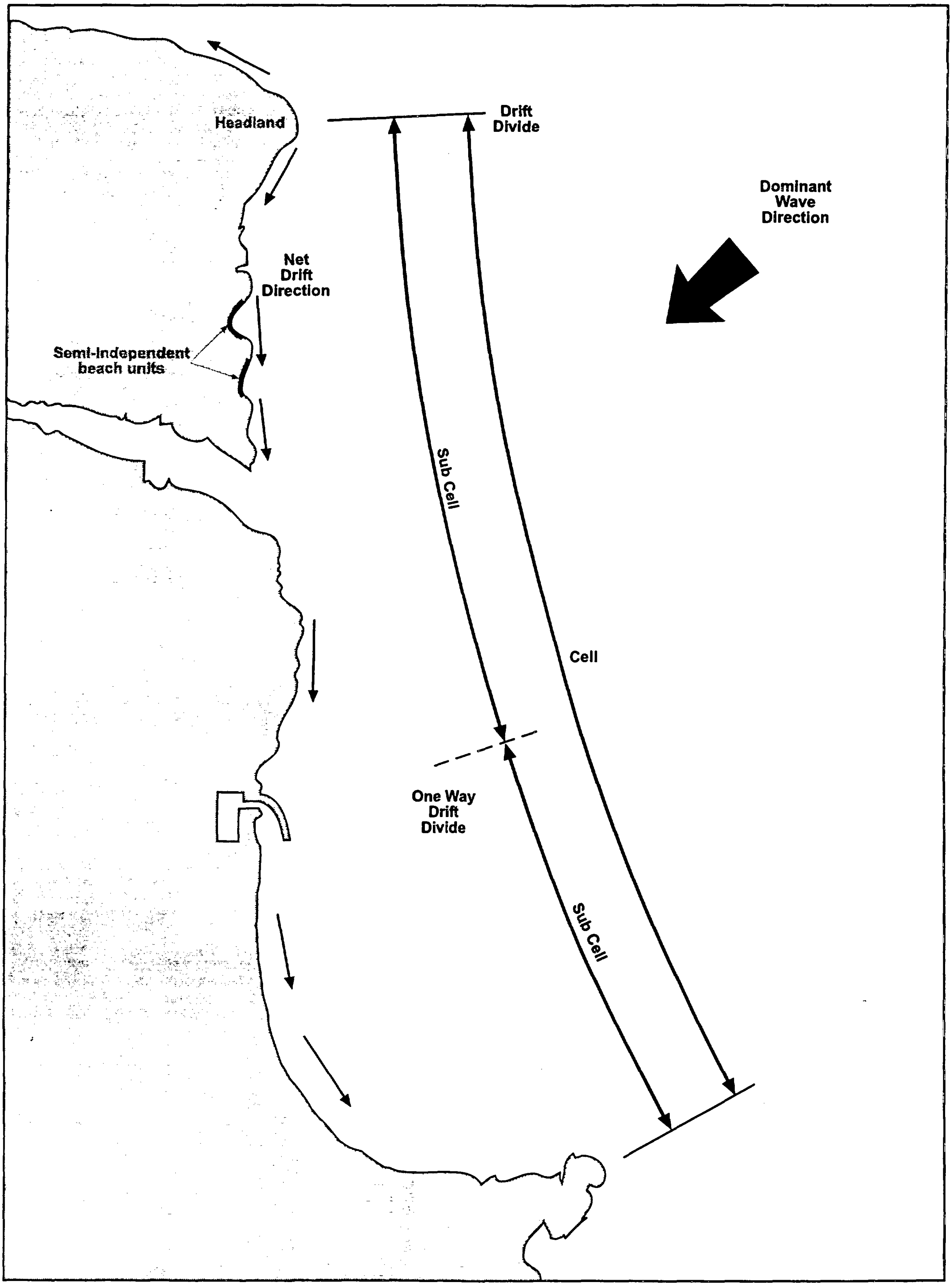


Figure 2 Idealised coastal cell

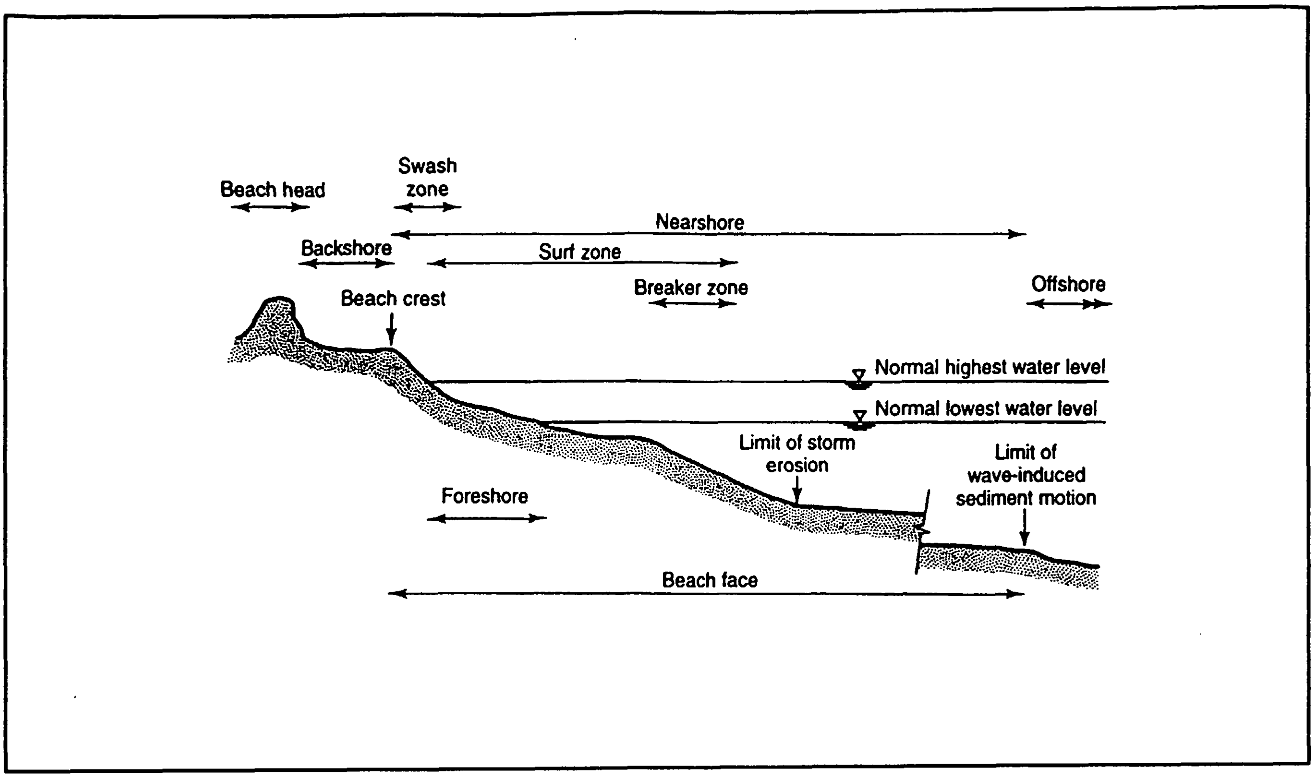


Figure 3 General beach profile and littoral zone

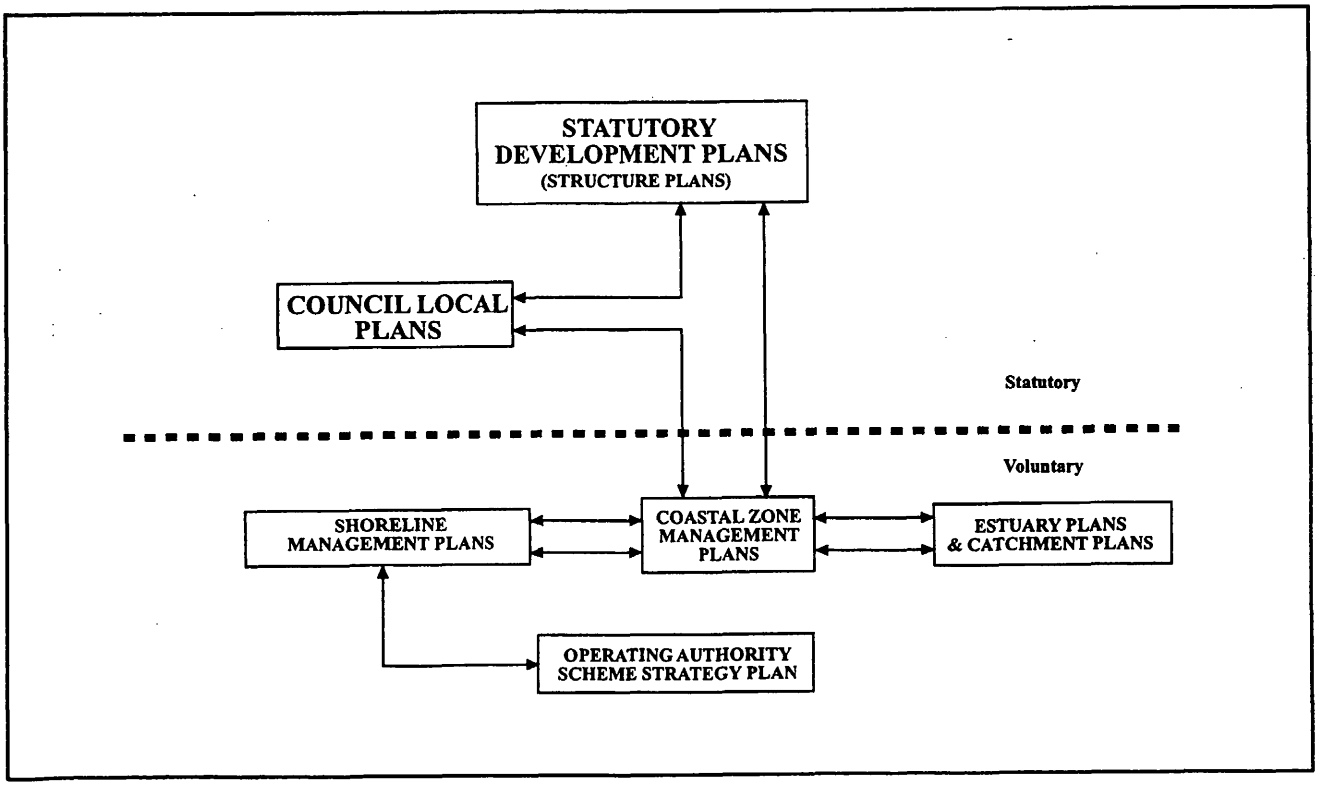


Figure 4 Relationship between coastal initiatives

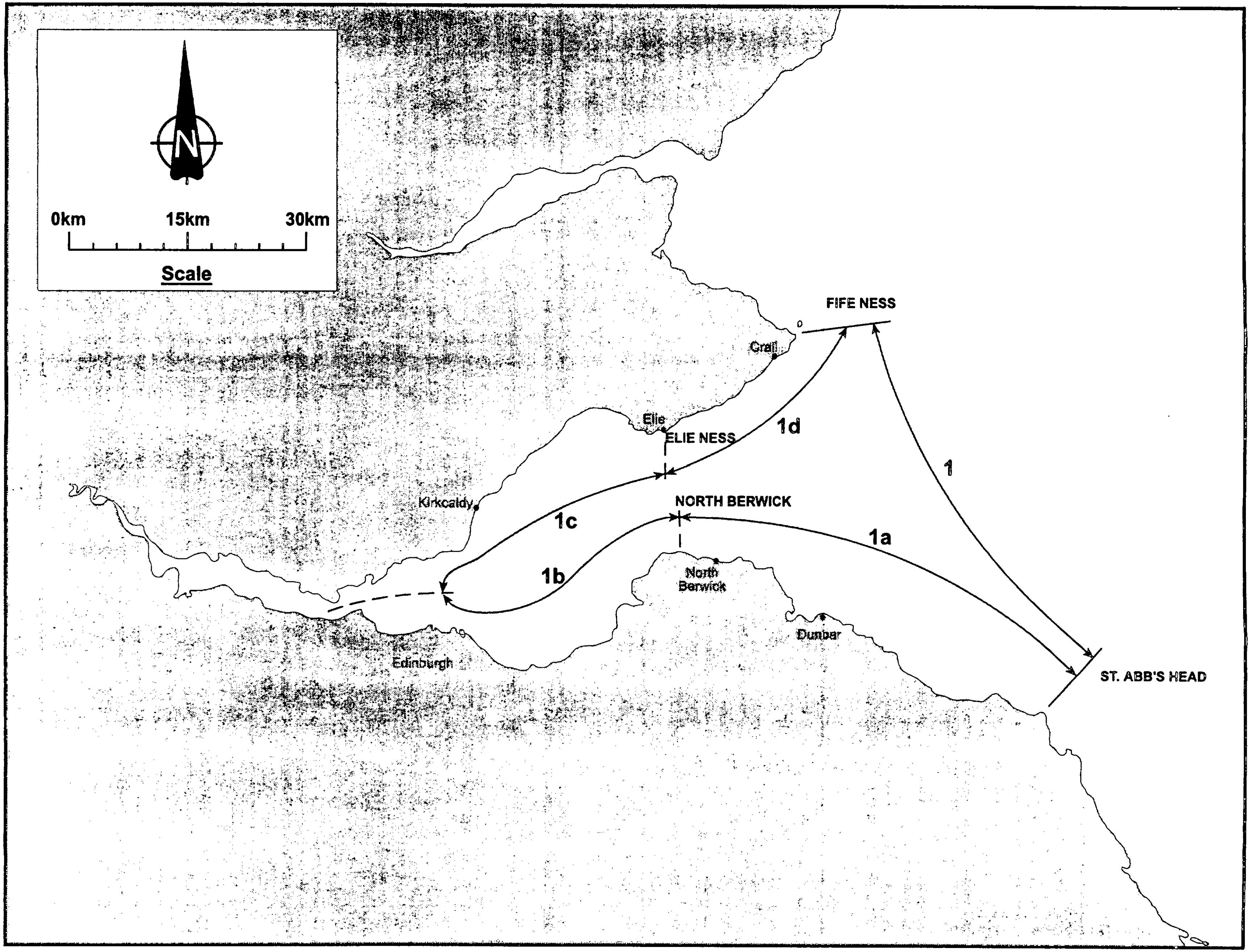


Figure 5 Cell 1 - St Abb's Head to Fife Ness

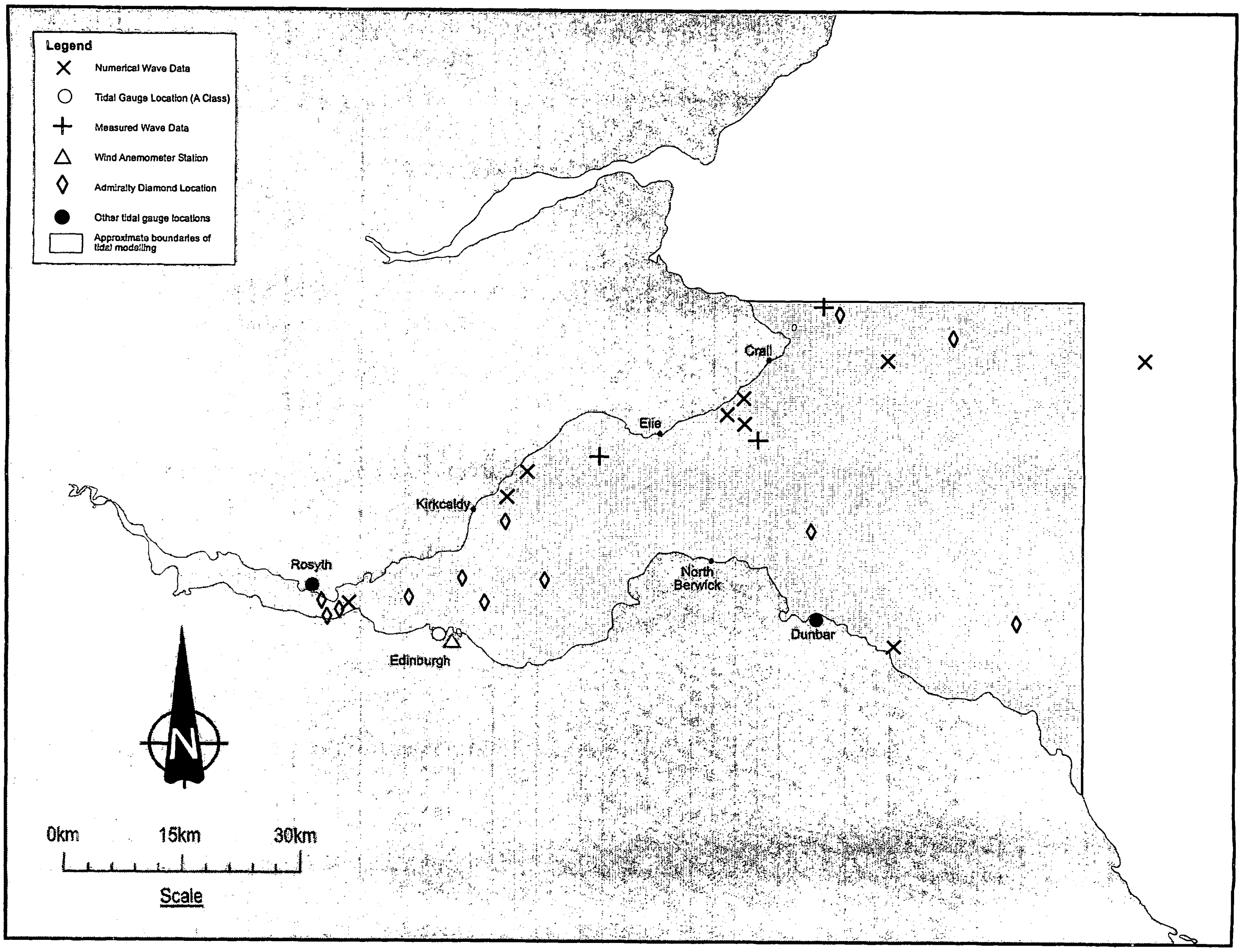


Figure 6 Cell 1 - Location of wind, tidal and wave data

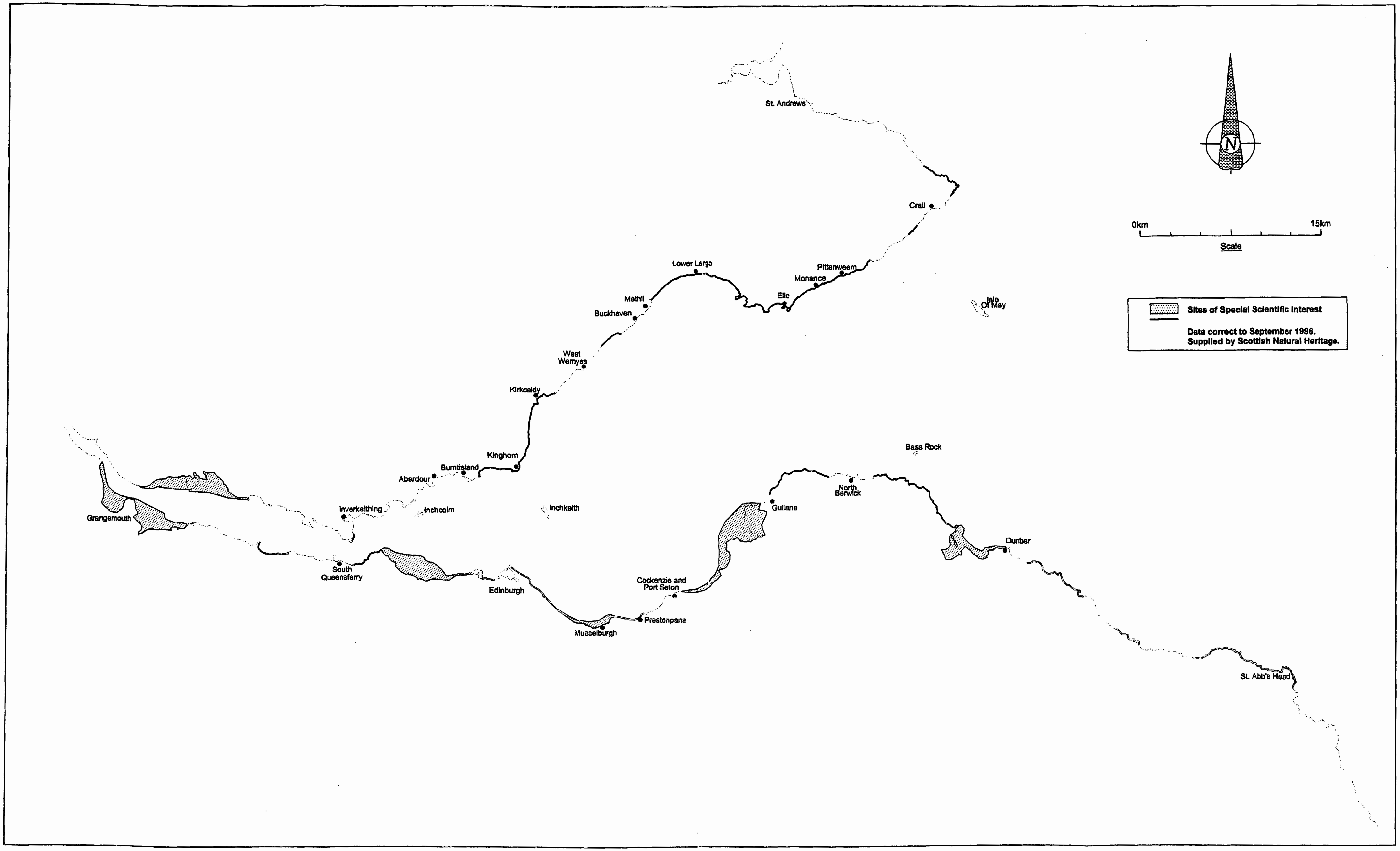


Figure 7 Cell 1 - Location of Sites of Special Scientific Interest

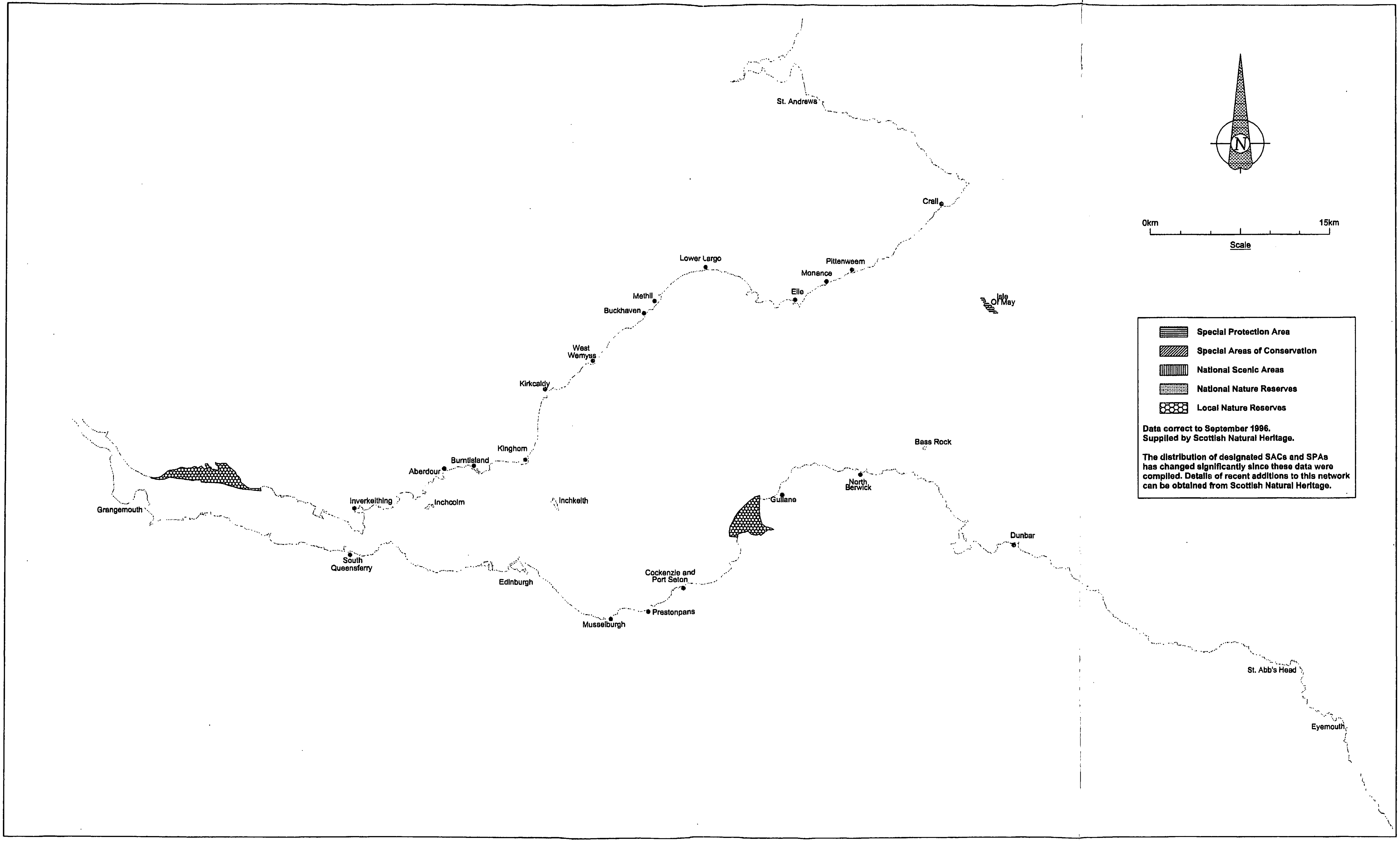


Figure 8 Cell 1 - Location of sites of natural heritage importance (other than SSSIs)

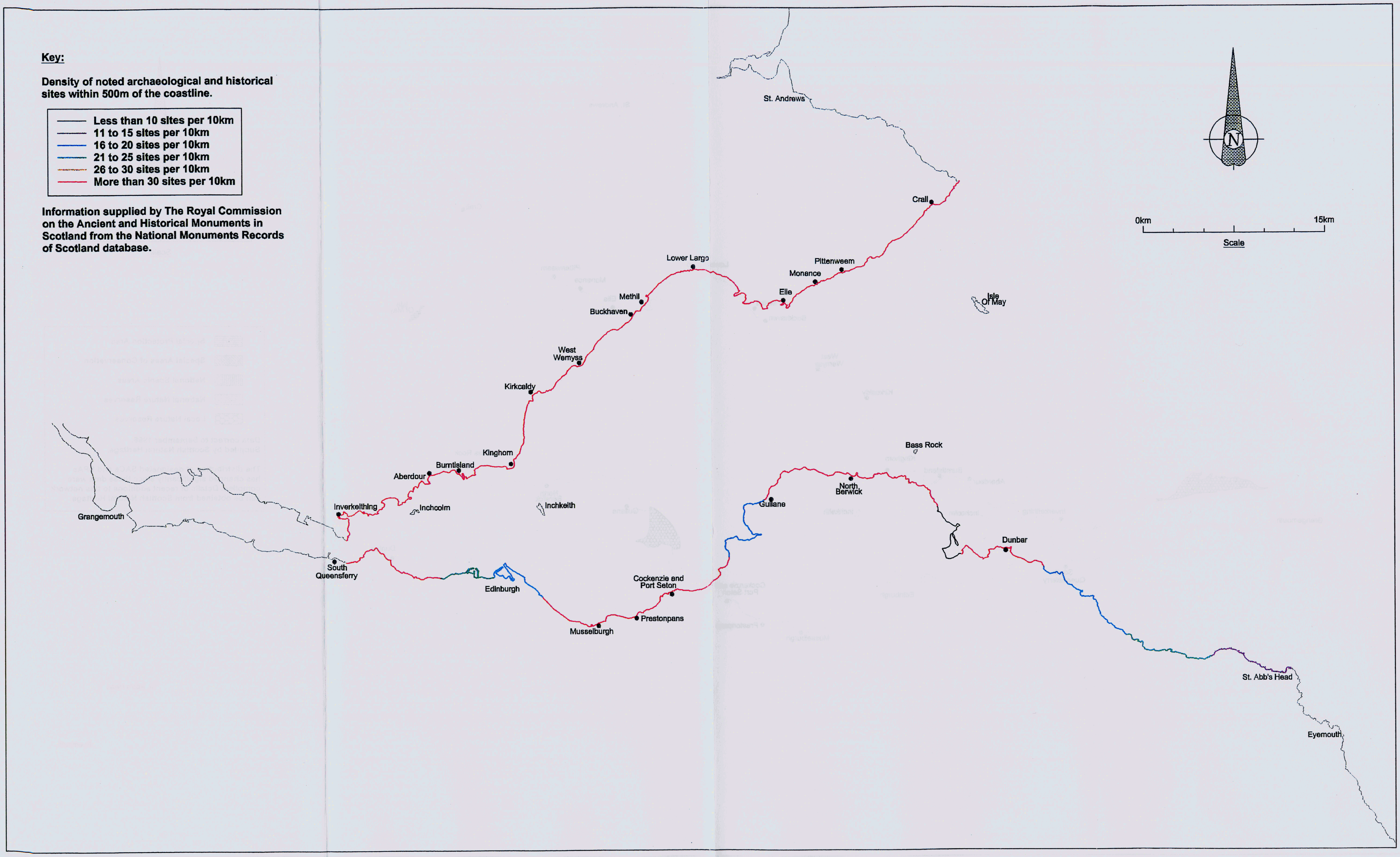


Figure 9 Cell 1 - Density of noted archaeological and historical sites

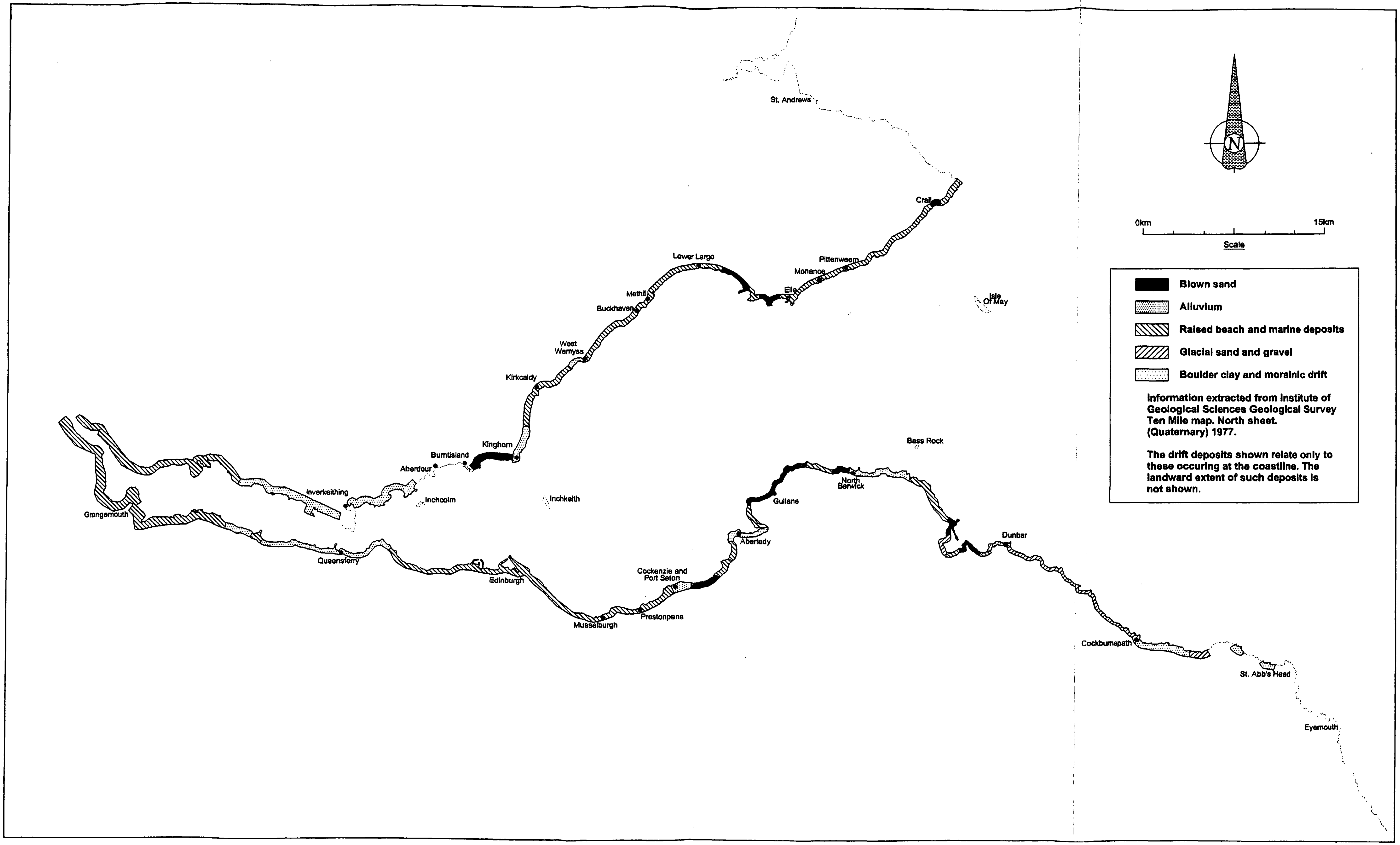


Figure 10 Cell 1 - Drift deposits

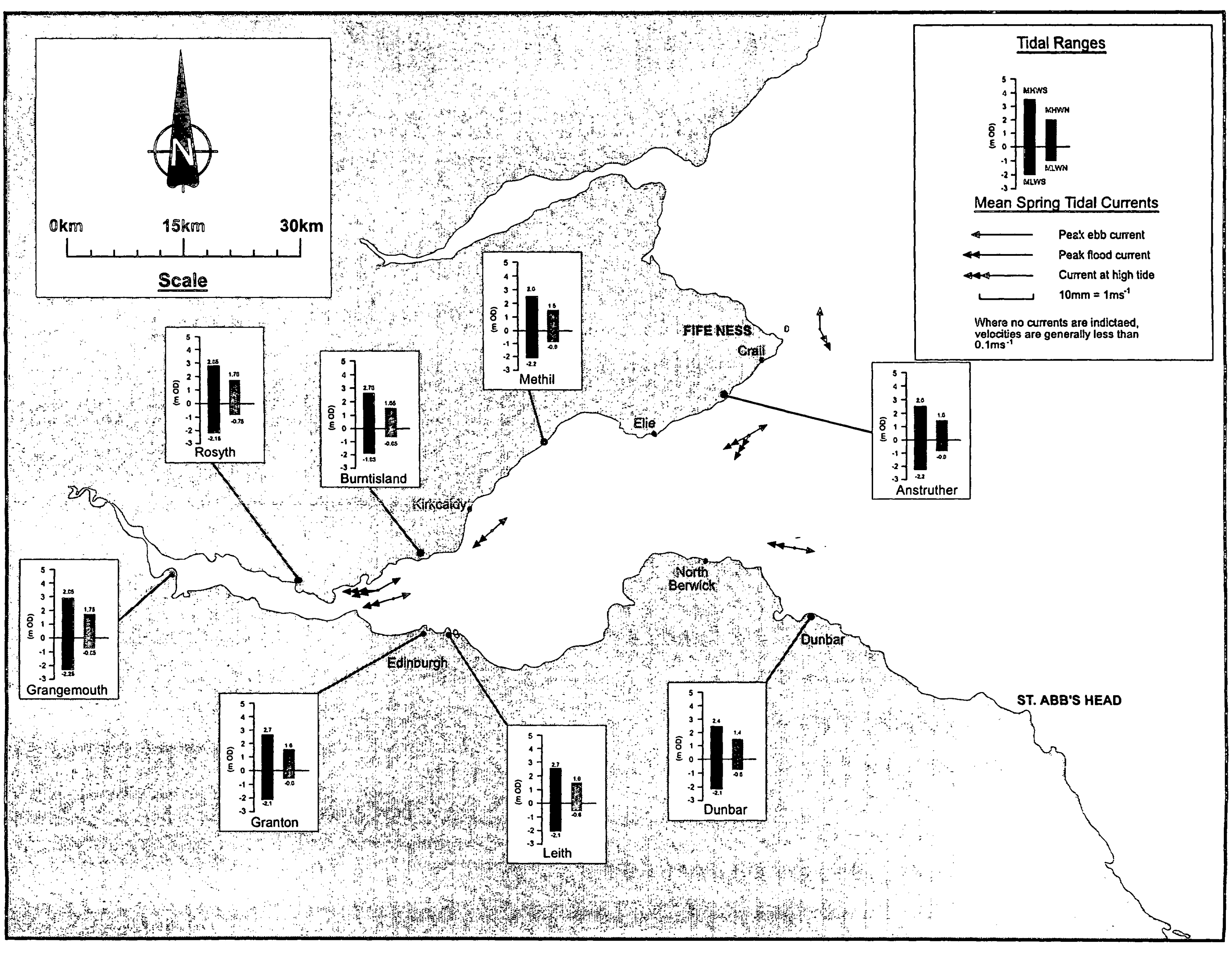


Figure 11 Cell 1 - Tidal levels and current information

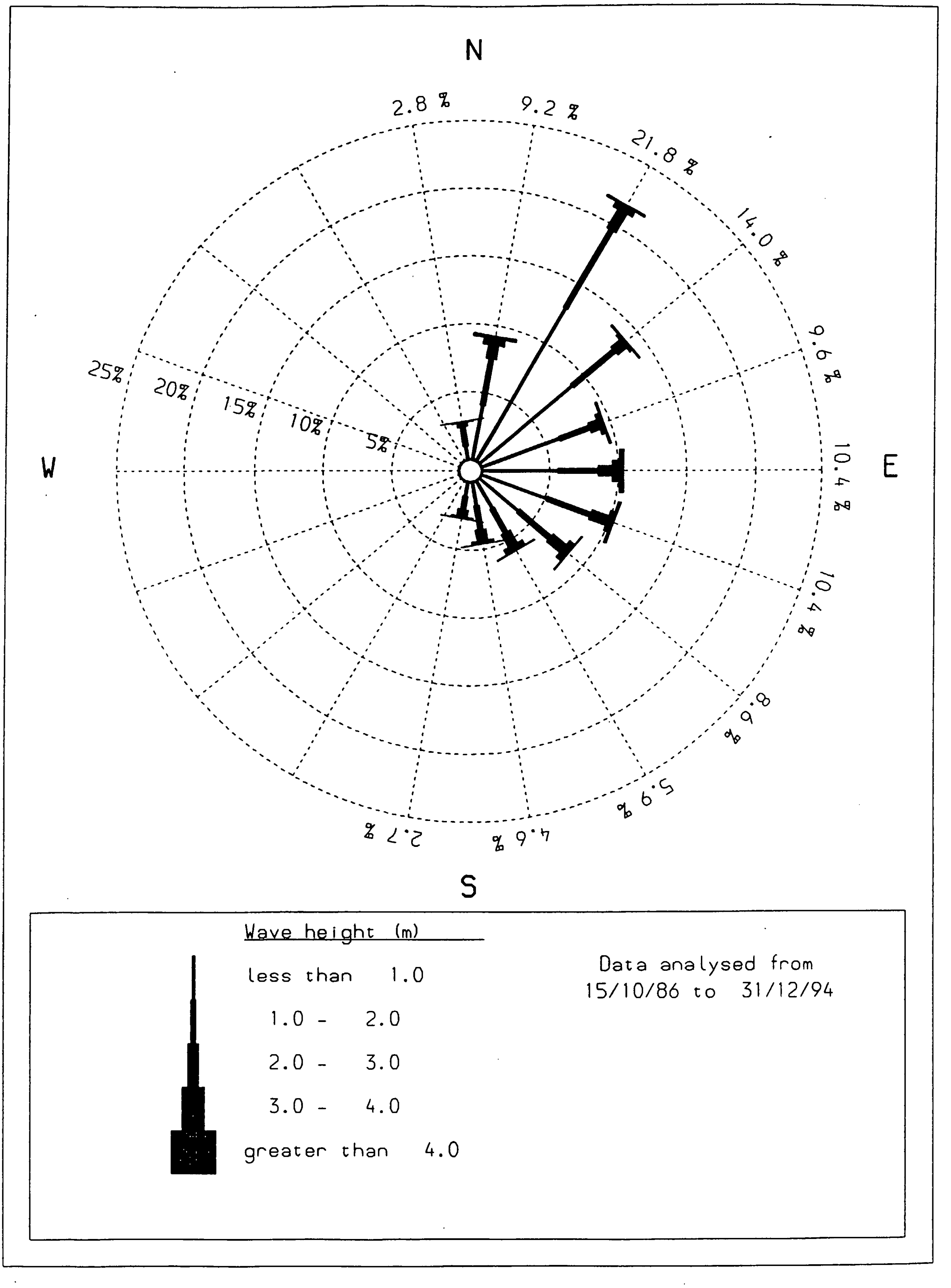


Figure 12 Offshore total wave climate east of the Firth of Forth

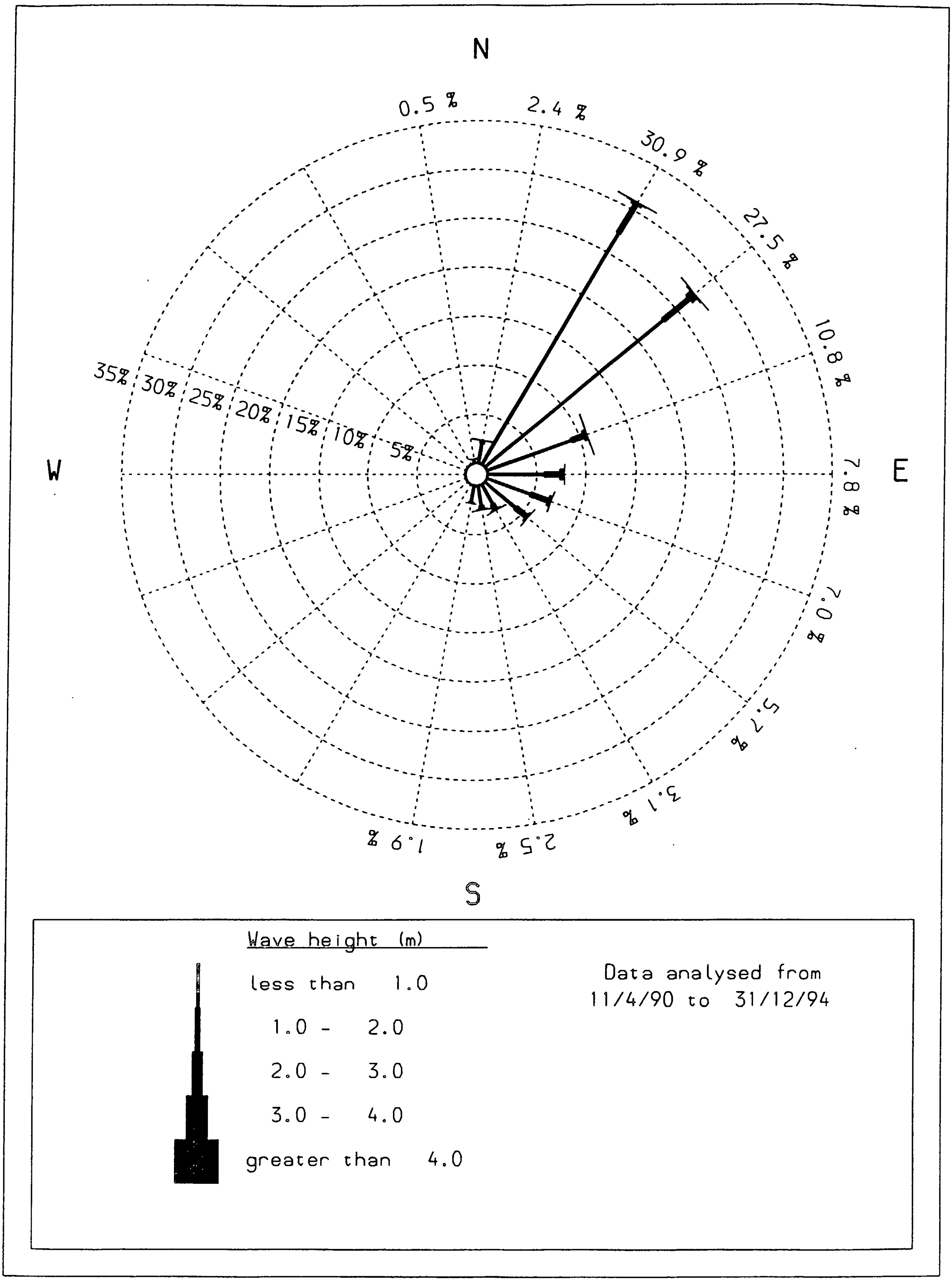


Figure 13 Offshore swell wave climate east of the Firth of Forth

Figure 14 Sub-cell 1a - Foreshore and hinterland characteristics

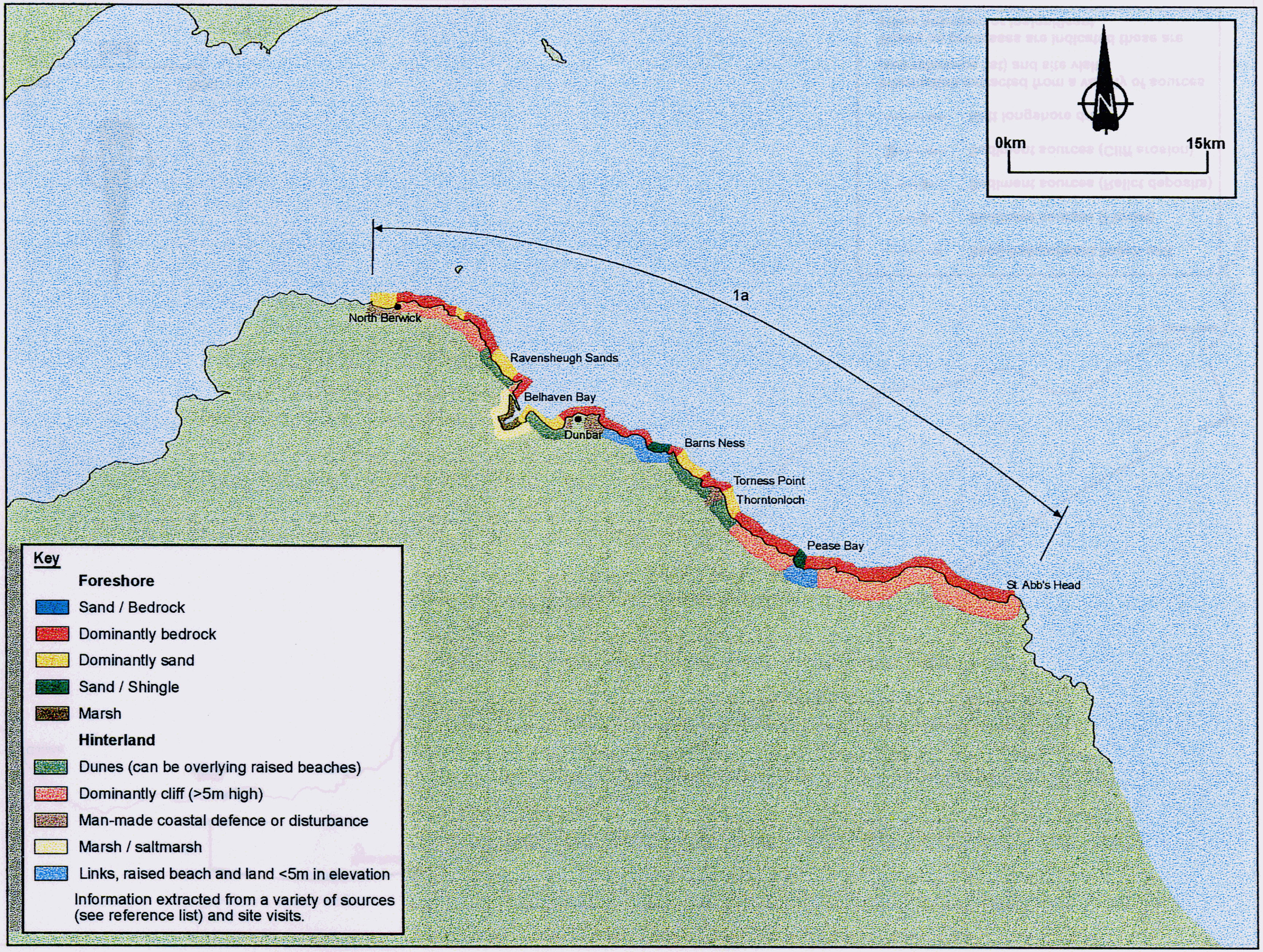
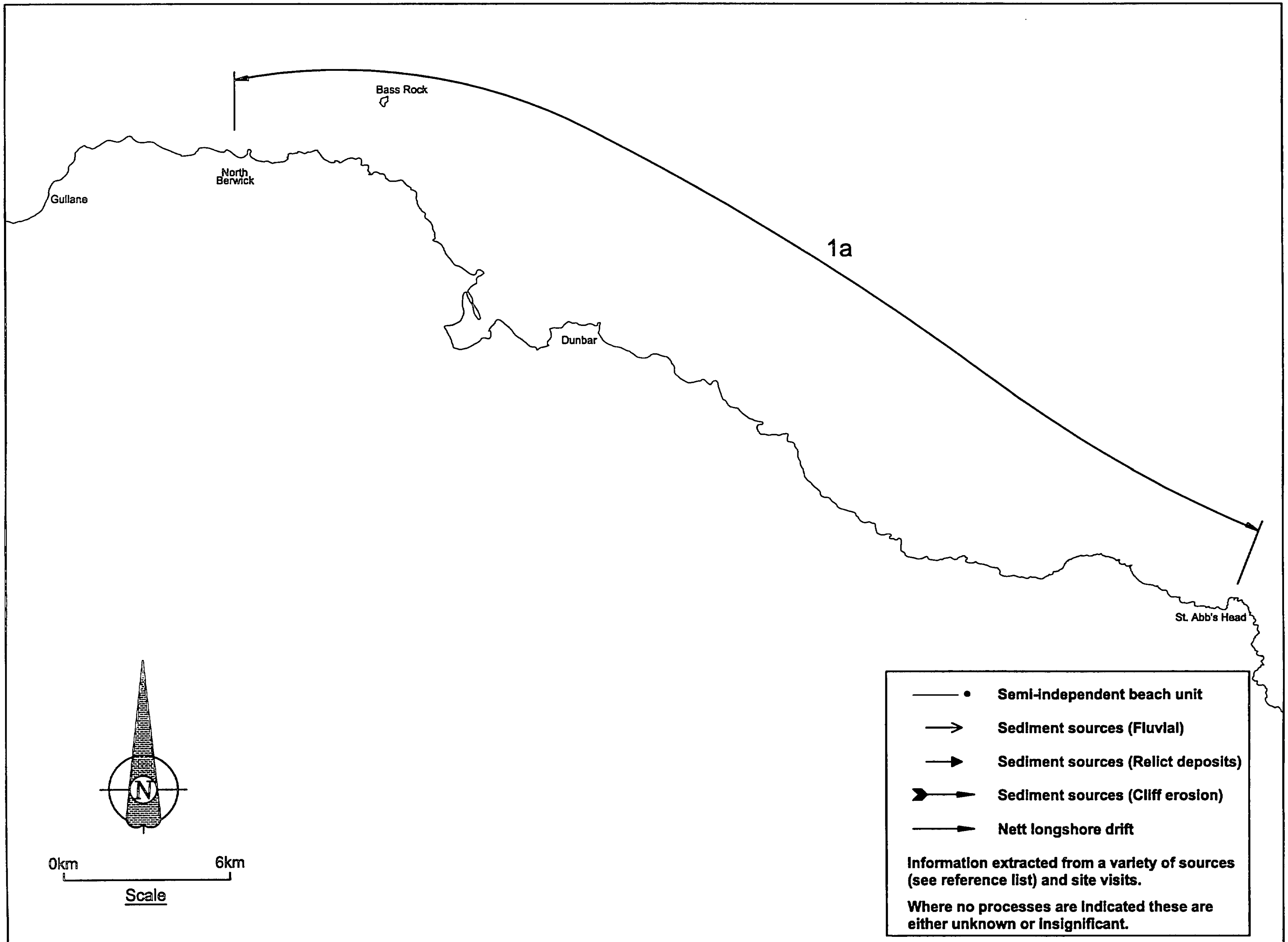


Figure 15 Sub-cell 1a - Dominant littoral processes



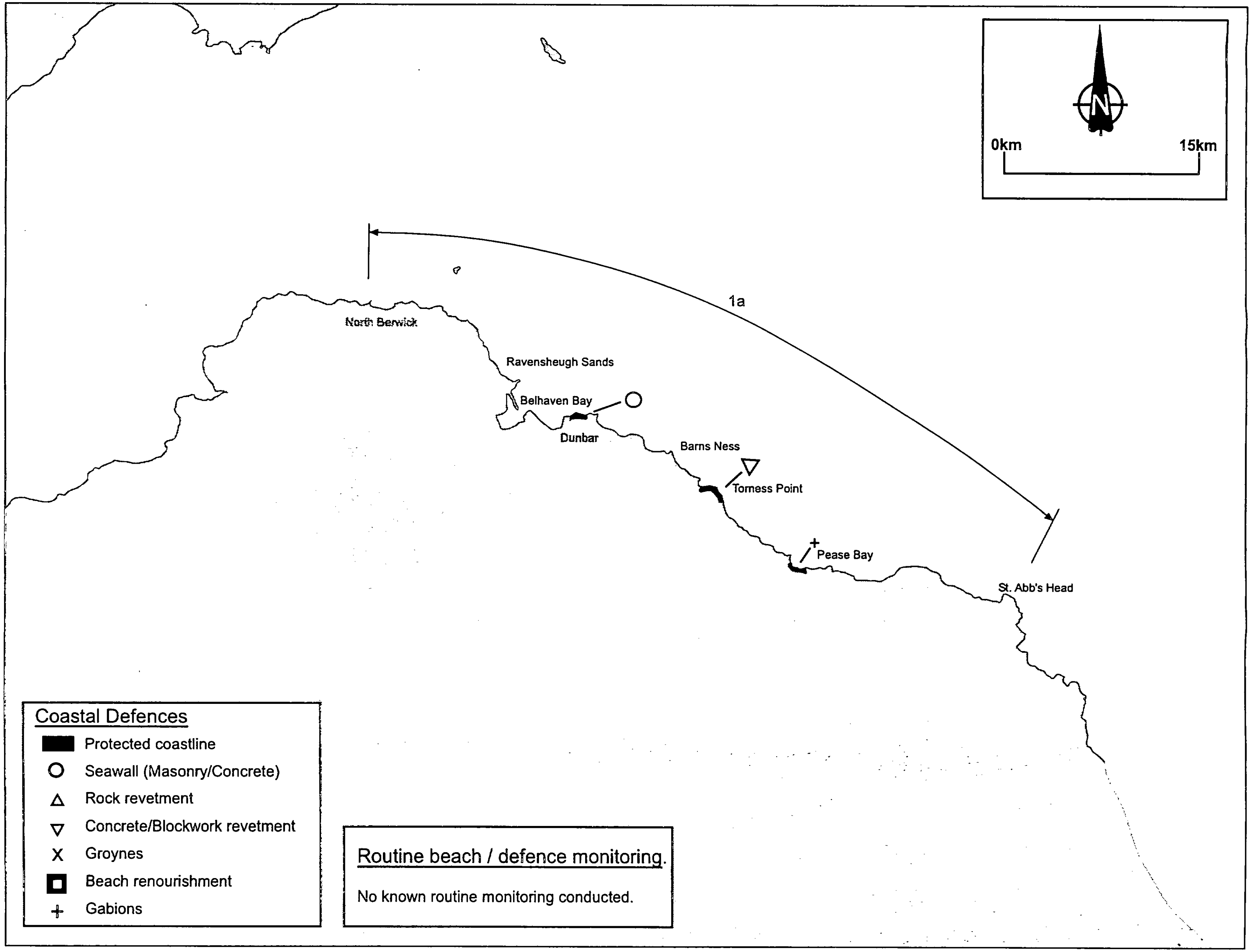


Figure 16 Sub-cell 1a - Coastal defences and monitoring

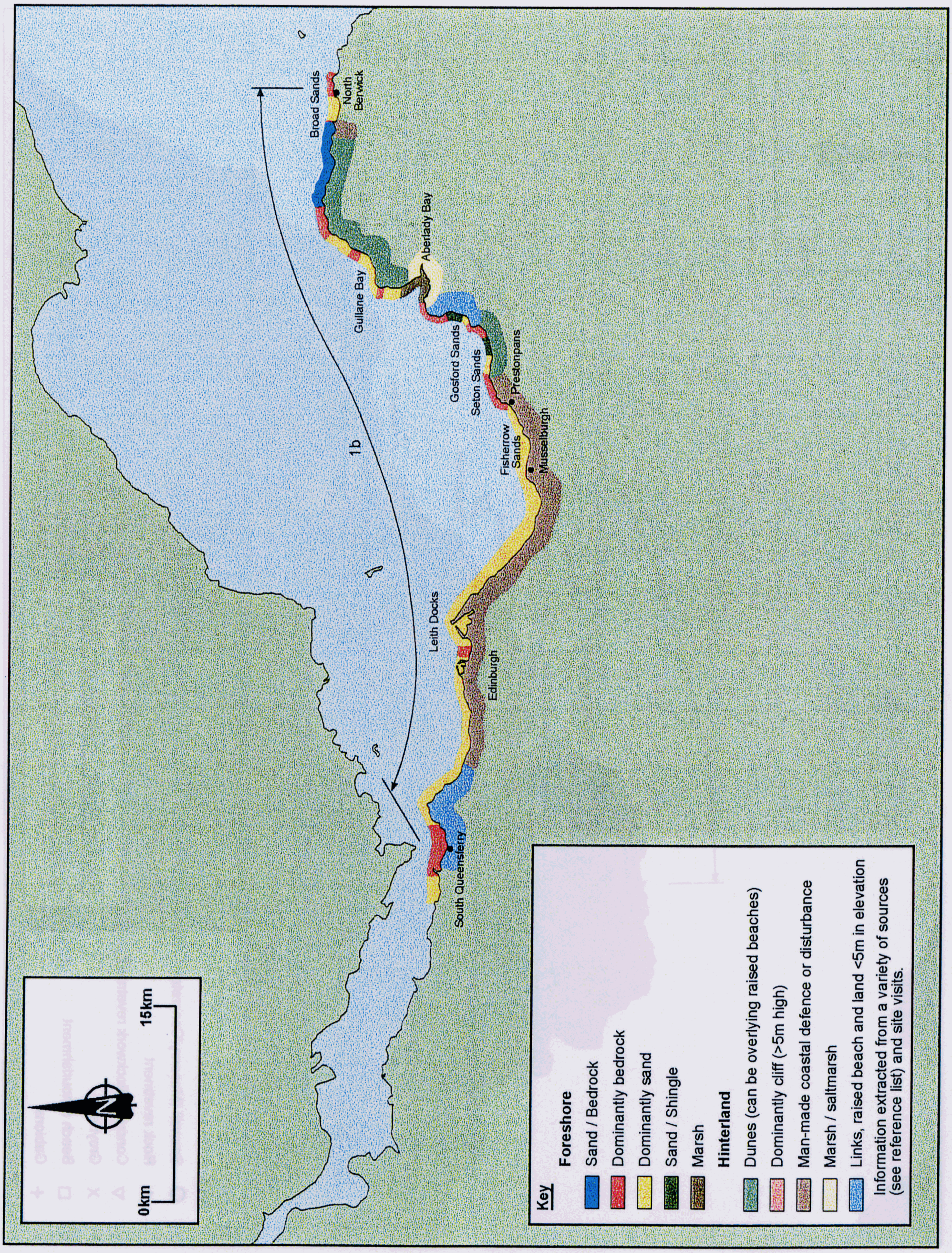


Figure 17 Sub-cell 1b - Foreshore and hinterland characteristics

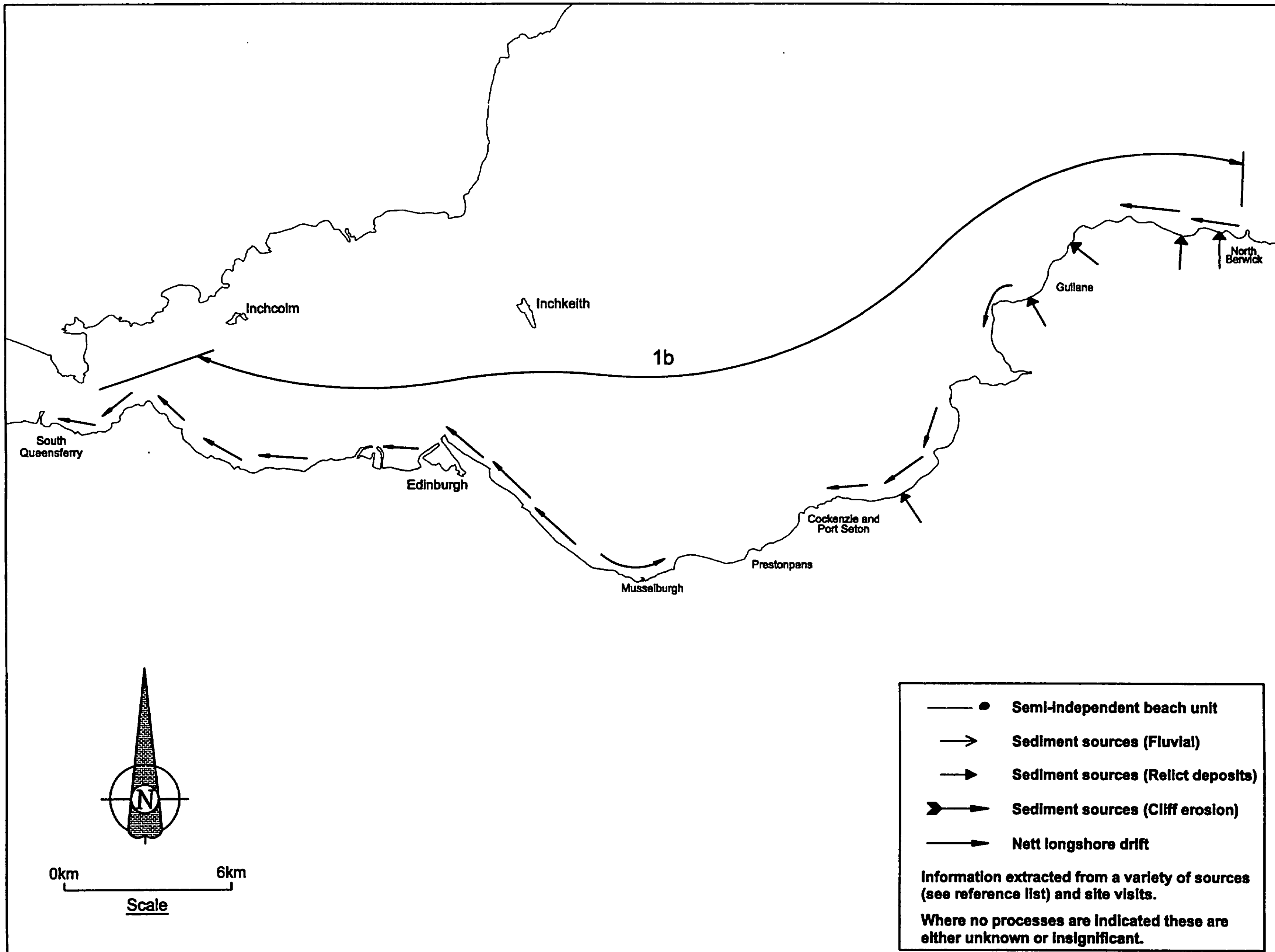


Figure 18 Sub-cell 1b - Dominant littoral processes

Figure 19 Sub-cell 1b - Coastal defences and monitoring

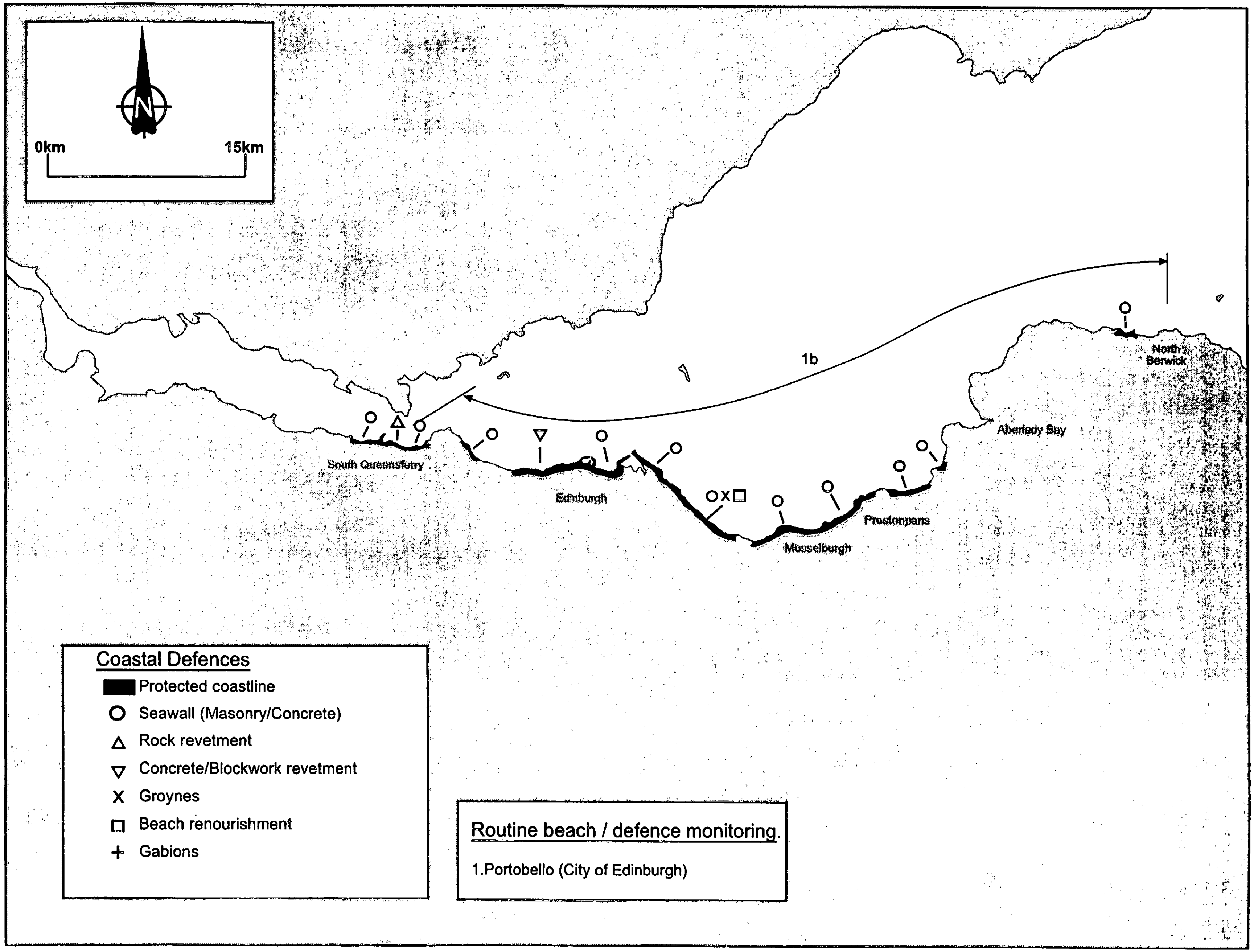
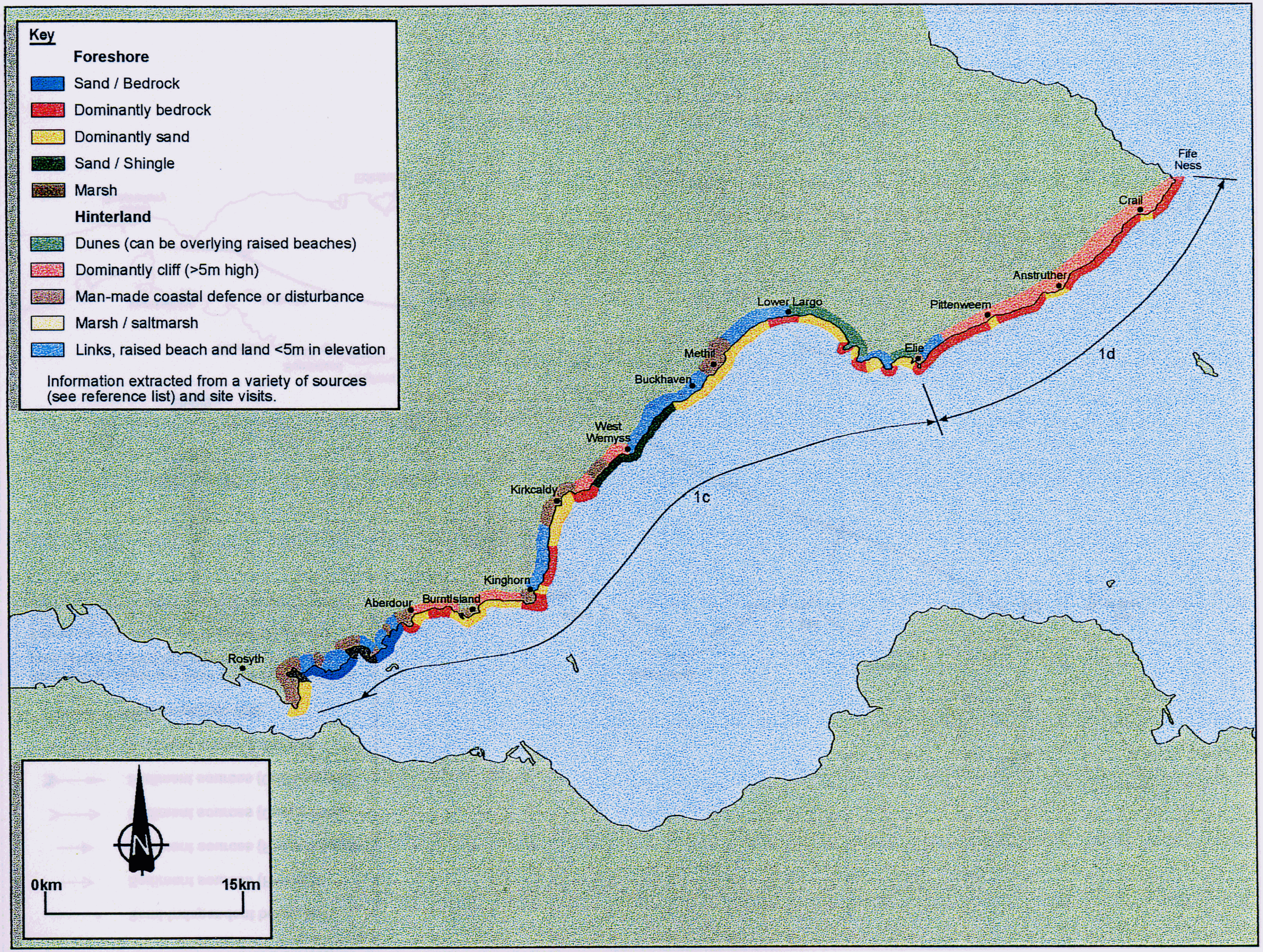


Figure 20 Sub-cells 1c&1d - Foreshore and hinterland characteristics



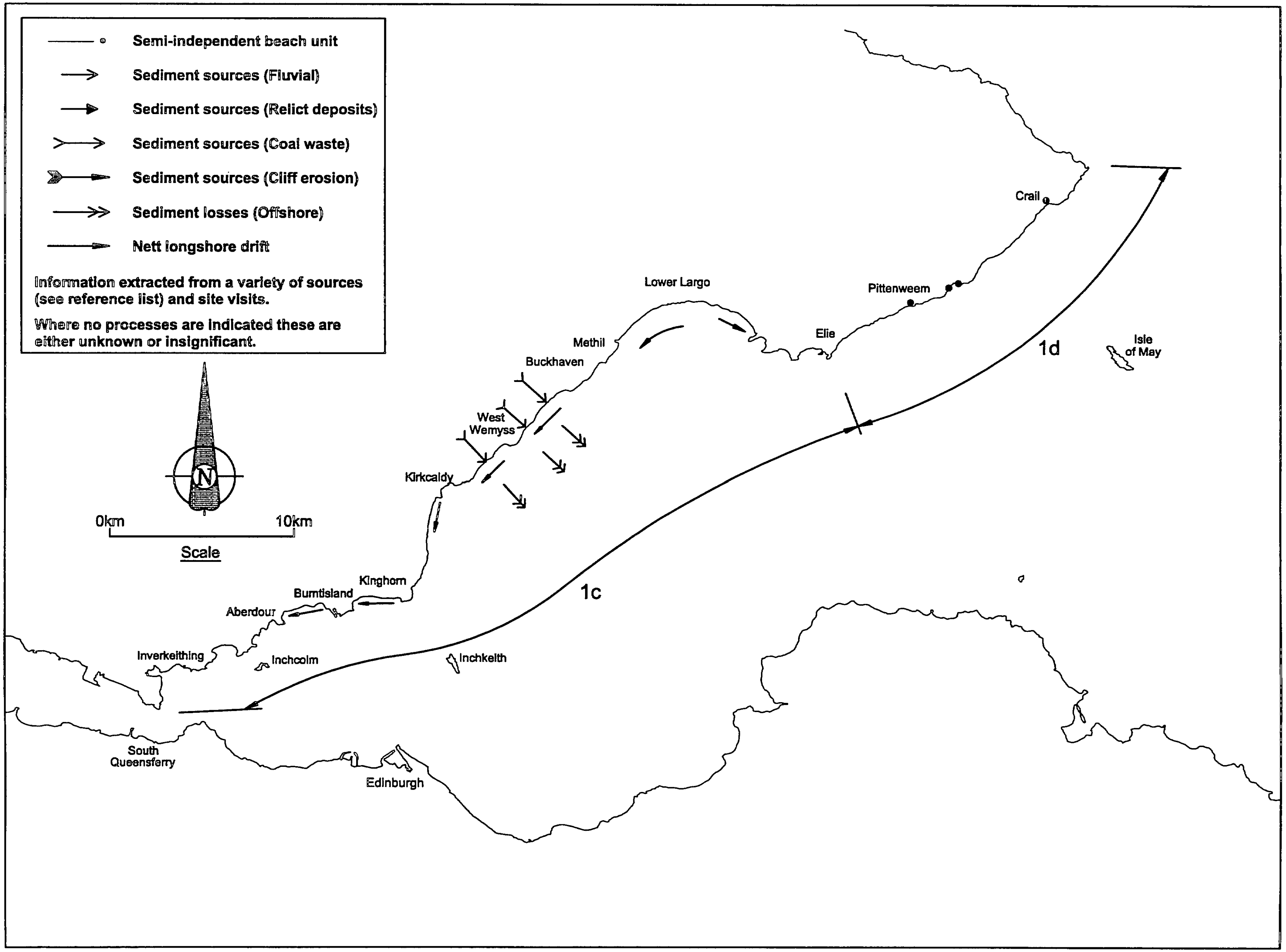
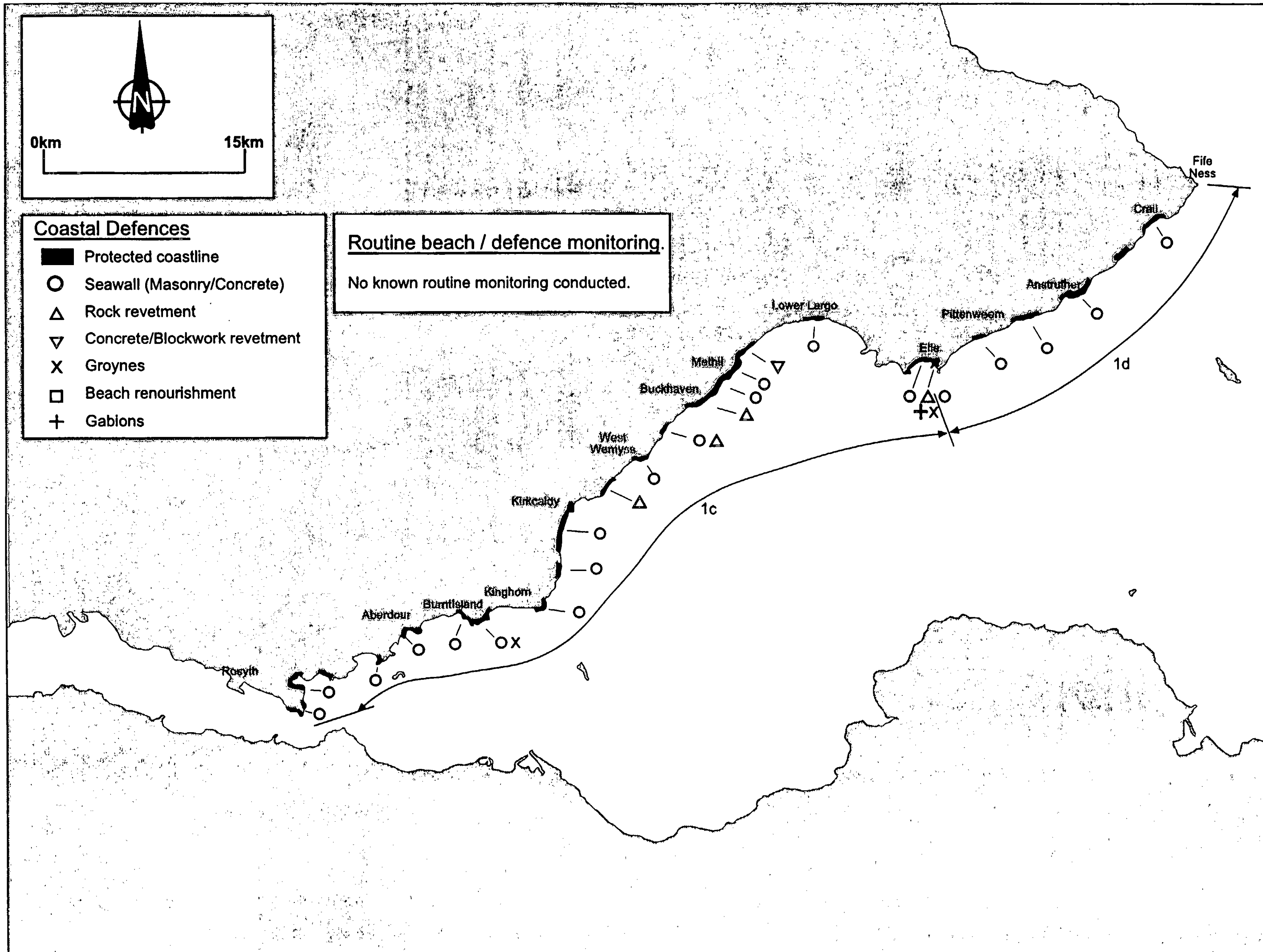


Figure 21 Sub-cells 1c&1d - Dominant littoral processes

Figure 22 Sub-cells 1c&1d - Coastal defences and monitoring



Appendix 1 Cell 1 - Details of Sites of Special Scientific Interest

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

Name	Grid Ref	Size (ha)	Date notified	Site Designation
St Abbs Head to Fast Castle	NT880699	257.3	1986	Geological interest. Open wate Sea cliff (hard rock) Dry grassland Woodland Flush or seepage line Scarce or rare plants Terrestrial invertebrates Seabirds breeding
Siccar Point	NT811709	5.7	1987	Geological interest
Pease Bay Coast	NT781718	64.8	1986	Geological interest Saltmarsh Vegetated shingle Sea cliff (hard rock) Dry grassland Terrestrial invertebrates
Barns Ness Coast	NT696781	271.3	1984	Geological interest Rocky shore Sand dunes Vegetated shingle Dry grassland Scarce or rare plants
Dunbar Coast	NT661793	81.2	1984	Geological interest. Rocky shore Sea cliff (hard rock). Dry grassland Seabirds breeding Site used by other wintering bird species.
Tyninghame Shore	NT640800	608.3	1984	Tidal flats Rocky shore Saltmarsh Sand dunes Vegetated shingle Dry grassland Maritime heath Waders breeding Wildfowl breeding Seabirds breeding Site used for wintering wildfowl. Internationally important. Site used for wintering wildfowl. Nationally important. Site used by other wintering bird species.

Name	Grid Ref	Size (ha)	Date notified	Site Designation
North Berwick Coast	NT601848	179.8	1984	Geological interest Sand dunes Sea cliff (hard rock) Dry grassland Seabirds breeding Site used for wintering wildfowl. Nationally important.
Forth Islands	NT513868	22.5	1983	Rocky shore Seabirds breeding
Gullane to Broad Sands	NT479841	294.0	1983	Geological interest Rocky shore Sand dunes Vegetated shingle Lower plants Wildfowl breeding Seabirds breeding Site used for wintering wildfowl. Nationally important.
Aberlady Bay	NT465815	866.2	1983	Geological interest Tidal flats Saltmarsh Sand dunes Dry grassland Fen Lower plants Terrestrial invertebrates Wildfowl breeding Seabirds breeding Site used for wintering wildfowl. Nationally important.
Gosford Bay to Port Seton	NT405760	317.7	1984	Tidal flats Site used for wintering wildfowl. Nationally important.
Leith to Prestonpans	NT315736	287.2	1986	Geological interest Tidal flats Rocky shore Site used for wintering wildfowl. Nationally important
Wardie Shore	NT238772	11.9	1987	Geological interest
Forth Bridge to Granton Shore	NT180785	742.3	1986	Geological interest Tidal flats Site used for wintering wildfowl. Locally important.
Dumbarnie Links	NO451017	39.9	1982	Saltmarsh Sand dunes Fen

Name	Grid Ref	Size (ha)	Date notified	Site Designation
Carlingnose	NT134806	5.8	1988	Sea cliff (hard rock) Dry grassland Maritime heath Woodland
Ruddons Point	NO457006	9.4	1983	Saltmarsh Sand dunes Dry grassland
East Wemyss to Anstruther Coast	NT465997	530.3	1991	Geological interest
Fife Ness Coast	NO625107	116.9	1987	Geological interest Saltmarsh Vegetated shingle Dry grassland Woodland Fen

Appendix 2 Cell 1 - 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 Cente (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 — Tel: 01733 562626
PE1 1JY — Fax: 01733 555948

Macaulay Land Use Research Institute
Craigiebuckler
Aberdeen — Tel: 01224 318611
AB9 2QL — Fax: 01224 311556

Marine Information Advisory Service (MIAS)
See Proudman Oceanographic Laboratory

Metoc plc (Metocean)
Exchange House
Station Road
Liphook
Hampshire — Tel: 01428 727800
GU30 7DW — Fax: 01428 727122

Ministry of Agriculture, Fisheries and Food
(Flood and Coastal Defence Division)
Eastbury House
30-34 Albert Embankment
London — Tel: 0207 238 6742
SE1 7TL — Fax: 0207 238 6665

National Museums of Scotland
c/o Royal Museum of Scotland
Chambers Street
Edinburgh — Tel: 0131-225 7534
EH1 1JF — Fax: 0131-220 4819

Ordnance Survey (Scottish Region)
Grayfield House
5 Bankhead Avenue
Edinburgh — Tel: 0845 605 0505
EH11 4AE

Proudman Oceanographic Laboratory
(British Oceanographic Data Centre, MIAS & Permanent Service for Mean Sea Level)
Bidston Observatory
Birkenhead
Merseyside — Tel: 0151-653 8633
L43 7RA — Fax: 0151-653 6269

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

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

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

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

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

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

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

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

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

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

Tel: 01344 420242
Fax: 01344 854412

UK Offshore Operators Association Ltd (UKOOA)
30 Buckinghham 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 toi 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.