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Coastal Cells in Scotland:
Cell 3 – Cairnbulg Point to Duncansby Head

D L Ramsay & A H Brampton

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REPORT

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Summary

This report reviews the coastline of Cell 3 between Cairnbulg Point and Duncansby Head on the north east coast of Scotland. It describes the various coastal characteristics and processes which affect the regime of this particular stretch of shoreline. The report includes a description of the major coastal features, processes, and defences along with other aspects of beach development. The stretches of coastline which, for coastal management purposes, can be treated as independent or semi-dependent cells, are also identified.

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

Note

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

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

1 *Introduction*

1.1 General

In January 1996, HR Wallingford was commissioned by Scottish Natural Heritage (SNH), the Scottish Office Agriculture, Environment and Fisheries Department (SOAEFD) and Historic Scotland, (HS) to extend an existing study (HR Wallingford, 1997) to define Coastal Cells and Sub-cells around the coastline of Scotland. This report, which reviews the coastline of Cell 3 between Cairnbulg Point and Duncansby Head, is one of a series of 11 reports covering the entire coastline of mainland Scotland, the Western Isles, Orkney and Shetland. The study concentrates on identifying and describing the various natural and man-made characteristics and processes which affect the behaviour of this particular stretch of coastline. The report includes a description of the dominant hydraulic processes, areas of erosion and accretion, coastal defences and various other aspects of the coastal regime. The aim of the report is to provide an overall understanding of the character and processes occurring within each sub-cell to allow as full an appreciation as is presently possible of the coastal regime on a macro scale.

1.2 Terms of reference

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

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

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

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

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

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

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

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

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

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

1.3 Outline of report

A general introduction to the concept of coastal cells, and how the concept has been applied to the coastline of Scotland is provided in Chapter 2. Chapter 3 provides some general background information on the coastal environment of Scotland in the context of coastal cells. Chapter 4 details available information of relevance to shoreline management in the Moray Firth. Chapter 5 forms the main body of the report. A brief description of Cell 3 detailing the cell boundaries, a description of its character and the processes occurring is given. An assessment of climatic change, sea level rise, and the likely effects on the coastline of Cell 3 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 of terms used are contained within the appendices of this report.

2 Coastal Cells

2.1 Coastal Cells

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

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

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

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 interrelationship 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 dependent on the authority promoting the scheme. The grant level can vary from between 20% to 80% at present.

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

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

Table 1 Required consents for proposed coast protection works

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

Notes

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

Abbreviations used:

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

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

3 *The marine environment*

3.1 Introduction

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

3.2 Geology and geomorphology

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

In geological terms, Scotland can be considered as being formed of 5 distinct units or divisions, each separated by a major fault or fracture in the Earth's crust:

- the north-west Highlands and Islands west of the Moine Thrust, composed of "ancient" Lewisian gneiss;
- the Northern Highlands between the Moine Thrust and the Great Glen Fault, composed of the eroded roots of the Caledonian Mountain Belt, consisting primarily of 1,000 Ma metamorphosed sediments of the Moine;
- the Central Highlands between the Great Glen Fault and the Highland Boundary Fault, composed of 800 Ma 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 3 Ma ago, extensive lava fields of the Ochils and Clyde plateau and the volcanic rocks of Edinburgh and the Laws of Fife and East Lothian; and
- the Southern Uplands, composed of sediments deposited in the former lapetus Ocean which, for over 100 Ma, separated Scotland and England.

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

The last ice sheet, which reached a thickness of 1500 metres in places, advanced from the Highlands over the entire Scottish mainland and most of the islands. Ice extended offshore and local ice-caps may have existed on the more remote island groups such as Shetland and the Western Isles. Sea level, worldwide, 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 offshore 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 offshore zone were reworked and moved into the present coastal zone, and fresh material was eroded from the glacial deposits on the coast. It is the material derived from these glacial deposits which supplied the majority of the sediment for the sand and shingle beaches of the present coastline.

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

When the ice first began to melt, between approximately 17,000 and 15,000 years ago, global or eustatic sea level rose, flooding over the continental shelf and engulfing many coastal areas. In some western areas, such as Jura and Arran, "raised" beaches were deposited on the coast at heights of up to 40m above present day high water mark.

Thereafter, isostatic uplift gradually overtook eustatic rise causing a relative fall in sea levels around most of the country. This trend continued, with local variations, until around 8,000-9,000 years ago, bringing sea level down to around or below present day levels in most areas. At that time, eustatic rise once more overtook isostatic uplift and relative sea level rose again (known as the Post-glacial Transgression) to attain a maximum height relative to the land, in most areas, around 5-6,000 years ago.

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

3.3 Hydraulic processes

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

Tidal levels

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

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

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

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

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

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

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

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

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

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

Tidal currents

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

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

Waves and swell

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

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

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

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

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

3.4 Littoral processes

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

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

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

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

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

3.5 Coastal defence, monitoring and management

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

- the structural condition of the defence,
- its capacity to prevent overtopping or flooding,

- the impact of the defence on the surrounding littoral regime.

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

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

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

3.6 Natural and cultural heritage

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

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

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

National Nature Reserves (NNR) Scottish Natural Heritage

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

Marine Nature Reserves (MNR) Scottish Natural Heritage

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

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

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

Special Areas of Conservation (SAC) Scottish Office

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

Special Protection Areas (SPA) Scottish Office

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

Ramsar sites Scottish Office

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

National Scenic Areas (NSA) Scottish Natural Heritage

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

Natural Heritage Areas (NHA) — Scottish Natural Heritage

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

Areas of Great Landscape Value (AGLV) — Local Authorities

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

Environmentally Sensitive Areas (ESA) — Scottish Office (SOAEFD)

These are designated by the Secretary of State under the 1986 Agriculture Act to encourage landowners to manage their land to safeguard and enhance the nature conservation, landscape and cultural interest of the land for which a grant is available.

Marine Consultation Areas (MCA) — Scottish Natural Heritage

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

Regional Parks and Country Parks — Local Authorities

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

RSPB Reserves — Royal Society for the Protection of Birds

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

Scheduled Monuments — Historic Scotland

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

4 *Cell 3 - Information sources*

4.1 General

Information on the physical characteristics and coastal regime is available from a variety of sources and organisations. The purpose of this section is to provide general details on the availability of such information and of any data sources of relevance to shoreline management within Cell 3. Further, site specific information, particularly on littoral processes and coastal defences, is contained within each of the sub-cell sections.

The UK Digital Marine Atlas (UKDMAP) which was developed by the British Oceanographic Data Centre, Birkenhead provides a reference database of the marine environment for the whole of the UK. It provides general information on a wide range of subjects including geology, hydrography, conservation and ecology. A review of information relating to the natural environment, the current protected status of coastal and marine habitats, communities 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). Scottish Natural Heritage have also recently produced *The Moray Firth Review* (Harding-Hill, 1993) which has collated and synthesised much of the available information on the physical, ecological, conservational and human features of the Moray Firth. More recently a series of reports covering the coastline of the UK has been produced by the Joint Nature Conservation Committee containing baseline environmental information for the coastal and nearshore marine zone. Information on the Moray Firth coast is contained in, *Coasts and Seas of the United Kingdom: Region 3: North-east Scotland: Cape Wrath to St Cyrus* (Barne et al, 1996).

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

4.2 Geology and geomorphology

The geology of the Moray Firth has been studied in detail in several studies, the most comprehensive being *British Regional Geology: The Northern Highlands of Scotland* (Johnstone & Mykura, 1989) and *The Grampian Highlands (Stevenson & Gould, 1995)*. The geology of the Moray Firth Basin is detailed in *The Geology of the Moray Firth* (Andrews et al, 1990). These reports reference a large number of more detailed localised studies conducted within the north east of Scotland. The British Geological Survey have also produced a series of solid and drift geology maps the availability of which is detailed in Table 2.

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

Table 2 Available geological maps

Map No.	Map Name	Solid/Drift Geology	Scale
97	Fraserburgh	Solid & Drift	1:50,000
96	Banff	Solid & Drift	1:63,360
95	Elgin	Solid & Drift	1:63,360
94	Cromarty	Solid & Drift	1:63,360
84E	Nairn	Drift	1:50,000
84W	Fortrose	Drift	1:50,000
84	Nairn	Solid	1:63,360
83	Inverness	Solid & Drift	1:63,360
93	Alness	Solid & Drift	1:63,360
94	Cromarty	Solid & Drift	1:63,360
103	Golspie	Solid & Drift	1:63,360
110	Latheron	Solid	1:50,000
110	Latheron	Solid & Drift	1:63,360
116E	Thurso	Solid	1:50,000

The geomorphology of the Moray Firth coast is described in several studies, the main ones being *The coastline of Scotland* (Steers, 1973) and *The beaches of North East Scotland* (Ritchie, Smith & Rose, (1978); *The beaches of East Sutherland and Easter Ross* (Smith & Mather, 1973) and *The beaches of Caithness* (Ritchie & Mather, 1970). Information on the geomorphology of estuaries within Cell 3 can be found in the Estuaries Review carried out by the Joint Nature Conservation Committee (Buck, 1993). Detailed reviews of the estuaries occurring around the Moray Firth have been conducted as part of the Focus on Firths initiative (Hansom & Black, 1996; Stapleton & Pethick, 1996; Gemmell et al, 1996). A shoreline management plan, for the coastline between Burghead and the Sutors of Cromarty has also recently been completed (HR Wallingford, 1996a). Offshore sediment movements within the Moray Firth have been studied by Reid (1988).

4.3 Bathymetry

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

Table 3 Available Admiralty Charts

Chart No.	Location	Scale
115	Moray Firth	1:200,000
213	Fraserburgh to Newburgh	1:75,000
222	Buckie to Fraserburgh	1:75,000
223	Dunrobin Point to Buckie	1:75,000
1077	Approaches to the Cromarty Firth & Inverness Firth	1:20,000
1078	Inverness Firth	1:20,000 & 1:5,000
1409	Buckie to Arbroath	1:200,000
1462	Harbours on the North East coast of Scotland	Various
1889	Cromarty Firth: Cromarty Bank to Invergordon	1:15,000 & 1:5,000
1890	Cromarty Firth: Invergordon to Dingwall	1:15,000
1954	Cape Wrath to Pentland Firth & Orkney Islands	1:200,00
2182B	North Sea: Central Sheet	1:750,000

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

4.4 Wind data

There are a number of anemometer stations where winds have been recorded and the information passed to the Met Office which could be useful in estimating wave conditions on the north east coastline of Scotland. At present the recorders at Lossiemouth, Tain Range and Wick are equipped with Semi-Automatic Meteorological Observing Systems (SAMOS) which produce wind statistics continuously for immediate archiving. The recorders at Kinloss and Dalcross 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 Shin and Invergordon Harbour a graphical recorder is used, which has to be hand-analysed to provide suitable data for archiving. Wind records have also been collected at Fraserburgh but this station has now closed. A summary of the available wind data is provided in the following table:

Table 4 Cell 3 - Availability of wind data

Location	Period covered	Anemometer Type
Dalcross	01/70 - Present	Digital Anemograph Logging Equipment (DALE)
Fraserburgh (closed)	01/70 - 12/91	Unknown
Invergordon Harbour	10/84 -Present	Data on Metform 6910
Kinloss	01/70 -Present	Digital Anemograph Logging Equipment (DALE)
Lossiemouth	01/70 -Present	Analysed anemograph from SAMOS station
Shin	01/70 -Present	Data on Metform 6910
Tain Range	< 5years	Analysed anemograph from SAMOS station
Wick	01/70 - Present	Analysed anemograph from SAMOS station

4.5 Tidal data

A-class tidal gauges within this Cell are installed at Wick and BARMAC's Yard at Whiteness Point. 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 can be used to provide local tide predictions, either by POL, or other organisations which have obtained the relevant computer programs to make such predictions. It should be realised, however, that the harmonic constants derived for these sites may not be as reliable as from an A-class gauge. Tidal gauges (which are not part of the A-class network) are also installed at Buckie and most recently within the Cromarty Firth.

Information on mean sea level can be obtained from the Permanent Service for Mean Sea Level (PSMSL) which is located at the Bidston Observatory in Birkenhead. This was set up in 1933 and is responsible for collecting monthly and annual mean values of sea level from approximately 1450 tide gauge stations around the world. The contents of the PSMSL data set are described in the report *Data holdings of the PSMSL* (Spencer & Woodworth, 1993) which can be obtained from the Bidston Observatory. Within Cell 3 mean sea level is recorded at Buckie, Wick and Invergordon.

Actual tidal levels, however, can and often do vary significantly from those predicted using harmonic analysis, due to meteorological effects (surges) (see Section 3.3). The UK Met Office Storm Warning Service operate a surge prediction model provided by POL. This has a 12km spatial resolution around the coast of the UK, and can provide information on surge conditions in the North Sea. To provide predictions at the coastline a more detailed numerical model would be required. There are two known locations where detailed tidal modelling of the nearshore seabed has been conducted within Cell 3. The first models the coastal zone around Fraserburgh and was developed to investigate current patterns and pollution flows as part of the feasibility study for a long sea outfall at Fraserburgh, (Binnie and Partners, 1991). The second tidal model covers most of the Caithness coastline (HR Wallingford, 1986).

Table 5 Cell 3 - Tidal modelling studies

Cell	Location	Study	Contact
3a	Fraserburgh (Troup Head to Peterhead)	Tidal flow modelling Water Quality Modelling	Binnie & Partners
3g	Pentland Firth (area north of Wick and extending 24.5km east of Duncansby Head)	Tidal flow modelling Pollutant transport modelling	HR Wallingford.

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 of the UK (Dixon & Tawn, 1997) and so includes the coastline of Cell 3. In practice, referring to these papers, or similar papers in the future, is likely to be the method used most often by coastal managers to determine extreme water levels in their area.

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

In addition the Admiralty also produce "Tidal stream atlases" with the offshore zone of Cell 3 covered in the North Sea: Flamborough Head to Pentland Firth (Hydrographer of the Navy, 1963). These show the currents over a wide area at various states of the tide. The flows are represented by arrows, annotated with the approximate speeds (again for Spring and Neap tides). However, this information is aimed at those navigating ships; it is rarely of much use in very shallow coastal waters or away from the main channels in estuaries.

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 (BODC) have a digital inventory of current meter data around the British Isles collected from a large number of both national and international organisations. The digital directory contains information up to 1991 and is available directly from BODC. The other source is from commercial survey companies carrying out site-specific studies.

A large number of current recording locations have been recorded in the BODC Digital Directory within Cell 3 (approximately 70 separate deployments). These have predominantly been located around the Beatrice Field (south west of Smith Bank) and at a number of locations along the southern coastline.

4.6 Wave data

Information on offshore wave conditions can be obtained from measured or recorded wave data or from synthetic wave data generated using numerical models. The only detailed record of instrumentally recorded wave data in Scotland is the MIAS catalogue (MIAS, 1982) which was compiled in 1982. An updated digital version is presently being developed. Wave recording is conducted occasionally by commercial organisations, normally in connection with a marine construction projects, e.g. harbour developments. Waves have been instrumentally measured at several positions in the region, Table 6. Data for the Beatrice Field are reasonably representative of conditions within the outer Moray Firth, whilst data for Kinnairds Head are more representative of those occurring offshore of the Outer Moray Firth Boundary.

Table 6 Cell 3 - Recorded wave information

Location	Lat/Long	Period covered	Mean Water Depth (m)	Contact
NNE of Kinnairds Head	57°55'48"N 01°54"06"W	23 Feb 1980 to present	unknown	MIAS
28km NNE of Kinnairds Head	57°55"48"N 01°54"06"W	Feb 1980 to Jan 1982	88m	MIAS
Moray Firth (South)	58°06"20"N 03°06"50"W	Nov 1977 to Jan 1980	40m	MIAS
Banff	-	Jan 1981 to Nov 1971	unknown	unknown
Beatrice 'A' Platform	-	1990	unknown	unknown
Moray Firth (North)	58°67'20"N 03°03"40"W	Nov 1976 to Sep 1978	40m	MIAS
Cromarty Firth (Entrance)	57°40'53"N 03°55"23"W	10 Apr 1975 to 31 Dec 1975	unknown	Cromarty Firth Port Authority

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

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

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

Two surface wave models at present run on an operational (daily) basis at the UK Meteorological Office. These are the result of an evolving series of such models, in use since 1976. They were designed primarily for offshore application, for example in ship routing and operation of offshore structures. The model calculations are carried out on a polar stereographic grid, whose exact spacing varies from one latitude to another. The European Wave Model (grid spacing about 30km) is nested within the Global Model (grid spacing about 150km) from which it takes its boundary wave conditions. The 30km grid size means that shallow water effects are not well represented in the model, and grid points closest to the land are not used for prediction purposes. Before use the model predictions therefore need to be transformed from 20-50km offshore to the shoreline (see below).

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

Modern numerical methods are 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. The final stage in numerical wave prediction is to transform such offshore wave information into corresponding nearshore conditions. This may be carried out just for a few offshore conditions (e.g. waves expected to occur only in exceptional storms), or for a whole wave "climate". For further details of the range of numerical techniques available, the reader is referred to a recent report by Dodd and Brampton (1995). However, in outline all such models start from a digital representation of the water depths between the offshore point at which waves are predicted, and the stretch of coastline under consideration. A number of alternative techniques are available that calculate the way that wave energy propagates shoreward; they all include the processes of refraction and shoaling, and many can include other effects such as frictional dissipation, the shelter provided by offshore islands or headlands, the effects of tidal currents (particularly important along the eastern frontage of this Cell) or the continuing growth of waves as they travel across the area being modelled. The accuracy of such transformation methods is generally good, provided an appropriate model has been chosen. The inshore wave climate has been derived at a number of locations along the coastline of this cell. These locations are detailed in Table 7.

Table 7 Cell 3 - Sources of numerically modelled wave conditions

Location	Offshore/Inshore Position	Period	Mean water depth (m)	Wave data	Contact
On a regular grid 0.25°lat. by 0.4°long.	Offshore: First point is normally less than 20km from the coast	1986 onwards	variable	Wind, swell and total sea climate and extremes	UK Met Office or HR Wallingford
Buckie	Inshore: NW of West Pier	-	-3m CD	1, 50 year extreme	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 3 the number of designated natural heritage sites is given in Table 8. The location of Sites of Special Scientific Interest is provided in Figure 7 with further information detailed in Appendix 1. Other natural heritage sites are shown in Figure 8.

Table 8 Cell 3 - Natural heritage designations

Designation	Number	Designation	Number
SSSI	35	NSA	1
NNR	2	NHA	-
MNR	-	AGLV	6
LNR	-	ESA	1
SAC	4	MCA	-
SPA	5	RSPB	2
RAMSAR	(7 proposed)	LWT	2

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

Advice on historical and archaeological matters is provided by a number of organisations, detailed in Table 9.

Table 9 Cell 3 - Information sources for sites of cultural heritage

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

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

The Royal Commission on the Ancient and Historical Monuments in Scotland (RCAHMS) maintain a GIS database (National Monuments Records of Scotland, NMRS) with the locations of scheduled Archaeological and historical sites. Only the location of sites within 50m of the coastline was requested from the 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 a 500m wide strip per 10km along the coastline of Cell 3. This will include a large number of sites which are not truly coastal sites. Only where more detailed surveying has been conducted can an assessment of the number of coastal sites be determined. Some survey work has been conducted in Caithness (Batey, 1984) which concentrated on identifying sites along a strip of ground of several kilometres next to the sea. Some work has also been conducted by the archaeologists of the former Highland Regional Council with known sites of archaeological and historical interest included in the Shoreline Management Plan developed for the coastline between Burghead and the Sutors of Cromarty (HR Wallingford, 1996a). However, for the majority of this cell there appears to have been little detailed survey work completed. There are also a large number of sites, e.g. Listed Buildings, which do not appear in the NMRS database.

5 *Cell 3: Cairnbulg Point to Duncansby Head*

5.1 General

Cell 3 has been defined, (HR Wallingford, 1997), as the coastline between Cairnbulg Point and Duncansby Head, Figure 5. The cell encompasses all of the Moray Firth coastline and has been split into seven sub-cells. Sub-cell 3a has been defined as the coast between Cairnbulg Point in the east and Portknockie in the west. At Cairnbulg Point there is a significant change in coastline orientation. Beyond Portknockie the general character of the coastline changes. Within Sub-cell 3a the coastal zone is dominated by the solid geology with beach areas generally small and limited to pocket beach types. Beyond Portknockie, in

Sub-cell 3b, the rocky coastline generally disappears with long beach areas occurring. The western boundary of Sub-cell 3b is defined as occurring at Burghead. Originally, in the initial Coastal Cells in Scotland report (HR Wallingford, 1997), the western boundary was defined at Lossiemouth. However, on further investigation it was decided that the promontory at Burghead was a much more effective one way drift divide.

Sub-cell 3c, between Burghead and Fort George, is probably the best example of a "coastal cell" found on the Scottish coast due to the strong westward nett sediment drift along this coastline. Fort George will tend to act as a one way drift divide but also marks a considerable change in the hydraulic climate from the exposed Moray Firth coastline to the relatively sheltered Inverness Firth coast. The Inverness Firth coastline has been designated Sub-cell 3d purely on account of the hydraulic climate. Chanonry Point tends to act as a drift convergence. The Inner Moray Firth between Chanonry Point and Tarbat Ness is designated Sub-cell 3e. Included in this sub-cell is the Cromarty Firth. However, the cells concept is not really applicable to this Firth as hydraulic processes tend to be estuarine dominated. Sub-cell 3f encompasses the coastline of the outer Dornoch Firth to Lothbeg Point in the north. To the north of Lothbeg Point, Sub-cell 3g, the character of the coastline changes, with the solid geology becoming dominant at the coastline and few beaches occurring. The boundary of the cell, at Duncansby Head, represents the outer limit of the Moray Firth and a significant change in orientation of the coastline (and hence hydraulic climate).

Within the sub-cells further possible boundaries, such as individual beach units, can be identified. For instance there is unlikely to be any significant interchange of beach material between the beach within Sinclairs Bay and the adjacent beaches further south and north. The locations of these "semi-independent beach units" are shown in the relevant littoral process maps.

Sections 5.2-5.9 describe the coastal regime occurring within Cell 3.

5.2 Cell 3: Physical characteristics

5.2.1 General

The characteristics and processes occurring within Cell 3 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 a number of 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 are also detailed. Any areas where significant tidal flooding occurs are noted. The offshore wave climate (both total sea and swell) has been predicted from the Met Office Wave Model along with a range of extreme offshore wave conditions. The dominant nearshore processes which affect the transformation of waves as they travel from offshore to inshore are also described.

The next section within each sub-cell describes the main littoral processes. Where known the dominant beach sediment sources and sinks are described. Where possible the main nett longshore transport directions are detailed with an indication of the dominant forces causing this drift. Areas of known 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. 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 source of siltation is given.

The final section details the location, type and influences of coastal protection work. Where possible the length of coastline protected has been given along with a brief indication of the present state of the defences and any significant impacts on the coast due to these works. Locations where beach monitoring or coastal surveys have been conducted are presented and where possible details of the length of such records and monitoring authorities given. Details of existing coastal defences and locations where regular monitoring is conducted are shown in the relevant figures for each sub-cell.

5.3 Sub-cell 3a: Cairnbulg Point to Portknockie

5.3.1 Geology

The solid geology along much of this coast is dominated by Precambrian rocks (formed > 540Ma) assigned to the Dalradian Supergroup. The Dalradian is a thick and variable succession of largely sedimentary rocks that have been deformed and regionally metamorphosed. Many comprise a variety of schists, but slate and schistose grit dominate at the coast. These rocks do not outcrop at any great elevation at the coast but are generally evident in the form of a wave cut platform within, or just above the intertidal zone.

The cliffed coastline which characterises the coastline between Quarry Head and More Head is of Middle Old Red Sandstone which unconformably overlies the much older Dalradian rocks. The lithology of this sandstone generally begins with basal conglomerate followed by shales and fish-bearing beds capped by sandstones and flagstones. These strata are susceptible to marine erosion, but at present lie above the intertidal zone being protected by rock platforms. However, erosion during former periods of higher relative sea levels has formed the "indented" coastline evident.

The solid geology dominates much of the coastline but glacial and post glacial influences are also very much in evidence on this coast, albeit less so than on the Spey and Burghead Bay coasts. Boulder clay caps much of the exposed solid geology with glacial sands and gravels also occurring at the coast. Reworked glacial deposits and evidence of previous sea levels are more evident at the western end of the sub-cell, particularly at Cullen where a wide raised beach area upon which the golf course is situated is backed by a fossil cliff line. Further east raised beach areas are less obvious and smaller, such as that backing Aberdour Bay and the narrow raised shorelines upon which the small villages of Crovie and Gardenstown are located.

5.3.2 *Hydraulic processes*

The tidal cycle experienced within this cell has a period of approximately 12.4 hours. The tidal range is macro-tidal with a mean spring range of 3.3m at Fraserburgh increasing slightly towards the inner part of the firth with a mean spring range at Buckie of 3.4m, Table 10. The tidal wave progresses from west to east with high tide taking just over one hour to travel the length of the sub-cell.

There is little information on storm surges or extreme water levels along this coastline. A 10mb drop in atmospheric pressure is capable of producing a 0.1m rise in water level. The 50 year return period storm surge is predicted to be approximately 1.25m along the southern coastline of the Moray Firth, (BODC, 1991) increasing slightly towards the inner part of the firth.

Table 10 Sub-cell 3a - predicted tidal levels and ranges

Location	MHWS (m OD)	MLWS (m OD)	Spring Range (m)	MHWN (m OD)	MLWN (m OD)	Neap Range (m)	OD to CD (m)
Fraserburgh	1.5	-1.6	3.10	0.7	-0.8	1.50	+2.20
Banff	-	-	3.10	-	-	1.70	-
Whitehills	1.9	-1.3	3.20	1.1	-0.3	1.40	+2.00

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 was based on tidal records from the A-class tide gauge network. In these publications there are no locations in sub-cell 3a where predictions of extreme water levels have been made, the closest being Aberdeen. However, the latest research into trends of extreme water levels (Dixon & Tawn, 1997) provides a spatial analysis at any location around the coastline of the UK mainland. In this study the predicted extreme water levels depend on the year of interest allowing for trends in mean sea level rise and hence have not been reproduced in this report. This research is likely to provide the most up-to-date and comprehensive analysis of extreme water levels available.

Tidal current speeds within the Moray Firth are generally low. The main flood tide originates from the north, dominantly through the Pentland Firth and flows in a south easterly direction across the entrance of the Outer Firth (and in an opposite direction on the ebb). Within sub-cell 3a, tidal currents are weak on all parts of the tide, with a peak Spring rate generally less than $0.25ms^{-1}$. (As a rough guide fine sand does not begin to move until the current at the sea-bed is greater than $0.25ms^{-1}$). During the northward flowing ebb tide at the mouth of the firth, the southern shore is protected from this flow which can cause a weak anti-clockwise eddy resulting in the easterly flowing current occurring for up to 9 hours of the tidal cycle. Due to the low tidal current speeds, wind and wave induced currents will have a significant effect on nearshore current velocities and patterns. Current directions will be variable and dependent on either wave direction and/or wind direction. Localised currents in the nearshore zone will also result from spate river flows.

Nearly all of the wave energy in the Moray Firth is generated further offshore in deeper water. These waves may be significantly changed between far offshore and the approaches to the Moray Firth and again as they travel inshore over the Firth itself. Figure 6 shows the locations where waves have been measured or wave climates generated. Data for the Beatrice Field (see Figure 6) are reasonably representative of conditions in the outer Moray Firth, whilst data for Kinnairds Head are more representative of conditions at the outer boundary of the Firth which extends from Wick to Fraserburgh.

At the Beatrice Field approximately 11% of the wave heights (and periods) are above 3m (and 6.5s), and approximately 2% are above 4.5m (and 8.5s). An extreme wave condition with a 1:50 year return period was predicted by HR Wallingford (1977), to have a significant wave height of 8.4m and period of 10.4s from the north-east. Wave measurements offshore of Kinnairds Head between 1980 and 1982 recorded approximately 11% of wave heights (and periods) above 3m (and 6.5s) and approximately 2% of wave conditions above 4.5m (8s). These figures are very similar to those for the Beatrice Field. However, the highest 1% of wave heights off Kinnairds Head tend to be larger than the highest 1% at the Beatrice Field. Using this measured data, the 1:50 year return extreme wave height was calculated to be 12.2m with a mean period of 11.8s (Thorne & Gleeson, 1986).

Wave climate data from the archives of the UK Met Office European Wave forecasting model is shown in Figures 12 and 13 for the total sea and swell offshore climate at the outer boundary of the Moray Firth respectively. At the outer limits of the Moray Firth, waves are experienced from every direction sector with there being a marginally dominant direction sector between 0°N and 40°N (approximately 20%) Significant wave heights of over 4m are experienced from any direction but are most frequent from the easterly sector where wave generation fetch lengths are much longer. Extreme total sea conditions for the region of the outer Moray Firth boundary are shown below:

Table 11 Total sea extreme wave heights

Return Period (Years)	Significant Wave Height (m)
1	6.84
10	8.17
100	9.41

Interpolating this data indicates a 50-year return period significant wave height of approximately 9m. This is marginally greater than that predicted at the Beatrice Field (HR Wallingford, 1982) due to the more exposed location but much less than predicted by Thorne and Gleeson (1986) where extremes were calculated from a very short data record.

Swell wave conditions experienced within the Moray Firth are dominated by waves generated from between 0°N and 40°N (approximately 57% of swell waves occur from this sector). Little swell is experienced from other directions due to restricted fetch lengths which prevent a sufficient distance for such waves to develop. Extreme swell wave conditions derived from the Met Office wave model data are detailed below:

Table 12 Swell extreme significant wave heights

Return Period (Years)	Significant Wave Height (m)
1	3.62
10	4.60
100	5.56

For the region immediately offshore of Sub-cell 3a, the magnitude and frequency of waves from the southerly sector will decrease significantly as fetch lengths reduce, whereas there will be a slight increase in the severity of extreme wave conditions from the north west quadrant.

The only known position where inshore wave conditions have been derived is at Buckie to the north west of the West Pier at approximately 3m CD (HR Wallingford, 1993b). For storm durations of 6 hours the largest wave conditions are experienced from the north westerly sector for both the 1 and 50 year return period. For longer storm durations (12 hours and 24 hours) the largest wave conditions occur from between 345°N and 45°N. Waves with the largest period approach this area from the north, while shorter periods waves occur from north west, where fetch lengths are restricted, and from the east, where wind conditions are not so frequent or severe. Such conditions are likely to be representative of the inshore wave conditions experienced within much of this sub-cell seaward of the wave breaking zone. In the immediate nearshore zone, effects such as the orientation of the coastline and diffraction around headlands will produce local variations in the wave climate.

5.3.3 Littoral processes

The beaches occurring within Cell 3a are generally characterised by pocket or bay type beaches strongly influenced by the solid geology of this region. The foreshore and hinterland characteristics are shown in Figure 14 with the dominant littoral processes shown in Figure 15. From Cairnbulg Point to Rosehearty the topography of the coastal edge is low. The 3km long sand beach at Fraserburgh is constrained between the two low rock headlands at either end. This is the largest beach and dune complex within this sub-cell. The only major source of material for the formation of the beach, dune and links area is from glacial offshore deposits moved onshore during periods of varying sea levels within the last 10,000 years. These sand deposits form much of the hinterland extending from Fraserburgh to Peterhead. Between Fraserburgh and Rosehearty the beaches are thin and lie upon a rock platform which outcrops almost continuously along this coastline. Despite the coastline between Cairnbulg Point and Rosehearty being extremely exposed to storm wave conditions from the north west through to the north east the offshore bathymetry is rocky and shallow sloping resulting in a high percentage of storm wave energy being dissipated before reaching the intertidal beach. Littoral processes are not all that significant with little wave induced coastal erosion evident.

To the west of Rosehearty the coastline is characterised by high cliffs and, in a number of locations, well-defined raised beach areas. Between Rosehearty and Macduff small pocket beach areas occur where Old Red Sandstone outcrops on the coastline, mainly between Aberdour and Gardenstown. Most of the present day beach material along this section of the coast has been provided by past marine erosion of these cliffs. There is very little present day supply of beach material from cliff erosion.

The land formations and geomorphological processes in Banff Bay have been studied by Hansom & Black (1996). The sand and shingle beach is enclosed between rock promontories which form a small bay at the mouth of the River Deveron. The beach sediments are dominantly derived from glacial deposits washed down by the River Deveron and possibly from offshore glacial deposits. In present times there is little fresh supply of beach sediments. The pocket beach is effectively a self-contained unit with little gain or loss of beach material. However, the beach material within the bay is relatively dynamic, being redistributed depending upon storm conditions and river flows. The beach is backed on all sides by hard linear defences. Wave reflections from these defences are causing beach lowering along the eastern side of the bay.

Small pocket beaches occur at Whitehills and Portsoy with a larger shingle and sand beach occurring at Boyndie. These are both in a relatively stable condition with little longshore transport evident. Pocket beaches also occur at Sandend and Cullen. These systems are both constrained between rock headlands. At Sandend the dominantly sand beach is backed by a healthy dune ridge. There is little input of fresh beach sediment but also little nett loss with the planshape of the bay relatively stable. Some frontal dune erosion is evident due to episodic storm events.

At Cullen the beach is a mixture of sand and gravel and is backed by a well-defined raised beach and fossil cliff. As with most of these beach systems there is little present day nett gain or loss of beach material. However, there has been considerable erosion along the edge of the golf course resulting in a rock revetment being constructed along the western part of the bay.

Dredging, (both maintenance and capital) is conducted at three harbours within sub-cell 3a. 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
Fraserburgh	Annually	Fraserburgh Harbour Commissioners	Fraserburgh
Macduff	Annually	Aberdeenshire Council	Macduff
Whitehills	1986	Whitehills Harbour Authority	Macduff

There is little information on the exact location of the dump sites or on the movements of the dumped spoil. However, it is unlikely that this source will supply any significant amount of material to the beaches along this coast.

Summary of erosion and accretion

Storm wave undercutting is occurring along virtually all the frontal dune systems along this coastline, particularly within Fraserburgh Bay, Sandend and Cullen. Many of the pocket beaches along this coastline are in a relatively stable condition with, at present, little loss or gain of beach sediments. Episodic storm damage will occur on much of the "soft" coastal edge and erosion will continue (albeit at a very low rate) on the sandstone cliffs which outcrop along much of this coast. There are no locations, along this coastline, presently accreting any significant amount of beach material.

5.3.4 Coastal defences

Information on the coastal defences occurring within the former Grampian Region are detailed in a report by Hay (1980). Since this report there has been little new coastal defence work completed along this frontage. The location and type of coastal defence work occurring in this sub-cell is shown in Figure 16.

To the south of the harbour at Fraserburgh, sections of stone wall and revetment protect the promenade. These defences are in a reasonable condition and have minimal impact on the beach frontage to the east. Small sections, mainly masonry wall and revetment, occur to the west of Fraserburgh and around Sandhaven. All are relatively old and generally in a poor condition. In Aberdour Bay a short length of rock revetment has been constructed to prevent backshore erosion at the car park. The revetment has been well designed with a low angled slope resulting in minimal impact upon the beach.

A variety of coastal defences protect a number of the small fishing villages, such as Pennan, Crovie and Gardenstown. These defences are generally founded on the solid rock platform with no beach fronting them and hence the impact on the adjacent coastal zone is minimal. Most of these defences, mainly due to their age, are susceptible to wave damage and have a high maintenance requirement.

The coastal edge at Macduff and Banff is almost continuously protected by coastal defence works. To the east of Macduff Harbour a low concrete and masonry seawall protects an access road and property. The coastal edge along this frontage suffers little wave damage as it is well protected by offshore rock reefs and a small shingle beach. Between the harbour and the mouth of the River Deveron a stepped revetment and high concrete recurve and a concrete seawall protects the A98. Both are in a reasonable condition but there is some evidence of beach lowering within Banff Bay at the southern end of the wall.

On the western side of Banff Bay, a stepped revetment and concrete upstand provides adequate protection to the town frontage, with little evidence of any major detrimental effect upon the immediate beach. Along the northern coastline of Banff, various masonry and concrete seawalls exist, many of which are in a relatively poor condition. At Whitehills, much of the town frontage is protected by a low concrete seawall which is in reasonably good condition. The elevation of the wall is insufficient to protect against severe overtopping during high tides and onshore winds, but much wave dissipation and protection is provided by intertidal rock outcrops across the foreshore.

At Portsoy Links, boulder have been placed against the coastal edge at the eastern end of the bay to stabilise the eroding coastal edge. Along the western side of the bay a low masonry seawall is present. These defences are in a reasonable condition and have minimal impact on the surrounding area, manly due to the lack of mobile beach material. Small sections of rock revetment and concrete seawall, in good repair, are found at Sandend.

Much of the Cullen frontage is protected. A stepped concrete wall with recurve protects the Seatown frontage with a further vertical concrete seawall section in front of the golf club house. Minor outflanking at the car park is noticeable and beach levels are relatively low fronting these defences. At the eastern end of Cullen Bay, part of the golf course frontage is protected by a recently constructed rock revetment which does not appear at present to have much impact on the sand and shingle beach fronting it.

5.4 Sub-cell 3b: Portknockie to Burghead

5.4.1 Geology

The solid geology, exposed at the coastline, of this sub-cell decreases in age from east to west. The cliffs between Portknockie and Buckie are metamorphic rocks. These slate and schistose grits occur over much of the north east coast and dominate the coastline to the east of this sub-cell.

The basement rocks are unconformably overlain by Old Red Sandstone (ORS) deposits of Devonian age subdivided here into middle and upper ORS. These underlie much of the Spey Bay coastline but are masked by the extensive drift deposits in this region except at the eastern end between Portgordon and Buckie.

The youngest rocks are of Permo-Triassic age and are found outcropping at the coast between Lossiemouth and Burghead. These rocks are characterised by fine, well-sorted, grey to reddish brown sandstones. At Burghead, sandstones with pebbly lenses and thin beds of siltstone of fluvial origin are evident in the cliffs above the harbour. To the east, at Hopeman, the cliffs are composed of fine to medium grained well-sorted aeolian sandstones with occasional pebble lenses. Hard, mineralised cherty rock outcrops along the Lossiemouth shore.

Glacial deposits are in abundance within this sub-cell. Much of Spey Bay is backed by extensive deposits of glacial sand and gravel with river gravels and terrace deposits occurring along the course of the River Spey. Many of these deposits have been reworked by wave action during former periods of higher relative sea levels to form the numerous relict shingle bars which occur over the hinterland within Spey Bay. Marine and fluvial erosion of these glacial and post-glacial deposits is the dominant source of beach material within this cell. Boulder clay deposits cap the cliffed coastlines between Portknockie and Buckie and around Hopeman.

5.4.2 Hydraulic processes

The tidal cycle experienced within this cell has a period of approximately 12.4 hours. The tidal range is macro-tidal with a mean spring range of approximately 3.5m and neap range of 1.6m, Table 13. High tide occurs at the west end of the sub-cell marginally before the eastern end.

In Table 13 the tidal elevations are quoted relative to Ordnance Datum Newlyn (the standard land based datum). The conversion to the local Chart Datum (where known) is shown in the final column.

Table 13 Sub-cell 3b - Predicted tidal levels and ranges

Location	MHWS (m OD)	MLWS (m OD)	Spring Range (m)	MHWN (m OD)	MLWN (m OD)	Neap Range (m)	ODN to CD (m)
Buckie	2.0	-1.4	3.4	1.1	-0.5	1.6	+2.10
Lossiemouth	2.0	-1.5	3.5	1.1	-0.5	1.6	+2.10

There is little information on storm surges or extreme water levels along this coastline. A 10mb drop in atmospheric pressure is capable of producing a 0.1m rise in water level. The 50 year return period storm surge is predicted to be approximately 1.25m along the southern coastline of the Moray Firth, (BODC, 1991) increasing slightly towards the inner part of the firth.

The most commonly referred to research on extreme water levels in the UK is that conducted by Graff (1981) and Coles & Tawn (1990). This analysis was based on tidal records from the A-class tide gauge network. In these publications there are no locations in sub-cell 3b where predictions of extreme water levels have been made, the closest being Aberdeen. However, the latest research into trends of extreme water levels (Dixon & Tawn, 1997) provides a spatial analysis at any location around the coastline of the UK mainland. In this study the predicted extreme water levels depend on the year of interest allowing for trends in mean sea level rise and hence have not been reproduced in this report. This research is likely to provide the most up-to-date and comprehensive analysis of extreme water levels available.

Tidal current speeds within the Moray Firth are generally low. The main flood tide originates from the north, dominantly through the Pentland Firth and flows in a south easterly direction across the entrance of the Outer Firth (and in an opposite direction on the ebb). Within sub-cell 3b tidal currents are weak on all parts of the tide, with a peak Spring rate generally less than $0.25ms^{-1}$. (As a rough guide fine sand does not begin to move until the current at the sea-bed is greater than $0.25ms^{-1}$). Due to the low tidal current speeds, wind and wave induced currents will have a significant effect on nearshore current velocities. Current directions will be variable and dependent on either wave direction and/or wind direction. Localised currents in the nearshore zone will also result from spate river flows, the most notable being the mouth of the River Spey.

The offshore wave conditions experienced in the Moray Firth are described in Section 5.3.2. No other information on the wave climate is available for the immediate offshore zone seaward of Sub-Cell 3b. However conditions will be similar to those experienced immediately offshore of sub-cell 3a. The magnitude of wave conditions experienced from the north westerly sector will decrease to the west as fetch lengths reduce.

No inshore wave information is available for this sub-cell but the same general pattern in wave conditions as in sub-cell 3a will be experienced. The largest wave conditions for storms of durations of 6 hours will be experienced from the north westerly sector. However, the reduced fetch lengths will result in these conditions not being as severe as those experienced further east. For longer storm durations (12 hours and 24 hours) the largest wave conditions occur from between 345°N and 45°N. Waves with the largest period approach this area from the north, while shorter periods waves occur from north west, where fetch lengths are restricted, and from the east, where wind conditions are not so frequent or severe. Such conditions are likely to be representative of the general pattern of inshore wave conditions experienced within much of this sub-cell seaward of the wave breaking zone. However the severity of wave conditions at the coastline will be much less than occurring in the sub-cell to the east due to a much shallower sloping nearshore bathymetry along the entire length of this sub-cell. In the immediate nearshore zone to the 20m CD contour, the seabed slope varies between 1:375 at the central part of Spey Bay to 1:150 to the western end of the bay approaching Lossiemouth. This will have the effect of dissipating much of the offshore wave energy before reaching the coastline and will result in wave conditions experienced at the coastline being sensitive to water level.

5.4.3 Littoral processes

The foreshore and hinterland characteristics occurring in sub-cell 3b are shown in Figure 14 with the dominant littoral processes which occur along this coast shown in Figure 15.

To the east of Portgordon the coastline is rocky and developed. There is little beach material, except between Buckie and Portgordon where there is a thin raised shingle beach, upon which the A98 runs, backed by fossil cliffs. Erosion of these deposits has allowed a shingle beach to build up against the eastern harbour breakwater at Portgordon.

To the west, the vast quantities of beach material which occur within Spey Bay (and to the west in the hinterland of Burghead Bay and Culbin) have derived almost exclusively from either offshore glacial deposits or glacial deposits reworked by fluvial processes and deposited at the coastline. In post-glacial times these deposits have been reworked by wind, waves and tidal currents as sea levels have fluctuated to form the present beaches and coastal hinterland. Within Spey Bay, the beach along the eastern and central section is dominantly shingle, although sand occurs over the lower foreshore at Tannachy Sands. Towards Lossiemouth the spit at the western end of the bay is dominantly sand and backed by a dune ridge. The hinterland of Spey Bay is the largest vegetated shingle complex in Scotland, extending from Portgordon to Lossiemouth and is, in places, some 800m wide. The area has been extensively studied (e.g. Riddell & Fuller,1994; Hansom & Black, 1996; Gemmell et al, 1996).

Littoral processes within Spey Bay are dominated by a wave induced nett westerly movement of beach material. Fresh beach material is supplied from the reworking (erosion) of glacial shingle deposits and importantly from shingle transported by the Spey. This is one of the few river systems in Britain still acting as a major source of beach material. The dynamic nature of the mouth of the River Spey is well documented. In general, the westerly drift rapidly forms a spit deflecting the river mouth westwards. Cuts in the spit have been artificially made at various times since around 1860 to attempt to maintain the river outlet position. Monitoring of beach levels at Spey Bay is presently undertaken by Moray Council. For a much more comprehensive review of this complex region please refer to Hansom & Black, 1996 or Gemmell et al, 1996.

At the western end of Spey Bay, a large sand spit deflects the outlet of the River Lossie to the west against the headland upon which Lossiemouth is situated. This feature is continuing to accrete due to the nett westerly drift of material, which results in a wide intertidal beach at the western end and is causing the outlet channel of the River Lossie to narrow. However, the feed of sand to the spit from further east is now very low due to much of this sand sized material having been winnowed out of the present shingle beach deposits (and transported westward). A summary of sand movements in the intertidal zone at the of the River Lossie is given by Hansom & Black (1996). Despite the width of the intertidal beach, frontal dune erosion due to storm wave action is evident. The dunes backing the beach along the spit are in an extremely eroded condition with large blowout corridors and deflated areas. The interaction of the wave induced westerly drift and river flows from the Lossie tends to push material around the headland at Lossiemouth resulting in a feed of material to the west. There are also some problems with siltation of the harbour entrance at Lossiemouth.

From Lossiemouth west to Covesea, the beach and intertidal zone is wide and dominated by sand, with the exception of a small shingle upper beach at the eastern end of the complex. Beach material is derived from reworked glacial deposits, but a feed of sand from the Spey Bay frontage may provide an important present day source. However, there is much less evidence of any nett westward longshore transport along this frontage than in Spey Bay. At Lossiemouth, the coastal edge at the eastern end is protected by hard linear defences which appear to cause some beach lowering in front of the structures. Further along the Stotfield Links and Covesea coast, there is little present evidence of serious erosion of the frontal dunes. Between Covesea and Burghead the coastal edge is dominated by rock outcrops. Two small sandy bays occur at Hopeman. Both are in a relatively stable state, although some frontal dune erosion due to wave action is evident to the west of the harbour.

Dredging, (maintenance) is conducted at two harbours within sub-cell 3b. 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
Buckie	Annually	Moray Council	Buckie
Lossiemouth	1992 & 1993	Elgin & Lossiemouth Harbour Co	Lossiemouth

There is little information on the exact location of the dump sites or on the movements of the dumped spoil. However, it is unlikely that this source will supply any significant amount of material to the beaches along this coast.

Summary of erosion and accretion

Episodic storm erosion occurs along the unprotected coastal edge to the east of Portgordon. Long-term erosion of the shingle deposits occurs along the eastern half of Spey Bay (i.e. west of Portgordon) due to the net westerly drift of beach material. There is little accretion at the western end of Spey Bay, at present. The spit feature east of Lossiemouth has previously been a region of significant accretion. The beach is still accreting sand at present, but much of the west moving longshore drift, will now continue around the headland at Branderburgh and onto the Covesea Skerries frontage.

5.4.4 Coastal defences

The coastline between Findochty and Portgordon is heavily developed and contains a variety of coastal defence works (Figure 16). Most of these defences are relatively old. There is also little beach material upon the foreshore with rock outcrops dominating. Hence the present day impacts upon the littoral regime are generally minimal.

At Sandy Creek, Findochty, a low concrete wall backs the beach. The wall is in good condition and has little impact upon the sandy beach. Various other short sections of concrete wall occur to the east of the harbour at Findochty. The Portessie and east Buckie frontage has a number of lengths of coastal defence works. Recent rock revetments have been constructed along the Portessie Bay frontage and at Whale's Wig to the east of the harbour at Buckie. These defences are in good condition. A number of masonry seawalls also occur to the east of the harbour. These are not in such a good condition and will require periodic maintenance.

Concrete seawalls protect the west Buckie frontage, with a rock revetment protecting the frontage to the west of Buckpool Harbour. These are in a reasonable condition. A rock revetment also protects the A98 where it passes close to the coastal edge between Buckie and Portgordon. Again this is in a reasonable condition and provides adequate protection. Along the Portgordon and Porttannachy frontage a vertical seawall with sloping masonry revetment on the upper section to street level protects the access road and properties. The revetment is showing signs of wave damage and overtopping is known to be a fairly frequent problem.

Within Spey Bay there is little requirement for coastal protection work, with the exception of the frontage at Tugnet, where a rock revetment is set into the beach, and at Kingston. A wide shingle beach presently fronts the properties of these villages. However, this beach is extremely dynamic and the revetment is not substantial enough to withstand direct wave attack. At the western end of Spey Bay, Lossiemouth promenade is protected by a masonry wall which requires frequent maintenance. Towards the harbour a masonry wall with concrete parapet is in a much better condition. To the west of the harbour a number of short stretches of stone revetments protect the promenade at the eastern end of the west beach. These defences are in a poor condition but appear to have limited impact on sand beach levels.

Approximately 50-100 metres of gabion baskets have been placed in the bay near Cummingston. The old railway line (Burghead to Hopeman) was formerly protected by a rock revetment and masonry wall in places. To the east of Burghead this raised embankment acted as a seawall. It is now eroding in places and the footpath has been re-routed inland at the railway line. There is little further coastal defence work apart from a reinforced concrete seawall, in a reasonable condition, protecting the Maltings at Burghead.

Monitoring of beach levels in Spey Bay is conducted by Moray Council.

5.5 Sub-cell 3c: Burghead to Fort George

5.5.1 Geology

The bedrock between Burghead and Portgordon is dominated by Upper Old Red Sandstone sediments which were laid down during the Devonian. These deposits are similar to those which underlie much of Spey Bay and consist of a variety of lithogies with layers of siltstone, fossil-fish bearing beds, mudstones and fine grained sandstones. These strata are not, however, actually exposed at the coastline, being masked by thick layers of drift deposits. Hence the influence of the solid geology upon (present day) littoral processes is minimal .

As in Spey Bay, the hinterland of Burghead Bay and Culbin is underlain by vast deposits of glacial sand and gravel which have been reworked into shingle ridges during periods of higher sea levels. Large volumes of meltwater, heavily laden with sediment brought down by the Rivers Spey and Findhorn, were also an important supply of sediment to the Burghead and Culbin Region. Reworking of these glacial and post-glacial deposits is the major present day source of beach material. Between Nairn and Fort George a wide raised beach of shingle and sand exists with relict cliffs backing the golf course further inland.

5.5.2 Hydraulic processes

The tidal cycle experienced within this cell has a period of approximately 12.4 hours. There is a slight diurnal inequality of approximately 0.17m at McDermotts Base on high water spring tides. At McDermotts Base the duration of the ebb tide is marginally longer than that of the flood. The tidal range is macro-tidal with a mean spring range of approximately 3.3m to 3.6m and neap range of 1.4m to 1.6m within this sub-cell (Table 14). High tide occurs along most of the coastline in this sub-cell at approximately the same time.

Table 14 Sub-cell 3c - Predicted tidal levels and ranges

Location	MHWS (m OD)	MLWS (m OD)	Spring Range (m)	MHWN (m OD)	MLWN (m OD)	Neap Range (m)	OD to CD (m)
Burghead	2.0	-1.5	3.5	1.1	-0.5	1.6	+2.1
Nairn	2.2	-1.4	3.6	1.0	-0.5	1.5	+2.1
BARMAC Yard	-	-	3.3	-	-	1.4	-

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.

There is little information on storm surges or extreme water levels along this coastline. A 10mb drop in atmospheric pressure is capable of producing a 0.1m rise in water level. The 50 year return period storm surge is predicted to be approximately 1.25m along the southern coastline of the Moray Firth, (BODC, 1991) increasing slightly towards the inner part of the firth.

The most commonly referred to research on extreme water levels in the UK is that conducted by Graff (1981) and Coles & Tawn (1990). This analysis was based on tidal records from the A-class tide gauge network. In these publications there are no locations in sub-cell 3c where predictions of extreme water levels have been made, the closest being Aberdeen. However, the latest research into trends of extreme water levels (Dixon & Tawn, 1997) provides a spatial analysis at any location around the coastline of the UK mainland. In this study the predicted extreme water levels depend on the year of interest allowing for trends in mean sea level rise and hence have not been reproduced in this report. This research is likely to provide the most up-to-date and comprehensive analysis of extreme water levels available.

Tidal current speeds within the Moray Firth are generally low. The main flood tide originates from the north, dominantly through the Pentland Firth and flows in a south easterly direction across the entrance of the Outer Firth (and in an opposite direction on the ebb). Within sub-cell 3c tidal currents are weak on all parts of the tide, with a peak Spring rate generally less than $0.25ms^{-1}$ except at the western end of the sub-cell and at the outlet of Findhorn Bay. (As a rough guide fine sand does not begin to move until the current at the sea-bed is greater than $0.25ms^{-1}$). At the entrance to the Inverness Firth, Spring tidal currents can reach $1.25ms^{-1}$ on the flood and $1.75ms^{-1}$ on the ebb. The streams are strongest off Fort George where there can be considerable turbulence during peak flows.

Wave induced currents are important in terms of littoral processes along the coastline of this sub-cell. The coastline is dominated by waves from the north east which approach the nearshore at an oblique angle. The effects of nearshore wave refraction as these waves enter shallower water results in a dominant west going wave induced longshore current.

Wind induced currents may also be significant, and cause temporal changes in tidal current patterns and velocities particularly where the nearshore zone is shallow, such as within Burghead and Findhorn Bays.

The offshore wave conditions experienced in the Moray Firth are described in Section 5.3.2. In the immediate offshore zone wave conditions have been calculated just offshore of Burghead Bay in approximately 40m of water (HR Wallingford, 1982). Calculations of extreme wave conditions calculated for this site are detailed in the following table:

Table 15 Extreme wave conditions offshore of Burghead Bay

Return Period (Years)	Significant wave height (m)	Wave Period (s)
1	3.2 ± 0.3	5.8 ± 0.7
10	3.8 ± 0.4	7.5 ± 0.9
100	4.3 ± 0.5	8.8 ± 1.0

The most severe wave conditions off Burghead Bay occur when waves at the outer boundary of the Moray Firth are from 45°N. From this direction the significant wave height during storm conditions offshore of Burghead Bay are about 40-50% of the wave height occurring at the outer boundary. For other directions this percentage decreases to between 30% and 40% from 0°N and 9% to 15% from 135°N.

Fetch lengths to the north west are small and consequently such waves are relatively insignificant in terms of littoral processes in this sub cell. Any effects on beach areas due to waves from this quadrant will be limited to severe storm events when larger wave conditions can be generated. From east to west on the southern coastline of the Moray Firth waves from the north east quadrant increasingly dominate littoral processes. The influence of any swell wave activity on the coastline will decrease significantly from east to west, with very little swell energy propagating into the Inner Moray Firth due to shallow water dissipative effects.

No inshore wave information is available for this sub-cell. Wave conditions will be dominant from the north east quadrant with wave heights restricted by short fetch lengths in all other directions. Inshore the nearshore seabed slope is variable, sloping gently (1:300) within Burghead Bay, but increasing in slope to the west along the Culbin frontage (1:50) before decreasing again to the west of Culbin. The shallow sloping sea-bed will result in substantial dissipation of wave energy before reaching the shoreline, with the magnitude of wave conditions experienced at the coastline heavily dependent on tidal levels. Towards the western boundary of the sub-cell at Fort George, direct wave action is experienced from a very narrow wave window to the north east, with offshore sand banks, such as Riff Bank, having a large dissipative influence on wave conditions.

5.5.3 Littoral processes

The foreshore and hinterland characteristics occurring in Sub-cell 3c are shown in Figure 17 with the dominant littoral processes shown in Figure 18. A detailed description of the character of the coastal zone and littoral processes occurring along the coastline between Burghead and Fort George is provided by HR Wallingford (1996a).

As in Spey Bay there are vast quantities of reworked glacial deposits contained within this sub-cell with littoral processes also dominated by a nett wave induced westerly movement of beach material between Burghead and Whiteness Head. Burghead Bay extends between the headland at Burghead and Findhorn. The planshape of the bay is controlled by the rock headland at Burghead and the dominance of waves from the north easterly sector with the bay formation having been developing since sea levels stabilised approximately 3,000 years ago. The present planshape of the bay suggests that an equilibrium planshape has not yet formed and that erosion along the eastern and central sections of the bay will continue. However, as the shape of the bay develops, the feed on material to the west gradually reduces. This can be seen in the comparison of the various spit features which have developed at Findhorn and along the Culbin frontage since the late 17th century.

The present day supply of material due to erosion of the hinterland deposits along the central Burghead Bay frontage is still an important feed for the development of the coastline to the east at Findhorn and at Culbin. At Findhorn a healthy shingle ridge has presently developed. However, material in this region can be extremely dynamic and a rock revetment and wooden groynes have been constructed to attempt to stabilise the shingle beach.

The morphology of the Culbin frontage is extremely complex and is discussed in detail in a number of texts (e.g. Steers, 1973; Ross, 1992; Comber et al, 1994). Many of the geomorphological features evident are due to the dominant westward nett movement of sand and shingle. At present these dynamic processes are occurring naturally with virtually no human activities influencing them. At present the feature known as The Bar is in the later stages of evolution and is presently migrating westward and landward. The westerly drift along this frontage results in accretion along Nairn East Beach where beach sediment has built up against the harbour breakwaters. However, there is such an abundance of sand in this system that sand bars have been bypassing the mouth of the harbour for some time. Due to the abundance of sand on the east beach, and the protection provided by The Bar from waves from the north east the dune system is in a healthy state (apart from erosion caused by trampling).

The Nairn frontage suffers from downdrift effects caused by the influence of the harbour breakwaters in restricting the westward movement of sediment from the Culbin frontage. The present westerly drift of sand across the mouth of the harbour is also bypassing Nairn West Beach. The west beach is dominantly sandy but with patches of fine shingle. Backshore erosion and falling beach levels due to both downdrift effects and wave reflections from the harbour breakwater has resulted in various rock revetments and gabions being placed along the edge of the links. Two concrete groynes appear to be controlling beach levels effectively although one is now almost completely covered. Localised downdrift erosion is evident at the western groyne.

Down drift erosion effects, due to a lack of longshore transport from the east, continue to affect the beach along the eastern section of the golf course frontage which has lead to increased erosion of the backshore shingle deposits of the raised shoreline upon which the golf course is situated. Much of this eroding coastline is now protected by various stretches of rock revetment and gabions which has lead to lowering foreshore levels due to a nett loss of sediment from this section of coast. Beyond the golf course, the shingle beaches are healthier. The nett longshore drift rate is not as great as that further east due to the orientation of the coastline resulting in waves approaching the coast along Whiteness spit being at a lower angle of incidence. Material bypassing the harbour breakwaters at Nairn will also tend to be moved onshore to the west of the golf club. However, Whiteness spit is displaying evidence of a lack of sediment supply in that the proximal end is extremely narrow and close to breaching. At the western end, sand material being moved along the spit to the west is deposited into the channel at BARMAC's Yard. Regular maintenance dredging is required to keep the access channel at a sufficient depth.

Whiteness Sands is sheltered from significant wave action with the frontage appearing to be relatively stable. Dredged material from BARMAC's Yard is dumped at the outer edge of Whiteness Sands, but much of this material is likely to be moved offshore into Riff Bank by the strong tidal currents. The character of the coastline to the south of Fort George indicates that little of this sediment appears to be transported to the south.

Maintenance dredging is also conducted at Nairn and Burghead Harbours. The following information is extracted from the Shoreline Management Plan for the Inner Moray Firth (HR Wallingford (1996a) from where more information on dredging rates and sedimentation sources is given.

Location	Year	Authority	Dump Site Name
Burghead	Annually	Moray Council	Burghead
Nairn	1989	Nairn Harbour Authority	Nairn
Whiteness Head	Bi-Annually	BARMAC	Whiteness Sands

Summary of erosion and accretion
Long-term erosion is occurring along much of the Burghead Bay frontage. At present substantial shingle deposits are accumulating at Findhorn, but the beach along this frontage is known to be particularly dynamic. The western side of Findhorn Bay and much of the eastern part of Culbin Forest is eroding as is the eastern part of The Bar. Nairn East Beach shows substantial accretion but the west beach, Carse of Delnies and the proximal end of Whiteness spit show significant erosion. The dredged channel at BARMAC's Yard intercepts much sediment being moved in a westerly direction along this coastline. Whiteness Sands is also accreting.

5.5.4 Coastal defences

Coastal defences within this sub-cell are clustered around Burghead, Findhorn and Nairn. Elsewhere little coastal defence work has been conducted or is required (Figure 19).

A masonry wall protects the town frontage at Burghead. At present the wall is in a reasonable condition. To the south of the Harbour there is a short stretch of rock revetment which extends along the caravan park frontage. These defences are causing some lowering of beach levels immediately in front of the structures which could lead to increased risk of damage.

At Findhorn approximately 1200m of rock revetment and timber groynes protect low lying land and the end of the spit. The defences are of recent construction and will have a long residual life. These defences help stabilise foreshore levels along this frontage, and in this respect have an impact on the littoral processes at the mouth of Findhorn Bay. The groynes will only trap shingle material; their impact on sand movements along the lower foreshore is minimal.

Along the frontage of Findhorn village on the eastern side of the bay, there are various ageing, low masonry seawalls. It is unlikely, due to the mild hydraulic climate that these walls will experience failure, but a slow deterioration will occur without periodic maintenance. Further gabion baskets and 14 "groynes" have been place in front of a property at the southern end of Findhorn village. The groynes are 2.4m long and 4 m apart. Approximately 500m of rock armour has been placed (1997) to the north east of Biasness on the west side of Findhorn Bay.

The Nairn frontage is heavily defended. The harbour breakwaters, although not coastal defence works, have had a large impact on the littoral regime by restricting the east to west longshore drift of beach material. Although sand is now bypassing these breakwaters little of this material will be transported onto the immediate Nairn town frontage. As a result, downdrift erosion has been a serious problem for many years. The frontage immediately to the west of the harbour is protected by a recently constructed rip-rap revetment with further lengths of gabion and rock rip-rap at the western end of Nairn West beach. Two concrete groynes are also located along the beach and appear to be controlling beach levels effectively. Both the groynes and the revetment have a relatively long residual life, but the gabions and the rock rip-rap are in a less sound condition.

Beyond the West beach, to the golf club, a low concrete seawall protects the promenade. This wall, due to the absence of any beach fronting the structure, has been previously subjected to wave damage and requires periodic maintenance. To the west of the seawall, the access road and much of the eastern part of Nairn Golf Course is protected by rock revetments and stretches of gabions. Most of these defences are susceptible to wave damage and require periodic maintenance. These linear defences do protect the hinterland, but cut off a supply of beach material from the reworking (erosion) of the sand and gravel deposits "stored" within the hinterland. To the east of Fort George a well-constructed rock revetment protects Ministry of Defence land.

Monitoring of defences is presently conducted by The Moray Council at Findhorn and by Highland Council at Nairn.

5.6 Sub-cell 3d: Inner Moray Firth (Fort George to Chanonry Point)

5.6.1 Geology

As in sub-cell 3c, the solid geology is dominated by Old Red Sandstones formed during the Devonian. Middle Old Red Sandstone strata occur around the whole of the Inverness Firth apart from the area around Ardersier where the slightly younger Upper Old Red Sandstone occurs. Again, the solid geology does not outcrop at the coast, being masked by drift deposits and hence has little influence at present on the morphological development of the coastline.

There are a number of glacial features within Inverness Firth. Alturlie Point and North Kessock are fluvio-glacial remnants which were modified by wave action during a period of previously higher relative sea levels. The forelands at Fort George and Chanonry Point are also wave-built features. Up to four different raised beach levels have been identified at Chanonry Point. Erosion of these deposits has supplied the small amount of beach material for the formation of the thin beaches within this sub-cell. A narrow strip of raised beach occurs to the north of Kilmuir with two elevated marine terraces evident to the south of Avoch. Within Munlochy Bay there is a range of shoreline fragments at various elevations with some shingle beaches present (raised marine deposits are also relatively common with the Beauly Firth).

5.6.2 Hydraulic processes

The tidal cycle experienced within this cell has a period of approximately 12.4 hours. There is a slight diurnal inequality of approximately 0.06m at Inverness on High Water spring tides. At Inverness the mean spring ebb tide occurs for approximately 0.13 hrs longer than that of the flood tide. The tidal range is macro-tidal with a mean spring range of approximately 3.3m at the entrance to the firth and 4.0m at Inverness (with corresponding mean neap tidal ranges of 1.7m and 1.9m respectively). High tide occurs at approximately the same time throughout the Inverness Firth.

Table 16 Sub-cell 3d - Predicted tidal levels and ranges

Location	MHWS (m OD)	MLWS (m OD)	Spring Range (m)	MHWN (m OD)	MLWN (m OD)	Neap Range (m)	OD to CD (m)
Fortrose	2.65	-	-	1.15	-	-	+2.25
Inverness	2.45	-1.55	4.0	1.35	-0.55	1.9	+2.25

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 was based on tidal records from the A-class tide gauge network. In these publications there are no locations in sub-cell 3d where predictions of extreme water levels have been made, the closest being Aberdeen. However, the latest research into trends of extreme water levels (Dixon & Tawn, 1997) provides a spatial analysis at any location around the coastline of the UK mainland. In this study the predicted extreme water levels depend on the year of interest allowing for trends in mean sea level rise and hence have not been reproduced in this report. This research is likely to provide the most up-to-date and comprehensive analysis of extreme water levels available.

Tidal current speeds are high in the narrows between Fort George and Chanonry Point and in the Kessock Narrows. At the entrance to the Inverness Firth, peak Spring flood tide current velocity is approximately $1.25ms^{-1}$ and corresponding peak Spring ebb tide current velocity of $1.75ms^{-1}$. The streams are strongest off Fort George where there can be considerable turbulence during peak flows. During the flood, the currents are of sufficient magnitude to suspend and transport sand sized beach material from the northern shorelines of the forelands at both Chanonry and Fort George. Throughout the flood, two current induced eddies form, on the southern sides of both forelands, producing a relatively weak current towards each point. On the ebb, the currents on the southern shorelines of the forelands are not as strong as the main stream is more central. However eddies do form to the north of both forelands again prompting a nearshore current towards the point of each foreland.

Current speeds are even greater at the Kessock Narrows with a peak Spring flood tide of $2ms^{-1}$ into the Beauly Firth and a corresponding peak ebb current of $3ms^{-1}$ in the opposite direction. The high ebb flow current can produce a clockwise eddy from mid to low tide within Longmans Bay. Elsewhere within the firth, current speeds can reach $0.5ms^{-1}$ in the central channels, but are much lower closer inshore. Wind induced currents can cause increases in current velocities and variable current patterns, particularly in the shallower intertidal areas of the firth. A detailed study of water movements within the Inverness and Beauly Firth was conducted as part of the Inverness Main Drainage Scheme, (EML, 1990) with a thorough summary provided by Stapleton & Pethick (1996).

Wave conditions within the Inverness Firth are dominated by locally generated "wind waves". Wave conditions within the Moray Firth will scarcely propagate into the Inverness Firth due to the narrow entrance between Fort George and Chanonry Point. The firth is orientated on a south-west north-east axis and will be affected by winds from the prevailing south westerly direction which are channelled though the Great Glen. Hence, unlike the Moray Firth coastline, the dominant wave direction will be from the south-west. Maximum fetch lengths along the south west - north east axis are limited to approximately 11km resulting in a maximum wave height of approximately 1.5m. However due to shallow water effects it is unlikely that waves of this magnitude will be experienced. Wave conditions at the coastline will be extreme sensitive to water levels due to the shallow sloping intertidal zones, particularly on the southern coastline.

5.6.3 Littoral processes

The coastline of the Inverness and Beauly Firths is sheltered from waves generated within the Moray Firth due to the promontories at Fort George and Chanonry. The intertidal zone of these firths is flat and generally silty or muddy and covered by a carpet of pebbles (Figure 17). A narrow shingle fringe is generally found above high water mark along much of the frontage. Much of the coastline is stable, with minimal erosion evident due to the restricted wave conditions. Only around Ardersier and Chanonry are there any appreciable quantities of beach material.

There is little present day input of beach material (Figure 18). The only source is from the reworking of raised beach deposits which back much of this coastline. However, wave conditions are not severe enough to cause significant erosion. There is still evidence of a very low nett eastward longshore movement of beach material towards Chanonry Point.

Maintenance dredging is conducted at Inverness (Beauly Firth). The following information is extracted from the UK Dredged Material Database, (MAFF, 1995b), for the period between 1985 and 1993:

Location	Year	Authority	Dump Site Name
Beauly Firth	1985	Inverness Harbour Trust	Inverness
Beauly Firth	1989	Inverness Harbour Trust	Inverness
Beauly Firth	1990	Inverness Harbour Trust	Inverness
Beauly Firth	1991	Inverness Harbour Trust	Inverness

Further information on dredging rates are detailed in the Shoreline Management Plan for the Inner Moray Firth (HR Wallingford, 1996a). There is little information on the exact location of the dump sites or on the movements of the dumped spoil. However, it is unlikely that this source will supply any significant amount of material to the beaches along this coast.

Summary of erosion and accretion
Much of the coastline of the Inverness Firth is relatively stable due to the mild wave climate. Erosion is ongoing at Ardersier and along much of the frontage between Avoch and Chanonry Point.

5.6.4 Coastal defences

There are a number of coastal defences works within this sub-cell (Figure 19). The promontory at Fort George is protected by a range of old masonry walls. To the south, the wall is low and is overtopped regularly during high tides. A low rock revetment, of recent construction, protects much of the frontage at the southern end of Ardersier. The revetment is at present in a good condition. Short lengths of gabion walls have been installed around Alturlie Point and at the sewage treatment works. These are in a good condition at present, but are not expected to have a long residual life.

Along the northern coastline of the inner Moray Firth there are a large number of localised coastal defence works. At Kessock the rock revetment is well designed and in a good condition. There is a good rock revetment at Kilmuir. To the north at Avoch, the access road is protected by low vertical concrete walls and immediately south of the river by gabions. The residual life of the walls is in excess of 10 years but for the gabions will be considerably less. To the north of Avoch the A832 is protected by various stretches of old concrete wall. These walls have required extensive repairs in recent years and are likely to require frequent maintenance in the future. Wave overtopping can affect the roadway backing the wall. Towards Fortrose a small stretch of rock revetment protects some land reclamation and a 500m stretch of gabion baskets protects the coast edge to the south of Fortrose. At a number of locations some rock armour has been placed over these baskets providing a much higher standard of defences.

To the east of the harbour at Fortrose a sloping masonry wall protects the coastal edge which requires periodic maintenance. Beyond this, to Chanonry Point, a variety of backshore defences, such as gabions, masonry, pebble and drystone walling and some dumped rock, all occur. These defences are in a generally very poor condition and do not provide an adequate defence.

5.7 Sub-cell 3e: Chanonry Point to Tarbat Ness

5.7.1 Geology

The south-east facing coastline of the Black Isle corresponds to the line of the Great Glen Fault. The solid geology outcrops at the coastline along much of the Inner Moray Firth frontage. Between Rosemarkie and Eathie and outcropping at both the North and South Sutors metamorphic rocks comprising mainly of Moinian schists occur. The rocks of the Rosemarkie inlier are, as yet, unassigned to either the Moine or Lewisian. Over much of the Moray Firth region the basement rock is overlain and obscured by Old Red Sandstone deposits. This is one of the few areas where these older rocks are evident at the coast. However, deposits of Old Red Sandstone (mainly middle ORS) are evident in the steep cliffs around South Sutor and outcrop at the coastline between North Sutor and Tarbat Ness.

Boulder Clay deposits cover much of the Black Isle. These are evident at the coastline along the southern coast of the Cromarty Firth and cap much of the cliffs along the northern coast of the Inner Moray Firth. The influence of previously higher relative sea levels is evident along much of the coastline, particularly that of the Cromarty Firth. Wide areas of raised beach deposits occur along much of the northern coast of the Cromarty Firth and are part of the same raised beach system which occurs at Balintore and Hilton of Cadboll.

At present there are few beach areas mainly due to the lack of wave action eroding (and providing an input of beach sediments) from these hinterland deposits. Many of these low-lying areas, such as around Invergordon, are also protected by coastal defence work limiting the reworking of such deposits further.

5.7.2 Hydraulic processes

The tidal cycle experienced within this cell has a period of approximately 12.4 hours. There is a slight diurnal inequality of approximately 0.18m at Invergordon on high water spring tides. The mean spring tidal range at Cromarty is 3.5m and decreases marginally to Tarbat Ness with a mean neap tide of 1.7m (Table 17). Within the Cromarty Firth the mean spring range is approximately 3.7m at Invergordon. High tide occurs along most of the coastline in this sub-cell around approximately the same time.

Table 17 Sub-cell 3e - Predicted tidal levels and ranges

Location	MHWS (m OD)	MLWS (m OD)	Spring Range (m)	MHWN (m OD)	MLWN (m OD)	Neap Range (m)	OD to CD (m)
Cromarty	2.2	-1.4	3.6	1.2	-0.5	1.7	+2.1
Invergordon	2.2	-1.5	3.7	1.2	-0.6	1.8	+2.1
Dingwall	2.2	-	-	1.3	-	-	+2.1

In Table 17 the tidal elevations are quoted relative to Ordnance Datum Newlyn (the standard land based datum). The conversion to the local Chart Datum (where known) is shown in the final column.

The most commonly referred to research on extreme water levels in the UK is that conducted by Graff (1981) and Coles & Tawn (1990). This analysis was based on tidal records from the A-class tide gauge network. In these publications there are no locations in sub-cell 3e where predictions of extreme water levels have been made, the closest being Aberdeen. However, the latest research into trends of extreme water levels (Dixon & Tawn, 1997) provides a spatial analysis at any location around the coastline of the UK mainland. In this study the predicted extreme water levels depend on the year of interest allowing for trends in mean sea level rise and hence have not been reproduced in this report. This research is likely to provide the most up-to-date and comprehensive analysis of extreme water levels available.

Tidal current speeds within the Moray Firth are generally low. The main flood tide originates from the north, dominantly through the Pentland Firth and flows in a south easterly direction across the entrance of the Outer Firth (and in an opposite direction on the ebb). On the Moray Firth coastline of this sub-cell tidal current velocities increase in magnitude from Tarbat Ness to Chanonry Point. Along this coastline the flood stream flows parallel to the coastline in a south west direction with the ebb flowing to the north east. Offshore of Tarbat Ness peak spring rates on both the flood and ebb are between $0.25ms^{-1}$ and $0.35ms^{-1}$. However, the magnitude of these currents can be affected by south westerly or north easterly winds. Towards Chanonry Point there is an ebb tide dominance with a peak spring rate of $1ms^{-1}$ on the ebb ($0.75ms^{-1}$ on the flood) in the North Channel. The east coast of the Chanonry peninsula deflects the south west going flood tide to the south and into the Inverness Firth. Peak spring rates are of the order of $1.25ms^{-1}$. The ebb tide, flowing out of the Inverness Firth, follows the central channel resulting in an anticlockwise eddy inducing a southerly going current along the eastern flank of the Chanonry peninsula. In the central stream the ebb current can reach $2ms^{-1}$.

The main tidal stream in the Inner Moray Firth flows across the mouth of the Cromarty Firth, but is locally influenced by flows in and out of the firth. In the entrance to the Cromarty Firth currents follow the main channel with an approximate peak rate of $0.75ms^{-1}$ on both flood and ebb with the peak ebb stream increasing to over $1ms^{-1}$ in the channel between Cromarty and Balnapaling. Between Cromarty and Invergordon the main tidal stream follows the deepwater channel with rates rarely exceeding $0.6ms^{-1}$. These rates increase at Invergordon to over $1ms^{-1}$ on the ebb. Along the north east coast around Invergordon streams can be variable with eddies occurring at all states of the tide.

The duration of the flood and ebb tides within the Cromarty Firth is affected by heavy rain or melting snow resulting in an increase in the duration of the ebb tide. Over the sand flats, such as at Nigg, current speeds are generally low, but can be significant in the drainage channels. Over these sand flats, wind-induced currents at high water levels may increase current velocities. As a rough guide, in shallow water wind induced current velocities on the water surface are approximately 2% of the wind velocity. Such currents will not be sufficient to suspend and move sediment on their own but may result in increased transport where sediment is already in suspension (e.g. due to wave stirring). On the Sands of Nigg, winds from the south west will tend to induce a landward (northward) flow of water which will be returned by the channels which drain the sands.

The offshore wave conditions experienced in the Moray Firth are described in Section 5.3.2. The dominant offshore direction in the outer Firth is from 0°N to 40°N. However, the south east orientation of the coastline between Chanonry Point and Tarbat Ness results in waves from this sector having little influence on this coast. The most severe wave conditions will be from a narrow wave window between 40°N and 90°N, but events from this sector are relatively rare. Locally generated "wind-waves" from the south easterly sector will be more frequent but will be restricted due to short fetch lengths. The magnitude of waves from this sector will increase towards Tarbat Ness as fetch lengths increase.

Swell wave energy contributes a significant proportion of total wave energy within the outer Moray Firth. However due to the orientation of the coastline, and the shallow depths and sloping bathymetry in the inner Moray Firth, a high proportion of swell wave energy will have been dissipated before entering the nearshore zone of this sub-cell.

A waverider buoy was deployed at the mouth of the Cromarty Firth, Figure 6 and Table 6, and the data analysed by Stapleton & Pethick (1996). This indicated a significant wave height of 3.55m for the 1 year return period and 5.92m for the 5 year return period. The 10-year and 50-year return period wave height was also calculated but some doubt must be expressed as to the accuracy of these predictions as only eight months of wave data were recorded and no account was taken of shallow water effects which would have reduced these extreme wave heights.

Within the Cromarty Firth there are no known locations where wave conditions have been measured. An assessment of wave conditions was conducted to the south west of the platform fabrication yard at Balnapaling, (HR Wallingford, 1975). This showed that only a small proportion of wave energy generated in the Moray Firth (and further afield) will propagate into the Cromarty Firth due to the narrow entrance to the Firth. To the south west of Balnapaling the ratio of the significant wave height to that in deep water within the Moray Firth rarely exceeded 0.3 for waves directly from the east, with the ratio being much less from other wave directions. The ratio is greater for waves from the north east than from the south east which can be attributed to Cromarty Bank which will have the effect of refracting waves from the north east into the entrance to the Cromarty Firth. The ratios also decreased with wave period indicating that very little swell wave energy is likely to propagate into the Cromarty Firth.

The dominant waves within the Firth will be wind generated with fetch lengths and, consequently, wave heights, dependent on water levels due to the shallow sand flats which occur over much of the Firth. The dominant wave conditions will occur from the south west but will be unlikely to exceed 1m.

5.7.3 Littoral processes

There are few beach areas on the northern coastline of the inner Moray Firth. At Rosemarkie a sand beach fronts the town. This material has derived from boulder clay deposits which cap the solid geology to the north. At present there is a very low input of fresh material. Towards Chanonry Point the upper beach is dominantly shingle which has derived from erosion of shingle deposits in the immediate hinterland. There is a low nett southerly drift of beach material along this frontage. The foreshore and hinterland characteristics are shown in Figure 17 with the dominant littoral processes detailed in Figure 18.

The coastline at Shandwick, Balintore and Hilton of Cadboll is fronted by a thin sand and shingle beach dissected by rock outcrops. Erosion of the low coastal edge provides a small input of fresh material.

Within the Cromarty Firth, shingle fringes the coastal edge. However, there is little wave induced transport of this material due to the restricted wave conditions. Tidal processes have a much greater influence upon this estuarine regime. A detailed summary of the present knowledge of such processes occurring within the Cromarty Firth is given by Stapleton & Pethick (1996).

Maintenance dredging is conducted at a number of locations within the Cromarty Firth. 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
Invergordon	1987	Cromarty Firth Port Authority	Evanton/Sutors
Invergordon	1988	Cromarty Firth Port Authority	Evanton/Sutors
Invergordon	1992	Cromarty Firth Port Authority	Evanton/Sutors
Invergordon	1993	Cromarty Firth Port Authority	Evanton/Sutors
Nigg	1987	Nigg Harbour Authority	Cromarty
Nigg	1988	Nigg Harbour Authority	Cromarty

The dredged material from Nigg is transported from the Cromarty Firth and dumped within the Moray Firth. This represents a nett loss of material from the Cromarty Firth. Much of this material will be fine silts and muds and will not provide a source of fresh material to the beaches within the Moray Firth.

Summary of erosion and accretion

There is little significant long-term erosion within the Cromarty Firth due to fetch limited wave conditions. Erosion is occurring (largely episodic storm damage) at Shandwick, Balintore, and Hilton of Cadboll.

5.7.4 Coastal defences

Details of the coastal defence work conducted within this sub-cell are shown in Figure 19. A low masonry wall protects Chanonry Point. The wall is in reasonable condition with the width of shingle beach fronting the structure resulting in wave interaction rarely occurring. Along the eastern flank of the promontory, a gabion revetment protects the coastal edge. At present this is covered with shingle but will be exposed to storm damage. At Rosemarkie the sand beach is backed by a low concrete wall which does cause some beach lowering.

Within the Cromarty Firth, rock revetments and seawalls protect Invergordon and the B817 as far north as Pollo. Due to the lack of wave action and beach material these defences have minimal impact on the immediate coastal regime. Rock revetments also protect the Nigg Fabrication Yard and around Cromarty and the B9163 west of Cromarty.

Various stretches of rock revetment and seawall protect property at Balintore. These are generally of a low cost nature and will have a short residual life.

5.8 Sub-cell 3f: Tarbat Ness to Lothbeg Point

5.8.1 Geology

The solid geology of the coastline between Tarbat Ness and Lothbeg Point is largely masked by the abundance of glacial deposits which occur in and around the Dornoch Firth region. Across the southern half of the sub-cell Old Red Sandstone underlies these superficial deposits. This is mainly Middle Old Red Sandstone but Upper Old Red Sandstone outcrops between Tarbat Ness and Tain and in a thin strip between Dornoch and Golspie. The Helmsdale Fault passes close to Golspie. To the east of the Fault, between Golspie and Lothbeg Point (and on to Helmsdale), much younger Mesozoic rocks occur, mainly formed during the Jurassic (208Ma to 146Ma). These beds are also largely masked by glacial and post-glacial deposits but outcrop as intertidal rock reefs, mainly consisting of shales and sandstones, at Lothbeg Point, Kintradwell and Brora.

The Dornoch Firth region has an abundance of glacially derived sands and gravels, with virtually the entire length of this coastline backed by raised beaches. The morphological development of the Dornoch Firth region is still relatively dynamic (for example the development of Dornoch Point and Morrich More). Details of the present knowledge of the post-glacial development of the Dornoch Firth region are summarised by Steers (1973) and Stapleton & Pethick (1996).

5.8.2 Hydraulic processes

The tidal cycle within this sub-cell has a period of approximately 12.2 to 12.4 hours. The mean spring tidal range varies from 3.4m at Portmahomack to 3.8m at Meikle Ferry, Table 18. High tide occurs approximately at the same time along much of this sub-cell.

Table 18 Sub-cell 3f - Predicted tidal levels and ranges

Location	MHWS (m OD)	MLWS (m OD)	Spring Range (m)	MHWN (m OD)	MLWN (m OD)	Neap Range (m)	OD to CD (m)
Portmahomack	2.0	-1.4	3.4	1.2	-0.4	1.6	+2.1
Meikle Ferry	2.3	-1.5	3.8	1.3	-0.6	1.9	+2.1
Golspie	1.95	-1.45	3.4	1.05	-0.55	1.6	+2.05

In Table 18 the tidal elevations are quoted relative to Ordnance Datum Newlyn (the standard land based datum). The conversion to the local Chart Datum (where known) is shown in the final column.

The most commonly referred to research on extreme water levels in the UK is that conducted by Graff (1981) and Coles & Tawn (1990). This analysis was based on tidal records from the A-class tide gauge network. In these publications there are no locations in sub-cell 3f where predictions of extreme water levels have been made, the closest being Aberdeen. However, the latest research into trends of extreme water levels (Dixon & Tawn, 1997) provides a spatial analysis at any location around the coastline of the UK mainland. In this study the predicted extreme water levels depend on the year of interest allowing for trends in mean sea level rise and hence have not been reproduced in this report. This research is likely to provide the most up-to-date and comprehensive analysis of extreme water levels available.

Tidal current speeds within the Moray Firth are generally low. The main flood tide originates from the north, dominantly through the Pentland Firth and flows in a south easterly direction across the Outer Firth (and in an opposite direction on the ebb). On the north side of the Moray Firth the flood tide flows parallel with the coastline (i.e. in a south westerly direction) and in the opposite direction on the ebb. Tidal currents on the Moray Firth coastline are generally weak. Directly offshore of Tarbat Ness peak rates on both flood and ebb do not exceed $0.25ms^{-1}$. Off Golspie there is little perceptible current, with rates to the north, off Brora Point, generally less than $0.35ms^{-1}$. Off Brora Point, the tidal stream is affected by the out-going ebb current from the Dornoch Firth with the north east going stream running for about 7.5 hours and the south west going stream only running for about 5 hours. This also results in current rates of the north east going stream being marginally greater. Only in the vicinity of the Dornoch Firth will tidal currents become important in terms of littoral processes. At Tain Bar the peak spring rate is approximately $0.25ms^{-1}$ on the ebb and marginally less on the flood. These rates increase into the Firth with the peak spring flood off Dornoch Point being approximately $0.5ms^{-1}$ and corresponding ebb $0.75ms^{-1}$ and off Ard na Cailc $1ms^{-1}$ and $1.25ms^{-1}$ respectively. Heavy rainfall or snow melt, and wind induced currents over the sand flats at high tide, will also affect current patterns and velocities.

Many of the geomorphological features occurring in the Dornoch Firth are thought to be tidally dominated. This is considered in general terms in the next section. A more comprehensive account of tidal patterns and currents in the vicinity of the Morrich More and the effect of these currents on the geomorphology of this region is covered by Hansom and Leafe (1990).

The wave conditions occurring at the outer boundary of the Moray Firth are described in Section 5.3.2. Closer to sub-cell 3f wave conditions measured and predicted for the Beatrice Field, (HR Wallingford, 1977) will be representative of conditions occurring directly offshore. Between Tarbat Ness and Dornoch, in the southern half of the sub-cell, the coastline is directly exposed to wave conditions from between 30°N through to 90°N. To the north of Dornoch, waves from the south easterly sector will also be experienced upon the coastline, but will be limited in magnitude due to a limited fetch.

A certain amount of swell wave energy, generated outwith the Moray Firth, will also affect the more exposed lengths of this coastline. The macro-scale crescentic planshape of the bay between Tarbat Ness and Dunrobin Point exhibits the characteristics of a headland dominated coastline shaped by swell conditions. This is particularly evident below the 10m CD contour. Closer inshore much of the swell energy will have dissipated and other wave influences are dominant. Due to the system of nearshore bars and banks very little swell energy will propagate into the Dornoch Firth. To the north of Dunrobin Point the south-east facing orientation of the coastline results in little swell being experienced directly.

No quantitative inshore wave information is available along any part of this coastline. Between Tarbat Ness and Dunrobin Point the nearshore seabed slope is gentle (approximately 1:250) which will result in wave crests from most directions approaching the coastline at a low angle of incidence. At the entrance to the Dornoch Firth, sand bars and banks, e.g. Tain Bar, Grizzen Bank etc, will act to dissipate much wave energy and cause significant wave refraction. For instance Grizzen Bank will tend to "bend" waves from the north easterly sector into the firth. Wave refraction calculations (Hansom & Leafe, 1990) concluded that, in general, for the most frequent wave directions wave energy was concentrated at the apex of Innis Mhor, but diverged along the Morrich More coastline to the south and along the Dornoch town frontage.

Due to the protection provided by the sand banks at the mouth of the Dornoch Firth, wave conditions within the Firth will be dominated by locally generated "wind-waves". Due to the limited fetch lengths, wave conditions are unlikely to exceed 1m in height and will have relatively short periods. As such winds and waves from the westerly sector will dominate in the Firth.

5.8.3 Littoral processes

The evolution and morphology of the Dornoch Firth, Loch Fleet and Golspie region is extremely complex with a variety of sand and shingle spits, bars and sand flats. A summary is provided by Steers (1973) and Stapleton & Pethick (1996) and, of the Morrich More region, by Hansom and Leafe (1990) and Hansom and Black (1996). Details of the foreshore and hinterland characteristics are shown in Figure 20 with the dominant littoral processes in Figure 21.

The abundant deposits of sand and shingle within this sub-cell have been derived from glacial sources which have been reworked during former periods of higher relative sea levels. At least three different raised beach levels have been identified. Sediment movements are a complex interaction of wave and tidal flows, but along the outer coastlines wave processes dominate.

In general terms, the eastern coastline of the Morrich More is accreting, being fed by offshore sand banks and material transported along the north west coastline. Despite this the area around the Innis Mhor appears to be particularly dynamic with periodic localised areas of erosion. Much of the north west facing coastline between Tain and Innis Mhor is eroding with material being transported to the north east. This erosion has resulted in the coastal edge of the golf course frontage and the Tain town frontage being protected by rock armour. In the inner parts of the Dornoch Firth to the west of Tain, the coastal edge appears stable with little wave action causing erosion.

On the northern coast, the nett drift of material along the outer coastline between Golspie and Dornoch Point is to the south. Map analysis by Stapleton & Pethick (1996) shows the dynamic nature of the spit at Dornoch Point as it has developed due to the feed of material from the north. The southerly development of the spit will also be influenced by flood and ebb tidal flows within this region of the Dornoch Firth. Dornoch Point shelters the intertidal sand flats of Dornoch and Cuthill Sands from any significant wave action in the Moray Firth. As a result there is little present day erosion of the coastal edge west of Dornoch Point.

The coastline between Golspie and the Dornoch Firth experiences a nett wave induced southward drift of beach material. The rate is likely to be moderately high. The map analysis of the Dornoch area (referenced above) indicates that there has been considerable seaward movement of the MHWS and MLWS position over the last 100 years. To the north of Dornoch the entire frontage is backed by raised beach deposits, the reworking (erosion) of which provides an input of fresh material into the coastal regime. At present, erosion of the backshore is evident along most of the frontage, with the exception of the area just to the south of Embo where rock outcrops provide protection to the coastal edge. Along the Golspie golf club frontage, a rock revetment has been constructed to prevent continuing erosion of the coastal edge. This will effectively cut off any fresh supply of beach material to this frontage which is already badly depleted of beach material due to the nett loss of material to the south. The geomorphology of Loch Fleet is detailed by Hansom and Black (1996).

The only other beach area of note is to the north of Brora. The beach is a mixture of sand and shingle and appears to be in a relatively stable condition with no significant evidence of longshore transport processes. The frontal dunes show some evidence of frontal erosion due to wave action but this is relatively minor.

Summary of erosion and accretion

The patterns of erosion and accretion within the Morrich More are complex. In general the north western coastline between Tain and Innis Mhor appears to be an area of long-term erosion. Much of the inner coast of the Dornoch Firth is stable. Other than this, long-term erosion is most evident to the south of the pier at Golspie.

5.8.4 Coastal defences

A number of mainly small localised coastal defence works have been constructed within this sub-cell, Figure 22. At Portmahomack, immediately south of the harbour, various old masonry revetments and seawalls protect the main town frontage, all of which are in a poor condition. Gabions, in a marginally better condition, protect the recreational land just to the west. More recent defences of gabion baskets and timber breastwork and a rock rip-rap revetment protects the frontage at the western end of the village. The only major impact of these defences upon the sand beach is along the frontage protected by the vertical gabion baskets and timber breastwork where wave reflections have lowered beach levels. This may well cause collapse of these defences as they are undermined.

At Inver, the north and west coastal edge is protected by a rock revetment. This does not experience significant wave action due to the protection afforded by the sand flats fronting it and the presence of Patterson Island. Given the mild hydraulic climate there is minimal impact due to these defences on the surrounding coast. A low rock sill protects a length of eroding dunes to the north east of Tain. A low rock revetment also protects part of the frontage to the south of the River at Brora.

To the south of the pier at Golspie, a stretch of vertical seawall and rock revetment protects the coastal edge along the golf course frontage. The pier acts as a groyne and downdrift erosion has occurred to the south for a long period of time. At present beach levels, particularly in front of the vertical seawall, are low. A low stepped concrete wall with wave return upstand protects the Golspie town frontage. There is some concern about beach lowering in this region and a study has recently been undertaken (HR Wallingford, 1996b).

5.9 Sub-cell 3g: Lothbeg Point to Duncansby Head

5.9.1 Geology

The solid geology of this sub-cell is dominated by Old Red Sandstone apart from localised outcrops of metamorphic, igneous and younger Mesozoic rocks which occur at the southern end of the sub-cell. Two divisions of the Old Red Sandstone occur. The Middle ORS (known here as the Caithness Flagstone Group) outcrops along much of the coastline to the north of Berriedale. These strata are generally hard, comprising fine mudstones and flagstones. Outcropping around Freswick Bay and Duncansby Head is Upper Middle Old Red Sandstone, known as the John O'Groats Sandstones. This is generally softer and less resistant to erosion.

To the north of Lothbeg Point a number of faults dissect the coast which has resulted in a varied lithology. The Helmsdale Fault extends from around Golspie and dissects the coastline just to the north of Helmsdale. Between the fault and the coast Mesozoic rocks of Jurassic age outcrop, mainly as intertidal rock reefs comprised of shales, sandstones and boulder beds. To the north of the Helmsdale Fault, an intrusive igneous outcrop of granite occurs at the coast between Dun Glas and a small fault at Ceann Ousdale. A similar granite outcrop also occurs at Lower Newport. Faulting has had a significant influence upon this coastline. Many of the small inlets, such as Dunbeath and Lybster, occur along fault lines.

Glacial deposits are much less widespread within this sub-cell being mainly restricted to boulder clay deposits which cap the underlying solid geology. During former periods of higher relative sea levels erosion of boulder clay deposits may have provided some of the beach material, particularly in Sinclairs Bay. Offshore deposits are also likely to have supplied material to both Sinclairs and Freswick Bays. Between Lothbeg Point and Helmsdale the coastal hinterland is in the form of a raised beach backed by a fossil cliff. At Lothbeg the raised beach area is wide with evidence of a number of different sea levels, but towards Helmsdale this width reduces.

5.9.2 Hydraulic processes

The tidal cycle experienced within this sub-cell has a tidal period at Wick of approximately 12 hours on the spring and 12.25 hours on the neap. The mean spring tidal range decreases to the north from 3.1m at Helmsdale to 2.8m at Wick, with the mean neap range decreasing in a similar manner, Table 19. The Highest Astronomical Tide is approximately 0.5m above high water on the mean spring tide at Wick. The tidal wave passes through the Pentland Firth and travels south along the coast taking approximately one hour to travel from Duncansby Head to Fraserburgh.

Table 19 Sub-cell 3g - Predicted tidal levels and ranges

Location	MHWS (m OD)	MLWS (m OD)	Spring Range (m)	MHWN (m OD)	MLWN (m OD)	Neap Range (m)	OD to CD (m)
Helmsdale	1.93	-1.27	3.2	1.13	-0.47	1.6	+1.97
Wick	1.79	-1.01	2.8	1.09	-0.31	1.4	+1.71

In Table 19 the tidal elevations are quoted relative to Ordnance Datum Newlyn (the standard land based datum). The conversion to the local Chart Datum (where known) is shown in the final column.

The most commonly referred to research on extreme water levels in the UK is that conducted by Graff (1981) and Coles & Tawn (1990). This analysis was based on tidal records from the A-class tide gauge network. In these publications there are no locations in sub-cell 3g where predictions of extreme water levels have been made, the closest being Aberdeen. However, the latest research into trends of extreme water levels (Dixon & Tawn, 1997) provides a spatial analysis at any location around the coastline of the UK mainland. In this study the predicted extreme water levels depend on the year of interest allowing for trends in mean sea level rise and hence have not been reproduced in this report. This research is likely to provide the most up-to-date and comprehensive analysis of extreme water levels available.

Along this coastline, the main flood stream flows through the Pentland Firth and flows in a south easterly direction and in the opposite direction on the ebb. A flood stream also flows south roughly parallel to the northern coastline and into the inner Moray Firth and in an opposite direction on the ebb. Tidal current rates through the Pentland Firth are high in magnitude and result in a clockwise eddy forming to the south of Duncansby Head. This causes a northward flow for up to 9 hours of the tidal cycle within Freswick Bay and a continuous east going eddy along the southern shore of Sinclairs Bay. To the south of Noss Head, the tidal streams run parallel with the shore in a NNE and SSW direction, rotating clockwise through the tide. Along the coastline, either side of Wick Bay, peak Spring current speeds are approximately $0.85ms^{-1}$ on both flood and ebb. This stream crosses the mouth of Wick Bay with there being little perceptible current within the bay. Further south, the magnitude of the currents reduce being approximately $0.5ms^{-1}$ on both flood and ebb at peak Springs off Dunbeath and $0.4ms^{-1}$ on both tides off Berriedale.

The offshore wave conditions occurring at the outer boundary of the Moray Firth are described in Section 5.3.2 and will be representative of conditions experienced directly offshore of this sub-cell. At Lothbeg Point the maximum wave window from which waves directly affect this coastline is between approximately 60°N and 200°N. Further north the orientation of the coastline changes and is more exposed to waves from the north-easterly sector.

The coastline of this sub-cell will experience swell wave energy from the north east, particularly to the north of Noss Head where the orientation of the coastline changes to face directly east. Shallow water effects will greatly reduce the magnitude of the offshore swell waves before they reach the coastline but such conditions will have had some effect in producing the planshape of Sinclair's Bay.

No quantitative information is available on inshore wave conditions along any part of this sub-cell. In Sinclair's Bay the nearshore contours run parallel with the coastline resulting in wave conditions at the coastline approaching at a low angle of incidence under normal wave conditions. Along the more rocky sections of the coast, the immediate seabed slope is steeper resulting in more severe wave conditions experienced at the coast.

5.9.3 Littoral processes

To the north of Lothbeg Point there are few beach areas in comparison with further south. A thin sand and shingle fringe beach formed from wave erosion of a thin raised beach occurs to the south of Helmsdale. The beach appears to be relatively stable but episodic storm damage does occur. A small shingle pocket beach occurs at Berriedale and is in a stable condition. The foreshore and hinterland characteristics within this sub-cell are shown in Figure 20 with the dominant littoral processes in Figure 21.

The two main beach systems in sub-cell 3g are at Sinclairs Bay and Freswick Bay. At Sinclairs Bay sand covers the lower foreshore with a shingle upper beach. Backing the beach is a mature dune and links area. The foreshore, and beach planshape, are at present in a stable condition with little evidence of any significant longshore processes. The shingle upper beach is vital in protecting the frontal dunes from wave attack. Where this shingle is thin, frontal dune erosion is evident. However, it is wind action which is having a much more detrimental effect, particularly upon the highest dunes around the mouth of the Burn of Lyth. Severe blowouts and deflation zones are occurring here.

Freswick Bay is deeply indented with a sand beach occurring along the central section and shingle, cobbles and rock outcrops along the flanks. The bay is extremely stable with little nett loss or gain of beach sediments and the planshape appears to be in equilibrium with the incident hydraulic conditions.

Dredging is conducted at the following locations in sub-cell 3g. 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
Helmsdale	1985	Helmsdale Harbour Authority	Helmsdale
Helmsdale	1989	Helmsdale Harbour Authority	Helmsdale
Helmsdale	1993	Helmsdale Harbour Authority	Helmsdale
Wick	1987	Wick Harbour Authority	Wick
Wick	1988	Wick Harbour Authority	Wick

There is little information on the exact location of the dump sites or on the movements of the dumped spoil. However, it is unlikely that this source will supply any significant amount of material to the beaches along this coast.

Summary of erosion and accretion

Storm damage can occur on the coastline between Lothbeg Point and Helmsdale. Erosion is also occurring of the frontal dunes within Sinclairs Bay. There are no locations where significant accretion is occurring.

5.9.4 Coastal defences

There are few coastal defences within this sub-cell other than seawalls associated with the main harbours, e.g. at Helmsdale and Wick.

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

5.10.1 Introduction

The natural and cultural heritage of the coastline of Scotland is rich and diverse. Much of the character and many of the features of natural heritage interest are due to the effects of the last Ice Age and subsequent post-glacial climatic variations. It is since the last Ice Age that evidence of the first inhabitants of Scotland can be traced. Effects of coastal processes have been instrumental in developing both the natural and cultural heritage around the coast. For instance many important coastal geomorphological features evident are due to processes acting at previously much higher sea levels. Archaeological sites also demonstrate changes in these processes over the last 10,000 years or so. For example Skara Brae in Orkney, now requiring engineering protection from the sea, was once some considerable distance from the shoreline. Remains in Gleann Sheillach south of Oban indicate that 6,000 years ago this site was at the head of a sea loch even though now it is 1.5km from the shoreline (Ashmore, 1994).

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

5.10.2 Natural heritage sites

Figure 7 details the location of coastal SSSIs within Cell 3, with a summary of the main characteristics provided in Appendix 1.

Most of the sites to the east of Burghead, the Rosemarkie to Shandwick coast and to the north of Golspie are designated, in whole or in part on account of the solid geology. Present day influences of coastal processes on SSSIs designated because of the solid geology are unlikely to have any great detrimental effect. Most of these sites are located on either fossil cliff, or are protected from wave action by intertidal rock reefs.

The major influences of coastal processes on SSSIs will occur on those designated on account of coastal habitat and / or their "soft" geomorphological features. There is a large number of such sites within the Moray Firth reflecting the abundance of glacial sediments and the effects of post-glacial sea levels. Many of these sites, such as Spey Bay, the Burghead Bay and Culbin frontage and the outer Dornoch Firth coastline are little affected by anthropogenic activities. Provided there remains little human influence the natural evolution of the geomorphological features occurring along this coastline will persist, (for example the Spey Bay, Burghead and Culbin frontages will continue to be dominated by the nett westerly drift of beach material). For a number of features this may mean a gradual loss of a particular land form. For instance The Bar at Culbin is in the later stages of its lifespan and will continue to migrate westwards and landwards. Similarly at Whiteness Head, the spit there is in a well-developed stage and showing the characteristic signs of a lack of sediment input. Breaching of the proximal end is expected to occur in the near future.

Most of the inner firths, e.g. Findhorn Bay, Munlochy Bay, Beauly, Cromarty, Dornoch and Loch Fleet have important saltmarsh and tidal flats. Findhorn Bay is accreting due to the supply of sediment from the River Findhorn and possibly due to beach material being transported into the bay. The remainder are all relatively stable under the present day coastal regime and are unlikely to change significantly unless significant changes in the present coastal regime occur, (e.g. due to climatic changes which are discussed in Chapter 6). Only at Whiteness Head is there a risk of a significant change to the present regime. The spit protects the hinterland saltmarsh from wave attack and hence erosion. Loss of part of this protection, e.g. due to breaching at the proximal end, may allow wave energy to propagate into the hinterland causing erosion of the saltmarsh.

5.10.3 Cultural heritage sites

The location of archaeological sites from the NMRS database is shown in Appendix 2. Little survey work appears to have been conducted along the coastline of Cell 3 to establish the present threat of coastal erosion to sites of cultural heritage (Ashmore, 1994). As part of the shoreline management plan conducted for the Burghead to Sutors frontage (HR Wallingford, 1996a) the Regional Archaeologist at Highland Regional Council (now Highland Council) was contacted and all known historical and archaeological sites occurring in the coastal zone identified and mapped.

Figure 9 shows that the density of known sites is much greater along the northern coastline of the Moray Firth, particularly along the Caithness coastline. However, much of this coastline is generally stable, being fronted by cliffs with a present low rate of attrition. Many of the noted sites are also within developed areas and not significantly at risk from coastal erosion.

It is where the coastline is most dynamic that the greatest risk of coastal erosion to sites of cultural heritage sites exist. Within cell 3 there are large stretches of coastline which are still relatively dynamic, e.g. Spey Bay, Burghead Bay to Whiteness Head and the Dornoch Firth coastline. For instance, in Burghead Bay, analysis by HR Wallingford (1996a) suggested that the planshape of the bay is still adjusting to the incident hydraulic conditions and that erosion along the eastern and central sections of the bay will continue. The lengths of frontage where cultural heritage sites are likely to be most at risk are detailed below:

Spey Bay	There are few recorded sites, but this may be due to a lack of investigation. The eastern half of the bay will continue to experience long-term erosion due to the westerly nett drift of beach sediments. The region around the mouth of the River Spey is also extremely dynamic.
Burghead Bay	There are few recorded sites, but again this may be due to a lack of information and/or the forestation of the hinterland. Long-term erosion is likely to continue along the central sections of the bay.
Findhorn Bay	There are a number of noted sites at the western side of the mouth of Findhorn Bay. The western coastline at the outlet of the bay tends to experience erosion due to the deflection of the outlet in that direction by the predominant westerly littoral drift along the outer coast.
Culbin frontage	There is likely to be little threat in the medium term due to the protection provided by the offshore barrier island (known as The Bar).

Nairn west frontage	The coastline between the golf club and Whitehead Ness is experiencing a nett loss of beach material to the west and hence a general (slow) landward retreat.
Dornoch Firth	The outer Dornoch Firth coast is relatively dynamic. At present the most seriously eroding sections are from Tain, along the north-west coast of the Morrich More and along the coastline from Dornoch to Golspie.
Sinclairs Bay	There is a high density of sites noted in the hinterland of Sinclairs Bay. There is slight frontal dune erosion within the bay but this is not too serious. However, the dunes along the central section are seriously deflated with shifting blown sand which could cover (or uncover) sites.

These are the main areas which are presently being affected by coastal processes and where the major effects of climatic change are likely to be most noticeable. However, there are likely to be many other localised sites occurring behind "soft" coast areas which may be at risk.

6 Climate change and its effect on coastal management

6.1 Introduction

The importance of climate change in the context of coastal management has generally been equated to the problems caused by an increase in mean sea level. This remains an important issue, particularly for low-lying areas where economically important assets are situated close to, or below, extreme tide level. However, recent winters in the UK have indicated a number of other potential impacts affecting the management of the coastline and its defences which may be more important, at least in the short-term. Such factors include an increased frequency of storms. Increased erosion of the coast may therefore be a greater concern in much of Scotland than flooding due to sea level rise. Much of Section 6.2 is taken from Brampton (1996).

6.2 Evidence of climatic change

6.2.1 General

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

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

The main greenhouse gases are carbon dioxide, methane, nitrous oxide and some industrial chemicals such as chlorofluorocarbons (CFCs) but also include water vapour. Significant modification of the atmosphere by human activities has occurred since the industrial

Revolution. However, the magnitude of greenhouse gas emissions has increased enormously in recent decades. Increased carbon dioxide is the most important driver of global change contributing about 64% of the radiative forcing that produces global warming (Houghton *et al.*, 1996).

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

6.2.2 *Tidal and sea level change*

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

It is important to note that an increase in <u>extreme</u> tidal levels may not, in the short-term, be the same as an increase in <u>mean</u> 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 <u>mean</u>

sea level was rising by about half that amount, i.e. about 10mm/annum. Therefore it can be assumed that there would be periods of rapid beach erosion and landward recession during these times (presumably followed 9 years later by periods of beach accretion as high water levels decline). At present we are at the end of one of these rapid rise periods.

6.2.3 Wave climate change

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

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

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

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

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

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

6.3 Effects on coastal management

6.3.1 Impact on beaches

General

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

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

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

Impact on the beaches in Cell 3

A significant change in the climate may have a significant effect upon the geomorphological response of the coastline within Cell 3 given the dynamic nature of much of the "soft" coastline of this cell. In general terms such changes are well documented, (e.g. Carter 1988), with much of the coastline responding to such changes in a relatively predictable manner. However, it is the magnitude of these changes which is much more difficult to quantify. A qualitative description of the possible impacts of climatic change upon the beach areas is given below.

The response of "soft" coastlines, such as occur in Spey Bay and the Burghead to Whitehead Ness frontage, to climatic change and sea level rise is dependent on the balance of the sediment budget, i.e. between sediment supply and sediment loss, (Carter, 1988). In considering the sand beach and dune systems on the Moray Firth coast, a rise in sea level will have the effect of pushing the beach landward. Along the unprotected sand beach and dune systems, for example Fraserburgh Bay, the Dornoch to Ferry Links coast or the North Brora coastline, coastal edge retreat will take the form of an erosional response. This erosion, induced by an increase in sea level is a result of changes in wave refraction and a decrease in distance to the zone of breaking, due to deeper water. Waves and currents also tend to act higher up the beach profile. In many of these beach areas, landward retreat of the coastal edge will not cause a serious problem (apart from possibly affecting golf courses) as there is a wide buffer zone containing a large supply of available beach material.

Overwashing of shingle ridges (such as occur in Spey Bay, and The Bar on Culbin) is likely to increase with either an increase in sea levels (particularly extreme levels) or an increase in the magnitude or frequency of storm wave conditions. This will cause rollover with beach material progressively transferred from the shoreface, pushed over the crest and onto the back face hence causing a landward retreat. The average rate of retreat is approximately proportional to the rate of sea level rise and the gradient of the beach. Where there is sufficient volume of shingle available the crest of the shingle beach will increase in elevation to accommodate sea level rise. However, if beach material is sparse any increase in elevation is at the expense of the width of the shingle ridge leading to an increase in the risk of breaching. Some of these areas are already experiencing such action, such as the proximal end of the spit at Whiteness.

Along the rocky coastlines, mainly in sub-cells 3a and 3g the main beach areas are in the form of pocket beaches, e.g. such as at Sandend, Cullen, Freswick Bay etc. The planshape of such beaches does not change dramatically, even if the offshore wave direction changes, as wave conditions at the shoreline are dominated by wave diffraction around the headlands at either end of the bay. Similarly as many of these pocket beaches have already adjusted and reached a position of no nett drift, a change in wave heights will have no effect on the longshore transport. Research into the influence of sea level rise on pocket beaches (Diserens et al, 1992) also concluded that there was no clear linkage between sea level rise and the position of the high water line. Hence it is unlikely that mean sea level rise will have a significantly noticeable effect. Of greatest impact on these pocket beach areas is likely to be any increase in extreme tidal levels as this will cause an increase in dune or backshore erosion. This will particularly affect those beach areas where there is little present day width between the high water mark and the frontal dunes/coastal edge or where streams run onto the middle of the beach causing beach levels to be lower (e.g. along parts of the eastern coastline of the Black Isle).

Along the Spey Bay, Burghead to Whiteness Head and Dornoch Firth coastline, changes in wave direction may be as important as changes in wave height or sea levels. Most examples of sustained coastal erosion are the result of changes in the longshore transport of material. Due to the dominance of waves from the north easterly sector, any increase in the frequency of events from this sector will increase the nett westerly drift of beach material (along the southern coast at least). This may cause an increase in the loss of beach material from existing problem frontages, such as the west Nairn frontage. Conversely, a decrease in events from the north east may well result in a decrease in the present rate of longshore transport.

The extent of coastal edge retreat will vary all along the coastline. Although simplified predictions exist, (e.g. Bruun, 1983), actual retreat rates will depend upon a whole range of interrelating factors, the effects of which can not be predicted quantitatively. Such changes will be gradual, (i.e. there will not be a sudden change in sea level), with the coastal regime gradually evolving in response.

With any increase in sea level rise, there is also an increase in the frequency and extent of any coastal flooding. At present there are few developed areas or infrastructures which are significantly affected by coastal flooding and as such it is unlikely to become a major problem in the medium term future. However, there are large areas of intertidal marsh and saltmarsh, e.g. within Findhorn Bay, at Whiteness Head, within the Cromarty and Dornoch Firths and in Loch Fleet. The effect on these saltmarsh areas depends on the rate of sea level rise. For instance there appears to be a threshold value, where for rates below the threshold the saltmarsh surface is able to accrete and keep pace with the change. Above this threshold the marsh becomes submerged and is lost. There is also evidence to suggest that erosion and the loss of saltmarsh is linked to increases in wave energy. This may be particularly important at Whiteness Head where a breach of the spit, allowing wave energy to propagate into the saltmarsh area, may cause significant erosion of the marsh.

6.3.2 Impacts on man-made defences

General

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

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

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

Impact on man-made defences in Cell 3

It is unlikely that there will be any significant increase in the occurrence of damage to structures within Cell 3 such as rock revetments in the short-term due to the relatively small climatic changes occurring. However, there are a number of structures where the present defences have a low margin of safety. Examples of these include the rock rip-rap and gabions along the Nairn golf course frontage and the various ad hoc defences on the western flank of Chanonry Point. These suffer substantial present day damage and will not withstand any increase in the frequency or severity of storm conditions.

An increase in the severity of wave conditions at the toe of linear structures, such as seawalls or rock revetments, can lead to either increased scouring of the toe or increased wave reflection causing beach levels to drop. This may, indirectly, lead to structural damage due to undermining of the structure. There are a number of locations where beach levels have been affected by the construction of linear hard defences, notably the eastern flank of Banff Bay, the rock revetment at Burghead and along the Golspie frontage. Similarly, where linear defences restrict landward recession, beach profile levels will drop as the mean Low and High water levels attempt to migrate landward. This can lead to the steepening of the intertidal beach, as the High Water Level is restricted by hard defences from moving further landward, "(coastal squeeze)", resulting in larger wave conditions propagating further inshore.

An increase in the magnitude or frequency of extreme wave or water level conditions will also cause an increase in the magnitude or frequency of overtopping of structures where such problems presently exist. Overtopping affects many of the defences on the southern coastline of the Moray Firth, particularly the old masonry defences which protect the many small coastal villages. An increase in the occurrence or volume of wave overtopping is likely to be the more noticeable than an increase in the occurrence of damage to structures.

6.3.3 Other effects

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

<u>Rainfall</u>
There is an observed variation in the rainfall pattern occurring in the UK. In the south of England an oscillation of about 40 years period has been observed. A similar oscillation has apparently been recorded by Stirling University when investigating River Tay flooding. As rainfall increases, a number of effects are likely to occur at the coastline:

- De-stabilisation of soft cliffs
- Cliff falls are usually caused by a combination of marine erosion, e.g. undercutting their front face, and geotechnical problems, e.g. rotational slips. The latter effect is increased by greater rainfall, and hence higher run-off, higher water tables etc.

- 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. The Rivers Findhorn and Spey are probably the only two river systems in Britain which still provide a significant input of fresh beach material. Increases in spate river flows may well increase the input of sand and gravel material into the coastal zone.

- Impacts on sand transport on beaches
  In locations where a beach is affected by surface water run-off from land, there are often localised erosion problems, e.g. around outfalls. The frictional resistance of sand is

reduced by the water, making it easier to be mobilised by waves and currents. It is therefore likely that increased rainfall will tend to cause localised beach erosion.

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

<u>Changes in wind</u>
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 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 at Fraserburgh Bay, Lossiemouth and Sinclairs Bay are likely to be affected most from such changes.

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

The impact of climatic change on the coastline of Cell 3 may well be noticeable given the amount of "soft" beach areas. However, the complexity of the coastal and nearshore zone makes it difficult to predict morphological changes due to the range of inter-relating parameters which affect it. 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.

7 *References and Bibliography*

7.1 References

Andrews I J, Long D, Richards P C, Thomson A R, Brown S, Chesher J A & McCormack M (1990). The geology of the Moray Firth. United Kingdom Offshore Regional Report. HMSO, Edinburgh.

Ashmore P J (1994). Archaeology and the coastal erosion zone. Towards a Historic Scotland policy. Historic Scotland Report.

Bacon S & Carter D J T (1991). Wave climate changes in the North Atlantic and North Sea. Journal of Climatology, **2**, 545-558.

Barne J H, Robson C F, Kaznowska S S, Doody J P & Davidson N C eds (1996). Coasts and seas of the United Kingdom. Region 3: North East Scotland: Cape Wrath to St Cyrus. Joint Nature Conservation Committee, Peterborough.

Batey C E (1984). Caithness Coastal Survey 1980-82; Dunnet Head to Ousdale. Durham University Department of Archaeology, Occasional Paper No 3. Durham.

Binnie & Partners (1991) Fraserburgh Long sea outfall feasibility study. Volume 1. Grampian Regional Council. Department of Water Services.

Brampton A H (1996). Climatic change and its effects on coastal management. In *Climatic change offshore N.W. Europe*. An assessment of impacts of changing meteorological and oceanographic (Metocean) conditions on offshore activities. Conference at Imperial College of Science, Technology and Medicine. Society for Underwater Technology.

British Oceanographic Data Centre (1991). United Kingdom Digital Marine Atlas. Proudman Oceanographic Laboratory, Birkenhead.

Bruun P M (1983). Sea level rise as a cause of shore erosion. Journal of the Waterways, Harbours and Coastal Engineering Division. ASCE, **88**, No WW1, 117-130.

Buck A L (1993). An inventory of UK estuaries, Volume 4: North and East Scotland. Joint Nature Conservation Committee, Peterborough.

Carter R W G. (1988) Coastal Environments. Academic Press, London.

CIRIA/CUR (1991). Manual of the use of rock in coastal and shoreline engineering. CIRIA Special Publication 83/CUR Report 154. Construction Industry Research and Information Association.

CIRIA (1996). Beach management manual. CIRIA Special Publication 153. Construction Industry Research and Information Association.

Coles S G & Tawn J A (1990). Statistics of coastal flood prevention. Philosophical Transactions of the Royal Society of London, **332**, 457-476.

Comber D P M, Hansom J D & Farey F M (1994). Culbin Sands, Culbin Forest and Findhorn Bay SSSI: Documentation and Management Prescription. Scottish Natural Heritage Research Survey and Monitoring Report No. 14.

Department of the Environment (1995). Policy guidelines for the coast. November 1995. Department of the Environment, London.

Dieserens A P, Motyka J M & Brampton A H (1992). Beach development due to climatic change. National Rivers Authority R & D Note 58. Confidential.

Dixon M J & Tawn J A (1994). Extreme sea levels at the UK A-class sites: Optimal site-by-site analysis. Proudman Oceanographic Laboratory Internal Document No. 65. Proudman Oceanographic Laboratory, Birkenhead.

Dixon M J & Tawn J A (1997). Spatial analysis for the UK coast. Proudman Oceanographic Laboratory. Document No. 112. Proudman Oceanographic Laboratory, Birkenhead.

Dodd N & Brampton A H (1995). Wave transformation models: a project definition study. HR Wallingford Report SR 400.

Doody J P, Johnston C & Smith B (1991). Directory of the North Sea coastal margin. Joint Nature Conservation Committee, Peterborough.

Environmental Management Ltd, Watson Hawksley & Strathclyde University (1990). Inverness main drainage scheme environmental assessment. Final study report and appendices. Highland Regional Council.

Gemmell S L G, Hansom J D & Hoey T B (1996). The geomorphology, conservation and management of the River Spey and Spey Bay SSSIs, Moray. Scottish Natural Heritage Research, Survey and Monitoring Report No. 57 – *in press*.

Graff J (1981). An investigation of the frequency distributions of annual sea level maxima at ports around Great Britain. Estuarine, Coastal and Shelf Science, **12**, 389-449.

Hansom, J D and Leafe, R N, (1990). The geomorphology of Morrich More: development of a scientific database and management prescription. Department of Geography, University of Sheffield. Unpublished report to Nature Conservancy Council.

Hansom J D & Black D L (1996). Coastal processes and management of Scottish estuaries. II. Estuaries of the Outer Moray Firth. Scottish Natural Heritage Review No. 51.

Harding-Hill R (1993). The Moray Firth Review. Scottish Natural Heritage. North West and North East regions, Inverness.

Hay, W D, (1980). Survey of coastline within Grampian Region. Grampian Regional Council, Aberdeen.

HR Wallingford, (1975). Cromarty Firth, Scotland. Wave refraction computations. HR Wallingford Report EX 686. HR Wallingford, Wallingford.

HR Wallingford, (1977). Beatrice field. Moray Firth. Extreme Wave Conditions. HR Wallingford Report EX 797. HR Wallingford, Wallingford.

HR Wallingford, (1982). Moray Firth. A wave refraction study. HR Wallingford Report EX 1078. HR Wallingford, Wallingford.

HR Wallingford (1986). Pentland Firth mathematical model study. HR Wallingford Report EX 1404. HR Wallingford, Wallingford.

HR Wallingford (1993a). Coastal Management: Mapping of littoral cells. HR Wallingford, Report SR 328. HR Wallingford, Wallingford.

HR Wallingford, (1993b). Armouring of the West Pier at Buckie Harbour. A study of the inshore wave effects. HR Wallingford Report EX2793. HR Wallingford, Wallingford.

HR Wallingford, (1996a). Shoreline Management Plan. Inverness Firth and part of Moray Firth (Burghead to Sutors). HR Wallingford Report EX 3230. HR Wallingford, Wallingford.

HR Wallingford, (1996b). Golspie seawall toe protection. HR Wallingford Report EX 3345. HR Wallingford, Wallingford.

HR Wallingford, (1997). Coastal Cells in Scotland. Scottish Natural Heritage Research, Survey and Monitoring Report No 56.

Hydrographer of the Navy (1963). North Sea: Flamborough Head to Pentland Firth. Tidal Steam Atlas.

Ibsen M L (1994). Evaluation of the temporal distribution of landslide events along the south coast of Britain between Straight Point and St Margarets. Unpublished M Phil thesis, University of London.

Jenkinson A F & Collison F D (1977). An initial climatology of gales over the North Sea. Meteorological Office, 13, Branch Memorandum, No. 62, Bracknell (unpublished).

Johnstone G S & Mykura W (1989). British Regional Geology: The Northern Highlands of Scotland. 4th ed. HMSO, Edinburgh.

Lamb H H & Weiss I (1979). On recent changes of the wind and wave regime of the North Sea and the outlook. Fachliche Mitterluugen. AMT fur Wehrgeophysik. Nr. 194, March 1979.

Legget I M, Beiboer F L, Osborne M J & Bellamy I (1996). Long term Metocean measurements in the Northern North Sea. In *Climate change offshore N.W. Europe.* An assessment of the impacts of changing meteorological and oceanographic (Metocean) conditions on offshore activities. Conference at Imperial College of Science, Technology and Medicine, 18 April 1996. Society for Underwater Technology.

Lynagh N (1996). Weather and climate variability since prehistoric times and recent indications of continuing fluctuations in the NE Atlantic. In *Climate change offshore N.W. Europe.* An assessment of the impacts of changing meteorological and oceanographic (Metocean) conditions on offshore activities. Conference at Imperial College of Science, Technology and Medicine, 18 April 1996. Society for Underwater Technology.

MAFF (1995a). Shoreline Management Plans. A guide for coastal defence authorities. MAFF, London.

MAFF (1995b). UK Dredged Material Licence Database. MAFF, London.

Marine Information and Advisory Service (MIAS) (1982). MIAS catalogue of instrumentally measured wave data. MIAS Reference Publication No 1, IOS, Wormley, Surrey.

Metocean (1994). Energy industry Metocean data around the UK. Metocean Report No 537.

Parker D E & Folland C K (1995). Comments on the global climate of 1994. Weather, **50**, No 8, August 1995.

Reid G S (1988). Sediment distribution in the Moray Firth, NE Scotland: Transport pathways, sources and sinks. Unpublished PhD thesis, University of Dundee.

Riddell K J & Fuller T W (1994). The Spey Bay Geomorphological Study. Earth Surface Processes and Landforms, **20**, 671-686.

Ritchie W & Mather A S (1970). The beaches of Caithness. Aberdeen University, Department of Geography. Report to the Countryside Commission for Scotland.

Ritchie W, Smith J S & Rose N (1978) The Beaches of North East Scotland. Aberdeen University, Department of Geography. Report to the Countryside Commission of Scotland.

Ross S (1992). The Culbin sands - Fact and Fiction. Centre for Scottish Studies, University of Aberdeen.

Scottish Office (1996). Scotland's coast. A discussion paper. HMSO, Edinburgh.

Scottish Office (1997). National Planning Policy Guideline (NPPG) 13. Coastal Planning. Scottish Office (Development Department), Edinburgh.

Smith, J S & Mather, A S, (1973). The beaches of East Sutherland and Easter Ross. Aberdeen University, Department of Geography. Report to the Countryside Commission for Scotland.

Spencer, N E & Woodworth, P L (1993). Data holdings of the Permanent Service for Mean Sea Level. Bidston Observatory. Proudman Oceanographic Laboratory.

Stapleton C & Pethick J (1996). Coastal processes and management of Scottish Estuaries. I. The Dornoch, Cromarty and Beauly/Inverness Firths. Scottish Natural Heritage Review No. 50.

Steers J (1973). The coastline of Scotland. Elsevier, Kidlington.

Stevenson D & Gould D (1995). British Regional Geology: The Grampian Highlands (4th Edition). HMSO, Edinburgh.

Thorne K L & Gleeson R (1986). Waves recorded off Kinnairds Head. IOS Report No 226. IOS, Wormley, Surrey.

Townend I H (1994). Variations in design conditions in response to sea level rise. Proc. Institution of Civil Engineers Proceedings. Water, Maritime and Energy, **106**, 205-213.

Woodworth P L (1987) Trends in UK mean sea level. Marine Geodesy, **11**, 57-87.

Woodworth P L, Shaw S M & Blackman D L (1991). Secular trends in mean tidal range around the British Isles and along the adjacent European coastline. Geophysical Journal International, **104**, 563-609.

7.2 Other publications

There are a number of other publications that may be of use that are not referenced within this report.

Dobbie, C H and Partner, (1983). Coast Protection, Findhorn - Report and recommendations. Report to Grampian Regional Council.

HR Wallingford, (1975). Wick harbour, Caithness. Hydraulic model studies of proposals for the improvement of conditions at the fishing harbour. HR Wallingford Report EX 706. HR Wallingford, Wallingford.

HR Wallingford, (1980). Nigg Bay - Cromarty Firth. Hydraulic effects of reclamation. HR Wallingford Report EX 931. HR Wallingford, Wallingford.

HR Wallingford, (1987). Pentland Firth: further mathematical model studies of tidal flow and pollution transport. HR Wallingford Report EX 1614. HR Wallingford, Wallingford.

HR Wallingford, (1988). Helmsdale harbour siltation. HR Wallingford Report EX 1667. HR Wallingford, Wallingford.

HR Wallingford, (1990). Coastal protection, Tain, Easter Ross, Highland Region. HR Wallingford Report EX 2170. HR Wallingford, Wallingford.

Mather, A S & Ritchie, W, (1977). The beaches of the Highlands and Islands of Scotland. Aberdeen University, Department of Geography. Report to Countryside Commission for Scotland.

Prus-Chacinski T M, (1963). Cutting a new mouth for the River Spey. Details of design procedure. Dock and Harbour Authority, **44**, No 512.

Prus-Chacinski T M, (1976). Re-opening a new mouth for the River Spey. Dock and Harbour Authority, **57**, No 669.

Reid, G S & McManus, J, (1987). Sediment exchanges along the coastal margin of the Moray Firth, eastern Scotland. Journal of the Geological Society of London, **144**, 179-185.

Figures 1-22

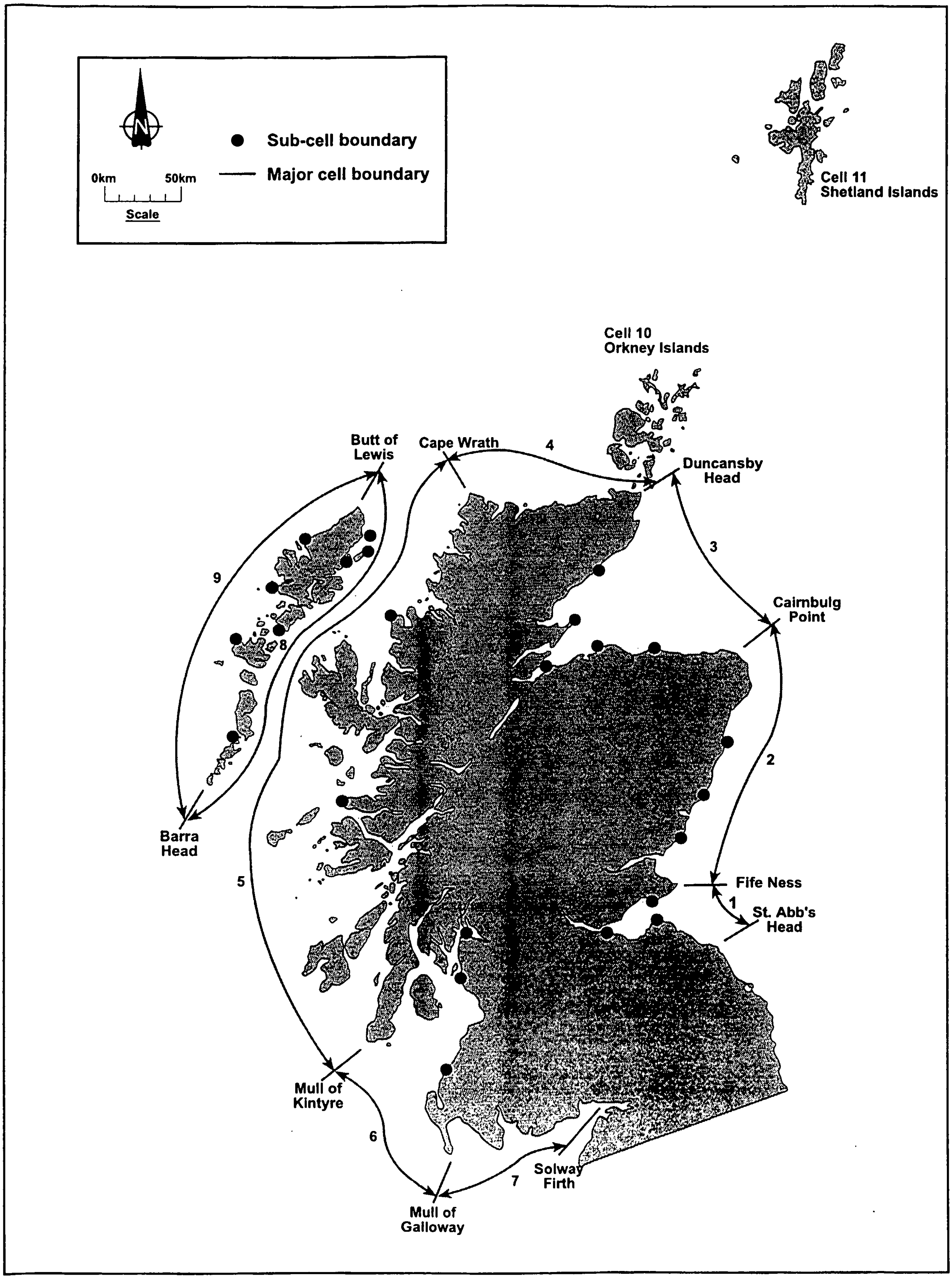


Figure 1 Coastal Cells in Scotland

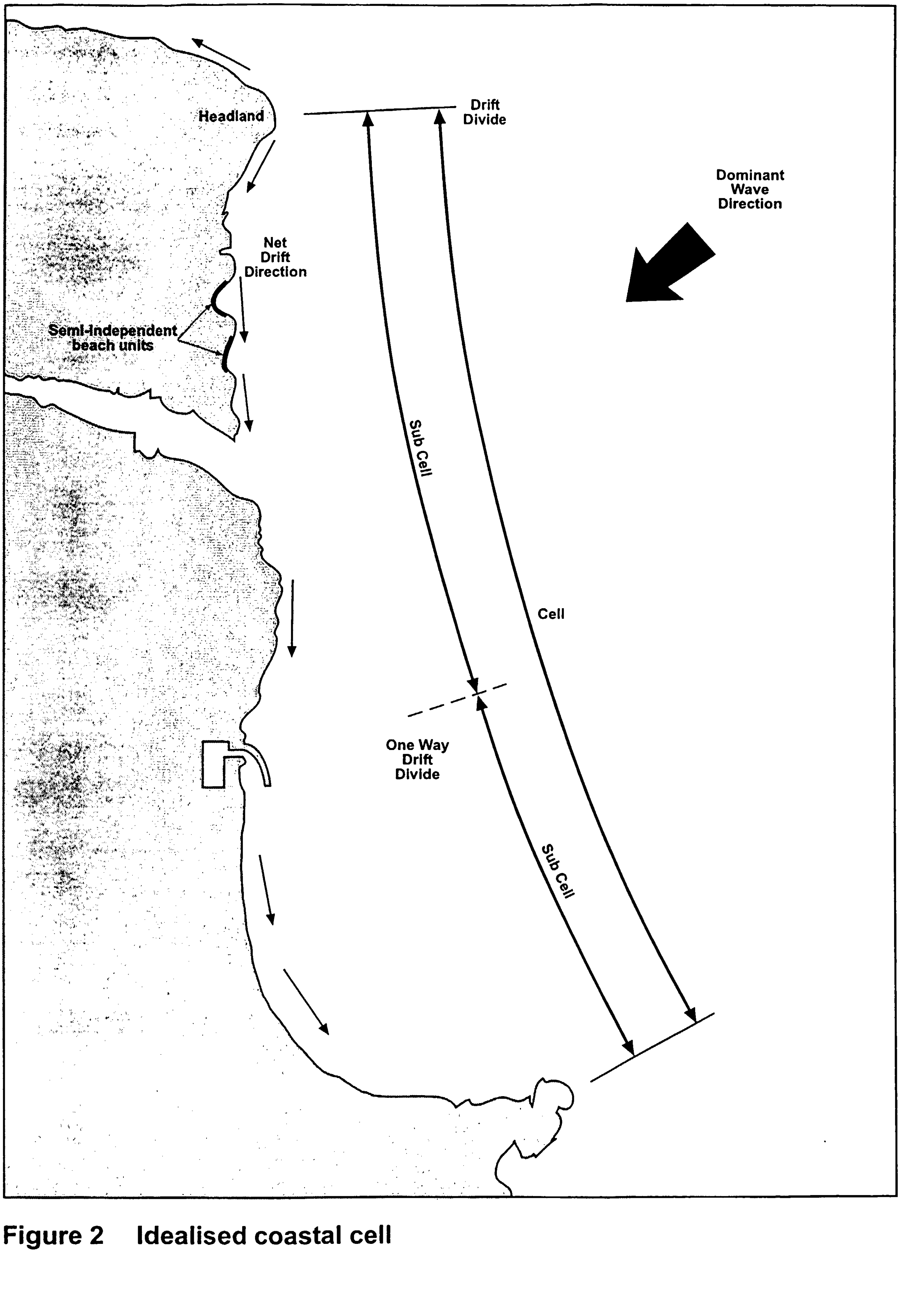


Figure 2 Idealised coastal cell

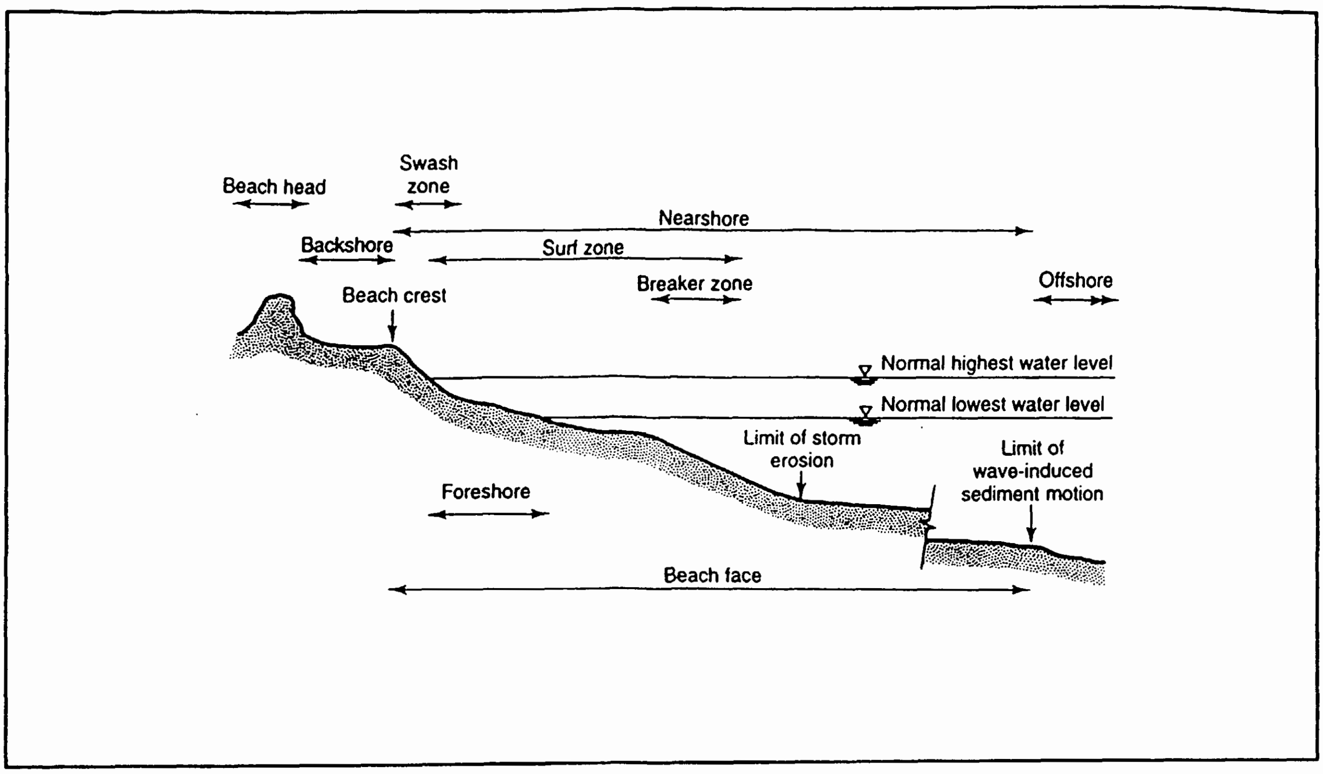


Figure 3 General beach profile and littoral zone

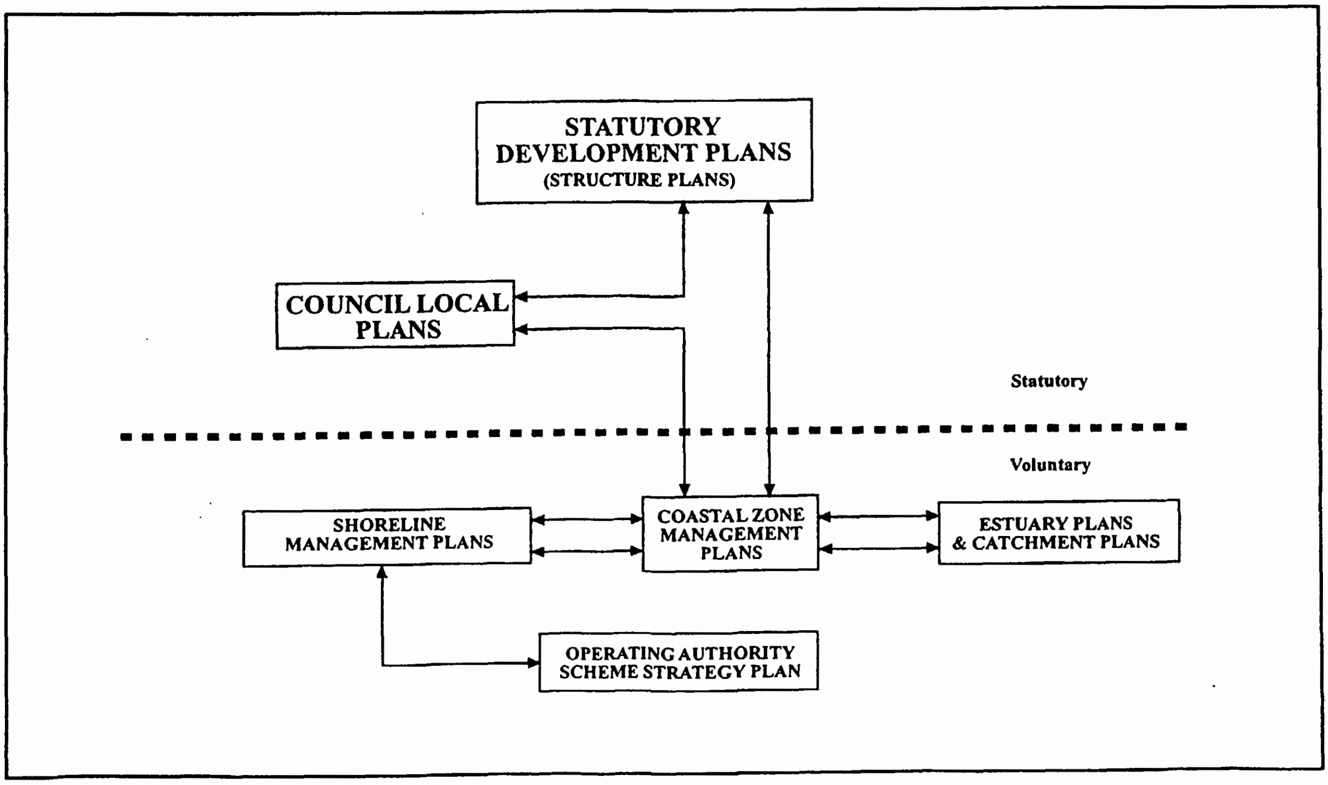


Figure 4 Relationship between coastal initiatives

Figure 5   Cell 3 - Cairnbulg Point to Duncansby Head

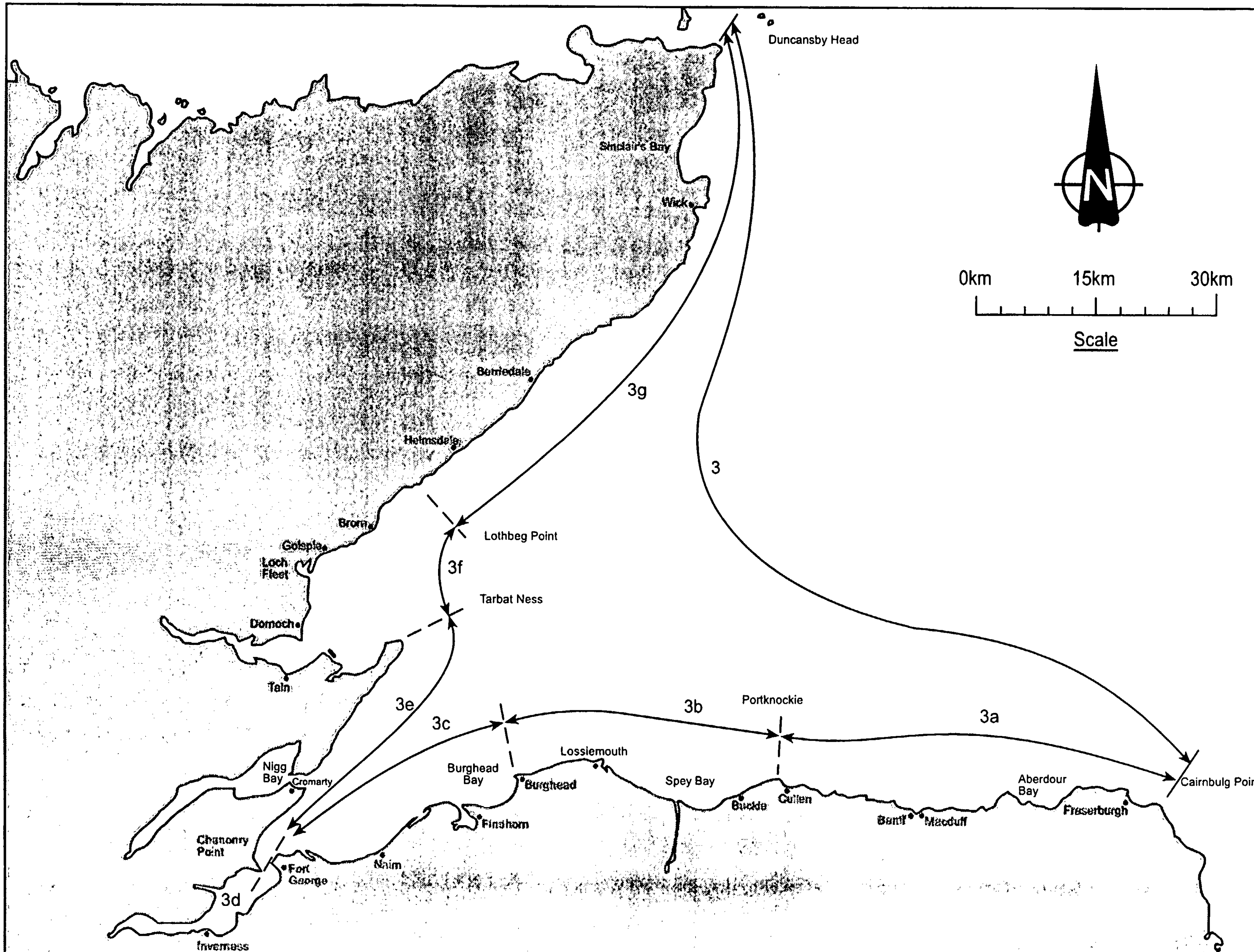
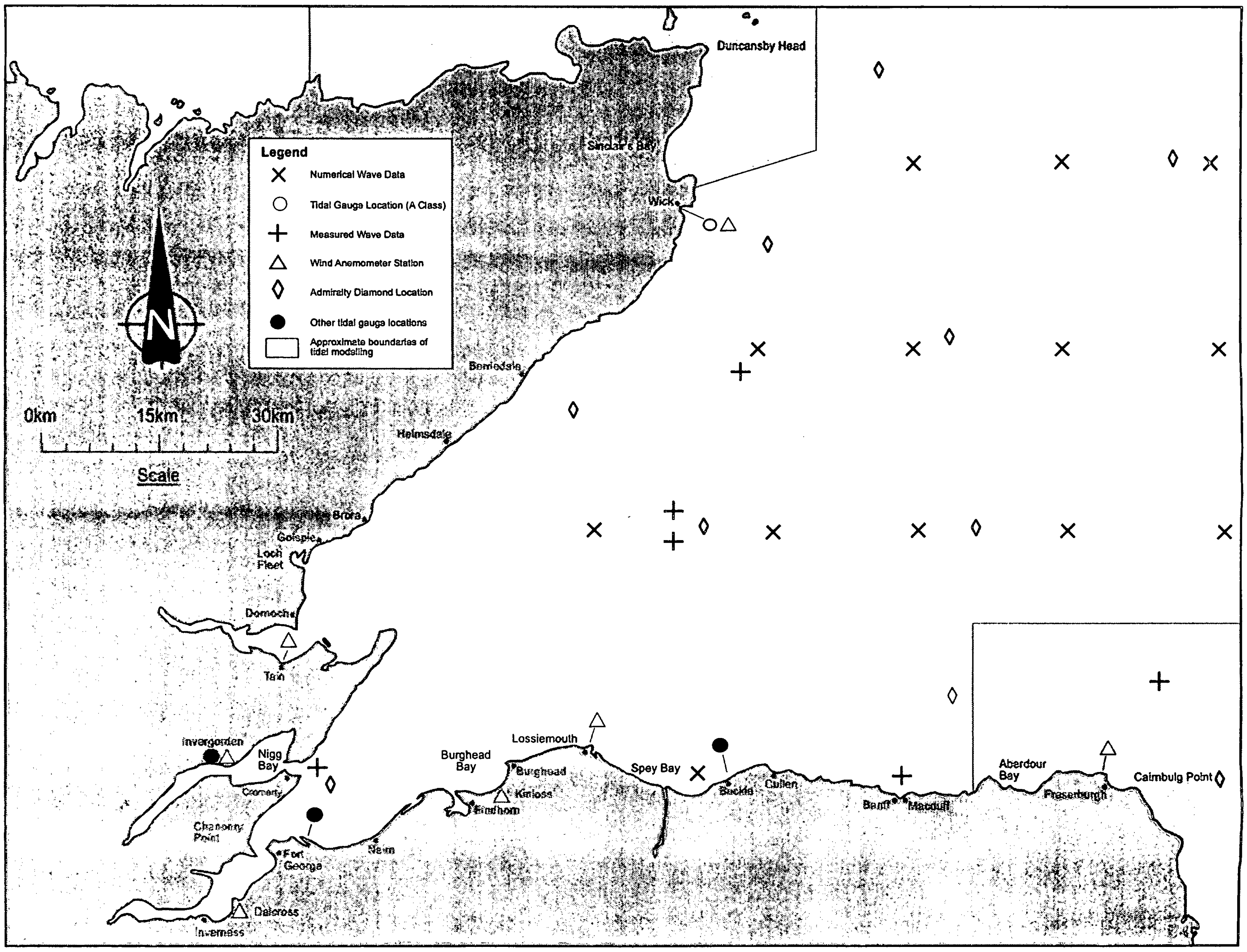


Figure 6 Cell 3 - Location of wind, tidal and wave data



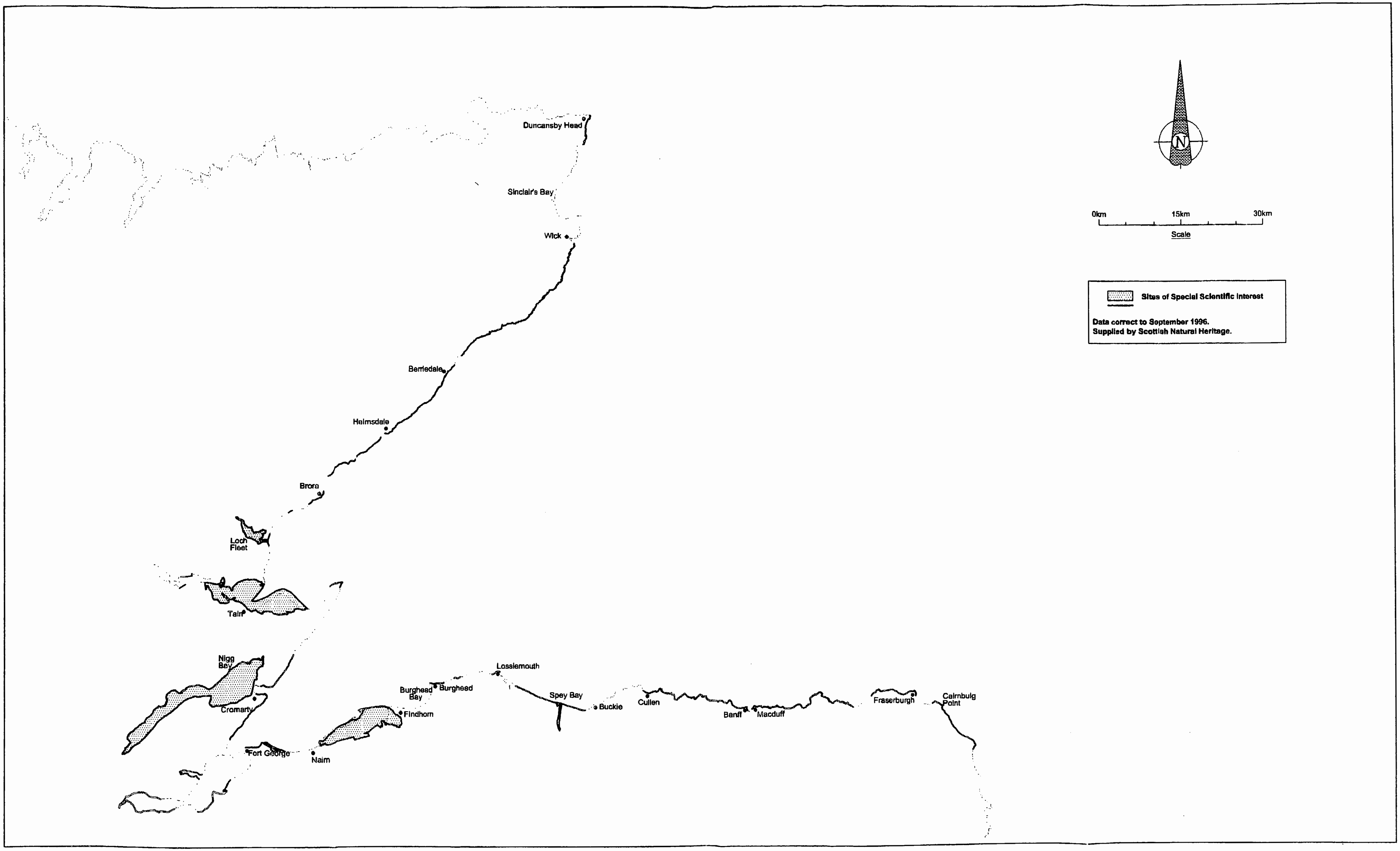


Figure 7 Cell 3 - Location of Sites of Special Scientific Interest

Figure 8 Cell 3 - Location of sites of natural heritage importance (other than SSSIs)

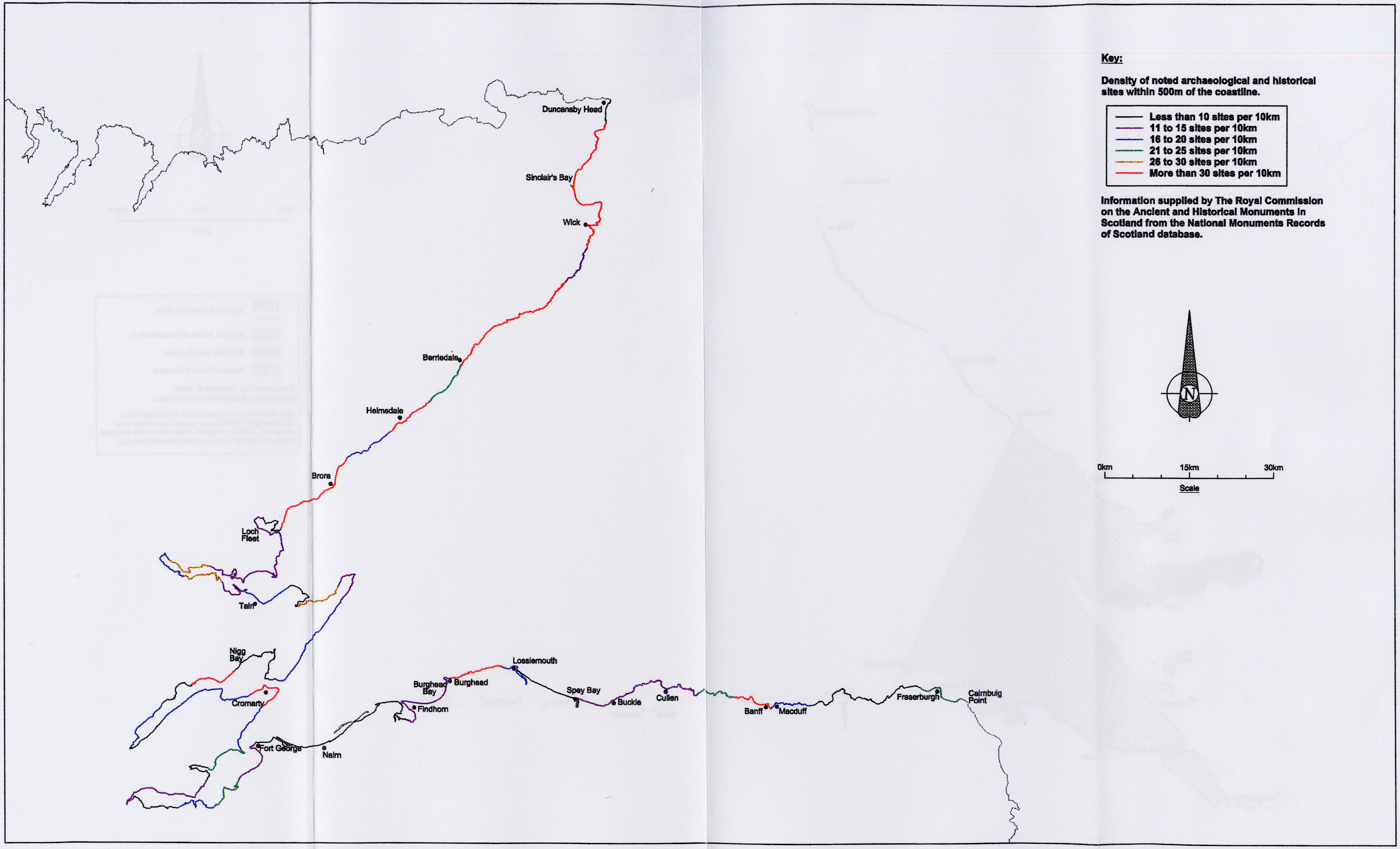


Figure 9 Cell 3 - Density of noted archaeological and historical sites

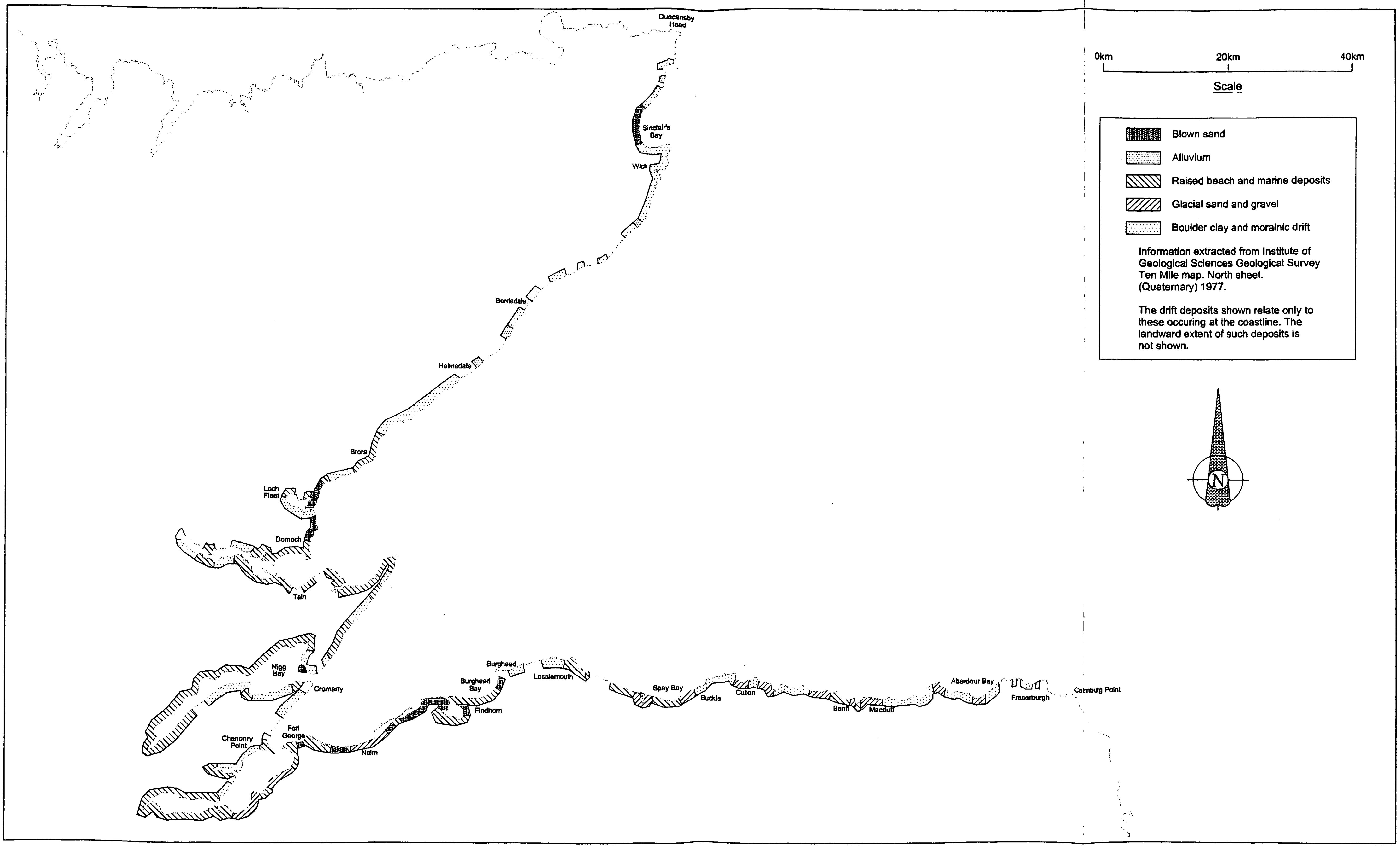


Figure 10 Cell 3 - Drift deposits

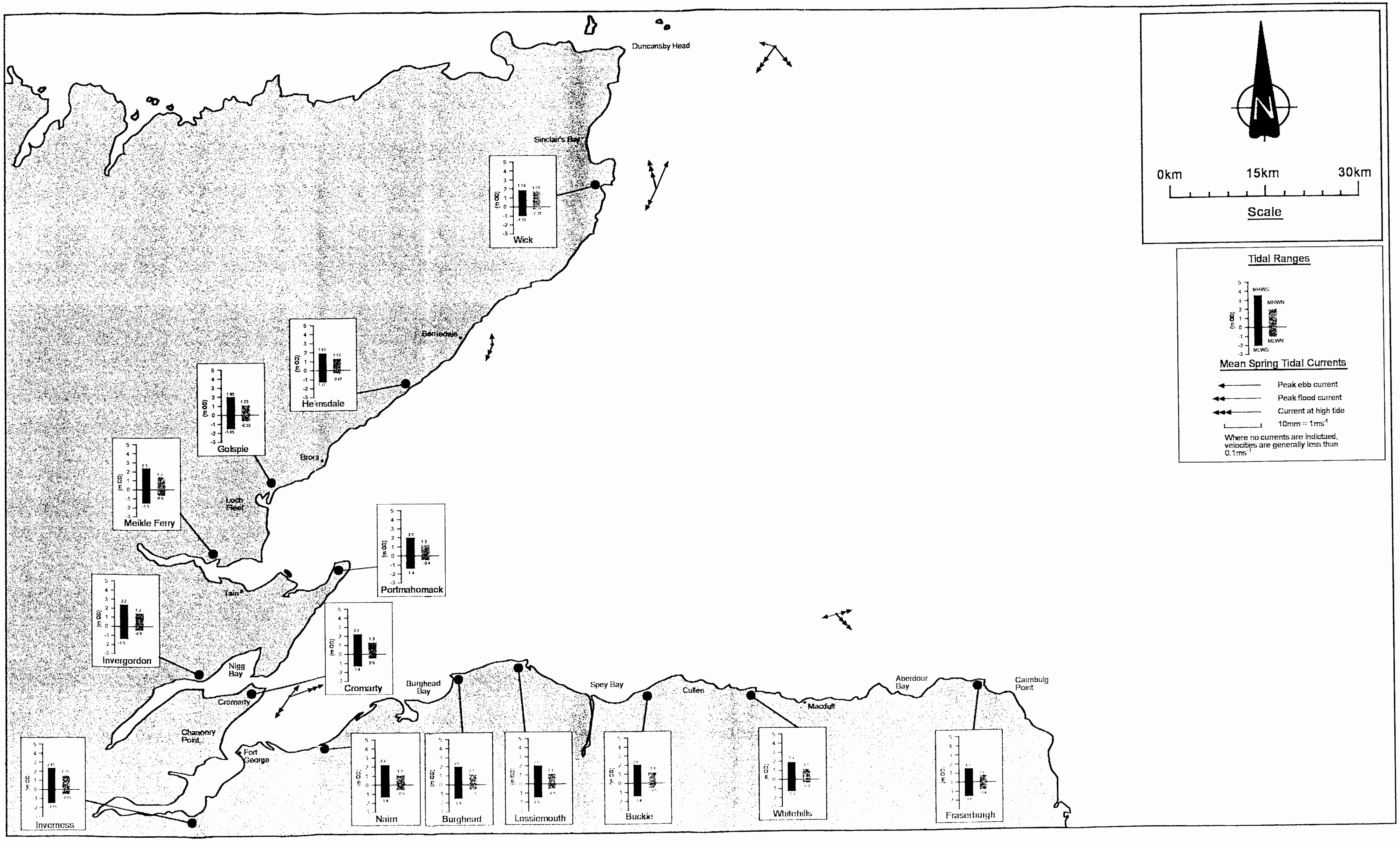


Figure 11 Cell 3 - Tidal levels and current information

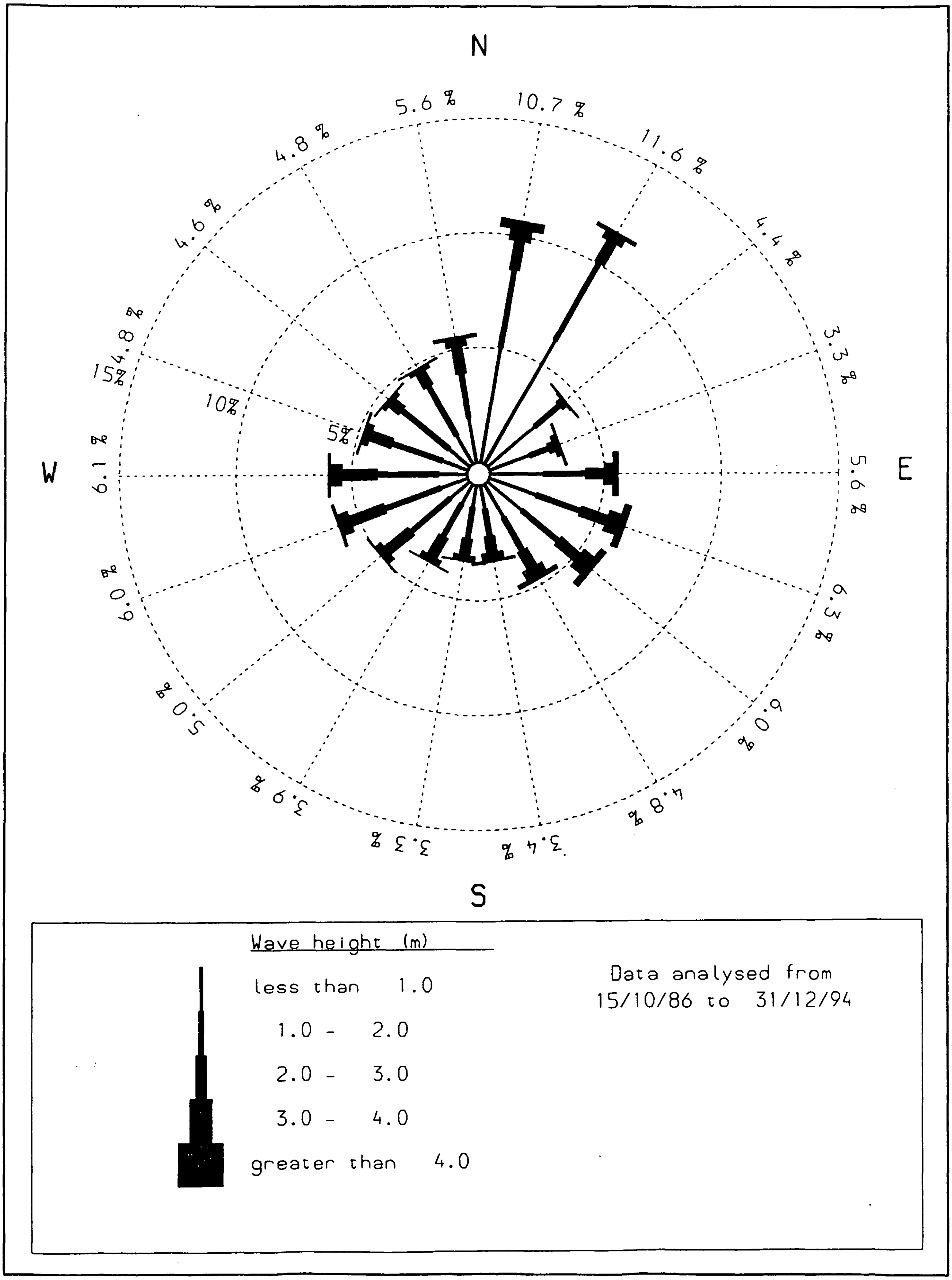


Figure 12 Total wave climate in the outer Moray Firth

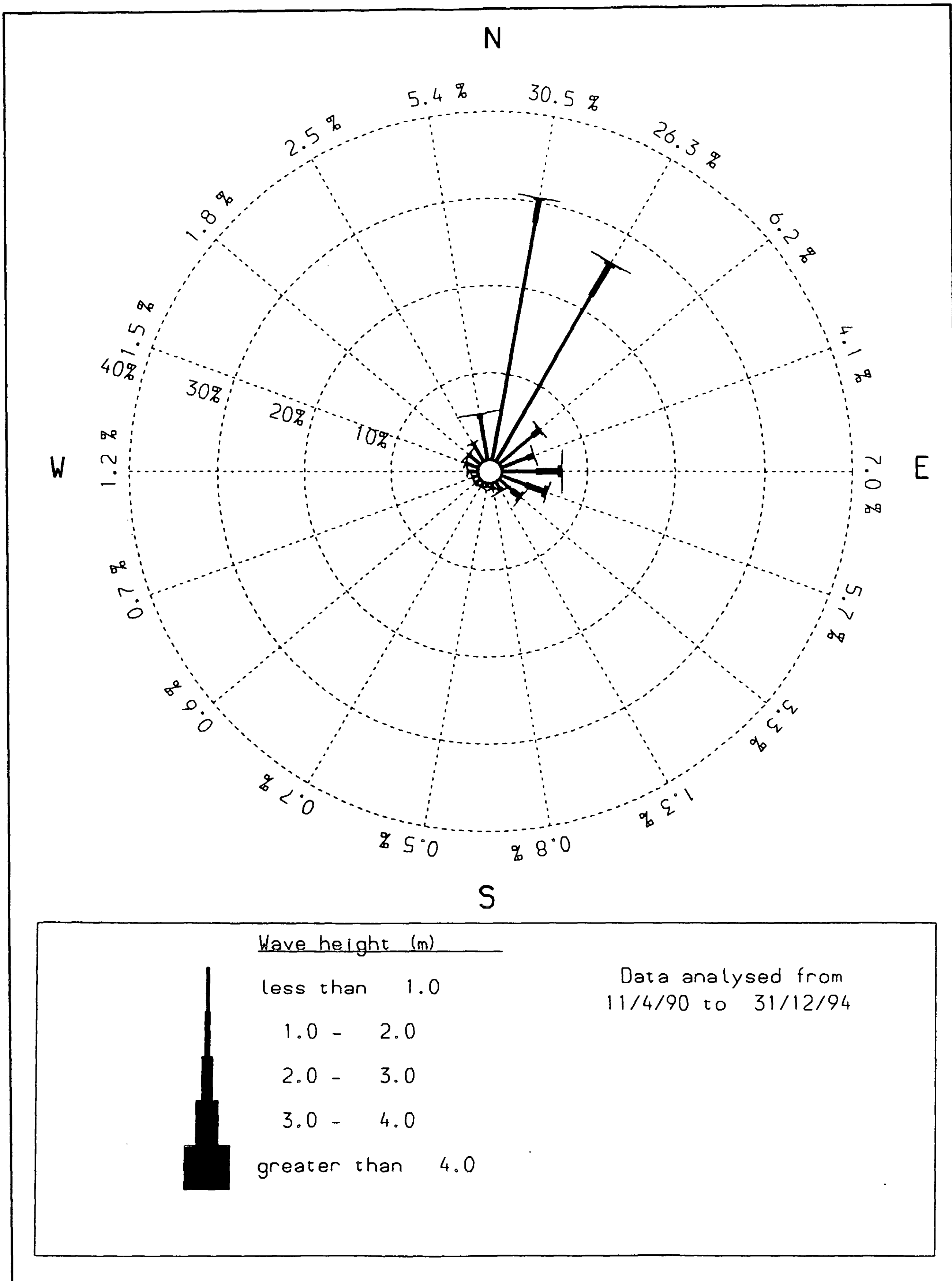


Figure 13 Swell wave climate in the outer Moray Firth

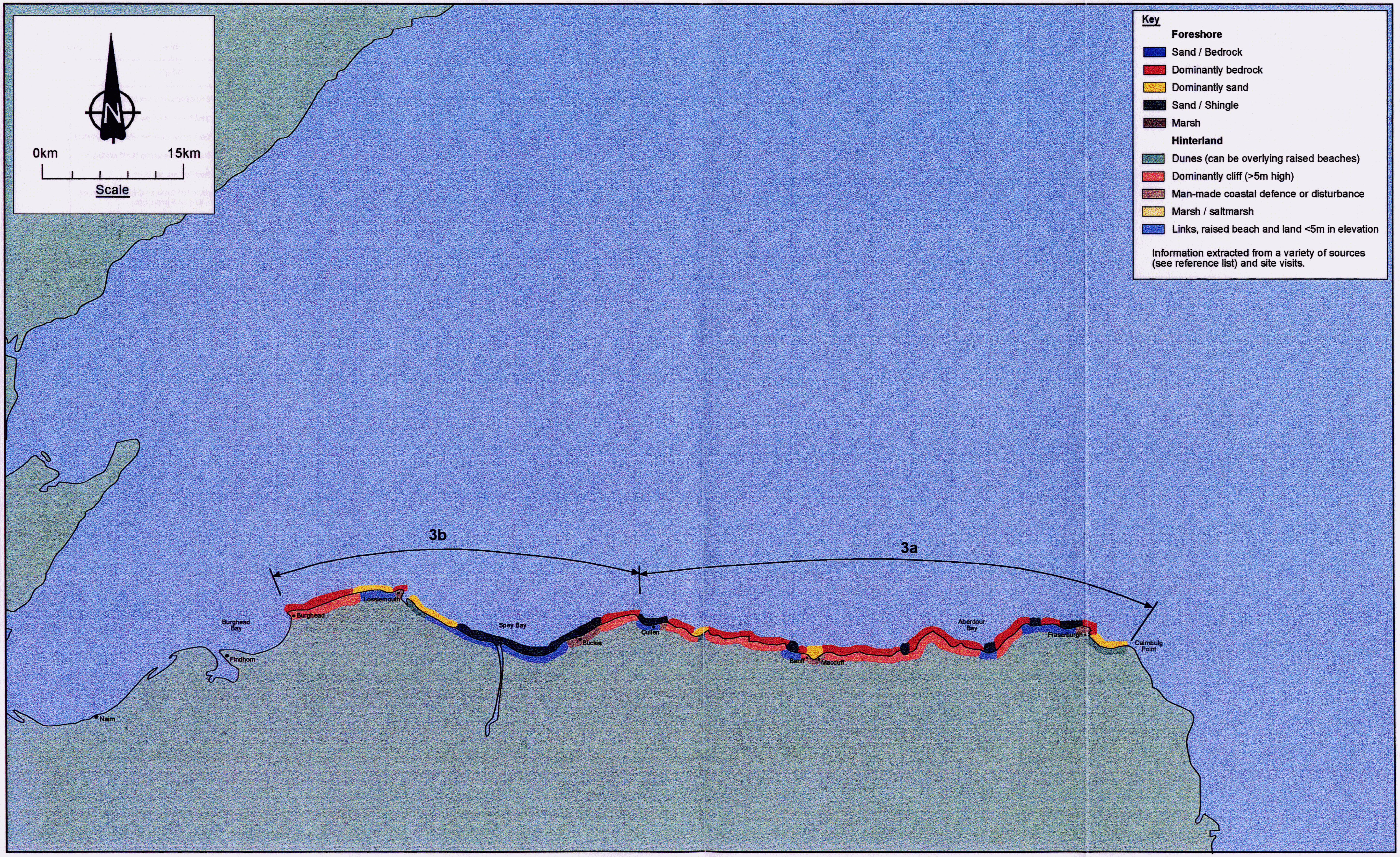


Figure 14 Sub-cells 3a & 3b - Foreshore and hinterland characteristics

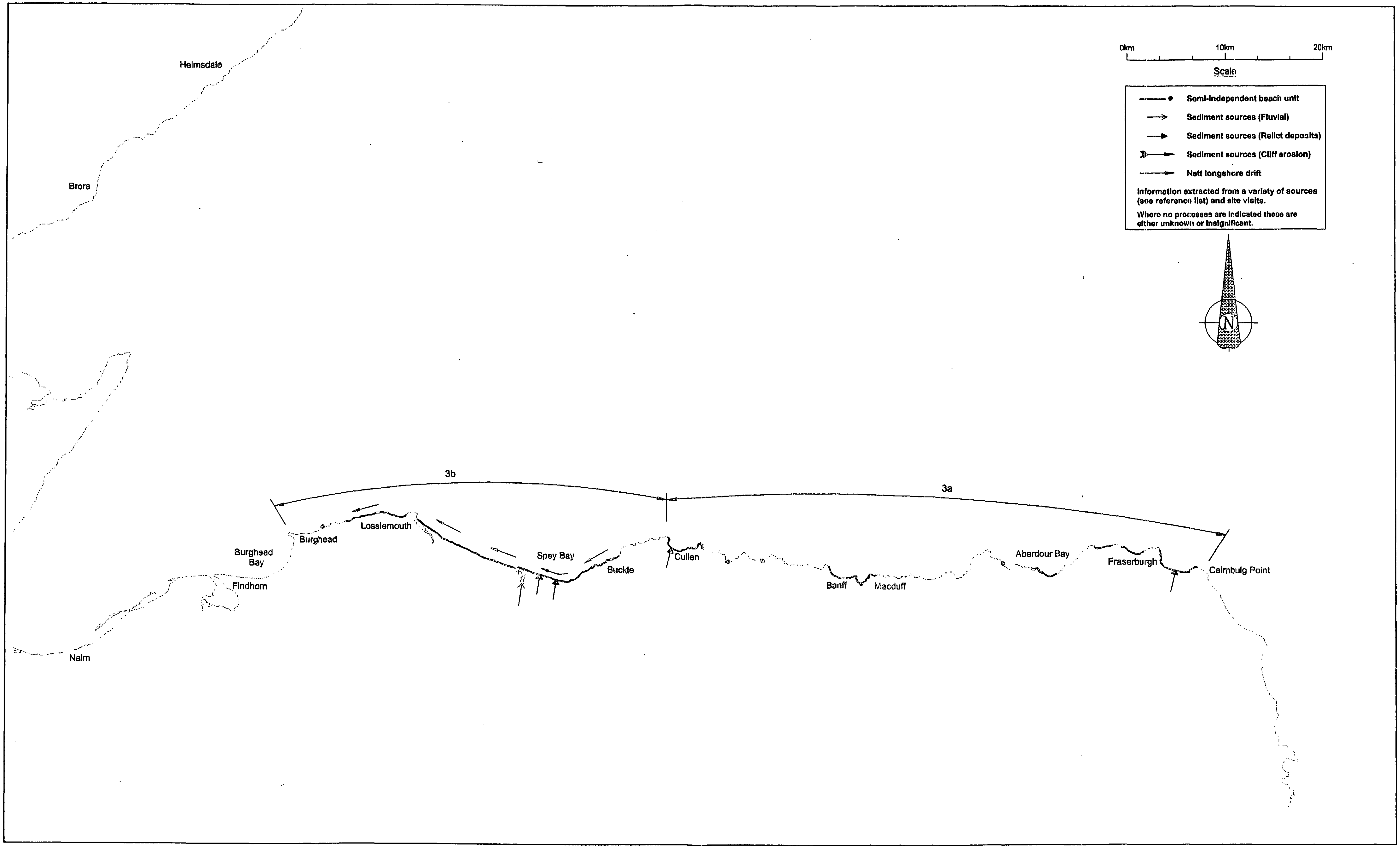


Figure 15 Sub-cells 3a & 3b - Dominant littoral processes

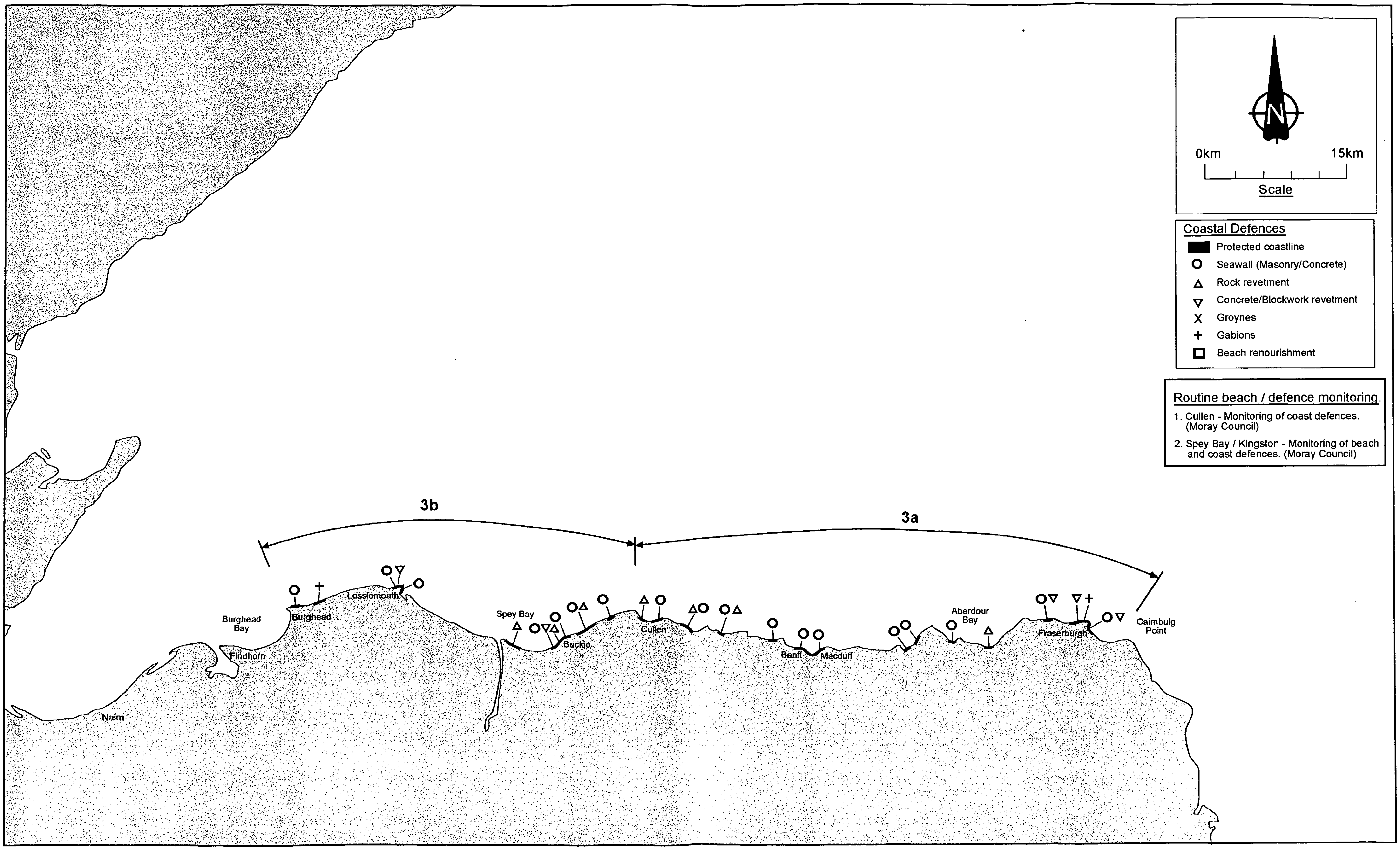


Figure 16 Sub-cells 3a & 3b - Coastal defence and monitoring

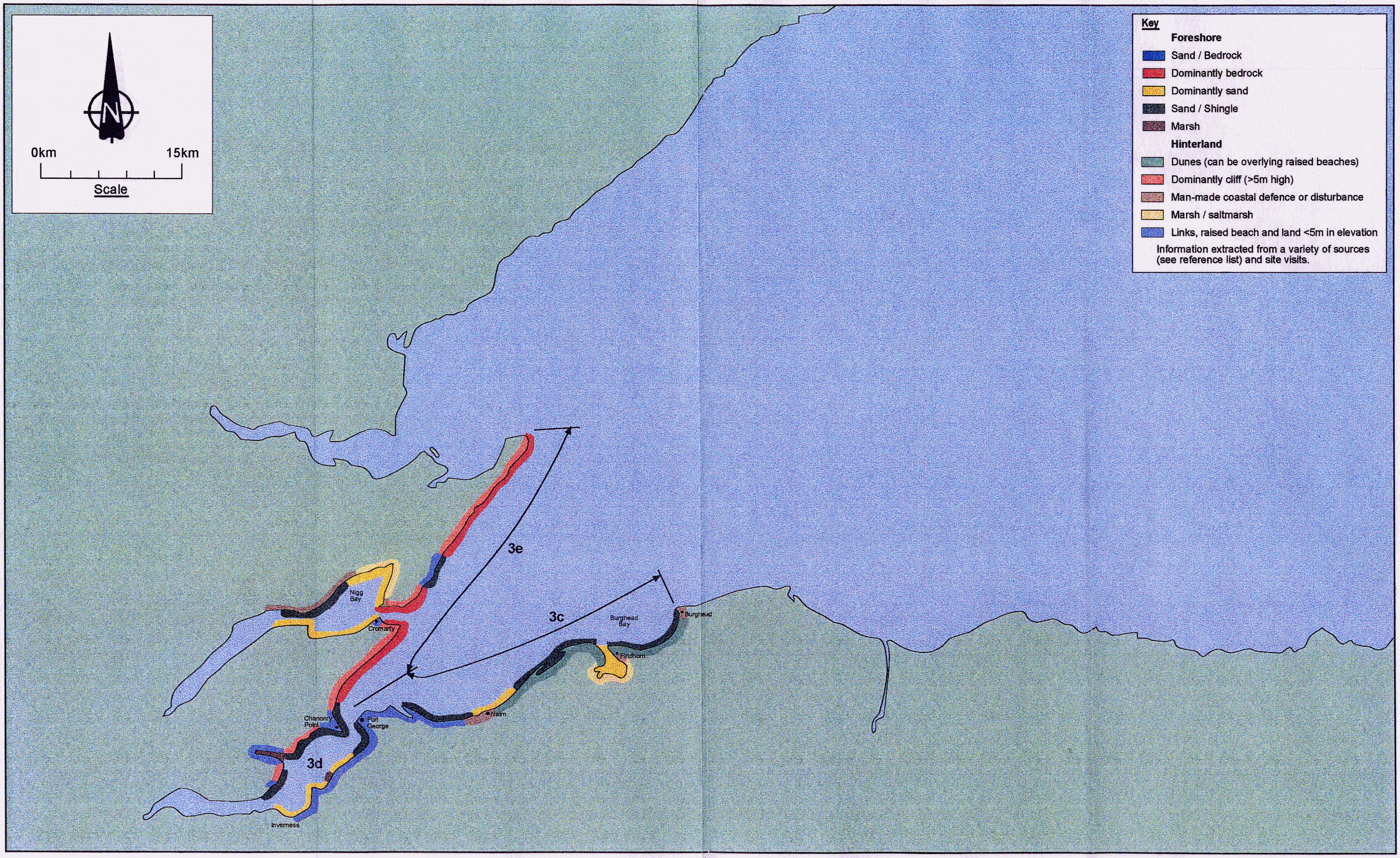


Figure 17 Sub-cells 3c to 3e - Foreshore and hinterland characteristics

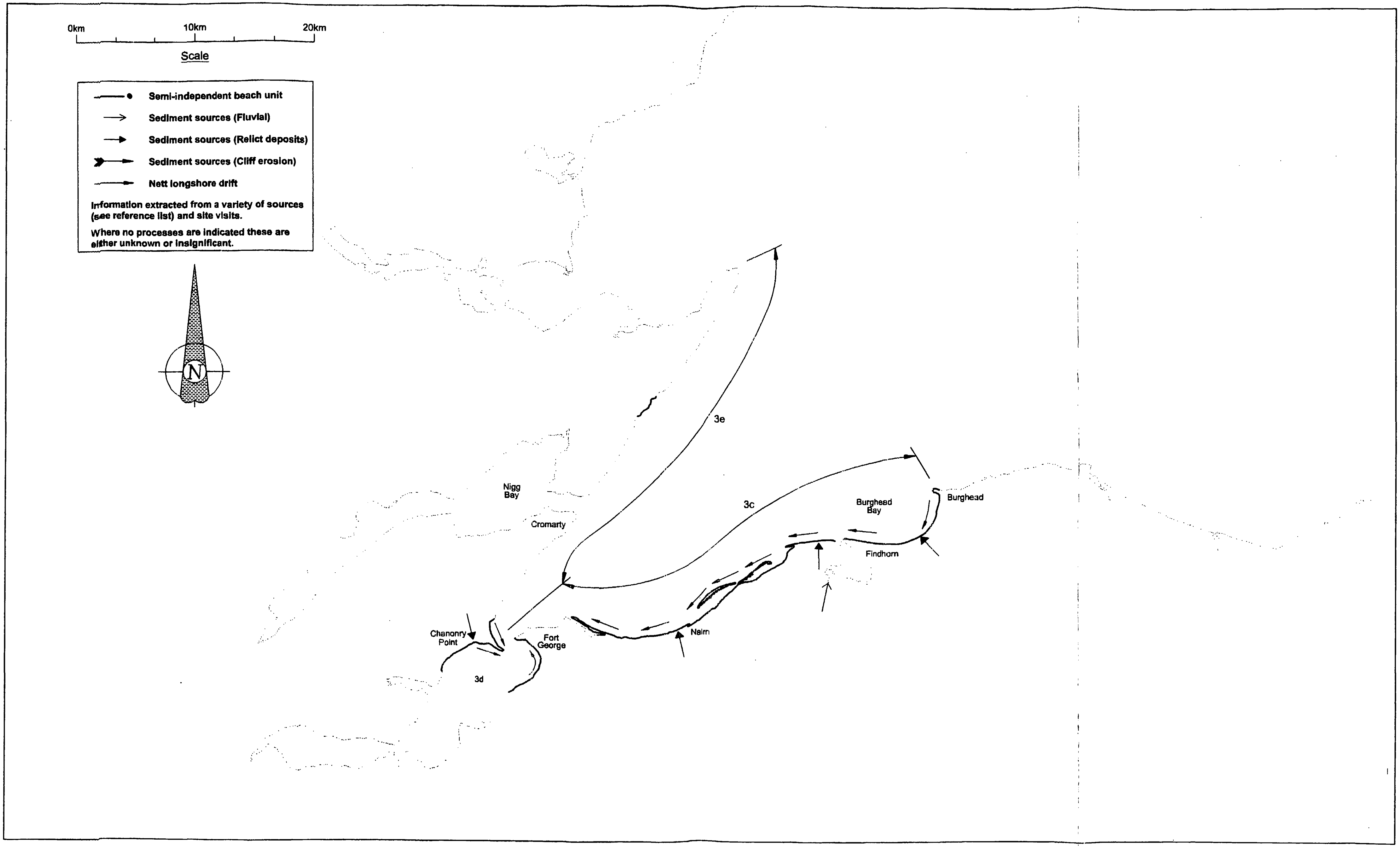


Figure 18 Sub-cells 3c to 3e - Dominant littoral processes

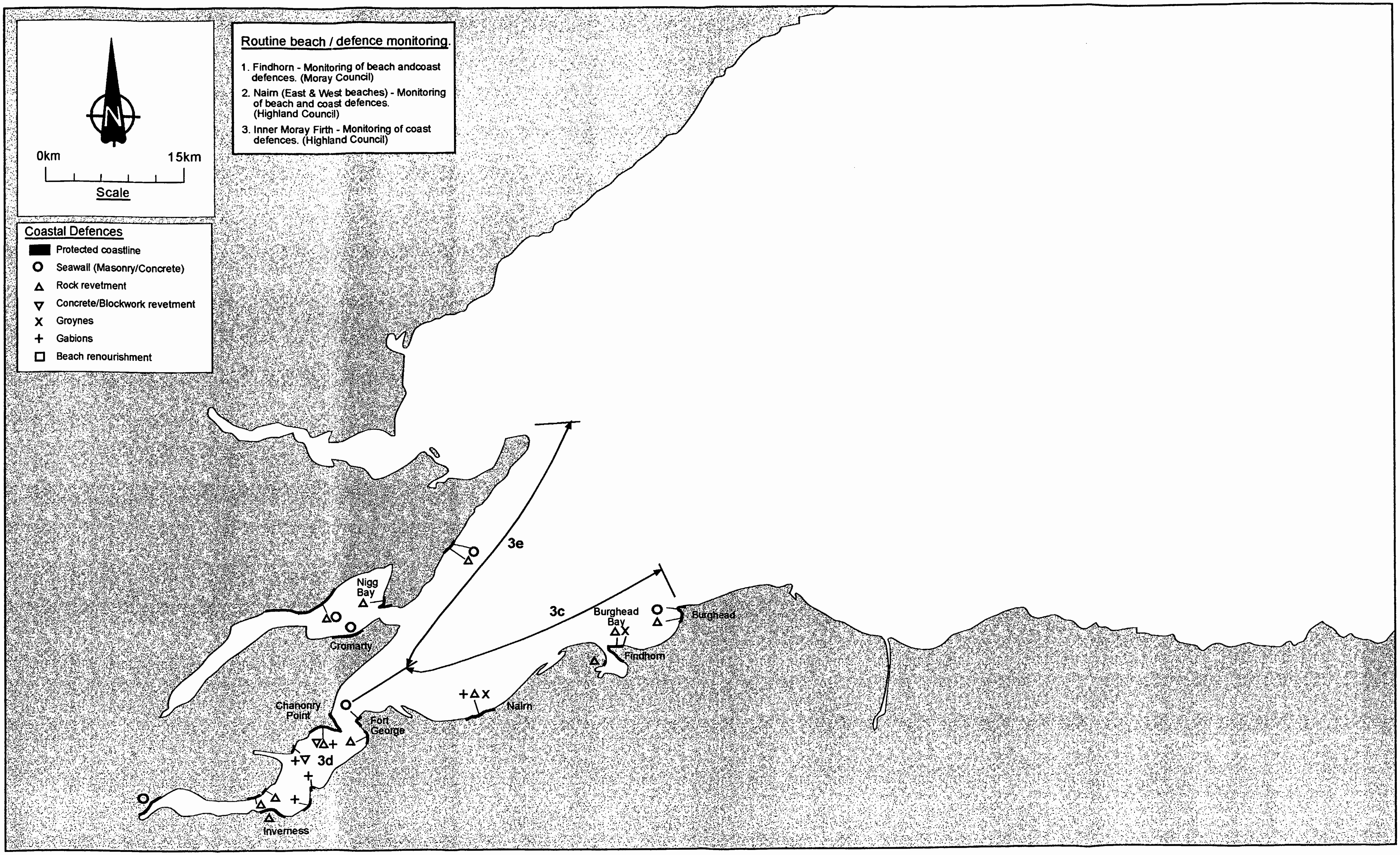
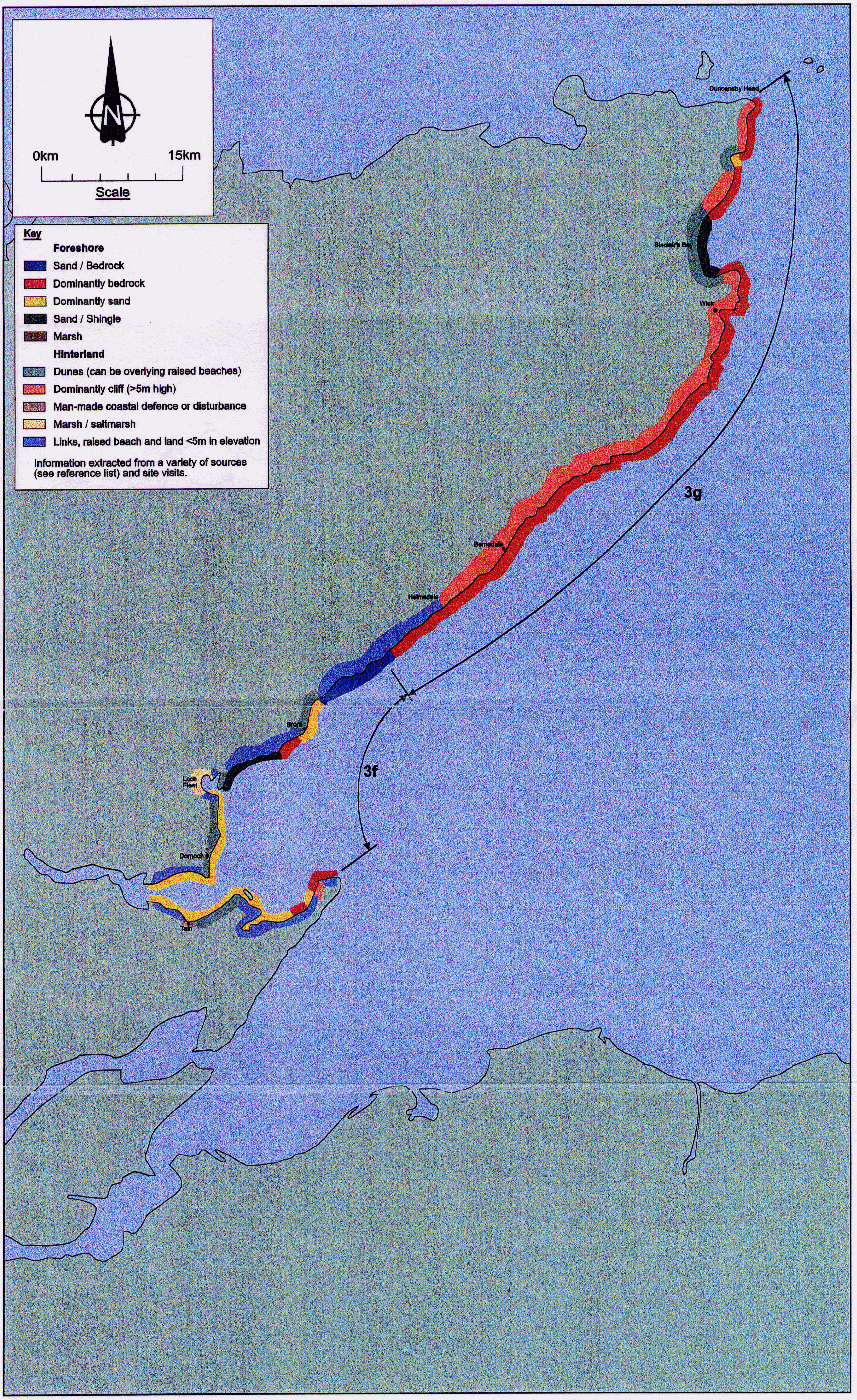


Figure 19 Sub-cells 3c to 3e - Coastal defence and monitoring

Figure 20 Sub-cells 3f & 3g - Foreshore and hinterland characteristics



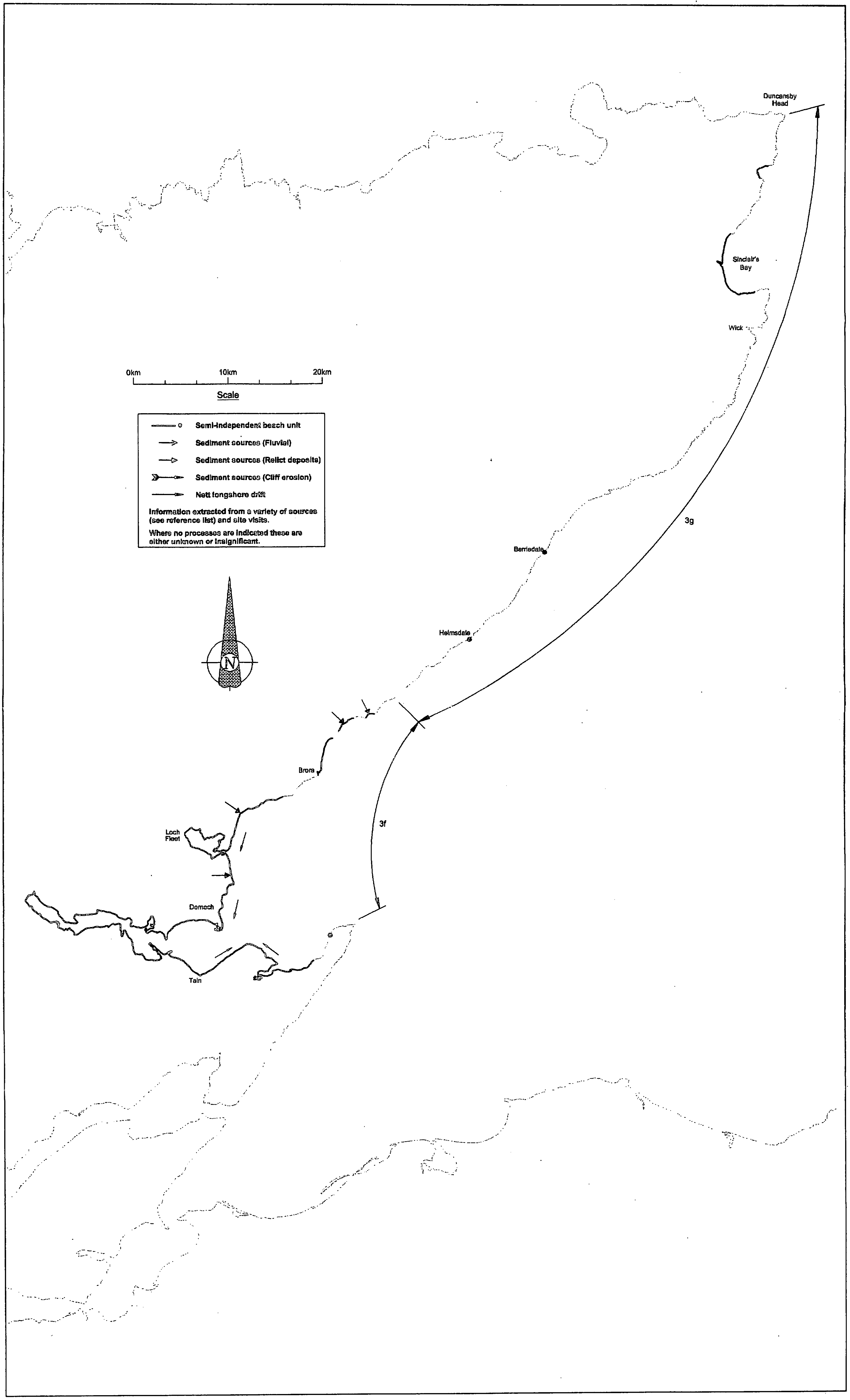


Figure 21 Sub-cells 3f & 3g - Dominant littoral processes

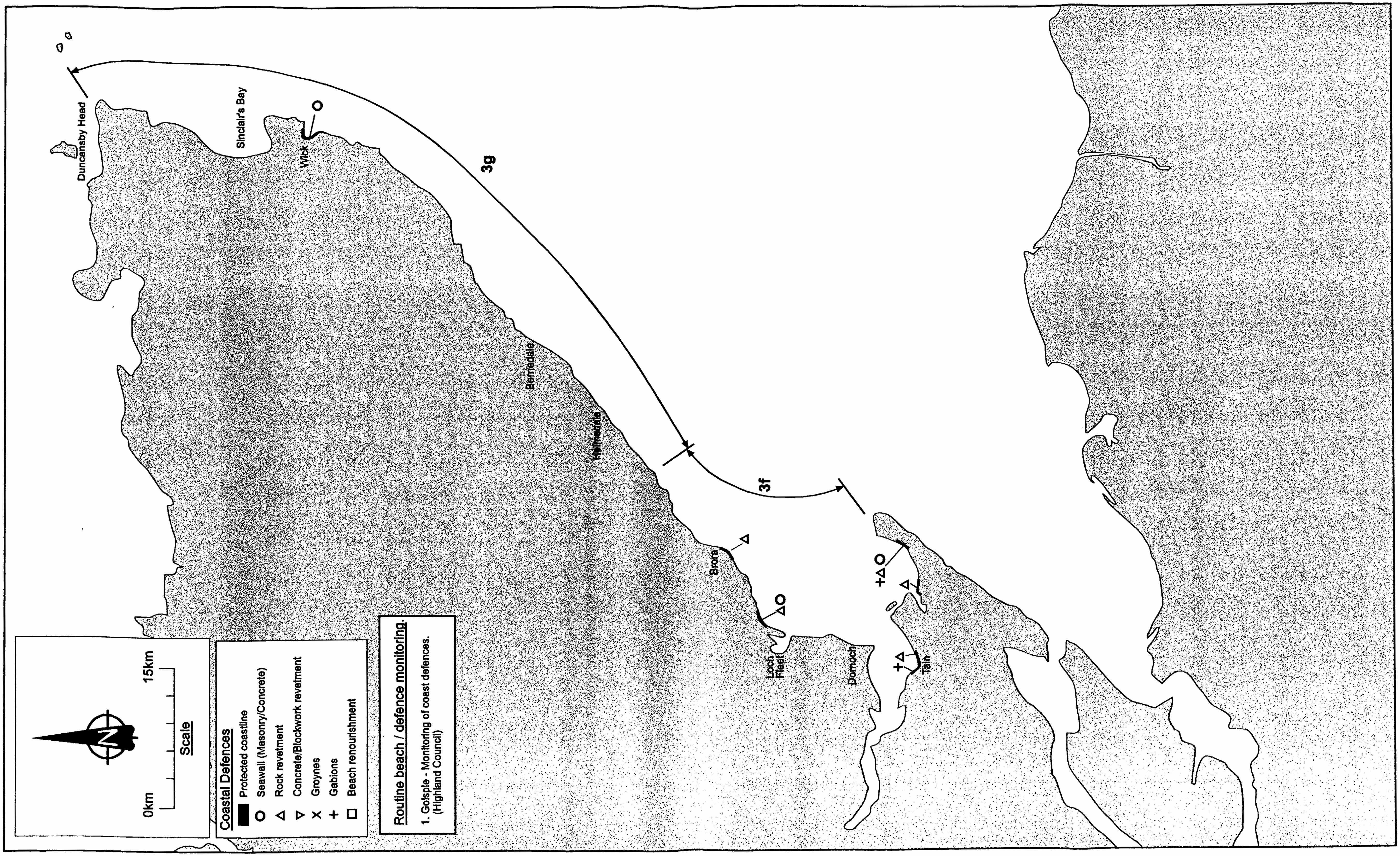


Figure 22 Sub-cells 3f & 3g - Coastal defence and monitoring

Appendix 1 Cell 3 - Details of Sites of Special Scientific Interest

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

Name	Grid Reference	Size (ha)	Date Notified	Site Designations
Gamrie to Pennan Coast	NJ824673	321.7	1985	Sea cliff (hard rock) Dry grassland Maritime heath Montane heath Woodland Flush or seepage line Seabirds breeding
Whitehills to Melrose Coast	NJ702645	93.9	1990	Geological interest
Cullen to Stakeness Coast	NJ574669	347.5	1985	Saltmarsh Sand dunes Sea cliff (hard rock) Dry grassland Maritime heath Flush or seepage line
Spey Bay	NJ325660	492	1986	Geomorphological interest Shingle heath Birch/Scots pine woodland Shingle slacks Fen and Carr woodland Saltmarsh Riverbank scrub woodland Wintering wildfowl Wintering waders Breeding terns Foraging ospreys
Lossiemouth Shore	NJ228711	7.9	1989	Geological interest
Clashach - Covesea	NJ167704	23.1	1989	Geological interest
Masonshaugh	NJ120693	36.7	1986	Geological interest
Culbin Sands, Forest & Findhorn Bay	NH990625	4916	1984	Geomorphological interest Tidal flats Open water Saltmarsh Sand dunes Maritime heath Woodland Fen Lower plants Terrestrial invertebrates Mammals noted Comments: Feeding & roosting area for wildfowl & waders.

Name	Grid Reference	Size (ha)	Date Notified	Site Designations
Whiteness Head	NH790580	411.7	1983	Geomorphological interest Tidal flats Saltmarsh Sand dunes Vegetated shingle Waders breeding Wildfowl breeding Wintering wildfowl & wader Seabirds breeding. Comments: Feeding/roosting area. Internationally important.
Longman & Castle Stuart Bays	NH715496	421	1997	Eel grass beds Wintering wildfowl & waders Comments: Internationally important
Beauly Firth	NH580480	2061.8	1988	Tidal flats Coastal lagoon Saltmarsh Woodland Fen Phragmites reedbed Fish noted Mammals noted Wildfowl breeding Site used for wintering wildfowl - Internationally important.
Munlochy Bay	NH672528	267.2	1985	Tidal flats Saltmarsh Flush or seepage line Phragmites reedbed Marine invertebrates Site used for wintering wildfowl - Nationally important.
Rosemarkie to Shandwick Coast	NH744586	450.6	1987	Geological interest Sand dunes Sea cliff (hard rock) Dry grassland Woodland Scarce or rare plants Marine biological interest Terrestrial invertebrates Seabirds breeding
Conon Islands	NH552570	287.0	1995	Saltmarsh Woodland Fen/grassland Terrestrial invertebrates Waders breeding Wildfowl breeding Site used for wintering wildfowl - Locally important.
Cromarty Firth	NH650670	3585	1988	Tidal flats Coastal lagoon Saltmarsh Vegetated shingle Lower plants Mammals noted Wildfowl breeding Seabirds breeding Site used for wintering wildfowl - Internationally important. Comments: Important for wintering waders.

Name	Grid Reference	Size (ha)	Date Notified	Site Designations
Tarbat Ness	NH949879	59.5	1985	Geological interest. Geomorphological interest. Dry grassland. Maritime heath. Site used by other wintering bird species.
Morrich More	NH830840	2975	1987	Geomorphological interest. Tidal flats. Saltmarsh Sand dunes Maritime heath/grassland Scarce or rare plants Lower plants Terrestrial invertebrates Wildfowl breeding Comments: Wintering wildfowl.
Dornoch Firth	NH760860	3577.4	1985	Tidal flats Saltmarsh Sand dunes. Maritime heath Woodland Scarce or rare plants Lower plants Marine biological interest
Kyle of Sutherland Marshes	NH515990	403.7	1988	Wet grassland/grazing marsh Dry grassland Woodland Peatland Fen Phragmites reedbed Scarce or rare plants Lower plants Terrestrial invertebrates Mammals noted Waders breeding Comments Wintering wildfowl
Loch Fleet	NH800960	1238	1984	Tidal flats Sand dunes Maritime heath Woodland Scarce or rare plants Lower plants Marine biological interest Site used for wintering wildfowl. Nationally important. Comments: Nationally important for wintering eider
Mound Alderwoods	NH765990	292	1986	Coastal lagoon Saltmarsh Woodland Fen Site used for wintering wildfowl. Internationally important Comments: Wintering wildfowl
Dunrobin Coast	NC856008	5.2	1983	Geological interest
Inverbrora	NC906033	55.9	1988	Geological interest
Helmsdale Coast	NC929077	148.4	1986	Geological interest

Name	Grid Reference	Size (ha)	Date Notified	Site Designations
Berriedale Cliffs	ND158280	234.4	1984	Dry grassland Maritime heath Seabirds breeding Site used for wintering wildfowl. Nationally important.
Dunbeath to Sgaps Geo	ND297371	146	1985	Dry grassland Maritime heath Seabirds breeding Site used for wintering wildfowl. Nationally important.
Craig Hammel to Sgaps Geo	ND362464	71.6	1985	Seabirds breeding Site used for wintering wildfowl. Nationally important.
Castle of Old Wick	ND371489	25	1985	Seabirds breeding Site used for wintering wildfowl. Nationally important
Long Berry Coast	ND377498	8.8	1988	Geological interest Dry grassland Maritime heath
Duncansby Head	ND397710	83.1	1985	Sea cliff(soft rock) Maritime heath Seabirds breeding Site used for wintering wildfowl. Nationally important.

Appendix 2 Cell 3 - Location of known archaeological and historical sites within 500m of the coastline

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

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

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

Appendix 3 Useful addresses

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

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

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

British Oceanographic Data Centre (BODC)
See Proudman Oceanographic Laboratory

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

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

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

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

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

Institute of Oceanographic Sciences
See Proudman Oceanographic Laboratory

Joint Nature Conservation Committee
Monkstone House
City Road
Peterborough — 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 Meteorological Office
Marine Consulting Service
Johnstone House
London Road
Bracknell
RG12 2UR
Tel: 01344 420242
Fax: 01344 854412

UK Offshore Operators Association Ltd (UKOOA)
30 Buckingham Gate
London
SW1E 6NN
Tel: 020 7802 2400
Fax: 020 7802 2401

Appendix 4 Glossary

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

Bed forms	Features on a seabed (e.g. ripples and sand waves) resulting from the movement of sediment over it
Bed load	Sediment transport mode in which individual particles either roll or slide along the seabed as a shallow, mobile layer a few particle diameters deep
Bed shear stress	The way in which waves (or currents) transfer energy to the sea bed
Benefits	The economic value of a scheme, usually measured in terms of the cost of damages avoided by the scheme, or the valuation of perceived amenity or environmental improvements
Berm	(1) On a beach: a nearly horizontal plateau on the **beach face** or **backshore**, formed by the deposition of beach material by wave action or by means of a mechanical plant as part of a **beach recharge** scheme (2) On a structure: a nearly horizontal area, often built to support or key-in an **armour layer**
Boulder	A rounded rock on a beach, greater than 250mm in diameter, larger than a **cobble** - see also **gravel, shingle**
Boundary conditions	Environmental conditions, e.g. waves, currents, drifts, etc. used as boundary input to physical or numerical models
Bound long wave	Long wave directly due to the variation in set-down at the breaker line due to wave groups
Breaching	Failure of the **beach head** allowing flooding by tidal action
Breaker depth	Depth of water, relative to **still water level** at which waves break; also known as **breaking depth** or limiting depth
Breaker index	Maximum ratio of **wave height** to water depth in the surf zone
Breaker zone	The zone within which waves approaching the coastline commence breaking, typically in water depths of between 5 and 10 metres
Breaking	Reduction in wave energy and height in the surf zone due to limited water depth
Breastwork	Vertically-faced or steeply inclined structure usually built with timber and parallel to the shoreline, at or near the **beach crest**, to resist erosion or mitigate against flooding
Bypassing	Moving beach material from the **updrift** to the **downdrift** side of an obstruction to **longshore-drift**
Chart datum	The level to which both tidal levels and water depths are reduced - on most UK charts, this level is that of the predicted lowest **astronomical tide** level (LAT)
Clay	A fine grained, plastic, sediment with a typical grain size less than 0.004mm. Possesses electro-magnetic properties which bind the grains together to give a bulk strength or cohesion
Climate change	Refers to any long-term trend in mean sea level, **wave height**, wind speed, drift rate etc.
Closure depth	The depth at the offshore limit of discernible bathymetric change between surveys.
Coastal cell	See Sediment cell

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Wave celerity The speed of wave propagation

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

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

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

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

Wave frequency The inverse of **wave period**

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

Wave generation Growth of wave energy by wind

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

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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.