INTERTIDAL SAND AND MUDFLATS &
SUBTIDAL MOBILE SANDBANKS
An overview of dynamic and sensitivity characteristics for conservation management of marine SACs

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PREFACE

The 1990s are witnessing a “call to action” for marine biodiversity conservation through wide ranging legislative fora, such as the global Convention on Biodiversity, the European Union’s “Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora” (the Habitats Directive) and more recently in developments to the Oslo and Paris Convention (OSPAR). These landmark legal instruments have in turn provided sufficient scientific rationale, legal mandate and social synergy to rally governments, NGOs, private industry and local communities into a new era of unprecedented conservation action.

Each of these initiatives identifies marine protected areas as having a key role in sustaining marine biodiversity. To manage specific habitats and species effectively there needs to be a relatively clear understanding of their present known distribution, the underpinning biology and ecology and their sensitivity to natural and anthropogenic change. From such a foundation, realistic guidance on management and monitoring can be derived and applied.

The Habitats Directive requires the maintenance and/or restoration of natural habitats and species of European interest at favourable conservation status across their biogeographical range. The designation and management of a network of Special Areas of Conservation (SACs) have a key role to play in this. The specific 'marine' habitats defined in Annex I of the Habitats Directive include:

- Sandbanks which are slightly covered by sea water all the time,
- Estuaries
- Mudflats and sandflats not covered by seawater at low-tide,
- Large shallow inlets and bays
- Lagoons
- Reefs
- Submerged or partly submerged sea caves

These habitats are vast in scope and challenging to quantify in terms of favourable conservation status, so there has been increased attention to 'sub-features' of these habitats which are in effect constituent components and/or key elements of the habitats from a range of biodiversity perspectives.

One initiative now underway to help implement the Habitats Directive is the UK Marine SACs LIFE Project, involving a four year partnership (1996-2001) between English Nature (EN), Scottish Natural Heritage (SNH), the Countryside Council for Wales (CCW), Environment and Heritage Service of the Department of the Environment for Northern Ireland (DOENI), the Joint Nature Conservation Committee (JNCC), and the Scottish Association of Marine Science (SAMS). While the overall project goal is to facilitate the establishment of management schemes for 12 of the candidate SAC sites, a key component of the project assesses the sensitivity characteristics and related conservation requirements of selected sub-features of the Annex I habitats noted above. This understanding will contribute to more effective management of these habitats by guiding the detailed definition of the conservation objectives and monitoring programmes and by identifying those activities that may lead to deterioration or disturbance.

A diverse series of sub-features of the Annex I marine habitats were identified as requiring a scientific review, based on the following criteria:

- key constituent of several candidate SACs;
- important components of Annex I habitats in defining their quality and extent;
- extensive information exists requiring collating and targeting, or there is minimal knowledge needing verification and extended study.

This resulted in the compilation a nine-volume review series, each providing an "Overview of Dynamics and Sensitivity Characteristics for Conservation Management of Marine SACs" for the following sub-features:

Vol. I	Zostera Biotopes
Vol II	Intertidal Sand and Mudflats & Subtidal Mobile Sandbanks
Vol III	Sea Pens and Burrowing Megafauna
Vol. IV	Subtidal Brittlestar Beds
Vol. V	Maerl
Vol. VI	Intertidal Reef Biotopes
Vol. VII	Infralittoral Reef Biotopes with Kelp Species
Vol. VIII	Circalittoral Faunal Turfs
Vol. IX	Biogenic Reefs.

Each report was produced initially by appropriate specialists from the wider scientific community in the respective subject. These reports have been reviewed through an extensive process involving experts from academic and research institutions and the statutory nature conservation bodies.

The results of these reviews are aimed primarily at staff in the statutory nature conservation bodies who are engaged in providing conservation objectives and monitoring advice to the marine SAC management schemes. However these reports will be a valuable resource to other relevant authorities and those involved in the broader network of coastal-marine protected areas. In order to reach out to a wider audience in the UK and Europe, a succinct 'synthesis' document will be prepared as a complement to the detailed 9-volume series. This document will summarise the main points from the individual reviews and expand on linkages between biotopes, habitats and sites and related conservation initiatives.

These reports provide a sound basis on which to make management decisions on marine SACs and also on other related initiatives through the Biodiversity Action Plans and Oslo and Paris Convention and, as a result, they will make a substantial contribution to the conservation of our important marine wildlife. Marine conservation is still in its infancy but, through the practical application of this knowledge in the management and monitoring of features, this understanding will be refined and deepened.

We commend these reports to all concerned with the sustainable use and conservation of our marine and coastal heritage.

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EXECUTIVE SUMMARY

Study aims

The EU Habitats Directive for the protection of species and habitats requires that management plans be created in order to detect and respond to man-induced change. In particular, such plans are to be prepared for the candidate Special Areas of Conservation (SAC), that are part of the UK marine SAC project biotope complexes. As part of this, the UK Marine SAC Project requires a detailed description of the features of selected biotope complexes found in Annex I habitats, the techniques for monitoring those biotopes and the proposals for the management strategies to be employed. The present report focuses on two sedimentary marine biotope complexes: *intertidal mudflats and sandbanks, i.e. those uncovered for part of the tidal cycle,* and *subtidal mobile sandbanks, i.e. those covered at all stages of the tide.*

Nature and importance of the biotope complexes

The primary features of these sedimentary biotope complexes are:

- by definition they are relatively homogeneous but often occur in highly variable environments such as estuaries and wave-dominated coastal areas. In the context of the Habitats Directive, this biotope complex is defined as ‘mudflats and sandflats not covered by seawater at low tide’. For the purposes of this report, the ‘**Intertidal mud and sandflats**’ biotope complex is taken to include all biotopes that can be found in sheltered (low energy) areas, in the case of mudflats, and all biotopes that can be found in areas along the exposure gradient (low and high energy) in the case of intertidal sandflats.

- ‘**Subtidal mobile sandbanks**’ biotope complex includes all biotopes likely to be found in subtidal non-vegetated mobile sands. The biotopes are also discussed in terms of change along a gradient of particle sizes or salinity, with biological communities changing as a result of the differing environmental requirements of the characterising species (Connor *et al*, 1997). The latter is particularly apparent in estuarine habitats.

- however, whilst there is a good inventory of intertidal sand and mud flats, which individually may cover areas from a few hectares to several km^2, there is no national inventory for subtidal mobile sand banks.

- they are highly important in covering large areas of shelf and estuarine beds and an integral part of the Annex I habitats: ***Estuaries***, ***Large Shallow Inlets and Bays***, and ***Lagoons***;

- their distribution and importance has produced good information on well-defined communities for certain areas, particularly the *intertidal sand and mudflats,* but less so for *subtidal mobile sandbanks.*

The value of these biotope complexes can be summarised as:

- in economic terms, it is related to conserving, protecting and creating resources valued by man, e.g. fisheries and shellfisheries, minerals for extraction, and land that requires protection.

- in scientific terms, it has been in providing an understanding of fundamental biological and environmental interactions and processes and the interdependence of habitats within dynamic marine systems.

- in conservation terms, especially for intertidal mud flats, it is as declining wetland areas which support internationally important populations of wading birds and nationally important populations of juvenile fishes.

Environmental requirements and physical attributes

An understanding of the physico-chemical conditions (as “environmental master factors”) is necessary to understand and interpret the evolution of sedimentary biotope complexes. The environmental master factors are: temperature, light, salinity, situation (including stability, exposure to air and desiccation and, by extension, depth regime), oxygen content, nutrients, currents (tidal, wind-driven, freshwater-driven and residual) and tides, and the nature of the bottom substratum.

The biotope complexes discussed can be regarded as a continuum from muds high in the intertidal region, through intertidal sands to subtidal sands. Each of these has their own characteristics and so they are treated separately despite there being common mechanisms responsible for their formation, e.g. hydrographic regime and sediment structure.

The primary physical features of the hydrographic regime (tides, waves, residual currents) together with the underlying physiography and geology will create the conditions for a given type of substratum to develop. The characteristics and nature of the hydrographic, sedimentary and depth regimes are intimately related and will create conditions for the colonisation by, and maintenance of, organisms of the biotope complexes, and for the delivery of food and colonising organisms.

Mudflats and sheltered intertidal sandflats reflect low energy conditions which are characterised by: particles of a small medium diameter, shallow slope, high water content, high sorting coefficient, low permeability and generally low porosity, high organic content and therefore high reducing conditions, high carbon to nitrogen ratio, high microbial population and high sediment stability.

Subtidal mobile sandbanks and exposed intertidal sands are found in high energy areas which are characterised by: particles of a high median diameter, low sorting coefficient, high permeability, generally high porosity (depending on compaction), low organic content, high oxygen content and therefore low reducing conditions, low carbon to nitrogen ratio, small microbial population and low sediment stability.

Whereas intertidal mud and sandflats will develop in low energy areas, subtidal mobile sandbanks will develop especially as the result of the physiography and large-scale current patterns producing gyres.

Biology and ecological functioning

In understanding the biology of the sedimentary biotope complexes, it is necessary to consider the structure of the communities and their functioning. The important and most widely-studied components of the systems are the primary producers (predominantly the microphytobenthos), the benthic macrofauna and meiofauna, the mobile epibenthos and the vertebrate predators.

Organic production supporting the system is autochthonous in the case of the mudflats and, to a lesser extent, the sandflats but allochthonous for these biotope complexes and especially the subtidal mobile sand banks. The intertidal sedimentary communities are well-categorised and fit with the Petersen's Boreal *Macoma* and *Tellina* assemblages whereas the subtidal mobile sandbank community is less well-defined but similar to the Boreal Offshore Sand Association.

The biodiversity of these sedimentary biotope complexes is influenced by habitat stability and sediment type. In particular the complexity of the substratum will determine the number of available niches and hence the diversity of the community.

High energy areas such as exposed sandflats and subtidal mobile sandbanks are characterised by a low diversity, lack of sedentary forms especially bivalve molluscs, and the numerical dominance of agile swimmers such as haustoriid amphipods and isopods. These species have a short life span and are characterised by their ability to withstand sediment disturbance. Low energy areas such as intertidal sheltered sandflats and mudflats favour the establishment of a predominantly sessile community of polychaetes and long-lived bivalves.

The intertidal sand and mudflats are important in supporting predator communities such as mobile macrofauna, overwintering and migrating wading birds and juvenile fish, whereas the subtidal mobile sandbanks support lower densities of epibenthos in addition to demersal fishes and seabirds taking sandeels (*Ammodytes* spp.). These have implications at local, regional and international scales.

In order to understand the processes structuring the biology of these areas, it is necessary to understand the way in which (i) the environmental parameters create available niches for colonisation (the 'environment to biology' relationships); (ii) the biological inter-relationships mediate the community formation (the 'biology to biology' links, including feeding, competition, recruitment processes) and (iii) the means by which the biota modify the sediment structure ('biology to environment' processes such as bioturbation and biosedimentation).

Sensitivity to natural events

The biota of these biotope complexes are sensitive to changes in several environmental and biological characteristics. These include:

- for both intertidal and subtidal biotope complexes - hydrographical changes and water activity, especially as the result of storm events, concomitant sediment change, and predator changes;

- for intertidal biotopes - sea level rise and tidal elevation change effecting 'tidal squeeze' when the upper tidal boundary is restricted, exposure and desiccation affecting the organisms as the result of their intolerance, and extremes of climate, including temperature and freshwater runoff. In particular, any stressor which changes the shore topography will affect all other biological and physical processes.

Sensitivity is reflected by the biotope complexes in several key physical and biological responses, including:

- as a response to seasonal changes but by their nature they are able to accommodate natural variability and have a benthic biota relatively resilient to these changes. By definition and their nature, the fauna of subtidal mobile sands can tolerate sedimentary disturbance whereas the sediment biomodification potential of intertidal mud and sandflat biota dictates that they can also withstand sediment changes.

- by changes to the benthic species composition and responses by predators. In turn, the biota are sensitive to inter- and intra-specific interactions such as competition. Similarly, changes in physical conditions will change settlement patterns and in turn affect the community structure. However, although biological interactions, such as competition for space or food, will be important in structuring the community, these are complex and poorly understood.

Sensitivity is also reflected in the stability of the biotope complexes:

- the sheltered intertidal habitats are relatively stable whereas the subtidal mobile sandbanks are more complex and may undergo fluctuating periods of stability and instability. However, there is poor information on the degree of natural variability in most of the physical and biological parameters, especially subtidally, and the relative stability of the systems is poorly understood in ecological timescales.

- the results of disturbance differs depending on the nature of the biotope and may range from short to longer term changes in diversity and species richness. The subtidal mobile sandbanks may be defined by transitional communities which are subject to a high degree of natural variability. Similarly, intertidal biotopes subject to salinity changes will experience large-scale localised changes in community structure.

Sensitivity to anthropogenic activities

It is likely that all human activities will affect these biotope complexes as they occur especially in estuarine and nearshore areas. However, the extent and duration of any impact differs with activity and biotope complex.

Intertidal sand and mudflats have a high potential for being impacted by land claim, barrages (amenity, storm-surge and tidal power), organic enrichment, industrial and domestic effluents, oil spills and recreation. *Subtidal mobile sandbanks* have a high potential for being impacted by dredging and dredged material disposal, aggregate extraction, fishing, oil and gas exploration and development. These impacts are summarised in a qualitative way below and detailed in the report.

Activity	Intertidal Sand And Mudflats	Subtidal Mobile Sandbanks
Land-claim (Reclaimation)	high	low
Barrages (amenity, storm-surge and tidal energy	high	moderate
Dredging and spoil disposal, and aggregate extraction	low	high
Fishing	low	high
Organic enrichment	high	moderate
Industrial and domestic effluent discharge	high	low
Oil and gas exploration, development and production	low	high
Oil spills and tanker accidents	high	low
Recreation	high	low

Several of the activities will affect the physical, chemical and biological integrity of these biotope complexes by changing the hydrographic regime, and thus the sedimentary regime, the sediment health, the nature of the infaunal communities and thus the usage by predators. The greatest threats to the biotope complexes are through the loss of habitat through barrage construction, land claim or the production of water quality barriers. The latter will degrade the sediment and consequently the infauna and its predators.

These biotope complexes are at risk from the removal by man of their environmental (physical) or biological resources, for example the sediment through aggregate extraction, or the biota through direct and indirect effects of fishing for round and flatfish and shellfish.

The quantitative nature of change to the biotope complexes is well understood and may be predicted for certain anthropogenic stressors, such as human disturbance to intertidal flats and organic enrichment. However, the effects of other stressors such as aggregate extraction and dredging cannot be quantitatively predicted.

Monitoring and surveillance

The biotope complexes require sampling and analysis to determine the natural variability (i.e. condition monitoring or surveillance) and to identify departures from that due to anthropogenic impacts (i.e. compliance monitoring). The latter should be further developed to determine whether predefined and agreed standards and objectives (as “Ecological Quality Standards and Objectives”) have been met.

In particular the monitoring will determine any interference, especially by human activities, to the physical forcing variables and changes to aspects of conservation value, in invertebrate biota and predators. Furthermore, the monitoring has to be sufficient to link biological and environmental variables.

While surveillance (as in condition monitoring) of the biotope complexes may be desirable at 3 or 5 year intervals, the high cost of monitoring may dictate that further surveys, and especially compliance monitoring will be carried out only following changes to the human uses and users of the area or if there is the indication of large-scale natural change.

The monitoring is required to determine the extent and health of the biotope complexes and the integrity of the physical and biological features. However, it is necessary to emphasise the value of easily-obtained information, such as from large-scale survey techniques, skilled-eye (“ACE”) surveys and chart information, which can cover large areas, typical of the intertidal sand and mudflats and subtidal sandbanks. Despite this, it is emphasised that ground-truthing by conventional techniques is necessary for remote-sensed data.

There are well-defined methods for monitoring the sedimentary biotope complexes, their physical and biological attributes although each method is often specific to a component and occasionally a site. In addition, all methods have advantages and disadvantages.

Finally, as the monitoring of different areas will be carried out by different workers but that the data produced will be centrally collated, it is necessary to emphasise the importance of Analytical Quality Control and Quality Assurance (AQC/QA) in monitoring.

Gaps and requirements for further research

There is a large amount of information available for the biotope complexes *Intertidal Sand and Mudflats and Subtidal Mobile Sandbanks.* However, there are many aspects where the knowledge or data are insufficient for understanding the links between the natural processes and the functioning of the physical and biological systems. In addition, the understanding or knowledge base for any one site may be insufficient for management of the site, especially with respect to temporal variability (changes through time) rather than spatial variability.

Many aspects have been identified as areas in which there is a limited or contradictory knowledge base and therefore which require original or further research or studies; some have particular relevance to the management of Special Areas of Conservation (SAC) whereas the remainder will increase the understanding of the habitats. In general, the information gained as the result of these studies can be applied to all areas. However, in certain circumstances, the information is required on a site-specific basis and thus at a scale covering a particular SAC, mud or sandflat or subtidal mobile sandbank.

The gaps in the knowledge can be separated into the following:
- fundamental knowledge of physico-chemical and biological aspects;
- knowledge of the biology linked to management;
- knowledge for impact management;
- knowledge for resource management: biological and physical resources.

Applications for conservation management

Management of the biotope complexes Intertidal Sand and Mudflats and Subtidal Mobile Sands will be designed to regulate the effects of human-induced impacts while letting natural processes operate. Because of this, the management should assess and allow for ***bottom-up controls***, whereby the physical system produces the conditions suitable for biological colonisation, and ensure ***top-down processes***, such as predators using the sedimentary biota.

The information required in managing the biotope complexes can be derived from existing sources such as databases, from rapid-survey techniques such as photography and from more quantitative surveys. An aim is to ensure that cost-effective monitoring is carried out in areas with the possibility of deleterious change.

Because of the nature of the changes, it is suggested that the following be noted:

- the spatial and temporal degree of monitoring should be dictated by the magnitude of the perceived or actual threats from human activities;

- recording of human activities and unusual events (e.g. climatic change) should be carried out to indicate any threats to the integrity of the system;

- initial and continued low-level surveillance (using skilled eye surveys and remote sensing) will indicate the possibility of change; and

- the latter will then act as a trigger and require more detailed and quantitative monitoring to indicate the magnitude of the change.

The biodiversity value of the biotope complexes is related more to the protection of their functioning rather than the presence of rare or fragile species. It is unusual for these biotope complexes to have rare or unusual species or communities.

In obtaining information for management, the parameters for study can be divided into: primary parameters, as the physical-chemical attributes that will cause habitat disruption, and secondary parameters, the biological attributes, that will reflect changes. The most appropriate physical features are:

- **Area**, as the expected size of the habitat, and in certain cases **Shape** of the habitat;

- **Substratum**, as the underlying nature of the bed material;

- **Depth and/or Tidal Elevation**, as indicating either the coverage by water for Subtidal Mobile Sandbanks habitats or the extent to which Intertidal Sand and Mudflats are exposed at Low Water; the depth also influences the light regime available to infralittoral plants;

- **Water Characteristics**, as the underlying water chemistry, including salinity, temperature and nutrient regime;

- **Hydrophysical regime**, as the summation of tidal, wind-induced and residual currents which influence the bed nature and the delivery of food and dispersive stages to an area;

- **Habitat Mosaic**, as an indication of the complexity of the environment created by the physical attributes and thus leading to biological complexity.

The **biological attributes** to be used include important features which describe community structure and functioning. The most appropriate features are:

- **Community Structure**, as the net result of taxa and individuals supported, the diversity of the area and, where necessary, the zonation created by the physical and biological features;

- **Biotopes**, as the number and mixture of representative biological-environment entities and including where possible those listed in site notification, including the quality of biotopes and the maintenance of balance between them;

- **Species**, especially those that are rare and/or included in any site notification, and the dominant species in terms of functioning and support of predators or as predators. The rare species could decline if their niche is removed, the area decreases or the supplying population declines; and

- **Community Functioning**, as an indication of the overall health of the system and its support for important grazer and/or predator populations.

These quantifiable features and attributes can be used to define the *Favourable Conditions* for the maintenance of the integrity of the biotope complexes and, in turn, to indicate the targets for management. Those *Favourable Conditions* can be linked to *Quality Objectives* for the sites, to indicate the desired status of the biotope complexes. However, with present knowledge, it is not possible to set quantitative standards for compliance monitoring which covers the impacts of all human-activities in *intertidal sand and mudflats* and *subtidal mobile sandbanks*. Although tentative standards have been given for well-defined causes of change in the marine system, these require to be tested and further developed for these biotope complexes. With further study, site-specific trigger points may be identified for use in the monitoring and management.

I. INTRODUCTION

A. STUDY AIMS

The objective of this report is to summarise and review the available information on '**Intertidal mudflats and sandbanks**' and '**Subtidal mobile sandbanks**'. The report is one of nine which aim to review the dynamics and sensitivity of 'biotope complexes' and link these to the habitats defined in the EU Habitats and Species Directive. The present report has brought these two biotope complexes together because of their common features and because an understanding of sedimentary systems is common to both. Distinctions between these sedimentary biotope complexes are discussed where necessary but the report focuses on the fundamental environmental and biological attributes of the overall sedimentary system. It indicates the sensitivity of these biotope complexes to natural and human-induced changes, and gives options for monitoring the important features that are relevant to the management of key aspects of these complexes.

The report is oriented around the following principles and logic:

- that physical environmental features create the fundamental structuring characteristics;
- once these are created, niches are available in which the biological community will be allowed to develop;
- the most important common feature in maintaining the integrity of the biotope complexes is their dependence on erosion and accretion processes and the hydrophysical regime required to maintain conditions such as sediment type;
- once the biological community has developed, it is necessary to consider the biological mediating phenomena, such as predator-prey relationships, and the ways in which the biota can modify the sedimentary environment, e.g. by bioturbation;
- then it is necessary to give the features defining the sensitivity of the biotope complexes to natural and anthropogenic changes;
- then it is necessary to consider the environmental and biological attributes of the systems for monitoring and surveillance; and
- finally, within this structure, it is necessary to indicate the strategies and procedures for management.

B. NATURE AND IMPORTANCE OF THE BIOTOPE COMPLEXES

1. General Descriptions Of The Biotope Complexes

In order to derive management plans and monitoring protocols for habitats designated under the

EU Habitats Directive, it is necessary to define and describe these habitats. These sedimentary habitats cover large areas of the available shelf and thus are integral components of the other designated biotope complexes. Because of the nature of the wider marine and estuarine system encompassing these habitats, it is also necessary to link their features to other habitats (and/or biotope complexes) such as estuaries and large shallow inlets and bays.

a. Intertidal mudflats and sandbanks

In the context of Annex I of the Habitats Directive, this biotope complex is defined as '**Mudflats and sandflats not covered by seawater at low tide**' (see **Appendix I**). The present report refers to this biotope complex as *'intertidal mudflats and sandflats'* and considers both low and high energy flats. For consistency in the present report, the term 'flats' are used for intertidal features whereas 'banks' are usually reserved for subtidal features. In addition, and for completeness, sand beaches, which are predominantly coastal, are included in the term 'sandflats'.

The community structure of intertidal flats is well studied and there are good background data for certain areas due to their importance and accessibility, especially their ease of study. This is particularly so for mudflats which contribute a large area of estuaries. There are well-defined communities such as Petersen's (1913) and Thorson's (1957) *Macoma* community for muds and *Tellina* for sands (**Tables 1.0** and **1.1** in **Appendix II** list the features and species common to the Biotopes within this Biotope Complex). It is of note that there are characteristically high abundances for muddy areas but relatively low for sandy areas. The abundances of those organisms are highly variable, with the common mudflat macrofaunal species being 10^2 - 10^6 m^2 whereas species richness is relatively poor (up to 20 spp.). It is considered that the importance of these habitats centres on their role in the biological and physical functioning of the ecosystems. For example, mudflats for producing material for predators, such as birds, fishes and mobile epibenthic invertebrates, and mud and sandflats for coastal protection. The protection of this functioning relies on maintaining the size of area, the tidal elevation and substratum type plus maintaining an input of colonising organisms and the predator populations.

b. Subtidal mobile sandbanks

In the context of Annex I of the Habitats Directive classification, this biotope complex is included in the broad habitat of '**Sandbanks which are slightly covered by sea water all the time**' (see **Appendix I**). These areas include current-swept sands, maerl beds and mixed sediments and as such occur collectively around all coasts of the British Isles although each of these types, especially the maerl beds, has a less widespread distribution. Associated biotope complexes included in other Marine SAC reports are 'Maerl beds' and 'Sea pens and burrowing megafauna'.

Subtidal mobile sandbanks are by definition highly dynamic and unstable with relatively coarse sediment, i.e. a high median sediment particle diameter and a low proportion of small particle material. In general, they support the *Venus* community of Petersen (1913) and Thorsen (1957) although elements of other classical communities will be present (see **Appendix II** for characteristic species). They are categorised by infaunal/epifaunal small crustaceans and molluscs which are adapted to the variable hydrography and mobile substratum. Where the proportion of silt increases slightly they are characterised by epifaunal and infaunal echinoderms and where light and hydrographic conditions permit, they will support macroalgae and maerl. The characteristic fauna of the faunal-dominated sandbanks contains, for example, magelonid polychaetes, the bivalve *Fabulina*, the sandeel *Ammodytes* and amphipods in very low abundances. They are usually dependent on an input of colonising organisms and have few species with benthic reproduction, thus any disruption to the water currents delivering colonising larvae will change the community. In addition, some sandbanks are likely to be sinks of materials at the centre of a gyre.

Mobile sandbanks are characterised by strong currents which may produce characteristic bed features such as mega-ripples (Pethick, 1984). These habitats are often important as fish nursery areas, e.g. for plaice (Lockwood, 1972). They may be characterised by low organic enrichment but there may be pockets of organic enrichment or it may receive anthropogenic waste, e.g. the Dogger Bank. The areas may be liable to severe substratum disturbance, e.g. 1 in 25 or 50 year storms which can turn over the sediment and disrupt the community. On a shorter time-scale and especially for sandbanks occurring in estuaries, there may be winter-summer erosion-deposition cycles and spring-neap erosion-deposition cycles, reflecting the periods of highest hydrodynamic energy (Dyer, 1998).

2. Distribution Of Biotope Complexes

Candidate and possible Special Areas of Conservation for *sandbanks which are slightly covered by sea water at all times* (annotated S on the Figure) and *mud and sandflats not covered by sea water at low tide* (annotated M on the figure) and related habitats are shown in **Figure 1.0**.

a. Intertidal Mud and Sandflats

These occur predominantly in estuaries and the adjacent sedimentary coastal areas, in sheltered marine bays and semi-enclosed areas including lagoons. As such they are amongst the most dominant marine and estuarine habitats and cover areas from a few hectares to several square kilometres within a site and several times this within any geographical area. **Figure 1.1** shows the distribution and size (ha) of intertidal flats on the (then) Nature Conservancy Council review sites.

b. Subtidal Mobile Sandbanks

These extend from a few hectares to a few km^2 in size although some areas have many contiguous sandbanks thus creating a large resource. The present report relates mainly to near-shore areas, i.e. those within the influence of coastal processes and hydrography and where SAC’s are designated. However, pertinent information relating to offshore features is also included.

The sandbanks are predominant in outer regions of estuaries, such as the Severn Estuary and Bristol Channel, and in the Scottish Firths such as the Solway and Tay (Davidson *et al*, 1991). They also occur in semi-enclosed marine bays where the hydrographic regime allows some accretion but of coarse material. There is no audit of these habitats such that the national resource, in area, is not known although Davidson *et al* (1991) describes their location and extent for estuarine sites (**Figure 1.2**). The resource described by Davidson *et al* (1991) was termed estuaries but it included estuarine-type habitats such as fjords and semi-enclosed embayments. The latter include the Wash and Morecambe Bay which have extensive areas of intertidal and subtidal sedimentary areas (e.g. Hemingway & Cutts, in press).

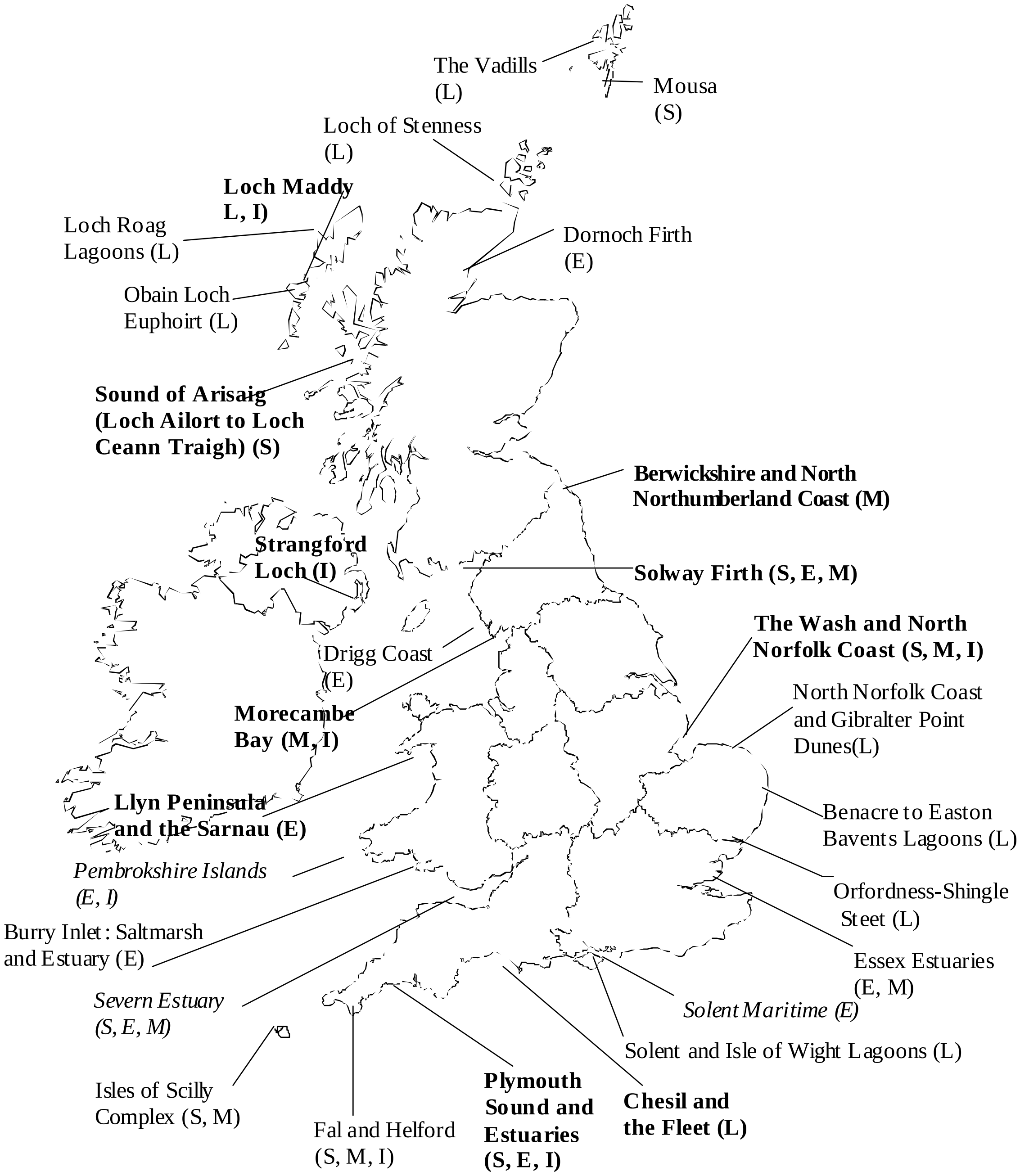


Figure 1.0 Candidate and possible Special Areas of Conservation for marine interest with regard to the present report:-
adapted from Newsletter for the UK Marine SACs Project, Summer Edition 1997

The sites:-
S - Sandbanks which are slightly covered by sea water at all times
E - Estuaries
M - Mud and sandflats not covered by sea water at low tide
L - Lagoons
I - Large shallow inlets and bays

Sites in bold are those included in the SAC project
Sites in italics are possible special areas of conservation

3. Linkages To Other Habitats

The extensive and dominant nature of the sedimentary biotope complexes dictates that the present report also mentions related habitats such as *Estuaries* (Habitats Directive Annex I and *Large Shallow Inlets And Bays* (see **Appendix I**). In addition, an additional habitat, *Lagoons* will support these sedimentary Biotope Complexes under appropriate conditions.

a. Estuaries

Depending on the precise definition used, there are more than 100 estuaries in the British Isles which gives the UK the largest part of the European estuarine resource (27% by area) compared to other north-eastern Atlantic countries. The status, number and type of these habitats is described fully in Davidson *et al* (1991) and they range from shallow coastal embayments which receive a freshwater input to deep fjordic systems. The predominant habitat types within estuaries, and often the reason for their biological and physical importance, are the habitats considered here - intertidal sand and mudflats and subtidal sandbanks. The mosaic of biotopes which constitutes an estuary dictates that each sub-area may require consideration and management as well as taking an overall view (D. Connor pers. comm. 1998).

Estuaries are primarily controlled by salinity combined with structuring due to their topographical features which create the hydrophysical regime (McLusky, 1989). The modification of salinity by changes to the hydroclimate regime is likely to lead to changes in species' distributions, especially the degree of landward penetration of marine organisms. In addition, the input of organic materials, from both allochthonous and autochthonous sources are required to support these primarily detritus-driven systems. Decreases in these inputs can lead to an oligotrophic condition whereas increases can produce hypernutrification and possibly eutrophication. In addition, the importance of estuaries is not only for those species resident during much of the year but also for migrant fish and bird populations (Elliott *et al,* 1990). The movement of predators to estuaries for feeding, reproduction, nursery and refuge is well described, as is their role as migration routes for fishes passing between sea and freshwaters.

b Large Shallow Inlets and Bays

There is no readily available inventory of the habitat as a whole although the component biotopes have been recorded (Connor *et al,* 1997). Most coasts of the UK have some shallow inlets and bays although many are relatively small. By definition many will have a soft sedimentary substratum in the body of the inlet or bay and will be bounded by hard substratum. The bays and inlets are created primarily by the underlying geological features and then infilled with the prevailing mobile substrata and modified by the hydrographic regime. The size and shape of the area together with these characteristics thus creates the available niches for colonisation.

The areas may be heterogeneous where there is a complicated coastline and where different niches are created. Although the shape of these habitats are relatively easy to define, the seaward boundary and thus the area is rather more difficult to specify. The areas are primarily marine and thus fully saline with little dilution by river runoff although they may have diffuse inputs of freshwater from land-runoff.

The sedimentary regime will be dictated by the hydrographic regime and thus may have high and low energy areas depending on the tidal, wind-induced and residual current patterns (see Chapter II). Where the habitats are open features, such as coastal embayments, then the direction of the prevailing currents and the length of fetch will be of importance in structuring the habitat. These features will dictate the relative composition of the component habitats, especially the subtidal sandbanks, the intertidal sand and mudflats, lagoons and reefs. The depth of the area will be defined by the tidal regime and underlying geology and bathymetry and will be variable. The coastal waters will allow good light penetration and thus support an extensive infralittoral area of algal and angiosperm growth. Each of the above conditions will create a mosaic of habitats which will include intertidal, infralittoral and circalittoral biotopes covering both hard and soft substratum.

4. Economic Importance

By definition, the economic value of the biotope complexes relates to their role in conserving, protecting and creating resources valued by man (Penning-Rowsell *et al*, 1992). In particular these are:

- support for fisheries, as they support large nursery populations of flatfishes and roundfishes prior to their movement offshore and eventual commercial exploitation (e.g. Lockwood, 1982; Elliott *et al*, 1990);

- support for shellfish and their exploitation, both as a feeding areas for shrimp populations and, in the case of sand flats and sand banks, as areas supporting large populations of cockles, *Cerastoderma edule*, and more recently razor fish (*Ensis* sp.) (Eastern Sea Fisheries Joint Committee unpubl.);

- providing minerals for extraction - the subtidal sand banks are exploited for aggregate extraction, possibly for building but also for beach nourishment;

- the subtidal mobile sandbanks may occur in areas subject to oil and gas exploration and exploitation;

- the protection of the physical resource as intertidal sedimentary areas provide integral protection for flood and coastal defences; they absorb wave energy and thus enable seawalls to be lower in protection against high tides and storm surges than otherwise would be the case. Similarly, subtidal sandbanks provide nearshore protection against shore-eroding conditions.

5. Scientific Importance

The scientific importance of these areas has been well-defined (see Chapters II and III) and their study has focused on:

- the biological functioning of systems, including fundamental research into the carrying capacity of marine systems (e.g. Goss-Custard, 1985) and the biological productivity of coastal areas (e.g. Elliott & Taylor, 1989b);

- they have provided an understanding of the interactions between the biological and environmental (physical) features and thus the features structuring the marine and estuarine system;

- the analysis of physical systems, in this case sediments, which are modified by biological processes such as bioturbation and biosedimentation ; and

- an understanding of the physical nature and dynamics of marine systems, for example the nature of coastal sedimentary cells, the interactions between adjacent cells and their role in coastal protection.

6. Conservation Importance

The biological conservation importance of many of these sedimentary habitats centres on their intrinsic value in supporting their own biological communities together with their support for the predators dependent on those communities. It is of note that many intertidal sedimentary habitats and their support for predators, especially wading birds in the case of mudflats, are the primary reason for estuarine areas being designated as SSSI (Special Sites of Scientific Interest) and SPA (Special Protection Areas under the EU Birds Directive). In addition, the intertidal habitats have a conservation importance in protecting other wetland habitats such as saltmarsh and reedbeds.

The conservation importance of these biotope complexes is assessed more fully in Chapter VIII, following from the review of their ecological functioning and sensitivity to environmental change.

C. STATUS WITHIN OTHER BIOTOPE CLASSIFICATIONS

The Marine Conservation Review (MNCR) biotope classification provides a hierarchical framework for differentiating and classifying the shallow-water benthic habitats and biological communities of the British Isles (Connor *et al*, 1997). The basic unit of classification is the **Biotope**, a recognisable **Community** of conspicuous species occurring in a **Habitat,** defined according to parameters of the physical environment such as substratum type or degree of wave exposure. Groups of biotopes with similar overall character, suitable for local mapping where biotopes consistently occur together and are relatively restricted in their extent, are termed **Biotope complexes**.

Intertidal Sand and mudflats and **Subtidal sandbanks** are characterised by a restricted number of biotopes due to the biological and physical homogeneity of these areas and the limited availability of niches (Connor *et al*, 1997). The relevant biotopes typical of ‘intertidal mud and sandflats’ and ‘subtidal mobile sandbanks’ from the MNCR classification are summarised in **Appendix II** (**Tables 1.0 and 1.1**) respectively. A working classification and full descriptions are given in Connor *et al* (1997).

For the purposes of this report, the '**Intertidal mud and sandflats**' biotope complex is taken to include all biotopes that can be found in sheltered (low energy) areas, in the case of mudflats, and all biotopes that can be found in areas along the exposure gradient (low and high energy) in the case of intertidal sandflats. The intertidal biotopes covered in the present report do not include those that consist of either eelgrass (*Zostera* spp.) or pioneering saltmarsh plants (*Salicornia* spp.). The '**Subtidal mobile sandbanks**' biotope complex includes all biotopes likely to be found in subtidal non-vegetated mobile sands. The biotopes are also discussed in terms of change along a gradient of particle sizes or salinity, with biological communities changing as a result of the differing environmental requirements of the characterising species (Conner *et al*, 1997). The latter is particularly apparent in estuarine habitats.

These biotope complexes, especially mudflats, are of particular importance as feeding grounds for wildfowl and waders (Davidson *et al*, 1991). The intertidal communities of invertebrates and algae that occupy this biotope complex can be used to define subdivisions of other habitats such as estuaries and large shallow inlets and bays, eelgrass communities that may be exposed for a few hours in the course of every tide (11.3 - CORINE European classification of communities), and brackish water and vegetation of permanent pools (11.4). This review excludes macroalgal dominated areas although their features are mentioned if appropriate. The biotope complex 'seagrass communities' are included in another Marine SAC review and thus are not considered here.

D. KEY POINTS FROM CHAPTER I

In considering these sedimentary biotope complexes with regard to monitoring for management it is necessary:

- to assess the physical environmental features which create the fundamental structure and thus niches for colonisation.

- to protect the sedimentary and hydrophysical regime in order to maintain the integrity of the biotope complexes.

- to assess the biological interrelationships, e.g. predator-prey and bioturbation which will modify the community and the substratum.

- to define which of these characteristics are sensitive to change and the monitoring of these characteristics for management.

The primary features of the sedimentary biotope complexes are:

- they are highly important in covering large areas of shelf and estuarine bed and an integral part of the EU designated habitats: ***Estuaries***, ***Large Shallow Inlets and Bays***, and ***Lagoons***;

- by definition they are relatively homogeneous but often occur in highly variable environments such as estuaries and wave-dominated coastal areas. However, whilst there is a good inventory of intertidal sand and mud flats, which individually may cover areas from a few hectares to several km^2, there is no national inventory for subtidal mobile sand banks.

- their distribution and importance has produced good information on well-defined communities for certain areas, particularly the intertidal mud and sand flats, but less so for subtidal mobile sandbanks.

The value of these biotope complexes can be summarised as:

- In economic terms, it is related to conserving, protecting and creating resources valued by man, e.g. fisheries and shellfisheries, minerals for extraction, and land that requires protection.

- In scientific terms, it has been in providing an understanding of fundamental biological and environmental interactions and processes and the interdependence of habitats within dynamic marine systems.

- In conservation terms, especially for intertidal mud flats, it is as declining wetland areas which support internationally important populations of wading birds and nationally important populations of juvenile fishes.

II. ENVIRONMENTAL REQUIREMENTS AND PHYSICAL ATTRIBUTES

In each of these biotope complexes, a particular set of environmental (physico-chemical) conditions create the biological communities on which, in turn, are dependent populations of predators. The dominant factors, termed the '**environmental master factors'**, can be summarised as: temperature, light, salinity, situation (including stability, exposure to air and desiccation and, by extension, depth regime), oxygen content, nutrients, currents (wind-driven, freshwater-driven and residual) and tides, and the nature of the bottom substratum (formation type adapted from Jones, 1950 and Erwin, 1983).

Each of these environmental master factors is important in providing the conditions and niches within which the biota can develop. The primary physical features of the **hydrographic regime** (tides, waves, residual currents) together with the **underlying physiography and geology** will create the conditions for a given type of substratum to develop. Once the **sediment type** has been established, it will create conditions for colonisation by organisms. If the integrity and health of the sediment is maintained then the biological colonisation will also be created and maintained. Hence it is highly important to have a good understanding of the environmental and other physical features in order to understand and interpret the features of the biota.

This chapter summarises the nature of the physical environment in which these biotope complexes exist and outlines the common and distinctive environmental attributes which are important in defining the characteristic features of that biotope complex. The sensitivity aspects of the gross physical determinants of **climate**, **temperature** and **salinity** are discussed in Chapter IV. The importance of climate and temperature regimes dictates the biogeographic zones (see Hiscock, 1998a) and has been used to determine large scale separation of assemblages (e.g. Glemarec, 1973). The more variable parameter **freshwater inputs** both within estuaries and over intertidal areas will create zonation.

A. SPATIAL EXTENT

The area of these biotope complexes is dictated by the physical conditions, especially the **physiography** and **underlying geology** coupled with the hydrodynamic regime which dictates where and how much sediment will be deposited. The intertidal areas will vary due to wave action with shingle beaches having the narrowest zone and muddy shores having the widest. The area of a subtidal sandbank will be influenced by the strength and dynamics of currents creating the area. For example, gyres created by conical headlands will produce subtidal sandbanks whose area is in proportion to the nature of the gyre (Mumford & McKerney, 1989). The area and shape of these biotope complexes are important in supporting and maintaining specific groups of animals (see below).

B. HYDROPHYSICAL REGIME

The hydrophysical regime of an area is regarded as the net result of all factors affecting water movement and any interference with this regime will affect the physical integrity of the sedimentary systems. In particular, the regime indicates an area's energetic nature; in this report the **low energy to high energy continuum** refers to the dynamics of sedimentary habitats and thus it excludes the very high energy conditions responsible for exposed rock areas. An understanding of the hydrodynamic (current) regime is important as it has the primary role of delivering particles, food and dispersal stages of organisms to an area:

- The **wind-driven currents** are dependent on the direction and strength of the prevailing wind climate and on the wave fetch.

- The **tidal currents** will depend on the location and topography in relation to amphidromic points where the tidal range is always zero (Open University, 1989) and the wider nature in relation to **tidal surges**. The currents close to the shore are influenced by the shape of the coastline with prominent conical headlands increasing the speed of tidal currents and causing gyres within adjoining bays (Barne *et al*, 1995). **Subtidal sandbanks** then often occur within those **gyres**. Within semi-enclosed areas such as estuaries there will be greater erosion potential during spring tides and less so during neap tides. These **spring-neap erosion-deposition** cycles will influence the stability of the sediment and the dispersal of organisms.

- The **freshwater-mediated currents** are important within estuarine and coastal areas receiving run-off. The less-dense freshwater will produce vertical stratification which will influence the transport and settlement of particles and dispersive stages of organisms. The high flows during the winter and the low flow during the summer may produce **winter-summer erosion-deposition cycles**. These may allow sediment to be washed downstream in winter and then tidally-pumped back in the summer. Associated salinity patterns will in turn affect the dispersal of organisms.

- The **residual currents** comprise that component of the hydrophysical regime which remains after the above influences have been removed. In particular this includes large scale hydrographic features such as Coriolis force which pushes water counter-clockwise when moving into an estuary or bay. The interaction of these currents together with the topography may produce **coastal counter-currents** (Dyke, 1996). The residual currents may also be manifest as long shore drift which will act as a sediment transport mechanism especially for intertidal sand flats. In addition, summer conditions may induce gyres which may influence bed conditions.

- In addition to the above, hydrographic features such as **fronts** will influence the delivery of physical and biological materials to an area of seabed (Open University, 1989).

1. *Intertidal Mud and Sandflats*

Intertidal areas are highly dynamic systems which are constantly influenced by local energy levels and, especially in the case of high energy sand flat areas, exhibit a micro-structure which is governed by repeated erosion and deposition during the reworking of the sediment (Swart, 1983). Although mud and sand flats have complex interactions between physical, chemical, geological and biological factors, the determining factors affecting beach systems is their exposure to wave, current and wind action (Eagle, 1973, Swart 1983).

Wave action, particle size and intertidal gradient are related to and influence each other in a cyclical manner (Pethick, 1984). Waves breaking on the shore cause sediment to be pushed up the shore by the swash and back by the backwash. The backwash is weaker because water percolates into the sediment. Coarse sediments with high percolation rates encourage the build up of steep beach profiles because the backwash is too weak to move the sediment down the beach, whereas fine sediments lead to flatter slopes. Gentle waves surge a long way up the beach where they lose energy by carrying sediment and lose water through percolation. In this situation backwash is weak hence beaches build up which makes them steeper. Steep storm waves break over a narrow area and do not move as far up the beach. Less energy is lost carrying sediment and less water through percolation. The backwash is strong and so sediment is carried seawards thus eroding the beach and giving it a shallower profile (Pethick, 1984).

Onshore winds from winter storms increase wave action and erode material from beaches and transport it to sea where it is deposited as a longshore bar. In the summer, less dynamic swell waves return the sediment to the beach. The strong seaward movement of sediment during storms is normally counter balanced by its slower rate of return during the rest of the year (Swart, 1983).

The above hydrographic and sedimentary processes on intertidal sand flats also control the mixing and dispersal of sediment bound contaminants (Dolphin *et al*, 1995). Sediment entrainment by strong spring tidal currents may be restricted to the middle and lower regions of the sand flat which are inundated during the peak tidal flows. The upper 2-3 cm of sediment is then re-worked across the middle and upper sand flat by mild storm events.

2. Subtidal Mobile Sandbanks

The hydrological regime affects the water characteristics in terms of salinity, temperature and dissolved oxygen. It also influences the rate of deposition and remobilisation of the sand and hence the nature of the substratum and the depth of the sand bank. The speed of the water movement and the rate of erosion and deposition of the sand are important in maintaining the integrity of these habitats. Some subtidal sandbanks experience very strong currents and are primarily physically controlled especially in high energy situations away from coastal silt input or where currents are sufficiently strong to prevent accumulation of fine sediment (Pethick, 1984). At certain times, particularly during storms, the top of a sand bank can be removed and then replaced during calmer conditions.

Tidal streams and wave action cause sediment transport and erosion which will affect the grain size of sandbanks; sediment will range from fine to very coarse depending on current strength and may be well to poorly sorted. Very strong currents may either produce channels around banks, where the sediment may be extremely coarse, or they may remove all of the surficial sediment. Large scale sand ripples (mega-ripples) may also develop and accumulate silt in their troughs.

The presence of headlands on cliffed coasts are important in determining the hydrodynamic regime, sediment dispersal and deposition and shoreline evolution. Headlands capture wave energy and their influence on tidal streams may lead to the development of residual current gyres (**Figure 2.0**). Sediment moving along shore will tend to enter the tidal stream at the headland and then accumulate within the gyre to form banks and shoals (Carter, 1988). The cyclic nature of tidal currents may result in the ebb and flow currents following different paths. This often leads to an ellipsoidal flow pattern which produce conditions suited for sandbank formation. The residual currents produced by asymmetric flood and ebb patterns are also extremely important in the transport of water and waterborne material such as sediment, pollutants and planktonic larvae (Pethick, 1984).

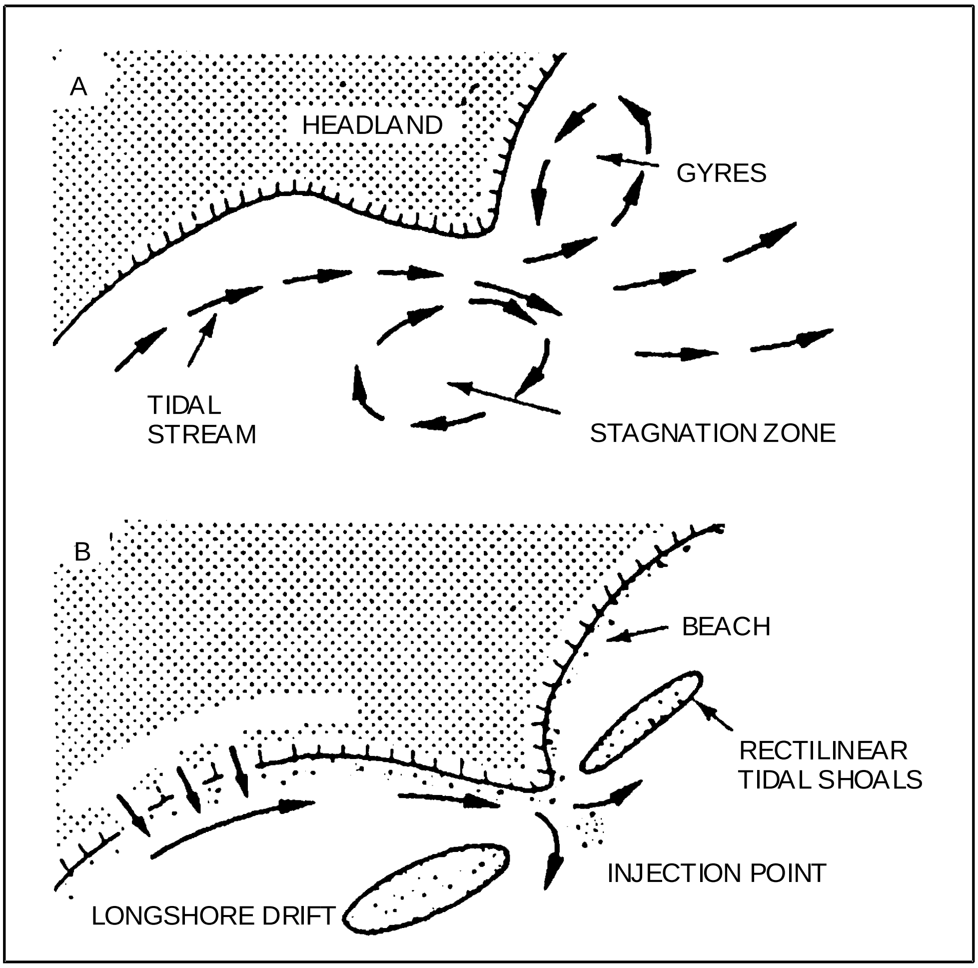


Figure 2.0. (A) Gyres and stagnation zones arising from a headland protruding into a coast parallel flow. (B) Development of rectilinear shoals resulting from seaward dispersal products at headlands (in Carter, 1993).

Figure 2.0 (B) Sediment sources are indicated by the 3 down arrows on the left of the diagram.

The water currents affect the distribution patterns of both permanent (holoplanktonic) and temporary (meroplanktonic) plankton species including the larvae of benthic species as well as waterborne pollutants. The fauna may be determined by chance settlement of species brought from external areas by these currents although the presence of a gyre over a subtidal bank can limit dispersion and to some extent limit the influx of larvae. This may help to maintain the integrity of the population as was shown for an *Abra* community in Oxwich Bay (Tyler & Banner, 1979). In addition, water movements may also affect the organisms through physical stress (Wood, 1987).

C. VERTICAL ELEVATION

1. Intertidal Sand and Mudflats

Intertidal areas by definition have low, middle and high tidal areas although in many cases the latter has been constrained by anthropogenic features, e.g. a seawall. The productivity of these areas differ with respect to the **tidal elevation and shore slope** (Gray, 1981) and most of the infaunal community, in terms of the abundance and biomass, is at the mid-tidal region. Any decrease in tidal height will take the area towards greater current speed near channels whereas an increase in tidal height will increase **exposure** and thus desiccation of the organisms. Changes in tidal height over the intertidal zone create a less predictable environment where there may be more extreme changes in temperature, salinity, dissolved oxygen and water content than in the sublittoral zone (Hayward, 1994). Such a change in tidal height creates aerial exposure of the sediment which in turn affects desiccation of any organisms and drying of the sediment in warm conditions and salinity stress during rain.

The **gradient of a shore** reflects the energy conditions - that of mud flats is shallow reflecting the low energy conditions in contrast to more dynamic sandy shores. Steeper shores are associated with larger grains and shallow profiles with fine sediment (Pethick, 1984). Most large shores have a narrow range of grain sizes in the swash zone and they are usually composed of fine to medium sand and although grains of around 200µm are too fine to be easily resuspended, they may be saltated. On a shore with plunging breakers, there is often a concentration of coarser sediment around the plunge point at mean water.

Shore slope has a complex relationship with **wave action** (**Figure 2.1**) and the distinction between a beach and a sandflat is subjective and based on a combination of conditions. Although beaches are on the periphery of the biotope complexes covered here, their features are of relevance in understanding **sandflat dynamics**. High energy wave action and/or fine particles (as with mud flats) result in flatter slopes where the wave energy is more evenly dissipated across the surf and intertidal zone (McLachlan, 1983). Exposed sandy shores can be defined as **reflective, intermediate or dissipative** based on the sum of their physical parameters.

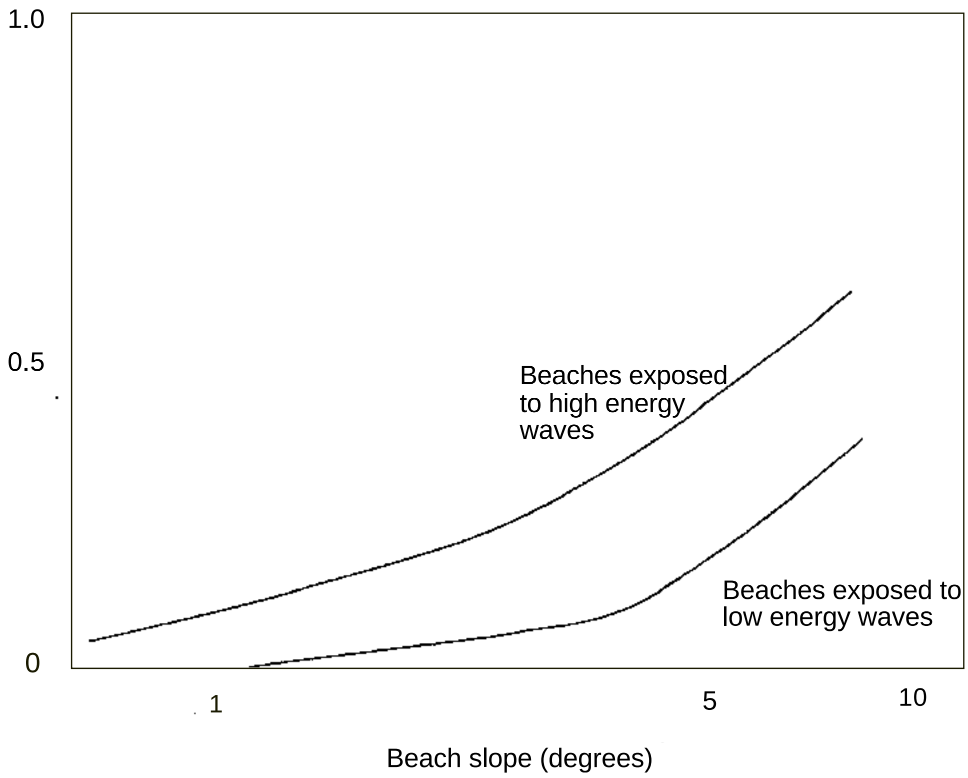


Figure 2.1 Relationship between beach slope and grain size on beaches exposed to low and high energy waves (after Komar, 1976 in Pethick, 1984).

Reflective beaches have coarse sand, low wave energy, small tidal ranges, steep slopes, no surf zones and wave energy reflecting out to sea; they tend to be dominated by plunging breakers which dissipate their energy over a short distance (Swart, 1983).

Dissipative beaches develop where there is fine sand, heavy wave action and large tidal ranges (McLachlan, 1990); they have flat slopes and wide surf zones where foaming or spilling breakers gradually dissipate their energy (Swart, 1983).

Intermediate beaches have moderate to heavy wave action with intermediate slopes and surf zones with bars, channels and rip currents (McLachlan, 1990).

These criteria are supported by Pethick (1984) who considers beaches to be energy sinks which must dissipate energy without changing themselves. High energy, steep waves are best buffered by a wide flat beach, whereas low energy waves are countered by a steep shore profile. Steep, coarse beaches can also dissipate the energy of high energy waves through friction and percolation. The aspects are of importance in considering the role of sandflats in coastal defence.

The profile of the shore influences the amount of erosion taking place during storms. Dissipative beaches with flat or even concave profiles are less affected by storms and may even have some consequent accretion. Steeper and possibly convex reflective beaches have more sand cut from the upper profile and this may be either transported off-shore or used to fill the lower profile (Fucella & Dolan, 1996). In addition to on and off-shore movement there is longshore transport which is influenced by wave height, current velocity and grain size (Swart, 1983). The volume of material transported may be considerable daily in storm conditions (Swart, 1983). Grain size characteristics also influence erosion by influencing the mobility of the particles and the sediment cohesiveness.

2. Subtidal Mobile Sandbanks

The **depth-related characteristics** of sand banks differ depending on whether they are within the infralittoral or circalittoral regions. The former is within the photic zone and thus will sustain attached primary producers whereas the latter will be faunal dominated (Hiscock, 1983). Any increase in either the depth or turbidity of the water will affect the **light penetration** and thus the primary producers although in the case of the biotope complexes covered here, the only primary producers of concern are the **benthic microalgae**. The quality of light (as critical depth for primary production) reaching such sandbanks will determine the type of microalgae colonising the sediment but there is little work on these aspects. In shallow or constricted areas the water above the banks may be very turbid (Carter, 1984) thus limiting primary production.

An increase in depth would change characteristics of the sandbank and its interactions with the hydrographic regime. If the depth decreased, the sand bank may become exposed on low spring tides which would decrease survival of subtidal fauna that cannot withstand exposure. The depth of a sand bank is also important for predator populations of birds which are restricted to certain diving depths. For example, the majority of wintering diving birds observed in a survey off the Flamborough coastline (IECS, 1993) were restricted to within

5km of the coastline, in areas of shallow water with a sandy substratum.

D. SUBSTRATUM

An understanding of the features of sediments of intertidal sand and mudflats and the subtidal sand banks and the inter-relationships between those features is necessary to interpret their influence on the biota. Marine sediments are often heterogeneous in containing particles of many grades and types but their characteristics will vary spatially depending on the nature of the adjacent coastline, the hydrodynamics of the water (which produce areas of high or low energy) and the contours of the sea bed. The underlying **geology, topography and physiography** will produce the basic shape of the coastline and its ability to be infilled with sediment (Pethick, 1984). The substratum is defined by the size range of its constituent particles and may be classified by the Wentworth scale (Buchanan, 1984; Buller & McManus, 1979; Tait & Dipper, 1998).

Intertidal mudflats are predominantly clay (particles <4µm), silt (4 - 63µm) and to a lesser extent very fine sand (63 - 125µm); **intertidal sandflats** contain all the grades of sand and to a lesser extent silt and clay, whereas **subtidal mobile sand banks** contain all the grades of sand (63µm - 1mm) with a very low silt and clay content.

The **settling velocity** of particles is dependent on particle size and water characteristics such that sands and coarser materials settle rapidly and particles >15µm diameter will settle out within one tidal cycle (King, 1975). In contrast, clay and silt (particles <4µm diameter) are unlikely to settle within one tidal cycle and, in addition, have settling velocities which are influenced by flocculation processes often mediated by surface electrostatic charge. Such phenomena are important in estuarine waters and intertidal muds subject to widely fluctuating salinity and pH.

Sediment deposition within an area is controlled by the type, direction and speed of the currents and the size of the particles. Fine grained material will move in suspension and will follow the residual waterflow, although there may be deposition at periods of slack water. The coarser grained material will travel along the bed in the direction of the maximum current and will be affected most by high velocities (Postma, 1967). Erosion of fine sand of 0.1mm particle diameter occurs at >30 cm s^{-1}, and deposition will occur at <15cm s^{-1}. Particles of 1-10 µm diameter have a similar relationship, although erosion requires faster current speeds because of consolidation and flocculation (Hedgpeth, 1967).

The distribution of grain sizes within a substratum is indicated by **sorting and skewness characteristics** (Buller & McManus, 1979). Sorting reflects the range of forces which have formed the sediment and it influences the gradient of slope of intertidal areas. In sediments that have a low degree of sorting, as a reflection of a greater mixture of particle sizes, small particles occupy the spaces between larger grains and thus reduce pore space or porosity. In intertidal areas this lowers percolation rate and creates steeper shore profiles (Pethick, 1984). Pore space also depends on the rate of deposition with rapid deposition leading to cubic packing which maximises the spaces between grains and leads to a more porous sediment (Pethick, 1984). Skewness indicates the shape of the tail of the frequency distribution of the sediment particles.

These characteristics of sediments are interrelated (**Figures 2.2, 2.3**) to create conditions conducive to supporting infauna. **Mudflats and sheltered beaches** consist of fine or silty sands and thus reflect low energy conditions. The characteristic features that define the substratum in low energy environments are noted below and illustrates in **Figure 2.2**:

- particles of a small median diameter (as the result of settlement by all sizes of particles);

- shallow slope and high water content (by an inability to drain through sediment packing and low porosity);

- high sorting coefficient, low permeability and generally low porosity (depending on compaction, but as the result of particles blocking pore spaces);

- high organic content (as the result of organic detritus settling and being formed, by growth of heterotrophic and autotrophic micro-organisms) and thus high microbial population and high sediment stability (as the result of cohesion); high carbon to nitrogen ratio (as an addition of carbon over its degradation (Russell-Hunter, 1970); and

- low oxygen content and therefore high reducing conditions (as the result of poor percolation of oxygenated waters together with high heterotrophic activity degrading organic matter).

The characteristic features that define the substratum in **exposed sandflats and subtidal mobile sandbanks** (areas of high energy) are summarised in **Figure 2.3**. The main substratum features which are common to these biotope complexes are:

- particles of a high median diameter with a low sorting coefficient, high permeability and generally high porosity (depending on compaction) and low sediment stability; and

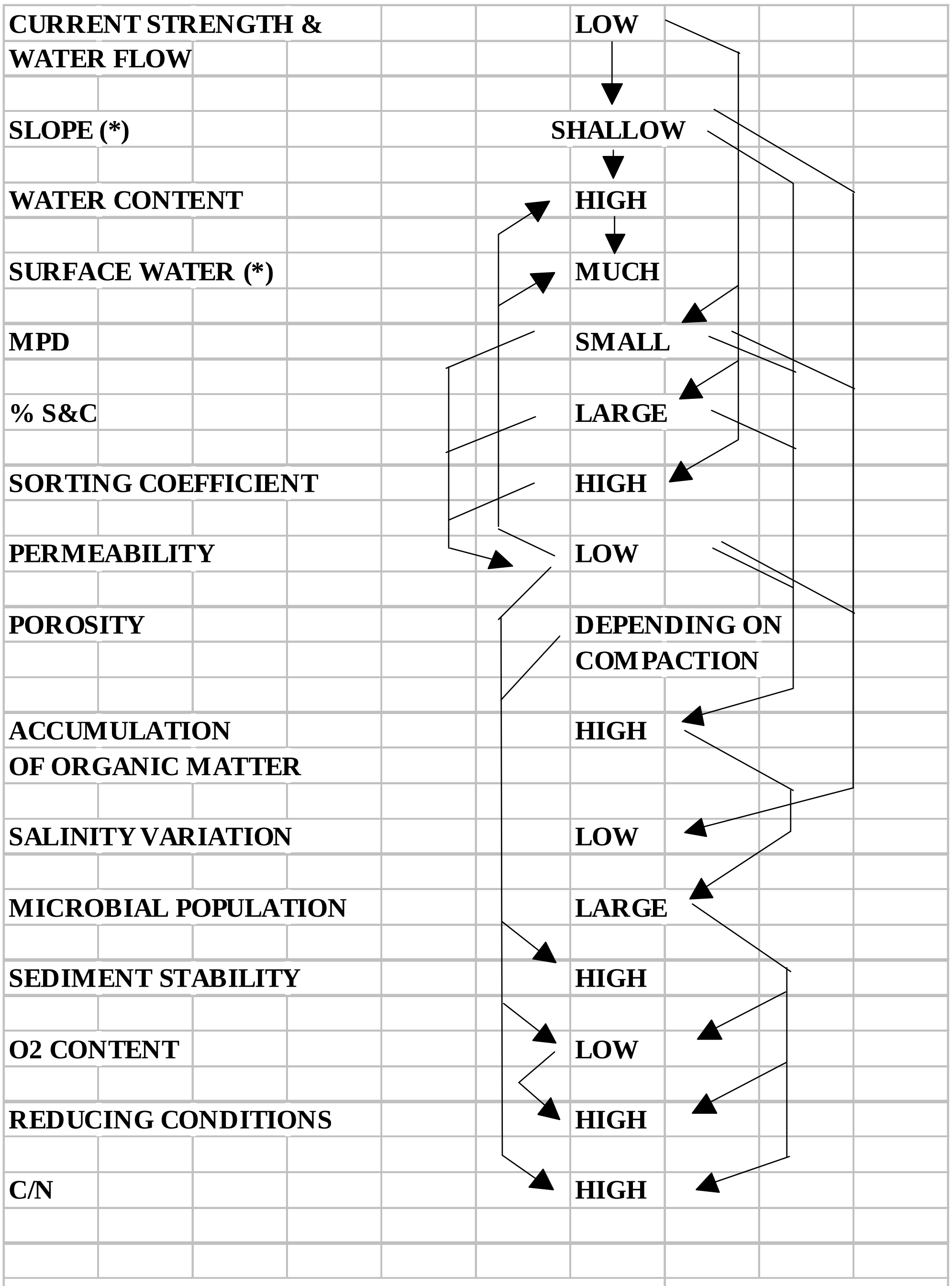
- low organic content; high oxygen content and therefore low reducing conditions; low carbon to nitrogen ratio and hence small microbial population.

The main features which distinguish these biotopes are aerial exposure, interstitial water movement and the presence and movement of the water table. Although, as indicated above, the biotope complexes share many of the main environmental features in being physically controlled, they differ in the central aspect that **subtidal sand banks** are highly dynamic and unstable and by definition always have a predominantly sandy substratum, a high median particle diameter and low proportion of silt and clay material. In contrast, the **intertidal sand and mud flats** have varying amounts of silt, clay and organic material and are generally more stable.

1. *Sedimentary Attributes*

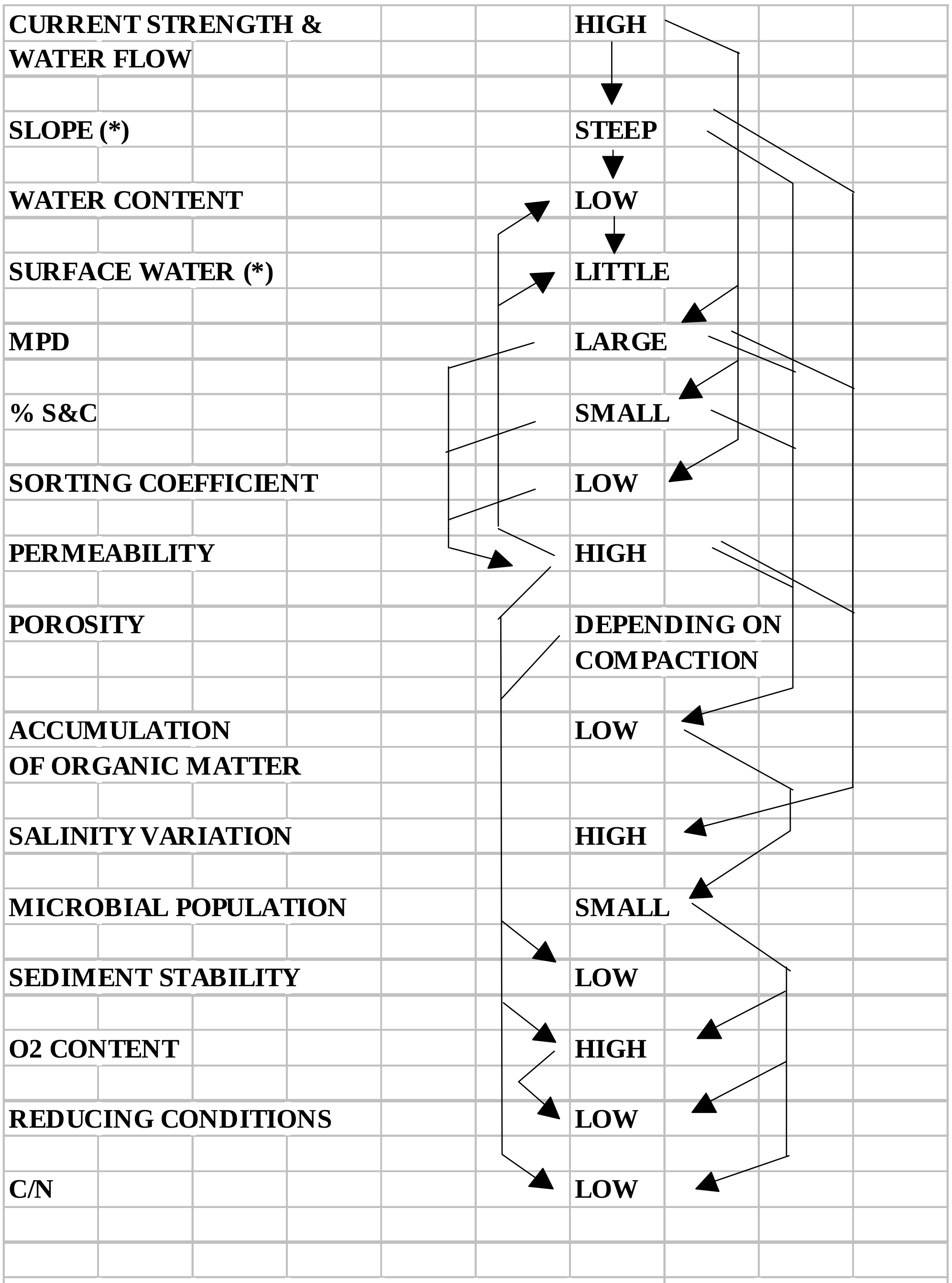
a. Particle size

The sediment provides two fundamental resources, space and food, required by the predominantly infaunal organisms which characterise these biotope complexes. It provides the 3-dimensional space for colonisation and the food source for the predominantly deposit and detritus feeders characteristic of the sedimentary communities.



CURRENT STRENGTH & WATER FLOW	**LOW**
SLOPE (*)	**SHALLOW**
WATER CONTENT	**HIGH**
SURFACE WATER (*)	**MUCH**
MPD	**SMALL**
% S&C	**LARGE**
SORTING COEFFICIENT	**HIGH**
PERMEABILITY	**LOW**
POROSITY	**DEPENDING ON COMPACTION**
ACCUMULATION OF ORGANIC MATTER	**HIGH**
SALINITY VARIATION	**LOW**
MICROBIAL POPULATION	**LARGE**
SEDIMENT STABILITY	**HIGH**
O2 CONTENT	**LOW**
REDUCING CONDITIONS	**HIGH**
C/N	**HIGH**

Figure 2.2 Sedimentary low-energy areas (*intertidal) (modified from Elliott, 1979)



CURRENT STRENGTH & WATER FLOW	**HIGH**
SLOPE (*)	**STEEP**
WATER CONTENT	**LOW**
SURFACE WATER (*)	**LITTLE**
MPD	**LARGE**
% S&C	**SMALL**
SORTING COEFFICIENT	**LOW**
PERMEABILITY	**HIGH**
POROSITY	**DEPENDING ON COMPACTION**
ACCUMULATION OF ORGANIC MATTER	**LOW**
SALINITY VARIATION	**HIGH**
MICROBIAL POPULATION	**SMALL**
SEDIMENT STABILITY	**LOW**
O2 CONTENT	**HIGH**
REDUCING CONDITIONS	**LOW**
C/N	**LOW**

Figure 2.3 Sedimentary high-energy areas (*intertidal) (modified from Elliott, 1979)

Intertidal mudflats

All mud contains some sand hence it has a high sorting coefficient, but the most important features are the high silt and clay content (%S&C, particles <63µm) and thus low median particle diameter (MPD) and deposits >80%S&C are described as mud (Dyer, 1979). Silts are very fine inorganic particles, which are usually held in suspension by slight water movement at the sediment surface. In contrast, clay is mostly colloids of hydrated aluminium silicate (<4µm diameter) together with iron and other impurities. Particles <2µm in diameter are mainly the clay minerals illite, kaolinite and montmorillonite whose flocculation is dependent on salinity (Whitehouse *et al*, 1960) and turbulence (Kirby & Parker, 1974).

Intertidal and subtidal sands

Particle sizes of sands range from coarse sands (0.5-1mm), medium (0.25-0.5mm) and fine sands (0.063-0.25mm), with the substratum structure being rarely homogenous and having a low sorting coefficient, i.e., it is often well sorted. The sorting will be the result of the prevailing hydrodynamic regime including long-shore drift and coastal gyres, in the case of intertidal sediments, and headland gyres in the case of subtidal sandbanks. The sand grains of beaches and subtidal sandbanks are usually quartz (silica) particles derived from erosion (Gray, 1981). Sediments containing >10 %S&C are commonly termed ‘muddy sands’ but ‘sandy mud’ if >30%S&C (Dyer, 1979).

b. Porosity, permeability, water content and sediment stability

Porosity denotes the amount of pore space in a sediment whereas permeability is the water flow through it. Particle size, its mixture and compaction influence the permeability or percolation rate (Pethick, 1984) especially those with a mixture of particles, i.e. low porosity and permeability in fine grained sediment and *vice versa* for sands. Porosities in different-sized material may be similar (Taylor *et al*, 1966) due to interaction between grain shape, the degree of sorting, the length of time since deposition and therefore the degree of settling and compaction.

Intertidal mudflats

Clays can have porosities ranging from 65-82% and silts 45-88% (Taylor *et al*, 1966). However, in extreme cases a mud flat which is composed largely of clay can become sufficiently compacted to supporting sessile fauna and even rock borers such as the burrowing bivalve *Pholas* (Eltringham, 1971). In contrast, **fine and very fine sands** have porosities ranging from 40-50% and medium sands 37-42% (Taylor *et al,* 1966) again depending on compaction coupled with the mixture of particles.

Sediment particles consolidate in low energy environment, e.g. in the middle estuarine mudflat areas of low energy and hence less vigorous mixing. In such cases the weight of overlying sediment forces out pore water and the floc structure collapses (Parthenaides, 1965). The consequence of the rearrangement of sediment particles gives the mudflat increased shear strength and thus resistance to re-erosion.

The **water content of mud and sandflats** is influenced by the porosity and compaction of the sediment, the shore slope and the potential for draining. Mud and sandflats may be extensive yet retain water at low tide as the result of their a shallow gradient and the capillary attraction of closely packed particles (Gray, 1981). The sediments may be **thixotropic** due the high water content (Chapman, 1949), thus allowing easier burrowing by infauna applying pressure to the sediment which becomes softer and easier to penetrate.

Silt and clay is more **cohesive** and when mixed with sand creates a more stable sediment. In the case of intertidal sediments, strong shoreward wave velocities move coarse sediments as bedload (under saltation) and fine particles as a suspension whereas weaker offshore velocities move only the finer bedload and suspended material (McCave, 1979, Buller & McManus, 1979).

Intertidal and subtidal sands

The permanent water content in an **intertidal sand flat** may be low as the interstices between the particles are filled with water which drains during exposure although draining is inversely related to organic and silt content. In water-logged sands, for example subtidal sand banks, particles are prevented from abrasion by a film of water surrounding them. The ease with which infauna can burrow depends upon the amount of water present, for example, **dilatant sands** (which have a low water content) are difficult to penetrate as the application of pressure causes them to harden.

In contrast to mudflats, both **intertidal and subtidal sands** are extremely **unstable** as the predominant material is unable to form cohesive clumps. This instability prevents the colonisation of vegetation but allows the development of interstitial populations of organisms. Most coastal sediments lack cohesion and have solid particles, i.e. not flocculates, usually greater than 0.06mm in diameter, which are held together by gravitational forces (Pethick, 1984).

c. Organic content, oxygen content, microbial activity and carbon/nitrogen ratio

Intertidal Mudflats

These contain a high proportion of organic matter which is deposited and accumulates in low energy areas due to its small and low specific gravity. **Allochthonous organic material** is derived from both anthropogenic sources (effluent, run-off) and natural sources (settlement of plankton, detritus). **Autochthonous organic material** on these sedimentary areas is restricted to **benthic microalgae (microphytobenthos)** such as diatoms and euglenoids and heterotrophic micro-organism production although mats of opportunistic green macroalgae such as *Enteromorpha* and *Ulva* will also develop (see Chapter III). The organic matter (measured as organic carbon or nitrogen) is degraded by the micro-organisms and the nutrients recycled (Newell, 1965; Trimmer *et al*, 1998). In addition, the high surface area to volume ratio of fine particles acts as a surface for the development of microfloral populations. These features, coupled with poor oxygenation of muds and hence low degradation rates, lead to an accumulation of organic matter.

Oxygen content is a function of the degree of oxygenation (aeration) and the inherent oxygen demand of organic matter. **Fine sands and muds** tend to have lower oxygen levels because their lower permeability leads to the trapping of detritus which, together with the large surface area for microbial colonisation, leads to higher oxygen uptake (Eagle, 1983). Much of the organic detritus therefore undergoes anaerobic degradation, with hydrogen sulphide, methane or ammonia produced, as well as dissolved organic carbon compounds which can be utilised by aerobic micro-organisms living on the surface (McLusky, 1989; Libes, 1992). These features produce a reducing layer (indicted by the **redox potential discontinuity** layer, RPD) very close (often <1cm) to the surface. In mudflats the **carbon to nitrogen ratio** is high due to high productivity and microbial activity in these areas (McLusky, 1989; Russell-Hunter, 1970). The C:N ratio reflects a high build up of labile organic matter in relation to a lower degradation rate, as shown by large micro-organism populations.

Microbial activity is high in muds which contain a large amount of detritus and microbes although at depth that bacterial activity will be chemosynthetic (Libes, 1992). Microbial activity has a valuable role in stabilising estuarine organic fluxes by reducing the seasonal variation in primary production, ensuring a relatively more-constant food supply, and allowing the reabsorption of dissolved nutrients (Robertson, 1988). The bacteria living on particulate or dissolved organic matter makes the primary production more readily available for animal consumption (McLusky, 1989). It has been calculated that the biomass of bacteria within mudflats may be of the same order of magnitude as the biomass of animals living in the sediment. Breakdown of organic matter to sulphides and sulphates by bacteria forms the sulphur cycle which determines the redox potential and pH of the sediment.

Sandflats and subtidal mobile sands

These have **low levels of organic matter** and are **well oxygenated** in the surface layers (Eagle, 1973) with the detritus derived from decaying seaweed, the faeces and remains of animals, and terrigenous sources (as wind blown material). Sands are usually sufficiently oxygenated by seawater which, at high tide, percolates from a few mm in fine, sheltered sandflats to several metres in coarse sand (Eagle, 1983). Interstitial oxygenation, may be poor below the surface layer particularly where the sand is fine or mixed and thus poorly drained or in cases of high concentrations of organic material such as decaying seaweed on the strand line (Hayward, 1994). In cases where the sublittoral sand banks are created at the centre of gyres, they will receive and concentrate organic materials and debris. However, the mobile and unconsolidated nature of the sediments will produce a high oxygenation and thus high biodegradation rate.

Intertidal and subtidal sands are well-oxygenated though the tidal pumping of overlying water. Their mobile nature produces a **deeper anaerobic layer** (>15cm) and that any organic matter incorporated into the sediment is degraded rapidly. High energy areas have a low carbon to nitrogen ratio due to the low organic content and reduced productivity and the rapid degradation of labile organic material. **Microbial activity** is low in areas of higher energy as there is limited organic detritus available for bacterial degradation coupled with the particles' comparatively low surface area to volume ratio providing a surface for microbial populations.

E. KEY POINTS FROM CHAPTER II

- An understanding of the physico-chemical conditions (as “environmental master factors”) is necessary to understand and interpret the evolution of sedimentary biotope complexes.
- The environmental master factors are: temperature, light, salinity, situation (including stability, exposure to air and desiccation and, by extension, depth regime), oxygen content, nutrients, currents (tidal, wind-driven, freshwater-driven and residual) and tides, and the nature of the bottom substratum.
- The primary physical features of the hydrographic regime (tides, waves, residual currents) together with the underlying physiography and geology will create the conditions for a given type of substratum to develop.
- The characteristics and nature of the hydrographic, sedimentary and depth regimes are intimately related and will create conditions for the colonisation by, and maintenance of, organisms of the biotope complexes, and for the delivery of food and colonising organisms.
- Mudflats and sheltered intertidal sandflats reflect low energy conditions which are characterised by: particles of a small medium diameter, shallow slope, high water content, high sorting coefficient, low permeability and generally low porosity, high organic content and therefore high reducing conditions, high carbon to nitrogen ratio, high microbial population and high sediment stability.
- Subtidal mobile sandbanks and exposed intertidal sands are found in high energy areas which are characterised by: particles of a high median diameter, low sorting coefficient, high permeability, generally high porosity (depending on compaction), low organic content, high oxygen content and therefore low reducing conditions, low carbon to nitrogen ratio, small microbial population and low sediment stability.
- Whereas intertidal mud and sandflats will develop in low energy areas, subtidal mobile sandbanks will develop especially as the result of the physiography and large-scale current patterns producing gyres.

III. BIOLOGY AND ECOLOGICAL FUNCTIONING

The previous chapter identified the predominant physical control on these systems and particularly it showed how the hydrographic regime and the sediments create space and niches for colonisation and how the hydrographic patterns can deliver recruiting organisms and food to an area. It also identified the e**nvironmental master factors** creating and modifying the conditions against which the biota could colonise these biotope complexes. The present chapter defines the **community ecology** of the biotope complexes and discusses the interactions both between the different species, and between the animals and their environment. It aims to describe the **structure and functioning** of the systems whereby structure refers to characteristics at one time, whereas functioning concerns the rate processes in ecosystems.

The biotope complexes discussed can be regarded as a **continuum** from muds high in the intertidal region, through intertidal sands to subtidal sands. Each of these has their own characteristics and so they are treated separately despite there being common mechanisms responsible for their formation, e.g. hydrographic regime and sediment structure.

The biota of primary importance in sedimentary habitats is:

- the **benthos**, including the organisms of different sizes (microbenthos, meiobenthos and macrobenthos) and subdivided into the infauna and epifauna;

- the **primary producers**, including any benthic microalgae (the microphytobenthos) and macroalgal mats;

- the **mobile epibenthos**, which may be megafauna, and the **vertebrate predators**, fishes and birds.

The sections below describe and consider each of these biological elements for each of the biotope complexes.

A. CHARACTERISTIC AND ASSOCIATED SPECIES

The most important features of the functioning of sand and mudflats and subtidal sandbanks is the abundance and biomass of a restricted set of species; the presence of internationally or nationally rare species is of less relevance here (see Chapter VIII). The species composition differs with substrata and other environmental variables and in shallow inshore areas subtidal sandbanks may be similar to intertidal sandflats (Willems *et al*, 1982; Atkins, 1983). The presence of any species in an area is dependent on its tolerance to those environmental variables such that considerable spatial and temporal variation occurs within estuarine and coastal sedimentary areas. As an example, the typical fauna that may be found in intertidal areas along a gradient of particle size is given in **Figure 3.0**.

1. Intertidal Biotope Complexes

a. Organic Production and Phytobenthos

Biological production of these areas is highly variable and relies on the quantity of nutrients being delivered or internally generated. Estuarine **mudflats** receive **primary production** from **benthic microalgae (microphytobenthos: diatoms, flagellates and euglenoides) and water-column phytoplankton** but this production may be light limited in these turbid environments. The mudflats receive a large input of nutrients, sediment and organic matter from the sea and land discharges of river water and sewage etc. and thus have a large productivity albeit from the low diversity created by salinity stress. More exposed sandflats are less productive as they are both harsher environments and with lower levels of organic matter. The intertidal mudflats in estuaries often have a higher production than subtidal areas as shown in the Forth Estuary (McLusky *et al,* 1992; Elliott & Taylor 1989b).

Intertidal sandflats only supports microphytobenthos in the interstices of the sandgrains. Mucilaginous secretions produced by these algae may stabilise fine substrata (Tait & Dipper, 1998). The microphytobenthos consists of **unicellular eukaryotic algae and cyanobacteria** that grow within the upper several millimetres of illuminated sediments, typically appearing only as a subtle brownish or greenish shading. The surficial layer of the sediment is a zone of intense microbial and geochemical activity and of considerable physical reworking. In many shallow ecosystems, the biomass of benthic microalgae often exceeds that of the phytoplankton in the overlying waters (McIntyre *et al*, 1996) such that benthic microalgae play a significant role in system productivity and trophic dynamics, as well as habitat characteristics such as sediment stability.

The predominant **macrophyte community** of intertidal sand and muds is usually poor unless there are some stones or shells for attachment of species such as *Chorda filum*, the bootlace weed. The community may include mats of *Enteromorpha* and *Ulva*, possibly in large aggregates to form the so-called **'green tides'** (Piriou, 1991). Seagrasses e.g. *Zostera*, occur in sheltered sand and mudflats both intertidally and in the shallow subtidal (see Volume I) whilst in sheltered brackish conditions on the upper shore saltmarsh plants such as the cord grass *Spartina* may become established.

b Benthic Fauna in Relation to Exposure

Intertidal Sandflats

The predominant factor controlling the intertidal community is **exposure** (Eleftheriou & McIntyre, 1976) and the type of community present ranges from more robust mobile forms in exposed areas to more sensitive sedentary forms in the more sheltered areas. Zonation schemes have been described for **macrofauna** on sandy intertidal areas, for example Dahl (1952) and Salvat (1964) based zones on the ability of the sediment to retain water. Some species are adapted to exposure to air e.g. *Scolelepis squamata* and *Haustorius arenarius* although many species are mobile and migrate to avoid prolonged exposure (McLachlan, 1983).

The **meiofauna** are likely to be important consumers of the microphytobenthic productivity, yet little is known about meiofauna herbivory in these environments (Montagna, 1995). Intertidal meiofauna, particularly **harpacticoids**, have a dependent relationship with their autotrophic food resources and can regulate their behaviour to maximise intake of food. However, many aquatic **nematodes,** which reach high densities in fine particle shores, are opportunistic feeders and may change feeding strategies in response to available food (Moens & Vincx, 1997). Harpacticoid copepods are common to intertidal and subtidal areas. Slender species inhabit the large interstitial spaces found on sandy beaches and larger epibenthic and shallow burrowing forms are more common in fine sediment habitats.

i. Exposed shores

Severe exposure with resulting coarser mobile sands produces low diversity, absence of sedentary forms, especially bivalve molluscs and a dominance of agile swimming forms (**Table 3.0**). These species have a short lifespan and are characterised by their ecological flexibility. This community was classified as the crustacean/polychaete community and in north-west Europe, consists of small, burrowing haustoriid and oedecerotid amphipods and polychaetes (McLachlan, 1996) in which diversity increases towards the low shore area (Eleftheriou & McIntyre 1976). Most fauna may live between mid tide level and the low water mark where Eleftheriou & McIntyre (1976) found crustaceans accounted for 52-98% of the individuals but the polychaetes, because of their greater size, 42-77% of the dry weight.

ii. Moderately exposed shores

These areas have fine sands which favour the establishment of a predominantly sessile community of polychaetes and long-lived bivalves, restricting swimming forms of amphipods and isopods and some errant polychaetes (Eleftheriou & Holme, 1976). Such areas encourage the colonisation of the intertidal area by subtidal species (denoted (s) in **Table 3.0**) and the other, intertidal, species follow a zonation pattern. The communities associated with these areas have been described as similar to the Boreal shallow sand association described by Jones (1950) and the *Tellina* (now *Angulus/Fabulina*) community. Where the sand mason, *Lanice* occurs in large numbers on medium sands, it has been described as a separate community (*Lanice* community).

iii. Sheltered shores

Sheltered shores are found in areas of low energy and have poorly sorted sediments with high levels of organic matter and an increased silt content (Dyer, 1979). Extreme shelter favours the establishment of a predominantly sessile tube-dwelling community of polychaetes which are often numerically dominant with bivalves also well represented (Atkins, 1983). Some species characteristic of subtidal areas may also occur (see **Table 3.0**). The heart-urchin *Echinocardium cordatum* occurs in both muddy and clean sands, although it grows much more slowly in the former (Buchanan, 1966).

Intertidal Mudflats

Estuarine mud flats (low energy areas) have well-defined macrobenthic community (see

Table 3.0, **Figure 3.0**) (Jones & Key, 1989; McLusky, 1989) which is similar to the Boreal shallow mud community described by Jones (1950) and also the *Scrobicularia* community. In addition, several tidal migrants occur including mysids, amphipods and decapods or drifting species associated with algal growths (e.g. *Melita obtusata*, *Dexamine spinosa*, *Stenothoe marina*, *Idotea* spp.). Often the fauna shows low species diversity, even though biomass may be high, but this depends on the amount of silt present. Many of the species described above for sheltered sandy mud shores will also colonise muddy shores e.g. *Arenicola*, and on estuarine mudflats enchytraeid and tubificid oligochaetes such as *Tubificoides benedeni* are often numerically very dominant.

In fully marine areas the organic content is lower and surface deposit-feeding terebellids e.g. *Lanice conchilega*, and spionid polychaetes and the filter-feeding bivalve *Cochlodesma* are common. The upper oxygenated layer of sediment extends from between about 3 and 7cm, but the larger tube-dwelling deposit feeding worms such as *Rhodine*, and the bivalve *Thyasira flexuosa*, which create extensive feeding channels in the sediment, are normally found in the deoxygenated zone but they extend their respiratory and feeding activities to the surface (Pearson & Eleftheriou, 1981). Firm muds may support piddocks such as *Barnea candida* and the boring spionid worm *Polydora ciliata*, while less well-consolidated muds are characterised by other nereid, spionid and capitellid worms.

2. Subtidal Biotope Complex: Subtidal Mobile Sandbanks

a. Organic Production and Phytobenthos

The physical environment of subtidal mobile sandbanks with stronger currents is often too harsh for vegetation to become established; they are less productive with lower levels of organic matter. However, sheltered subtidal sandbanks may support the sugar kelp *Laminaria saccharina* attached to stones and shallow conditions with adequate light will maintain a microphytobenthic community. Similarly, adequate light conditions will allow maerl to develop (see Volume V).

b. Benthic fauna in relation to hydrography

i Macrofauna

Mobile sandbanks are colonised by infaunal/epifaunal small crustaceans, polychaetes and molluscs which are **adapted to the changing hydrography and substratum**; they are able to reburrow rapidly following being washed-out of the sediment during storms (Vanosmael *et al*, 1982). For example, the body form and mobility of magelonid polychaetes and species such as *Nephtys cirrosa* and *Micropthalamus similis* are well suited to burrowing in mobile sands. These features indicate that the communities are clearly shaped by physical rather than biological forces.

The sediment in a mobile sandbank system may range from fine to coarse clean sands, and the density of individuals and species richness is often highest in the coarsest grade, mainly due to large numbers of interstitial polychaetes (Vanosmael *et al*, 1982). The mean macrobenthic diversity and species richness of clean mobile sandbanks is generally lower than the surrounding sea bed (reflecting the greater stresses inherent in these environments) although the fauna is essentially comparable with that of the open sea. The mouth of the Teign estuary has been noted to only contain *Scolelepis squamata*, *Eteone longa*, *Anonides oxycephala*, *Nemertea* indet. and an occasional juvenile *Mytilus edulis* in the mobile sandbanks.

Due to the continual **sediment disturbance**, the community may have a large opportunistic component with species such as *Chaetozone setosa* and may be prevented from reaching a climax community. For example, subtidal areas along the eroding Holderness Coast have large populations of *C. setosa* indicating a community held in a disturbed condition (Allen, in prep.).

The fauna of nearshore sandbanks vary geographically and are often impoverished extensions of the communities found at exposed intertidal areas, especially where currents are high and the substratum is clean sand. The MNCR classification of clean mobile subtidal sands describes the fauna as barren or characterised by *Pagurus bernhardus* and *Ammodytes* species (Connor *et al*, 1997). However if pockets of silt develop e.g. between ripples on the sand banks, a richer fauna may develop (Vanosmael *et al*, 1982) and substratum with an increased silt content may be characterised by epifaunal and infaunal echinoderms. As in intertidal areas, species which help to consolidate the substratum such as the reef forming polychaete *Sabellaria spinulosa* will help promote the settlement of other fauna.

The characteristic fauna of the subtidal mobile sandbanks is similar to Peterson's *Venus* community (in broad terms) which is comparable to the **'boreal offshore sand association'** (**Table 3.0**) with the number of species reflecting the stability of the area. Depending on the hydrodynamic regime of the area, the assemblage may also have elements of the **'boreal off-shore gravel association'** of Jones (1950) (Vanosmael *et al*, 1982). More stable sandbanks comprised of finer sediments may also resemble the **'boreal offshore muddy sand association'**. Such an association is often better characterised by less frequent species than by dominant ones, and the interstitial polychaetes and archiannelids, especially, seem to be characteristic of the communities described by Petersen (1913) and Jones (1950).

As an example, Vanosmael *et al* (1982) found that sandbanks off the Dutch coast were characterised by mobile and rapid-burrowing crustaceans and polychaetes such as *Nephtys cirrosa*, *Hesionura elongata* and *Microphthalmus listensis.* Sessile tube building polychaetes were represented by only a small number of individuals. *Hesionura augeneri* (an interstitial polychaete) made up 55% of the macrofaunal population which occurred in the highest densities in the coarser sediments. The polychaetes *Micropthalmus listensis, Nephtys cirrosa* and *N. hombergii* occurred separately because of differing sediment preferences. The mollusc *Spisula elliptica* was common in muddy sand, fine sand and shell gravel banks and the crustaceans, *Tanaissus lilljeborgi and Bathyporeia elegans* were the most common species on the sand banks, both showing a preference for fine sand. The macro-crustacea may be generally more abundant in finer sediments (Willems *et al*, 1982a).

Various epifaunal brittle stars are associated with this biotope complex e.g. *Amphiura filiformis* which extends its arms up into the water column to feed on suspended material. The heart urchin *Echinocardium cordatum* may also be common but replaced by another heart urchin, *Brissopsis lyrifera* in siltier areas. Sandeels e.g. *Ammodytes tobianus* and *A.*

marinus, are widespread (and Corbins sandeel and the greater sandeel to a lesser extent) on subtidal mobile sandbanks.

ii Meiofauna

The **meiofauna** also form an important component of the sandbank fauna. Interstitial organisms occur in sediments with a median grain size above 200 µm and polychaetes are found to be abundant (although they also live in finer sediments) in sediments with a particle size above 300 µm (Willems *et al*, 1982a). The meiofauna may be characterised by low densities of nematodes and high densities of copepods, annelids and halacarid mites. The meiofauna (particularly nematodes and copepods) are not correlated with sediment type although ostracods and halacarids may be more numerous in coarser sediments. In finer sediments, studies showed most copepods were species of *Cylindropsillidae* and *Parameschridae,* (the smallest harpacticoids). In coarser sands, above 300 µm median particle diameter, interstitial fauna included the nematode families, Ameiridae, Ectinosomatidae and Diosaccidae.

The occurrence of **rare species and very high diversity** is unusual in mobile sandbanks. However, three important species of interstitial polychaetes were recorded by Vanosmael *et al* (1982) in mobile subtidal sandbanks in the North Sea: *Polygordius appendiculatus,* (with a preference for coarse and medium sands), *Protodriloides chaetifer* (fine medium and coarse sands) and a species of the genus *Protodrilus.* The nematode densities in these sandbanks were generally higher than the surrounding seabed. Whilst the generic composition of the nematode communities in mobile sandbanks is similar to those of other clean sandy biotopes the large number of Epsilonematidae and Draconematoidea (Nematoda) found in this study is exceptional for offshore communities. These are adapted to the extreme instability of the substratum of the sandbanks and are confined to these biotopes. The fauna of these unstable habitats consists largely of erratic colonists brought in by water movement (Willems *et al*, 1982).

Table 3.0. Typical fauna found in the Biotope Complexes and their Subdivisions (s) Denotes subtidal species found intertidally. Table derived from references in text

Infauna	**Intertidal Sandflats:** **Exposed**	**Intertidal Sandflats:** **Moderately Exposed**	**Intertidal Sandflats:** **Sheltered**	**Intertidal Mudflats**	**Subtidal Mobile Sandbanks**
Amphipoda	*Haustorius arenarius* *Bathyporeia* spp. *Urothoe* spp.	*Perioculodes longimanus* (s) *Bathyporeia pelagica* *B. elegans* *B. pilosa* *Eurydice pulchra* *Pontocrates novegicus* *P. arenarius*		*Corophium volutator*	*Bathyporeia* spp. (e.g. *elegans)* *Pontocrates* spp.
Isopoda	*Eurydice pulchra*				
Tanaidacea					*Tanaissus lilljeborgi*
Polychaetes	*Nerine cirratulus* *Ophelia rathkei* *Scolelepis squamata* *Nephtys cirrosa*	*Chaetozone setosa* (s) *Owenia fusiformis* (s) *Exogone hebes* (s) *Arenicola marina* *Nephtys caeca* *N. cirrosa* *N. hombergi* *Scoloplos armiger* *Lanice conchilega* *Nerine cirratulus* *Ophelia rathkei* *Paraonis fulgens* *Spio filicornis*	*Arenicola marina* *Lanice conchilega* *Nerine foliosa* *Notomastus latericeus* *Scolelepis fuliginosa* *Nephtys* spp.	*Nereis diversicolor* *Nephtys hombergii* *Arenicola marina* *Pygospio elegans* *Manayunkia aesturina*	*Magelona* spp. *(e.g. mirabilis*) *Nephtys* spp. (e.g. *cirrosa*) Phyllodocidae (e.g. *Hesionura*) Hesionidae (e.g. *Microphthalmus*) *Sthenelais limicolor*

(Cont. on next page)

Infauna	**Intertidal Sandflats:** **Exposed**	**Intertidal Sandflats:** **Moderately Exposed**	**Intertidal Sandflats:** **Sheltered**	**Intertidal Mudflats**	**Subtidal Mobile Sandbanks**
Molluscs	*Donax vittatus* *Fabulina fabula* *Ensis siliqua*	*Fabulina fabula (s)* *Angulus tenuis* *Donax vittatus*	*Ensis ensis* *Macoma balthica* *Mya arenaria* *Cerastoderma edule* *Venus spp.* *Abra alba* (s) *Nucula turgida* (s)	*Macoma balthica* *Cersatoderma edule* *Retusa obtusa* *Hydrobia ulvae* *Scrobicularia plana*	*Venus* spp. *(e.g. striatula)* *Fabulina fabula* *Dosinia lupinus* *Gari fervensis* *Abra prismatica* *Ensis ensis* *Spisula* spp.
Epifauna					*Liocarcinus* sp *Cancer pagarus* Paguridae *(e.g. Pagurus bernhardus)* Pennatulacea
Megafauna	*Echinocardium cordatum* *Ammodytes* spp.		*Echinocardium cordatum*		*Echinocardium cordatum* *Ammodytes* spp.
Meiofauna	Nematodes Harpacticoid copepods				Nematoda *(e.g. Epsilonematidae)* Copepoda Archiannelida (e.g. *Protodrilus*)

B. ECOLOGICAL FUNCTIONING AND PREDATOR-PREY RELATIONSHIPS

The previous section details the components and structure of the communities found in these biotope complexes. However, it is emphasised that these communities are relatively poor in diversity but that, especially in the case of intertidal mud and sandflats, they have high abundances. Because of this, it is necessary to detail the functioning of the ecosystems and the support by prey for predator populations. Important predator populations in the intertidal and subtidal sedimentary areas include bird and fish species. In addition to the effects of other major biotic and environmental factors, the size of the any productive will area affect its carrying capacity in supporting wading birds (Meire, 1993) and fish.

1. Intertidal Mud and Sandflats

a. Mobile epibenthos

Intertidal mud flats are important in the functioning of estuarine systems and may have a disproportionately high productivity compared to subtidal areas (Elliott & Taylor, 1989b). Conversely, coastal sandflats have a very poor productivity (McLachlan, 1996). Epifaunal organisms associated with these biotope complexes are predominantly **mobile predatory**

species such as crabs e.g. *Carcinus maenus* and shrimps e.g. *Crangon crangon*, which take infaunal populations of small bivalves, polychaetes and crustacea. Organisms associated with silty sands are predominantly mobile species, including the crabs *Liocarcinus depurator*, *Atelecyclus rotundatus* and *Macropodia* spp.

Carcinus maenus has been shown to significantly reduce the numbers of *Manayunkia aesturina* on mudflats (McLusky, 1989) and *Carcinus* and *Crangon* may reduce the population of *Corophium volutator* in estuaries by over 50% (Pihl, 1985). The shrimp *Crangon crangon* is a significant predator of the smallest sizes of plaice during and immediately after the fish settle on sandy beaches when predation rate is strongly dependent on the size of both the predator and the prey (Gibson *et al*, 1995). This size dependency is caused principally by the superior escape capabilities of larger fish once captured rather than differences in the ability of different sizes of shrimps to capture prey.

Polychaete worms are dominant predators within the substratum and tend to be **opportunistic** and actively pursue prey (although they may have size preferences); their numbers may be closely related to those of their prey which includes other worms and crustaceans (Meire *et al,* 1994). Many infaunal species also scavenge e.g. *Nephtys* and the isopod *Eurydice pulchra* and quantity of food input determines the density of **scavengers** (Hayward, 1994, Ansell *et al,* 1972). Scavengers may dominate on coarse steep shores and are found in high numbers near kelp beds where there is a large amount of macrodebris (McLachlan, 1983).

b. Fishes

Intertidal areas are well-defined as **juvenile fish feeding areas** (Costa & Elliott, 1991). Mud and sandflats are important **nursery areas** for plaice (Lockwood, 1972; Marshall, 1995; Marshall & Elliott, 1997), as well as feeding areas for sea bass and flounder (Elliott & Taylor, 1989). Fish such as dover sole, *Solea solea* and gadoids frequent sandy areas, but many also occur on coarser and mixed grades of sediment. Smaller fish (e.g. plaice) may settle on mudflats while larger fish are found on sandflats (Gibson, 1973; Gibson & Robb, 1992). **Migratory species** such as salmon and shad can also be found in these areas on passage to other wetlands, e.g. saltmarshes and freshwater areas, although they appear to have no requirement for the mud and sandflats.

The most important marine predators on intertidal sand and mudflats are particularly the **flatfish** *Solea solea* (sole), *Limanda limanda* (dab), *Platichthys flesus* (flounder) and *Pleuronectes platessa* (plaice) which feed on polychaetes and their tails (e.g. of *Arenicola* and *Nereis*), bivalve young and siphons (e.g. of *Macoma* and *Angulus*) and tidally active crustaceans such as *Bathyporeia* and *Eurydice* species (Croker & Hatfield, 1980; McDermott, 1983; McLachlan, 1983; Zwarts *et al,* 1985). In summer, large numbers of plaice and dab juveniles move over flats at high tide to feed on mobile epifauna, sedentary infauna and protruding siphons and tentacles (Elliott & Taylor 1989a). Within estuaries and on mud and sandflats, however, many demersal fish are **opportunistic predators** and the prey choice will reflect the infaunal species distribution of the area (Marshall & Elliott, submitted; Costa & Elliott, 1991).

Flatfish use several **feeding strategies** in estuarine areas with plaice and flounder using tidal migration feeding only at high tide on the intertidal flats. Dab and sole do not migrate tidally and feed continuously in the subtidal areas (McLusky, 1989). Gobies e.g. *Pomatoschistus* spp. are another important predator on mudflats and prey heavily on *Corophium volutator* and they have a significant impact as both predator and prey in estuarine ecosystems. Small juveniles (e.g. plaice) settling on fine sediments are less likely to be predated than those that are settled but do not bury in coarser sediments (Gibson & Robb, 1992).

Tidal elevation influences population size in fish, for example, plaice populations are largest at the water's edge at a depth of 1-2m suggesting that they **migrate** with the tide up and down shore (Gibson, 1973). The young of many species, such as plaice, enter the intertidal zone to feed as the tide floods. There is also a relationship between the size of the fish and depth (for plaice specifically), as the body length increases, the depth of the water that the fish inhabits increases (Gibson *et al*, 1995). Depth and salinity may also influence flounder distribution (Armstrong, 1997).

b. Wading birds and wildfowl

These biotope complexes are used by important wintering and passage birds for **feeding and roosting** (a simplified food web of a depositing shore is shown in **Figure 3.1**). Shorebirds form important predators on NW European intertidal mud and sandflats during long migrations over long distances from breeding to wintering grounds. Particularly dependent species are brent geese, shelduck, pintail, oystercatcher, ringed plover, grey plover, bar-tailed and black-tailed godwits, curlew, redshank, knot, dunlin and sanderling, whilst grey geese and whooper swan may use this habitat for roosting (Jones & Key, 1989; Davidson *et al,* 1991). Bird communities are highly mobile and usually exhibit patterns of activity related to tidal water movements. However, the **carrying capacity**, in terms of space or food, of these biotope complexes has not been determined. The carrying capacity is reached when every new individual entering the habitat causes emigration or death of another bird (Goss Custard, 1984).

Where mudflats occur within estuaries, any change in salinity will affect their prey structure but not necessarily their functioning. For example, on mud flats *Nereis* may be replaced by *Nephtys* following an increase in salinity with reduced river flows (McLusky & McCrory, 1989). Although the species composition is seen to have changed along the environmental gradient, the community still functions as prey for the birds.

In analysing the **feeding preferences** of different species, it was initially suggested (Green, 1968) that both physical and behavioural adaptations have been shown for shore birds including bill lengths which correspond to the depth of specific prey items. Species such as the bar-tailed godwit takes cues from new *Arenicola* casts and the shelduck which feeds extensively on *Hydrobia ulvae* has five distinct feeding methods relating to the tidal state and the behavioural patterns displayed by *Hydrobia* (Bryant & Leng, 1976). However, more recently, waders are regarded as **opportunistic feeders** with only a general relationship between depth of prey and size of bill (McLusky, 1989).

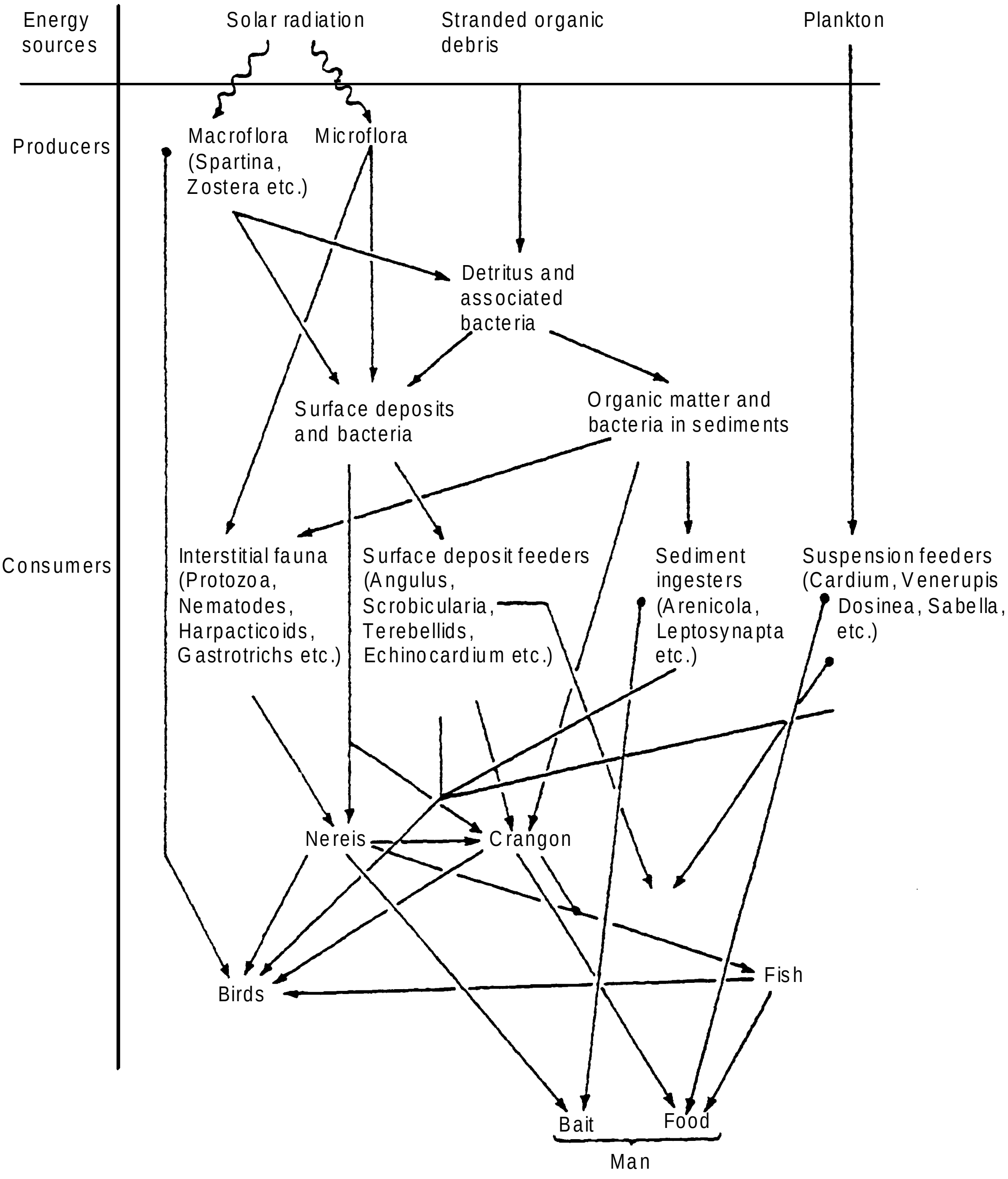


Figure 3.1 Simplified food web of a depositing shore (in Tait & Dipper, 1998).

Different bird species exploit different areas of an intertidal area, for example the redshank and the shelduck feed on the intertidal area at low water or the water's edge, usually on *Macoma*, *Hydrobia* and other small invertebrates such as *Corophium*. Waders such as sanderling are efficient croppers of macrofauna at the low tide waters' edge both in summer and winter (McLachlan, 1983). Eider ducks, however, feed in the shallow water at low tide on species such as *Mytilus edulis*. The diet of the black-tailed godwit consisted mainly of the bivalve mollusc *Scrobicularia plana* with a small proportion of ingested biomass being *Nereis* and *Hydrobia* (Moreira, 1994). The sizes taken reflect those available although optimal foraging occurs.

Feeding behaviour differs within intertidal sand and mudflats with variations in the percentage of shorebirds engaged in feeding, roosting and other behaviours dependent on location, date, time, tide and species. Burger *et. al* (1997), studying spring migrations in Delaware Bay, found that a higher percentage of shorebirds fed during the middle of migration, in early to mid-morning, and during low and rising tides than at other times. Some shorebirds fed on the marshes and mudflats during all tidal states, but none fed on beaches at high tide (beaches were too narrow). Within each habitat, the highest percentage of shorebirds foraged during low tide (marshes) or rising tides (mudflats and beaches). The percentage of shorebirds engaged in foraging as an indication of **foraging value** for each habitat type, showed that a mosaic of habitat types ranging from mudflats to high marshes is essential to sustain the high populations of shorebirds.

2. *Subtidal Mobile Sandbanks*

The subtidal mobile sandbanks provide prey for **demersal fishes**, especially the mobile small crustaceans which migrate from the sediment and thus become available for predation (Costa & Elliott 1991; Marshall & Elliott, submitted). The areas are often important as fish nursery areas, e.g. plaice (Gibson, 1973), and may be characterised by low organic enrichment though there may be localised pockets of organic matter or areas which receive anthropogenic waste, e.g. the Dogger bank.

The sandbanks are also important areas for **crab populations**, for example the Race Bank and Docking Shoal off the Norfolk coast support a large population as well as numerous other epifauna, particularly echinoderms. The epifaunal component may represent a large proportion of the biomass of the sand bank fauna with large numbers of echinoderms such as *Asterias rubens* and brittle stars such as *Ophiura albida*. Predatory fauna such as hermit crabs e.g. *Eupagurus bernhardus*, *Liocarcinus depurator* and the edible crab *Cancer paguras* may also be present.

Birds such as the guillemot, razorbill, puffin and the terns will feed on the fish such as sandeels (*Ammodytes* spp.) which are found in mobile subtidal sands (Batten *et al,* 1990). Both the arctic tern and the puffin rely on populations of sandeel as their predominant food source. The sandeel is also an important food source for wintering birds such as scoters, little terns and the red-throated diver (Gibbons *et al*, 1993). Guillemots and razorbills although not as selective as puffins and terns will also eat sandeels.

C. BIOLOGICAL AND ENVIRONMENTAL INTERACTIONS

It is the physical hydrodynamics which controls substratum type which, in turn, affects the biological features of these habitats (McLachlan, 1983, 1996). Within the biological niches created by the physical environment, biological factors such as predator/prey relationships operate. Furthermore, the biological components will also affect the physical conditions, e.g. bioturbating organisms rework and bind the sediment changing the properties of the substratum (Peterson, 1991). These interactions between the physical features and biota (**'environment to biology'**), the relationships between the biological components and processes (**'biological mediating relationships', 'biology to biology'**), and those whereby the biological processes modify the environmental conditions (**'biology to environment'**) are summarised in **Figure 3.2**. The interactions between the attributes produces several related features which can be used for defining the condition of the habitats. For example, the spatial extent and the tidal regime and elevation of the biotope complexes dictates the size of the primary consumer populations supported which in turn are prey for the fish and birds (Gray, 1981).

1. 'Environment To Biology' Links

Although the effect of one or more environmental factors acting singly or in conjunction with others is important, the primary factor controlling the dynamics of the intertidal sand and mudflats and the subtidal mobile sand banks is the **hydrophysical regime** (see Chapter II). The interactions of all physical factors will determine the composition and density of the infauna (Eleftheriou & McIntyre, 1976). Species in the biotope complexes are somewhat protected against the **sedimentary instability** and **variability in temperature, salinity, exposure and predation** by burrowing (Eagle, 1973).

Marine organisms have fundamental tolerances which dictate their large scale geographical distribution (Glemarec, 1973). On a regional scale, temperature tolerances will produce **'biogeographical zones'** (e.g. Arctic, Boreal, Lusitanian assemblages) and **salinity tolerances** will dictate the extent of distributions within freshwater-affected environments such as estuaries (McLusky, 1989).

Unstable sediments support fewer organisms than stable ones and only those mobile species which can re-establish their position, e.g. the haustoriid amphipods and *Eurydice pulchra*, can survive in very unstable conditions (Allen & Moore, 1987). Some species of macrofauna, in particular the **crustaceans**, are adapted to living in sediments exposed to heavy wave action mainly through their ability to burrow rapidly (Brown, 1983). On NW European shores these are usually small amphipods such as *Bathyporeia spp.* and *Pontocrates* spp. which live in the water column but burrow into the sediment as the tide level falls. These organisms probably depend on the washouts in high-energy (mobile) sands for feeding and migration.

In general, decreasing exposure to wave action correlates with increases in abundance, species richness and biomass of **polychaetes** and a decrease in abundance of crustaceans (Dexter, 1990). Polychaetes are often limited to *Nephtys* spp., *Scolelepis squamata* and capitellids with molluscs either present in very low numbers or absent (Angus, 1979). Survival rates of organisms such as sedentary polychaetes, living in the sediment decrease when surface sediments are disturbed daily although it is possible that small ones are simply relocated (Brown, 1982). Motile species such as *Scolelepis squamata*, however, are adapted to life in unstable sediments and survive through rapid burrowing (McDermott, 1983).

Insert Figure *3.2*

Allen and Moore (1987) found correlations between community structure and the prevailing physical conditions including shore stability for both individual organisms and guilds. The relationships were more evident lower down the shore where other factors such as desiccation were less important. For example, *Bathyporeia sarsi* was found in stable and unstable conditions and *Paraonis fulgens* and *Arenicola marina* at moderately unstable sites. *P.fulgens* is able to anchor itself in the sediment and *A. marina* can burrow to depths of 0.2 m where wave action does not penetrate. *Nephtys cirrosa* was the only errant polychaete strongly associated with unstable sediments. Rasmussen (1973) and Wolff (1973) give the ecological preferences of many other intertidal and shallow organisms.

Species diversity as well as overall community structure, is influenced by the habitat stability and sediment type. Coarse sediments, which are unstable and difficult to burrow into, are dominated by epifauna, while fine sediments are increasingly dominated by infauna. Many species are found in or on a range of sediment types, but others have a more restricted distribution (Wolff, 1973). For example, each of the five species of the bivalve *Nucula*, which occurs in subtidal muddy-sands, prefers a particular grade of sediment (Wood, 1987). The greatest diversity of macro-infaunal species is generally associated with poorly-sorted sands because they are physically heterogeneous, and thus have a large number of ecological niches, are reasonably stable and contain a supply of deposited organic matter.

Sedimentary features influencing the distribution of **feeding guilds**, e.g. suspension and deposit feeding benthos (Sanders, 1958), where high silt-clay fractions (relating to greater amounts of food) partly explained the presence of the deposit-feeding benthos. **Deposit feeders** dominate over **suspension feeders** in areas with higher percentages of silt-clay. They feed on the bacterial and microphytobenthos film surrounding sand and mud particles and therefore tend to dominate mud flats and sheltered shores. A non-selective deposit feeder such as *Arenicola marina* is dependent on detritus as its main food supply while living micro-organisms providing nutrients such as vitamins. Nutrients from the faecal cast may be reabsorbed either directly or from the bacteria degrading the cast (termed **'gardening strategy'**).

The distribution of suspension feeders is greatly affected by sediment instability as muddy sediment and high turbidity clog the filtering organs. In addition, subtle changes in the relative proportions of sand/silt/clay will affect an organisms' ability to maintain a burrow (Meadows & Tait, 1989). Suspension feeders such as *Lanice conchilega* tend to dominate more exposed shores and coarser sediments where food supply may be limited but constant and with their abundance determined by the supply of particulate organic material and plankton in the water (Brown, 1983; McLachlan, 1983; Peterson, 1991).

2. Biological Mediating Relationships

a. Predation

The main predators in intertidal and subtidal areas are birds, fish and epifaunal crustacea such as crabs and shrimps (Meire *et al*, 1994). These aspects of mediating relationships have been detailed above.

b. Competition

The faunistic variation in these physically controlled environments reflects the species tolerance and sensitivity to those conditions. Competition between organisms occurs in response to a **limitation of resources** - the abundance of reproductive mates (intra-specific competition) and food and space (**inter- and intra-specific competition**). Competition for space and food is unlikely to be a limiting feature in the high energy sedimentary environments (sandbanks). This is because the populations are small, due to the harsh conditions, and many organisms swim and feed in the water column at high tide and only shelter temporarily in the sediment at low tide (Peterson, 1991). Densities are kept low by the disturbance of sediment in high energy areas and so there is probably no limitation of space (Peterson, 1991).

In many marine, sedimentary communities, deposit and detritus feeders compete for food and suspension feeders compete for space (Levinton, 1979). Thus the large populations inhabiting intertidal mudflats and, to a lesser extent intertidal sandflats, will have inter- and intra-specific competition for food. Because of this, **resource partitioning** may occur among certain deposit feeders to avoid competition as shown for the gastropod *Hydrobia* and the amphipod *Corophium* which ingest different size food particles (Fenchel, 1972). Inter-specific competition may be relatively low in intertidal mud and sandflats because of the restricted community diversity.

c. Recruitment and lifecycles

Most macrofauna are iteroparous in that they breed several times per lifetime. The fecundity is closely linked to the limited food supply with temperature changes an important controlling factor. Many polychaete worms including *Nephtys* spp. and spionids release eggs and sperm into the water where, after fertilisation, the larvae enter the plankton for a short time before settling to the substratum (Rasmussen, 1973). The **passive movement** of these stages again reinforces the importance of understanding the hydrographic regime to interpret the factors influencing the community structure.

i Intertidal sand and mudflats

The presence of high densities of adult invertebrates may inhibit the **recruitment** of potential colonising stages from the water (Olafsson *et al,* 1994). This may account for juveniles occupying less favourable parts of the intertidal areas, for example juvenile *Arenicola* and *Nephtys* settle at areas outside the optimal distribution for the adults. However, many juveniles and adults are mobile and can enter the water column and relocate themselves. Larvae from species such as *Nephtys* settle in low energy areas and then migrate to the more favourable areas favoured by the adults (Peterson, 1991). Recruitment is then linked with the hydrographic regime which allows the dispersal and eventual settlement of metamorphosing larvae. This then allows for the **'hydrographic concentration'** of new recruits to a population.

Although some sediment dwellers have a **benthic and brooding mode of reproduction** (e.g. amphipods and oligochaetes), most are planktonic spawners (Rasmussen, 1973) and the settlement of *Nephtys caeca* did not take place in the intertidal zone, suggesting sublittoral larval recruitment. The number of larger individuals increased markedly with decreasing level on the shore. *Nephtys caeca* is polytelic (which is discrete, iteroparous) and on European coasts breeds in its second and subsequent years (Olive *et al*, 1981). The **spawning is highly synchronised**, and an elevation of the water temperature could be the triggering factor for gamete release (Olive, 1978). *Nephtys caeca* has a diverse population structure which allows a better recovery from a poor recruitment. Some species show **spatial variation in their life cycles**, for example, different populations of *Corophium volutator* display one or two generations per year depending on their location.

ii Subtidal mobile sandbanks

Severe exposure such as that occurring on subtidal mobile sandbanks restricts diversity, by eliminating sedentary forms, especially bivalve molluscs, and encouraging the numerical dominance of agile swimmers such as haustoriid amphipods and isopods. These species have a short life span (*r strategists*) and the fauna is characterised by its flexibility. The population dynamics of the fauna in exposed habitats may be based on long term breeding success, e.g. 6-7 years for tellinids with a cohort produced which may then dominate the population (Pearson & Barnett 1987). The opportunist pollution-tolerant polychaete *Capitella capitata* (which is also an r strategist) has both benthic and planktonic larvae and breeds throughout the year, this means it is able to colonise impacted or stressed areas very quickly.

Subtidal mobile sandbanks are usually dependent on **an input of colonising organisms** and have few species with benthic reproduction, thus any disruption to the delivering currents will cause changes. In addition, some sandbanks are likely to be sinks of materials as centres of gyres. The community of these areas in most cases will not contain rare species given the dispersal mechanisms of the species and the nature of the areas. The larvae of many benthic species e.g. *Ophelia bicornis, Protodrilus* spp., *Pygospio elegans* and *Phoronis* spp. can differentiate between substratum types and settle upon the preferred grade of sediment. The larvae of the reef forming polychaete *Sabellaria spinulosa* seeks contact with the tubes of adults and will settle in these areas before commencing metamorphosis, hence some of the biological components influencing other biological components.

3. Biology To Environmental Links

The basic biological community established under the prevailing environmental conditions has the capacity to modify the sedimentary regime (**biomodification**). There are several categories of biomodification:

- by organisms with an ability to stabilise the sediment, (**biostabilisation**) as shown on intertidal mud and sand flats, for example, by spionid tube beds (e.g. *Prionospio elegans*, by affecting boundary conditions), microphytobenthic mats (by mucopolysaccharide production), and eelgrass meadows (by sediment binding with rhizome production and by disturbing the sediment-water interface turbulence);

- by organism behaviour leading to **biodestabilisation**, which in turn may lead to increased erosion (**bioerosion**); this may result from excessive reworking (**bioturbation**) by mobile infaunal organisms (e.g. *Macoma balthica*) on mudflats;

- by feeding behaviour increasing the supply of sediment from the water column to the seabed through the production of faeces and pseudofaeces (**biosedimentation**), for example by suspension feeders such as mussels (*Mytilus edulis*) on mudflats and cockles (*Cerastoderma edule*) on sandflats.

Each of these processes modifies the sedimentary regime with the potential of increasing its heterogeneity and thus the number of niches available for colonisation. For example, extensive reworking increases the depth of surface-phenomena such as oxygenated sediments as well as increasing **rugosity (surface roughness)**. Surface roughness disrupts the sediment-water boundary conditions and the ability for organisms to settle although it may also increase erosion.

Heterotrophic marine organisms are predominantly deposit or suspension feeders. Deposit feeders may feed at the surface or at depth within the sediment, resulting in the production of faecal pellets and the movement of organic material from deeper within the sediment to the surface. The **vertical and lateral movement of mobile deposit feeders** causes the mixing and transport of particles, interstitial water and dissolved gases (Rhoads, 1974). In muddier areas the production of faecal pellets by deposit feeders are of a size which may be ingested or otherwise manipulated by other benthic invertebrates hence increasing sediment reworking. As a consequence, the degree of bioturbation tends to be greater in fine muds dominated by deposit-feeders than in coarse grained substrata (Rhoads, 1974).

The factors most highly correlated with bioturbation are feeding method and location in relation to the sediment-water interface, organism size and degree of mobility, population density, burrowing depth and the density and spacing between animal tubes (Rhoads, 1982). Many of these processes are population size and temperature dependent. In addition, Reichelt (1991) identified three main processes leading to bioturbation: feeding activity, burrow or tube construction and migration within the sediment column due to tidal and diurnal cycles. For example, sedentary deposit-feeding polychaetes often form dense tube aggregations which have a stabilising effect on the sediments. Suspension feeders actively or passively entrap suspended seston which is later deposited at the sediment surface in the form of faecal pellets or un-pelleted pseudofaeces. The upper size limit of particles ingested by suspension feeders is generally smaller than that of deposit feeders (Jørgensen, 1966 in Rhoads, 1974).

Faecal pellets have higher deposition rates than their constituent particles and therefore settle out near the site of production. Deposit feeders may have a more quantitatively significant role in pelletization of the sea floor than suspension feeders or zooplankton (Rhoads, 1974). However, the production of non-pelleted pseudofaeces also contributes to the rate of sedimentation in many mudflat areas.

D. KEY POINTS FROM CHAPTER III

- In understanding the biology of the sedimentary biotope complexes, it is necessary to consider the structure of the communities and their functioning. The important and most widely-studied components of the systems are the primary producers (predominantly the microphytobenthos), the benthic macrofauna and meiofauna, the mobile epibenthos and the vertebrate predators.

- Organic production supporting the system is autochthonous in the case of the mudflats and, to a lesser extent, the sandflats but allochthonous for these biotope complexes and especially the subtidal mobile sand banks.

- The intertidal sedimentary communities are well-categorised and fit with the Petersen's Boreal *Macoma* and *Tellina* assemblages whereas the subtidal mobile sandbank community is less well-defined but similar to the Boreal Offshore Sand Association.

- The biodiversity of these sedimentary biotope complexes is influenced by habitat stability and sediment type. In particular the complexity of the substratum will determine the number of available niches and hence the diversity of the community.

- High energy areas such as exposed sandflats and subtidal mobile sandbanks are characterised by a low diversity, lack of sedentary forms especially bivalve molluscs, and the numerical dominance of agile swimmers such as haustoriid amphipods and isopods. These species have a short life span and are characterised by their ability to withstand sediment disturbance.

- Low energy areas such as intertidal sheltered sandflats and mudflats favour the establishment of a predominantly sessile community of polychaetes and long-lived bivalves.

- The intertidal sand and mudflats are important in supporting predator communities such as mobile macrofauna, overwintering and migrating wading birds and juvenile fish, whereas the subtidal mobile sandbanks support lower densities of epibenthos in addition to demersal fishes and seabirds taking sandeels (*Ammodytes* spp.). These have implications at local, regional and international scales.

- In order to understand the processes structuring the biology of these areas, it is necessary to understand the way in which (i) the environmental parameters create available niches for colonisation (the 'environment to biology' relationships); (ii) the biological inter-relationships mediate the community formation (the 'biology to biology' links, including feeding, competition, recruitment processes) and (iii) the means by which the biota modify the sediment structure ('biology to environment' processes such as bioturbation and biosedimentation).

- Species diversity as well as overall community structure, is influenced by the habitat stability and sediment type. Coarse sediments, which are unstable and difficult to burrow into, are dominated by epifauna, while fine sediments are increasingly dominated by infauna.

IV. SENSITIVITY TO NATURAL EVENTS

Assessment of the sensitivity of these biotope complexes to naturally occurring events is complicated due to the many important and measurable physical and biological features. This chapter attempts to identify the responses of the biological and physical features to natural events and the sensitivity of these features to such incidents. **Vulnerable biotopes and species** are identified with regard to their **stability**, **recoverability** and the frequency of the natural influences.

The long term stability of benthic communities is relatively poorly understood. The community dynamics of **intertidal sand and mudflats** are reasonably well known and barring severe changes to the sedimentary regime by wave action or other impacts they may appear more stable than subtidal environments. The long term dynamics of **subtidal areas** are much less understood due to the increased complexity of the environment, the large number of species involved and the difficulty in sampling the habitats. However subtidal areas including sandbanks undergo periods of stability followed by periods of instability which may extend over several years. This may be linked to winter temperature variation and biological interaction as well as changes in the physical regime or influx of organic matter.

A. POTENTIAL AGENTS OF CHANGE

Subtidal mobile sandbanks are not subject to periodic exposure to the air and subsequent drying out as in intertidal areas but many parameters (summarised in **Table 4.0**) which influence intertidal sand banks do affect subtidal sand banks. The natural influences affecting subtidal mobile sand banks vary depending on their location. Sand banks occurring in estuarine or semi-estuarine conditions e.g. the Solway Firth may be subject to some fluctuation in salinity and temperature. Fully marine sandbanks generally will be less affected by these parameters.

Table 4.0. Important natural parameters which influence the habitat features.

Stressor	Intertidal Mudflats	Intertidal Sandflats	Subtidal Mobile Sandbanks
Hydrophysical regime, water activity and concomitant sediment change	Yes	Yes	Yes
Sea-level rise/tidal elevation	Yes	Yes	Unlikely
Exposure/Desiccation increase	Yes	Yes	Unlikely
Predator changes	Yes	Yes	Yes
Extremes of climate (temperature, storms, freshwater runoff	Yes	Yes	Storms only

1. Climatic Conditions

a. Hydrophysical regime

i Responses Common to Both Biotope Complexes

The hydrophysical regime is very variable and, while it is possible to consider ‘average’ exposure, it is essential to recognise that for both biotope complexes and particularly subtidal sandbanks, **extreme conditions** have profound effects (Hiscock, 1983), even when they only persist for a short length of time. Water movement due to wave action is the more erratic because it fluctuates considerably on a seasonal basis. Movements caused by tides and currents varies in regular patterns but it is not only the strength but also the type of movement that affects the distribution of marine organisms. Uni-directional, multi-directional and oscillatory movements each represents a different type of stress or confer particular advantages (Wood, 1987). **Storm events** will inflict extreme changes in wave action both in terms of strength and direction (Pethick, 1984; Carter, 1984).

Both these intertidal and subtidal biotope complexes will be sensitive to changes in the hydrophysical environment (see Chapter II). For example, periodic increases in wave action can severely alter the appearance of the intertidal region as the top 20cm of sand can be removed by storm events (Dolphin *et al*, 1995). Such storms are an important mechanism which can re-sort the sediment, leaving coarser particles, and release of sediment-sequestered contaminants (Dolphin *et al*, 1995).

Increased wave action causes stress to the infauna by disrupting feeding and burrowing activities and reduces species richness, abundance and biomass. The infauna are sensitive to **changes in sediment** as many are adapted to burrow through certain grades of sediment (Trueman & Ansell, 1969). Coarse material is more difficult to burrow through and species have to be robust in order to survive the stronger currents/wave action in these areas. Changes in sedimentary features may also influence the trophic status of the infauna and the proportions of suspension and deposit feeding animals (Sanders, 1968). The distribution of suspension feeders is greatly affected by **sediment instability** and they are sensitive to increases in the silt/clay content of the substratum and suspended sediment. In turn, changes to the infauna will affect the predators (Chapter III).

Changes in the hydrophysical regime and thus substratum will change the faunal composition of the biotope complex. Major changes in the former will produce mortality and reduce species richness. Although many species are capable of living in a variety of substrata, the species most affected will be those which are restricted to a particular grade of sediment.

ii Intertidal Sand and Mudflats

The strength of wave action affects the **topography** (as **flatness/steepness** and **shore width**) of the intertidal area therefore a significant change in wave action will affect the **physical and biological integrity** of that habitat and the exposure regime. The topography of the shore is equally important as flatter shores dissipate energy and generally have a more stable fauna (McLachlan, 1993). For example, the exposure of the intertidal flats on the Severn estuary to the prevailing gales, together with the large tidal range, caused large areas of surface mud and hence its invertebrates to be removed (Ferns, 1983). Many of the shorebirds moved temporarily to other, more sheltered areas.

Intertidal mudflats are by definition sheltered environments and hence relatively stable in sedimentary terms. Any increase or decrease in grain size, silt content etc. will affect species numbers/richness but these should return to normal levels if the disturbance is temporary. In addition, the **sedimentary heterogeneous nature** of mudflats reflects the species greater tolerance of different particle sizes. The high bioturbatory potential of mudflat organisms (see Chapter III) will decrease their sensitivity to sediment changes such as smothering by any influx of new sediment.

Intertidal sandflats will be more or less subject to disturbance by hydrodynamic changes depending on their exposure regime. More sheltered sandflats, which may have a large population of tube dwelling polychaetes for instance, will be severely affected by storm events and a large reduction in species richness and abundance may occur. This may lead to the development of a transitional community dominated by opportunist species and more mobile infauna such as Haustoriid amphipods and errant polychaetes (see Chapter III). **Recovery** of the community will be determined by the **degree of change**. Longer term changes as an increase in grain-size following intense wave action or a changed wave-field may lead to a more permanent change in the faunal composition of the biotope, with species such as *Fabulina fabula, Donax vittatus* and Haustoriid amphipods becoming more dominant. Increased deposition of finer material will lead to increased dominance by species preferring finer sediments such as *Angulus tenuis*. More exposed sandflats have a poorer community with elements more tolerant of increases in wave action so changes will be less severe.

iii Subtidal Mobile Sandbanks

Wave action is also important subtidally in shallower areas as it can disturb the sediment, particularly during storms. **Disturbance** of this nature may affect shallow and deep sand banks (Perkins, 1974) and may result in large scale sediment transport. In many areas the predominant factor influencing the structure of subtidal sand banks and other shallow subtidal areas are tidal streams. These currents lead to constant change in the size shape and position of sand banks and in some areas e.g. in the Solway Firth where tidal streams are particularly strong, sandbanks may move considerably over one tidal cycle (Perkins, 1974).

Hydrographical changes operate at **different spatial scales**, for example in the North Sea broad scale communities were influenced by temperature and depth also relating to the presence of different water masses (Glemarec, 1973; Basford *et al*, 1990). As substratum effects are superimposed over these variables, wide-scale physical effects can lead to community replacement. By definition, subtidal mobile sandbanks are subject to continued reworking of the sediment by wave action and tidal streams and thus are dominated by species capable of tolerating severe changes in the hydrophysical regime.

At more sheltered sandbanks, changes following severe **hydrodynamic stress** will be greater although continued or regular disturbance may give rise to a transitional community dominated by species such as *Chaetozone setosa*. As **recruitment** to subtidal sandbanks is due to chance influx of species from external areas, which will be dictated by the hydrodynamic regime (Chapter III), the **post-transitional community** may be difficult to determine. In addition, transitional communities by nature are unpredictable. In areas of mixed sediment, the recruitment of species such as *Sabellaria spinulosa* will stabilise the sediment and allow the influx other species, an thus an increase in diversity, as well as increasing the heterogeneity of the substratum. The **timing during the year** of the disturbance in relation to the settlement patterns of different species will influence the structure of the community.

b. Other seasonal influences

Seasonal changes occur in **subtidal community structure** (e.g. Boesch, 1973) and environments that have characteristic seasonal patterns of species composition are relatively unstable and often 'physically-controlled' (Sanders, 1968). In **estuarine, intertidal and shallow-subtidal habitats** with characteristically large seasonal fluctuations in environmental parameters, changes in the biotope complex are likely. For example, high temperatures and calm conditions may lead to stratification of the water column and to hypoxia in the near bottom water will be exacerbated by high sedimentary organic matter (see below).

i Intertidal sand and mudflats

The **extreme temperatures** experienced in the intertidal habitat also influence their populations' behavioural and reproductive activity and food and oxygen availability (Eltringham, 1971). For example, summer water temperatures may control the number of generations per year of *Corophium volutator*. Many intertidal species have wide **tolerances** for temperature and can also alter metabolic activity, or simply burrow deeper in the sediment or move seaward to combat temperature change (Brown, 1983). Severe changes in temperature in intertidal areas will result in a seasonal reduction in benthic species richness and abundance, although the species are well adapted to such changes. Temperature is also an important factor explaining dynamics of **microbial activity** and **microphytobenthic primary production** on intertidal mudflats (Blanchard & Guarini, 1996) so microbial activity on intertidal mudflats.

ii Subtidal mobile sandbanks

These will not be subjected to such extreme changes in temperature as intertidal areas although fluctuations will occur in **stratified waters** or on the **boundaries of frontal systems**. Changes in the salinity or temperature may occur on the sea bed if the stratification of the water column is broken down by storm events or by shifts in the position of front. Despite this, the main source of temperature variation at subtidal sandbanks will be between summer and winter which may be 5° to 10 °C depending on depth. This variation may be secondary to changes in the sedimentary regime but may have short term but significant effects on diversity (Buchanan & Moore, 1986).

These variations may also affect the **succession** of macrobenthic species with the occurrence or survival of different groups of species related to periods of mild or cold winter temperatures. For example, Buekema (1992) showed that one third of the macrobenthos of the Wadden Sea is sensitive to winter temperature, with mild winters inducing changes in the structure and functioning of the ecosystem.

iii Predator sensitivity to seasonal change

Predator use of sedimentary habitats is influenced by seasonal changes. For example, offshore movement of fish populations is caused by avoidance of low temperatures in winter, **avoidance** of greater turbulence (storm-induced) in autumn and winter, or feeding migration. Juvenile (0-group) plaice recruitment to intertidal and shallow areas is influenced by wind strength (Pihl, 1990; Modin & Pihl, 1996).

Waders generally have little difficulty in meeting **energy needs** at the end of summer when food is abundant and weather mild. In contrast, in cold periods, waterfowl are close to their energy balance threshold and so are sensitive to additional disturbance. Greater **foraging** is required through scarcer prey at the same time as energy demand for **thermoregulation** increases, thus requiring greater food intake (Davidson & Rothwell, 1993) or the use of body reserves. In spring and autumn many waterfowl lay down large stores of fat and protein in preparation for their migration between Arctic breeding grounds and their wintering grounds in Europe and Africa. The direct and indirect effects of **disturbance** are highest during the autumn moult when energy demands are high because of the growth of new feathers. Waterfowl concentrate on large estuaries during the moulting season and this is considered to be an adaptation to reduce disturbance or predation (Prater, 1981).

As indicated above, **intertidal invertebrate prey** populations vary with temperature and wading birds differ in their sensitivity to this change. Some birds are less vulnerable to changes in their main prey species, for example, a change in the dietary composition of the black-tailed godwit occurred over the winter, probably in response to changes in the availability of *Nereis* and small *Scrobicularia* (Moreira, 1994).

2. Freshwater Runoff and Salinity

Intertidal sand and mudflats are sensitive to increased rainfall and thus an increased **freshwater input**. This may cause scouring of intertidal areas, changes in intertidal creeks and possibly a reduction in **salinity** in localised areas. Salinity is an important variable which influences the populations of intertidal and subtidal areas, especially in estuaries where it is the dominant factor (McLusky, 1989). On open coasts it is less important but it may have a significant local influence.

The **physiological affects** of salinity change are well described (e.g. McLusky, 1989) and species in intertidal areas are adapted to tolerate changes in salinity by **osmoregulation**, reducing oxygen consumption and reducing metabolic activity to conserve energy (Brown, 1983) or by moving seaward if they are mobile. Thus **salinity gradients** over intertidal mud and sandflats will produce **zonation** in the fauna. In extreme cases of run-off and freshwater dilution, euryhaline species such as *Macoma balthica*, *Corophium volutator*, *Nereis diversicolor*, *Hydrobia ulvae* and brackish oligochaete species may become permanently established at the top of beaches.

3. Ecological Relationships

a. Benthic invertebrates

Each species is sensitive to changes in **intra- and inter-specific interactions** which will influence the development of the benthic communities and the stability and persistence of benthic communities is influenced by biological interactions. The interactions between infaunal species may be in **competition for space** (Woodin, 1976) or as the result of survival, migration and recruitment patterns. For example, surface active *Nereis diversicolor* had a negative effect upon *Corophium* spp. (Jensen & Andrew, 1993). Species which are commensal, parasitic, symbiotic or epizoic depend on the presence of other species as hosts or partners. Environmental changes removing the latter will cause the species reliant on them to disappear.

Community composition will be sensitive to synchrony (or otherwise) between the **population dynamics** of predators and the different prey species and species reproducing during times of minimal predator activity could significantly reduce the effects of predation. For example, as shown by Eagle (1975) and Tyler & Banner (1979) where **larval settlements** of predators of *Abra alba* were consumed by the dominant epifauna. Settlement activity and timing is also important in determining community type as some species such as *Pygospio*, *Protodrilus* and *Ophelia* are attracted by certain sediments on which they settle but they have different times of settlement.

The community composition is sensitive to changes in **food availability**. For example, Buchanan and Moore (1986) found that a decline in quantities of organic matter changed the infauna of a deposit feeding community which is essentially food limited. This was by largely reducing the *Ophelina acuminata* population which had previously out competed the other species and dominated the benthic population. In turn, this removed the **competitive pressure** from the other species and produced a period of instability as several species became dominant.

Decreased grazing by macrofauna can affect intertidal sediment stability with the resultant increase in diatoms correlated with an increase in sediment shear strength (Underwood & Paterson, 1993). For example, the feeding activities of *C. volutator* may reduce sediment stability of intertidal mudflats by decreasing shear strength. The latter is the result of lowered mucopolysaccharide production, caused by the removal of the microflora by *Corophium*, and increased water content, due to bioturbation (Gerdol & Hughes, 1994).

b. Predator populations

Wading bird predators of intertidal sand and mudflats **regulate the macrofaunal community** and factors that increase the predation may affect this regulation. This may be in a direct way or indirectly by altering the behaviour of certain species e.g. the crawling behaviour of *Corophium* in response to feeding activity of sandpipers (Boates *et al*, 1995). In addition, predators are sensitive to other **predators' behaviour**, for example, Thrush *et al* (1994) discussed the negative predation interaction between shorebirds and eagle rays on the infaunal community.

Size-dependant predation is important for the study of the dynamics of size-structured populations such as those on intertidal sand and mudflats (Gibson *et al*, 1995). In general, density dependent mortality can arise from patchy distributions or predator-behaviour which influences the overlap in time or space between predator and prey. For example, the brown shrimp *Crangon crangon* is a major predator of juvenile plaice and flounder (Pihl, 1990) and predation rates are inversely related to the size of the fish. **Predator-prey interactions** could be enhanced also by high densities in small nursery areas, simply due to an increased encounter rate and possibly increased habitat overlap (Modin & Pihl, 1996).

Plaice and flounder have developed different **temporal and spatial strategies** to avoid predation during settlement (Modin & Pihl, 1996). Thus, an early arrival of plaice on the nursery grounds ahead of the predatory shrimp gives time for the predation risk to be reduced by growth. Flounder settle in the high-risk period during or subsequent to the immigration of shrimp but survivors occupy less predator-hazardous habitats.

4. Sea Level Rise

a. Influence on area and drying/exposure times

Sea-level rise is occurring naturally as the result of **isostatic rebound** following the last ice-age. The increasing land height in northern European areas is causing certain low areas, for example the eastern English coast, to sink relative to sea level. While nearshore subtidal mobile sandbanks will be less sensitive to this change, although greater depth will influence the wave climate and thus sedimentation patterns, intertidal sand and mudflats will be sensitive. Such a change will increase the **'tidal-squeeze'** acknowledged for these area (Davidson *et al*, 1991). The inland movement of the low water region coupled with a fixed upper shore boundary, due to shore protection, produces that squeeze. Without restriction, sea level rise would move the high-water mark gradually further inland but this is prevented by the construction and maintenance of sea-walls. This reduction also affects the shore dynamics including its slope. In turn, this **reduces the area available** for colonisation by invertebrates and affects the **feeding regime** of wading birds and fishes.

c. Influence on predator use

The relationship between **tidal depth** over intertidal sand and mudflats (see Chapter III) dictates that any changes in tidal elevation by **sea level rise** or otherwise will therefore **affect fish populations** which in turn will affect the infaunal community. These changes may increase the time for feeding but reduce the area and hence the **carrying capacity**. The long term **climactic changes** resulting in sea level rise are outside the scope of this report although they may affect **integrity** of the biotope complexes. Reductions in the width of the intertidal habitats due to sea level rise will lower the **carrying capacity** of the area for **wading bird populations**. The size of the area available to birds may also influence the level of impact that a disturbance may have on a bird population (Davidson & Rothwell, 1993) (see Chapter V).

B) KEY POINTS FROM CHAPTER IV

1. The biota of these biotope complexes are sensitive to changes in several environmental and biological characteristics. These include:

- For both intertidal and subtidal biotope complexes - hydrographical changes and water activity, especially as the result of storm events, concomitant sediment change, and predator changes;

- For intertidal biotopes - sea level rise and tidal elevation change effecting ‘tidal squeeze’ when the upper tidal boundary is restricted, exposure and desiccation affecting the organisms as the result of their intolerance, and extremes of climate, including temperature and freshwater runoff. In particular, any stressor which changes the shore topography will affect all other biological and physical processes.

2. That sensitivity is reflected by the biotope complexes in several key physical and biological responses:

- As a response to seasonal changes but by their nature they are able to accommodate natural variability and have a benthic biota relatively resilient to these changes. By definition and their nature, the fauna of subtidal mobile sands can tolerate sedimentary disturbance whereas the sediment biomodification potential of intertidal mud and sandflat biota dictates that they can also withstand sediment changes.

- By changes to the benthic species composition and responses by predators. In turn, the biota are sensitive to inter- and intra-specific interactions such as competition. Similarly, changes in physical conditions will change settlement patterns and in turn affect the community structure. However, although biological interactions, such as competition for space or food, will be important in structuring the community, these are complex and poorly understood.

3. The sensitivity is reflected in the stability of the biotope complexes:

- The sheltered intertidal habitats are relatively stable whereas the subtidal mobile sandbanks are more complex and may undergo fluctuating periods of stability and instability. However, there is poor information on the degree of natural variability in most of the physical and biological parameters, especially subtidally, and the relative stability of the systems is poorly understood in ecological timescales.

- The results of disturbance differs depending on the nature of the biotope and may range from short to longer term changes in diversity and species richness. The subtidal mobile sandbanks may be defined by transitional communities which are subject to a high degree of natural variability. Similarly, intertidal biotopes subject to salinity changes will experience large-scale localised changes in community structure.

V. SENSITIVITY TO ANTHROPOGENIC ACTIVITIES

This chapter focuses on anthropogenic activities that are known to have an impact on the important features of intertidal sandbanks and mudflats and subtidal mobile sandbanks, and which are relevant to the monitoring and management of SACs. Again the chapter discusses the **repercussions for the biota of changes** to the physical integrity of these biotope complexes. For example, changes in substratum type, area and the tidal regime are major **threats to the integrity** of both biotope complexes and their carrying capacity in supporting wading birds and juvenile (and adult) fishes. The potential effects of major anthropogenic activities to the physical and biological attributes of the biotope complexes are summarised in **Table 5.0** below and detailed in **Tables 5.1**. and **5.2** on subsequent pages. In Table 5.0, the impacts are considered subjectively to be low, moderate or high to reflect the likelihood of change as indicated in Tables 5.1 and 5.2. It should be emphasised that for many of the aspects discussed on tables 5.0, 5.1 and 5.2 there is no qualitative information on the magnitude of the response.

Table 5.0 Overview of the Potential for Anthropogenic Impacts.

Activity	Intertidal Sand and Mudflats	Subtidal Mobile Sandbanks
Land-claim (Reclamation)	high	Low
Barrages (amenity, storm-surge and tidal energy)	high	Moderate
Dredging and spoil disposal, and aggregate extraction	low	High
Fishing	low	High
Organic enrichment	high	Moderate
Industrial and domestic effluent discharge	high	Low
Oil and gas exploration, development and production	low	High
Oil spills and tanker accidents	high	Low
Recreation	high	Low

Table 5.2 Potential effects of major anthropogenic activities to the biological features of the biotope complexes.

	Biotopes	**Benthic community**	**Fish and shellfish communities**	**Bird community**
Reclamation	Reduction of existing biotope abundance and/or diversity		Reduction of specific prey species and feeding area	Reduction of specific prey species or feeding area
Barrage (amenity and tidal energy)	Predominant biotopes may change	Reduction due to loss of intertidal area Change of feeding types	Reduction of prey species to support fish communities but increase in fish feeding areas	Reduction of prey species and carrying capacity to support bird communities
Dredging activities and aggregate removal	Reduction of existing biotope abundance and/or diversity Change towards biotopes typical of unstable sediment	Reduction in species diversity and abundance due to habitat disruption and smothering	Loss of prey species	Reduction of specific prey species
Fishing activities; shellfish harvesting, bait digging, trawling and potting	May change due to reduction in target benthic species (altered community dynamics) or due to damage to the integrity of habitat	Change to community structure due to loss of target species (bait digging). Also damage to habitat from trawling	Change to community structure due to loss of target species (bait digging) and non-target species. Also damage from trawling. Reduction in specific target species and non target species	Reduction of specific prey species
Organic enrichment	Will change in response to tolerance to anoxia and/or increased nutrients	Decrease in species richness and increase in opportunistic species indicative of organic enrichment, eg. *Capitella*	Lethal and sublethal effects. Reduction of specific prey species. Loss of resource for harvesting.	Reduction or possible change in specific prey species, change to the palatability of prey
Industrial and domestic discharge	Elimination of vulnerable biotopes to which the toxins are most available	Lethal and sublethal effects. Decrease in species richness and increase in opportunistic species tolerant of pollution	Lethal and sublethal effects including bioaccumulation. Reduction of specific prey species. Loss of resource for harvesting.	Reduction or possible change in specific prey species; possible tainting of prey.
Oil and gas exploration, development and production	Elimination of vulnerable biotopes due to oil spills and/or other discharges. May change due to destruction or smothering of biotopes	Lethal and sublethal effects. Reduction in species diversity and abundance due to habitat disruption and smothering	Noise effect from seismic activity. Lethal and sub lethal effects. Reduction of specific prey species	Reduction or possible change in specific prey species
Recreational disturbance	Trampling of fragile intertidal biotopes	High activity may cause increased pollution	High activity may cause increased pollution	Disturbance to foraging and roosting area and time

Continued next page

Table 5.2 (cont.) Potential effects of major anthropogenic activities to the biological features of the biotope complexes.

	Recruitment	**Vulnerability to the change in physical environment**	**Sensitive components**
Reclamation	Reduction	Increase due to loss of habitat integrity	All biotopes in area of reclamation and predator species
Barrage (amenity and tidal energy)	Reduction in certain species due to changed hydrophysical regime	Increased instability or changes in environmental parameters due to changed hydrophysical regime	Intertidal biotopes and predator species
Dredging activities and aggregate removal	Benthic spawning area disruption	High risk of smothering or damage/destruction of fauna. Increased instability	Selective elimination of fragile and sedentary infauna and the destruction of the large epifaunal and infaunal organisms eg. *Ammodytes*
Fishing activities; shellfish harvesting, bait digging, trawling and potting	Benthic spawning area disruption	High risk of smothering or damage/destruction of fauna due to trawling. Increased instability of substratum	Sensitivity of target and non target species to elimination. Habitat destruction due to trawling methods
Organic enrichment	Reduction or possible change in levels of recruitment for some species, effects on metamorphosis	_______	Decrease in organisms that cannot tolerate a low oxygen environment. Sensitivity of certain predator populations that rely on specific prey items.
Industrial and domestic discharge	Sublethal effects on reproduction	Sublethal effects of pollution may have a synergistic effect with other stressors	Decrease in organisms that cannot tolerate the polluted environment. Sensitivity of certain predator populations that rely on specific prey items.
Oil and gas exploration, development and production	Reduction or possible change in levels of recruitment for some species.	High risk of smothering or damage/destruction of fauna. Increased instability	Selective elimination of fragile and sedentary infauna; sensitivity of organisms to oil pollution
Recreational disturbance	Reduction in recruitment/reproduction time	Damage to habitat integrity due to recreational activities such as diving	Increased disturbance effects to sensitive species eg. curlew.

A) ACTIVITIES KNOWN TO AFFECT THE BIOTOPE COMPLEXES

1. Land-claim (Reclamation)

a. Effects on habitat integrity

Extensive areas of intertidal mud and sandflats have been removed through land-claim coupled in some areas with **rising relative sea-levels** (Davidson *et al*, 1991; Burd, 1992). Some estuaries have lost up to 80% of the available area, most of which has been the land-claim of intertidal mud and sand flats. In addition, sea level rise and the constraining of the upper shore boundary will produce **'coastal squeeze'**. Hence there is increasing **potential for conflict** arising from the conservation interests and the use of estuaries and other coastal areas by people for recreational and many other purposes.

b. Effects on use by predators

A reduction in the area and biological integrity of these biotope complexes will reduce their **carrying capacity** for supporting bird and fish predator populations. For example, removal of intertidal areas for industrial developments such as those in the late 1980s in the Port of Felixstowe resulted in the loss of feeding grounds and subsequent reduction in foraging time for waterfowl (Evans, 1996). The remaining areas, in industrialised estuaries, are then often subject to a variety of **pressures such as degradation** through high levels of pollution and waste discharge, and damage to habitats and **disturbance to wildlife** by high levels of recreational pressure (McLusky, 1987).

The greatest impact of land reclamation is due to **depletion of the main prey** rather than simply to area loss and each prey and predator species will differ in their response (McLusky *et al*, 1992). Although the area of intertidal mudflats in estuaries is smaller than the subtidal area, it provides the dominant feeding area for the fish populations (Elliott & Taylor, 1989a). For example, land-claim in the Forth Estuary has removed 24% of the natural fish habitats in the estuary but 40% of their food supply (McLusky *et al*, 1992). The greatest effect of land claim in this area is on flatfish such as flounder and juvenile plaice.

Construction associated with land claim, for example in the Orwell estuary, destabilised sediments which may in turn have reduced populations of wading birds (Evans, 1996). The reduction in feeding densities coincided with the changes in the substratum, from mud to sands, a result of the **infilling during land-claim**. Species such as oystercatcher and dunlin may then lose feeding grounds as they prefer a muddy substratum whereas a sandier substratum would favour the bar-tailed godwit and ringed plover.

In the Forth Estuary (McLusky *et al*, 1992), numbers of most bird species, such as dunlin and bar-tailed godwit, declined or remained fairly constant after the loss of 20% of the intertidal area whereas shelduck and curlew increased. Similarly, dunlin and redshank were susceptible to changes in their environment on the Tees Estuary and this resulted in a population decline when intertidal mudflat feeding grounds were lost to industrial development (Pienkowski, 1993). The grey plover and the bar-tail godwit also showed reductions in numbers and marginal changes were seen in the knot and curlew whereas oystercatcher and shelduck showed no declines.

Although some species can tolerate or **habituate to disturbance** of their habitat (McLusky *et al*, 1992), in areas where land-claim narrows the width of intertidal flats available to birds for feeding, the effects are increased for some shy species which avoid feeding on narrow shores (Bryant, 1979). Shorebirds are seldom distributed evenly over their feeding grounds hence land claim may have a **disproportionate effect** in relation to its size (Goss-Custard & Yates, 1992) and site surveys are required to determine the number of birds whose feeding areas are directly affected. At a larger scale, land claim may reduce the carrying capacity (Goss-Custard, 1985) of the entire migration and winter feeding grounds. Finally, **diminishing prey levels** may intensify **competition** and increase winter mortality rates, with a consequent effect on equilibrium population size (Goss-Custard & Durell, 1990).

2. Barrages (amenity, storm-surge and tidal energy) and Marine Constructions

Barrages **restrict tidal amplitude**, effectively raising the low water mark although, in the case of amenity barrages, the tidal influence is entirely removed. Intertidal sand and mud flats will be lost through an increase in the low water area following **channel modification** or in upper areas by **marsh colonisation**. Tidal and storm-surge barrages may lower the high-water mark, so that existing upper saltmarshes and mudflats dry and develop terrestrial vegetation.

A **reduction in the exposed area** or tidal range may increase the **fish feeding** area at the expense of **bird-feeding period**. The construction of a storm surge barrier on the Oosterschelde resulted in the loss of 33% of intertidal habitat (Meire, 1993). The Oosterschelde study showed that the populations of those species of birds dependent on mudflats for food decreased in numbers, and this was probably due to the reduction in the available space for feeding.

The barrage impact is complex depending on patterns of **sediment redistribution** as they can increase periods of tidal inundation at upper levels or alter deposition patterns and steepen the shore (Davidson *et al*, 1991). In addition, subtidal areas, including sandflats, behind a barrage will have their salinity regime affected due to the restricted exchange of seawater (Davidson *et al*, 1991).

The **construction of rigs, jetties and harbours** will interfere with hydrographic patterns which in turn will influence the **deposition and erosion** processes and the delivery of colonising organisms and organic matter. These activities may also reduce the **heterogeneity** of the bed and thus the number of niches available for colonisation.

3. Dredging Activities, Spoil Disposal and Aggregate Extraction

Both dredging and spoil disposal will affect the **sediment and hydrographic regimes.** In addition, any activities upstream of subtidal sand banks will affect the **hydrographic regime** and/or the sediment balance. **Dredging** of subtidal mobile sandbanks will occur where they interfere with **navigation** and also dredging to deepen and widen channels for shipping will affect the low water mark and thus directly remove parts of the biotope complex. It can cause loss and damage by the indirect effects of **increased scour and erosion** on artificially steepened slopes. **Dredged material disposal** over subtidal mobile sandbanks will occur where the latter are adjacent to dredged areas. However, in areas of strong tidal currents

dispersion of dredge plumes may be high and thus the effects minimal. For example, in one of a few cases, dredging of a subtidal mobile sandbank produced low levels of suspended sediment and did not appear to smother the benthos (Poiner & Kennedy, 1984). Furthermore the substratum changed little during sampling.

Dredging and dredged material (spoil) disposal has the potential to:

- increase the amount of suspended particles and thus influence turbidity, light penetration and primary production of the water column and substratum (Iannuzzi *et al*, 1996);

- modify the sediment composition where the dredge spoil is of a different nature to the receiving area (SOAEFD, 1996);

- smother the benthos, if it is unable to migrate through the material, and clog feeding or respiration apparatus, especially of suspension feeding invertebrates, hence there may be a change in the feeding guilds present;

- create a disturbed benthic community and possibly reduce the number and diversity of benthic species and affect larval recruitment (Rosenberg, 1977); however, there may be an initial increase in species richness following dredging, possibly due to an increase in available resources or an increase in the number of available niches (Poiner & Kennedy, 1984; Stephensen *et al*, 1978; Jones & Candy, 1981; SOAEFD, 1996); and

- produce an upstream addition of sediment-bound contaminants through sediment disturbance or liberation and hence affect water quality. Similarly, as many banks are at the centre of a gyre (see Chapter II), this may increase the delivery and accumulation of polluting materials. However, resuspension and liberation of sediment-bound contaminants may be a short-term phenomenon.

However, it is emphasised that subtidal sandbanks are the result of relatively **high energy conditions**. As such they will be **naturally disturbed** by large changes in the hydrographic conditions, e.g. by storms. The ability of the community to recover from sediment disturbance is high because of the predominant mobile nature of the component species (Rees, 1994; Kaiser & Spencer, 1996). Similarly the influx of material either by natural phenomena or man-induced conditions such as dredge spoil, will be accommodated by the community.

Communities in the dynamic and physically-controlled environments of subtidal mobile sand banks will be able to tolerate sediment movement and, after disturbance, will be **re-established more rapidly** than those in more stable environments. For example, as was shown by an experimental dredging operation carried out in a small sandy bay, with the aim of quantitatively assessing the effects of scallop dredging on the benthic fauna and the physical environment. The infaunal community, which consisted of bivalve molluscs and pericarid crustaceans, which were **adapted morphologically and behaviourally** to a dynamic environment, did not show any significant changes in abundance or biomass.

The most important effect shown by Eleftheriou and Robertson (1992) was on the epifaunal and large infaunal organisms whereby sessile forms such as polychaetes decreased and the burrowing urchin *Echinocardium* was reduced in the dredged area. Large numbers of molluscs, echinoderms and crustaceans were killed or damaged by the dredging operations. Very large numbers of the burrowing sandeel *Ammodytes* were also destroyed. Thus the effect of dredging may be limited to the selective removal some fragile and sedentary components of the infauna, and the destruction of the large epifaunal and infaunal organisms.

The **speed of recovery** of the benthic community, through an influx of colonising organisms, is dependent on the **timing** of the dredging in relation to the timing of reproduction and or migration. While this may only be on a few occasions during the year for the macrobenthic organisms, studies of meiofaunal recolonisation after sediment disturbance indicate that partial recovery occurs within a few tidal cycles (Sherman & Coull, 1980) following recruitment through hyperbenthic populations. Both **passive suspension** and **active emergence** to ensure rapid dispersion and recolonisation has been observed in harpacticoids (Palmer, 1988) and turbellarians (Giere, 1993).

In addition to dredging and disposal effects, subtidal mobile sandbanks may be in demand for **aggregate extraction**, depending on the relative mixture of coarse and medium sand and the size, depth and nature of the deposit (IECS, 1995). This may be of particular concern for commercial crustacean populations. Crab and lobster spawning areas occur where sand banks meet rocky areas and thus they are affected by changes to the sandbanks.

4. *Fishing Activities*

Commercial shell and fin-fisheries potentially can have a large effect on the integrity of these biotope complexes, their physical structure and their biological components (Jennings & Kaiser 1998; Elliott, 1998). The effects of commercial fishing depend on the **type of gear** used, **substratum type** and nature of the **resident fauna**. Megafaunal benthic species (i.e. organisms >10mm) are in general more vulnerable to fishing effects than macrofaunal species because they are slow growing and thus slowly recover from disturbance and harvesting. If **recovery** is not permitted, the changes in community structure, such as a decrease in diversity, may be permanent (Jones, 1992).

The **potential effects** of fisheries on or adjacent to subtidal mobile sandbanks and intertidal areas are summarised as:

- removal of non-commercial sized fish (especially juveniles) and thus affecting the nursery function of the biotope complexes (e.g. juvenile plaice on mobile sandbanks);

- removal, scattering or damage to individuals of non-commercial benthic and demersal species, especially the larger sessile benthic fauna such as the urchin populations (Kaiser, 1996);

- the reduction of community diversity and species richness, for example by commercial digging for worms and other macrofauna in intertidal mud and sand flats (Brown & Wilson, 1997);

- the effects of discards, e.g. an increase of scavengers and a deterioration of water and sediment quality through the organic input;

- the removal of target species leading to community and population changes at the ecological and genetical levels, and the effects on competing predators, e.g. the removal of bait organisms such as *Arenicola* from intertidal flats and the effects on shorebird predation, and the removal of sandeels, *Ammodytes*, from subtidal mobile sandbanks and the effects on seabird populations;

- delayed effects on the sea bed, including post-fishing mortality of organisms and long-term change to the benthic community structure (Jones, 1992);

- the change to the physical integrity of the sediment system (through scraping, digging or ploughing of the seabed and intertidal sediments, destruction or disturbance of bedforms, and damage to the benthos) (de Groot, 1984);

- the change to the physical integrity of the water column (by increased resuspension during trawling);

- contamination of the area (through discharges of soluble pollutants and large and small particulate materials, including litter and gear loss); an

- the creation of infrastructure e.g. harbours, jetties (leading to habitat loss, especially of highly productive intertidal areas, and to a disturbance of hydrographic patterns).

The **direct and indirect effects** of commercial fishing activities on subtidal mobile sandbanks and intertidal sedimentary habitats are **poorly quantified**; there are few precise case-studies of the effects of multiple fishing methods on these biotope complexes. Similarly, there is no quantitative information of the effects of fishing over other habitats which then has a knock-on effect to the biotope complexes considered here. For example, the margins of **subtidal mobile sandbanks** adjoining rocky areas are likely to support edible crab and lobster populations and thus will be the site of commercial potting and creel fishing which could disrupt the communities. Similarly, adjacent areas are likely to support beam trawling which will disturb the substratum and the benthic infaunal and epifaunal populations, such as shrimps, and remove juvenile flatfish using the areas as a nursery (see Chapter III).

By their nature, the mobile sediments of subtidal sandbanks and their infauna may be more resistant to the sediment disturbance caused by commercial fishing, especially trawling. However, the **recovery** from the removal of biota, both the target species, often the predators (fishes and macro-crustaceans), and other species, is less well known both for subtidal sandbanks and intertidal flats.

An example of an environmentally-sensitive and conservation important area with multiple fishing activities and sedimentary habitats is Strangford Lough in Northern Ireland (DOENI, 1994). Its commercial trawl fishery for the queen scallop, *Aequipecten opercularis*, creates conflict with conservation groups through the perceived damage caused to the Lough bed by trawling, principally of the diverse communities associated with the horse mussel, *Modiolus modiolus* populations (Brown, 1989). The direct effect of trawling may be to reduce benthic diversity by disturbing the *Modiolus* reefs which provide further niches for colonisation (Erwin *et al*, 1986). However, the effect of the fishery on adjacent subtidal sandbanks and intertidal flats is not known.

5. Organic Enrichment

The effects of organic enrichment on sedimentary systems and their benthos is well documented and shows a consistent sequence of response - the **Pearson-Rosenberg model** (Pearson & Rosenberg, 1978). The organic matter may be as particulates or dissolved, including nutrient enrichment and can be derived from many sources: **sewage**, either discharged as domestic or industrial effluent to intertidal and inshore areas, or as sludge dumped to subtidal areas, food and waste from **aquaculture**, **pulp and paper-mill** effluents, and degraded **petroleum hydrocarbons**. The major causes of such changes are **point-sources** in which the **assimilative capacity** of the receiving waters is insufficient to degrade the organic matter.

In essence, high organic inputs, coupled with **poor oxygenation** leading to conditions of slow degradation will produce anaerobic chemical conditions in the sediments. In turn, this increases microbial activity and reduces the **redox potential** of the sediments (Fenchel & Reidl, 1970). Ultimately this increases the production of toxins such as hydrogen sulphide and methane. The changed status to **anaerobiosis** will limit the sedimentary macroinfauna in anoxic/reducing muds to species which can form burrows or have other mechanisms to obtain their oxygen from the overlying water.

The changes to the **primary benthic community** parameters of species richness, biomass and abundance as the result of organic enrichment are described by **SAB curves** (Gray, 1982). Moderate enrichment provides food to increase the abundance and a mixing of organisms with different responses increases diversity (Elliott, 1994). With greater enrichment, the diversity declines and the community becomes increasingly dominated by a few pollution-tolerant, **opportunistic** species such as the polychaetes *Capitella capitata*, in sand flats, and *Manayunkia aesturina* in mudflats. In grossly polluted environments, the anoxic sediment is defaunated and may be covered by sulphur-reducing bacteria such as *Beggiatoa* spp. Such a change will affect the **palatability of the prey** and thus impair **functioning** of marine areas. This sequence has been observed on intertidal mudflats (e.g. McLusky, 1982) as the result of organic petrochemical effluents, sandflats and sandbanks (e.g. Majeed, 1987) as the result of hydrocarbon pollution.

Any nutrient stimulation of marine areas may be regarded as **hypernutrification** which, if not controlled, produces symptoms of **eutrophication**, defined as the adverse effects of organic enrichment (Scott *et al*, 1997). Such a symptom on intertidal sand and mudflats is an increased coverage by opportunistic green **macroalgae**, such as *Enteromorpha*, which will create anoxic conditions in the sediment below the mats, reduce the diversity and abundance of infauna and interfere with bird feeding (Simpson, 1997).

Changes in the species composition and density of **benthic diatoms** of an intertidal brackish mudflat diatom populations is also evident after organic enrichment (Peletier, 1996). This may be the result of the reduced densities of the macrofaunal diatom grazers *Nereis diversicolor* and *Corophium volutator*. As a consequence of this change in the microphytobenthos, because of the role of their role in mucous production, there may be a reduction in the stability of intertidal mudflats (see Chapter II).

Of particular concern in certain parts of the marine environment is the increase in the inshore

aquaculture of salmonids and its high potential for increasing organic enrichment of sedimentary areas. This industry produces a point-source input of waste, excess food and excretory material (e.g. Gowen & Bradbury, 1987; Brown *et al*, 1987). However, although small and marginal **intertidal mudflats** in sealochs may be affected, it is unlikely that subtidal sandbanks, typical of more open coastlines, will be degraded. The present management practices, in selecting sites with good water exchange, will reduce the possibility of organic enrichment by enhancing the dispersal of solid waste.

6. Industrial And Domestic Effluent Discharge

Industrialised and urbanised estuaries and coastlines receive effluent discharges which contain **conservative contaminants**, i.e. those with a **long half-life**, are likely to **bioaccumulate** (remain within the food-chain) and thus have a **toxic effect** (Clark, 1997). Such contaminants include heavy metals, both essential (e.g. copper, zinc) and toxic (e.g. mercury, cadmium), radionucleides and synthetic organic compounds (e.g. dieldrin and polychlorinated biphenyls). The **lethal and sub-lethal effects** of these pollutants vary according to the state and availability of the compound and the characteristics and organisms of the receiving systems. Some effects may be lethal, by removing individuals and species and thus leaving pollution tolerant and opportunistic species. Other effects may be sub-lethal, in affecting the functioning of organisms such as the reproduction, physiology, genetics and health, which will ultimately reduce the fitness for survival (Nedwell, 1997).

Sheltered, low-energy areas such as **intertidal mudflats** in enclosed bays or estuaries will be most susceptible to these pollutants as dispersion is low and the finer substrata in these areas will act as a sink (e.g. McLusky, 1982; Nedwell, 1997; Ahn *et al*, 1995; Somerfield *et al*, 1994). The pollutants will then enter the food chain and be accumulated by predators, as shown by the seasonal loading of heavy metals in tissues of wading birds in the Wash (Parslow, 1973). However, the industrialisation and urbanisation of these areas results in them receiving **complex mixtures** of pollutants. For example, intertidal areas in Southampton Water (Coughlan, 1979) and the Tees (Langslow, 1981) had reduced benthic communities through contamination by phenols, oil effluent, sulphides and nitrogen compounds.

In contrast to the low-energy areas, the higher-energy sedimentary biotopes are less likely to receive and/or retain these contaminants. The coarser sediments of exposed **intertidal sandflats** and the hydrodynamic characteristics, including high dispersion, at **subtidal sandbanks** dictates that there are few cases of severe pollution in these areas. However, chemical pollution of intertidal sands can occur and will remove elements of the fauna, for example effluent from a pharmaceutical plant created a degraded community in intertidal sands near Montrose (SEPA East, unpublished).

7. Oil And Gas: Exploration, Production and Transport

The exploration and production of oil and gas is wide-spread in coastal areas and has well-defined environmental effects (e.g. Clark, 1997; GESAMP, 1993). For example, the release of **refinery effluent** to intertidal **mudflats** will result in anoxic sediments, a **degraded infaunal** community and changes to predator-prey relationships through a possible decrease in the palatability of prey (Elliott & Griffiths, 1988).

Oil-spills resulting from tanker accidents can cause large-scale deterioration of communities in intertidal and shallow subtidal sedimentary systems (e.g. Majeed, 1987). Oil covering **intertidal muds** prevents oxygen transport to the substratum and produces anoxia resulting in the death of infauna whereas **tidal-pulsing** will push an oil into **intertidal sands**. In both biotopes, the changes will favour the development of opportunistic communities. Oil pushed into coarse sands will destabilise the sediment and produce an oxygen demand where oxygen is available but little degradation at depth where aeration does not occur.

Subtidal sandbanks will be less at risk from **oil spills** unless dispersants are used in clean-up operations or if wave action allows sediment mobility and thus oil to be incorporated into the sediments. In nearshore and sedimentary areas of oil and gas exploration, such as Morecambe Bay, the release of **drill cuttings** will cause deterioration of the sediments and the fauna. **Seismic testing** for oil and gas exploration can affect fish spawning areas on coarse substrata (IECS, 1993).

8. Recreational Disturbance

a. Effects on Habitat Integrity

Increased recreational use of intertidal areas has several consequences although these may be minor for intertidal sand and mudflats. Greatest visitor pressure occurs on recreational beaches, for example the impact of beach cleaning which removes organic inputs and affects the cohesiveness of sediment (Pearce, 1998).

b. Effects on Use by Predators

Human disturbance changes **bird behaviour** in accessible areas such as **intertidal sand and mudflats** (Smit & Visser, 1993). Disturbances to waterfowl in estuaries and nearshore areas includes movements by people, dogs and horses, helicopters and light aircraft, and from water sports such as windsurfing, sand yachting and boating. The **intensity** of disturbance is related to the **species** of bird and the **speed and duration of the stressor** and the direction in relation to bird flocks (Smit & Visser, 1993). For example, aircraft cause widespread and long lasting disturbance and, on tidal flats, moving people and dogs generally create greater disturbance than stationary ones. Furthermore, the impact of human disturbance requires to be assessed in relation to other activities such as land-claim. Industrial and urban development may restrict the adjacent areas suitable receiving displaced birds.

The impact of **disturbance** has been **quantified** although this differs according to **species, type and scale**. For example, for some shy species such as the curlew as few as twenty evenly distributed people could prevent birds from feeding on over 1,000 ha of estuary, an area of tidal flats equivalent to estuaries such as Hamford Water or Southampton Water (Goss-Custard & Verboven, 1993).

Even the same species of bird can react in different ways at different times and at different areas - for example, sometimes by **habituating** to repeated disturbance and at others becoming increasingly nervous. Species such as the brent goose, redshank, bar-tailed godwit and curlew are more ‘nervous’ than others such as oystercatcher, turnstone and dunlin. One person on a tidal flat can create a large disturbance in which birds stop feeding or fly off, affecting approximately 5 ha for gulls and 13 ha for dunlin up to 50 ha for curlew (Smit & Visser, 1993). In some cases, for example wigeon on parts of the Exe Estuary, a single disturbance incident at the wrong time can deter birds from feeding until the next tidal cycle (Fox *et al*, 1993).

Disturbance will cause birds to fly away and in **response** they could either (i) increase their **energy intake** at their present (disturbed) feeding sites when undisturbed, or ii) **move to an alternative feeding site**. Such a response will affect energy budgets and thus survival, with particular consequences for overwintering wading birds (Davidson & Rothwell, 1993). There may be little overlap of use by overwintering birds as recreational activities occur mainly in the summer and early autumn. However, in late summer/early autumn, (and sometimes spring) when most recreational activities take place, intensity of use is greatest, and waterfowl are more vulnerable. This period coincides with the latter part of the breeding period for some species and the arrival and moulting of the more northerly breeding populations.

B) KEY POINTS FROM CHAPTER V

- It is likely that all human activities will affect these biotope complexes as they occur especially in estuarine and nearshore areas. However, the extent and duration of any impact differs with activity and biotope complex.

- Intertidal sand and mudflats have a high potential for being impacted by land claim, barrages (amenity, storm-surge and tidal power), organic enrichment, industrial and domestic effluents, oil spills and recreation.

- Subtidal mobile sandbanks have a high potential for being impacted by dredging and dredged material disposal, aggregate extraction, fishing, oil and gas exploration and development.

- Several of the activities will affect the physical, chemical and biological integrity of these biotope complexes by changing the hydrographic regime, and thus the sedimentary regime, the sediment health, the nature of the infaunal communities and thus the usage by predators.

- The greatest threats to the biotope complexes are through the loss of habitat through barrage construction, land claim or the production of water quality barriers. The latter will degrade the sediment and consequently the infauna and its predators.

- These biotope complexes are at risk from the removal by man of their environmental (physical) or biological resources, for example the sediment through aggregate extraction, or the biota through direct and indirect effects of fishing for round and flatfish and shellfish.

- The quantitative nature of change to the biotope complexes is well understood and may be predicted for certain anthropogenic stressors, such as human disturbance to intertidal flats and organic enrichment. However, the effects of other stressors such as aggregate extraction and dredging cannot be quantitatively predicted.

VI. MONITORING AND SURVEILLANCE

The emphasis in surveillance and monitoring strategies for the biotope complexes **Intertidal sand and mudflats** and **Subtidal mobile sandbanks** should be to determine the **natural and anthropogenic variability** of the important features. This will also establish **baseline data** so that any gross changes due to natural or human-induced events can be identified and quantified. As shown throughout this report, these sedimentary biotope complexes have common environmental and biological attributes and so they will require similar methodologies for their monitoring and surveillance. It is emphasised that any monitoring and surveillance of **Special Areas of Conservation (SAC)** will have to include concurrent surveys of all their component biotopes and biotope complexes.

As shown in Chapters II and III, there are extensive **linkages** between and within the **environmental and biological attributes**. This dictates that monitoring to assess and thus protect one feature of conservation importance, such as the infaunal community structure, should include the environmental features required for the well-being of that biota. Hence the **monitoring philosophy** to be employed is to assess:

- any interference to the physical forcing variables such as hydrographic regime and sediment type;

- and changes in the aspects of conservation biodiversity value, especially the support of predator populations; and

- but through an emphasis on the monitoring of macrobenthic community as this will reflect changes in the physical variables and influence the predator communities.

This chapter gives brief details for the monitoring of the invertebrate, bird and fish communities, and the environmental parameters. The methods for the monitoring of the environmental and biological features are summarised in **Table 6.0**. and details relating to the particular use of methods are given in **Appendix III** and the references cited therein.

A. MONITORING STRATEGIES RELEVANT TO SACS

As described by Hiscock (1998a) and Elliott and de Jonge (1996), monitoring and surveillance refer to different types of analysis and have differing objectives. **Monitoring** involves surveying an area with a view to detecting **departures from agreed or predicted conditions**. The attributes for those conditions may be qualitative or quantitative. This analysis may also be regarded as **compliance monitoring**. In contrast, **surveillance** records the features of the system and attempts to detect **unanticipated changes or impacts** which may be wide ranging and subtle, thus it may be regarded as **condition monitoring**. The precise methodologies to be used will reflect this difference in objectives and outcomes of the analysis.

A **provisional monitoring sampling** regime is given below bearing in mind the information given on sampling techniques (given in **Appendix III**). It is emphasised that the methodologies used in the monitoring of these biotope complexes in SACs will differ depending on the objectives of the study.

By definition, monitoring implies the repeated use of techniques to assess features and determine change. While surveillance (as **condition monitoring**) of the biotope complexes may be **desirable at 3 or 5 year intervals**, the high cost of monitoring may dictate that further surveys, and especially **compliance monitoring** will be carried out only following changes to the human uses and users of the area or if there is the indication of large-scale natural change.

The **primary aims** in the monitoring and surveillance of any biotope complex in SACs (see Hiscock, 1998b for further details) is to:

- establish the location and extent of the biotopes and features present in the SACs;
- determine the biotope characteristics or attributes (species composition, environmental features) and note the health of the biotope, and the presence of rare/sensitive species, special biotopes etc.; and
- monitor change in the SAC and determine acceptable levels of change.

1. Determining The Location And Extent Of Biotopes

a. Intertidal Sand and Mudflats

The **presence and extent of biotopes** within the biotope complexes should be established using core and quadrat samples and ACE surveys intertidally and by making use of current literature. Information from aerial photography and remote sensing where available will also be useful in larger intertidal areas.

b. Subtidal Mobile Sandbanks

Acoustic surveys are likely to be the most cost-effective means of determining the spatial extent of subtidal habitats but the information obtained should be **ground-truthed** by quantitative grab sampling. In areas where turbidity is not a problem, towing of Remote Operated Vehicles (ROV) and still and video photography may also be employed where appropriate.

2. Characterisation Of The Biotopes.

In order to determine the **community structure** and evaluate the scientific and conservation importance of biotopes within the biotope complexes it is necessary to examine the species composition of the areas and the **physical and chemical attributes** of their habitats. Existing data should be thoroughly examined where possible to reduce survey costs. In most areas, the macrofauna (and in some areas, the meiofauna) will provide the best assessment of the biological nature of the biotope.

3. *Monitoring Change*

In areas where the biotopes/biotope complexes encountered within a SAC are important scientifically or for conservation reasons **repeated monitoring** at selected sites should be carried out to determine any change and identify **causes for change**. Due to the labour intensive, time consuming and thus expensive nature of the sampling involved, the information obtained should be of maximum use, minimising redundant or unnecessary sampling. Detailed information on methods for detecting change in the biotopes present or their components are given by Hiscock (1998a) and Kramer *et al* (1994) and statistical considerations, to ensure cost-effective sampling effort, are discussed in Green (1979).

B. MONITORING OF ENVIRONMENTAL ATTRIBUTES

1. *Substratum*

a. Sampling methods and parameters to be analysed

Sediment is often **heterogeneous** in nature such that a single sample for a physical-chemical characterisation may not provide a reliable description of that area. **Multiple sampling** and analysis may be required offers better possibilities. Separate samples may be pooled (homogenised) but this will remove indications of structural differences within the site. Samples should be **collected concurrently** with benthic samples, at the same time and location otherwise interpretation of biological data will be invalid or not possible. **Intertidal sand and mud flats** will require core sampling to provide sufficient material together with quadrat sampling to indicate surface features such as ripples, casts and heterogeneity. **Subtidal mobile sandbanks** will require remote sampling via corers or grabs, diver operated corers and underwater photography.

Analysis should be made of the nature of the substratum as this, together with the hydrodynamic regime, are often the most important factor in determining species distribution. **Particle Size Analysis** (PSA) including % sand, silt and gravel, mean and median grain size, and sorting coefficient will indicate change and other factors such as the **organic content** and **redox potential** will indicate sediment health. In some cases where pollution of the SAC from industrial sources is a potential cause of change, levels of contaminants should be monitored. **Appendix III** discusses these features in detail and the parameters to be analysed are in **Table 6.0.**

Table 6.0 Sedimentary parameters to be analysed.

Parameter	**Requirements/comments**
particle size and distribution	monitor always
porosity and permeability	Desirable
organic content	monitor always
redox potential	desirable if organic enrichment suspected
trace metals and other persistent contaminants	desirable if inputs suspected
oils by gravimetry and polycyclic aromatic hydrocarbons (PAHs)	desirable if inputs suspected
synthetic organic hydrocarbons, e.g. PCBs	desirable if inputs suspected

2. Hydrological Regime

Measurements of the hydrological regime parameters, such as topography and bathymetry, circulation patterns, tidal paths, current speeds, temperature, salinity, and turbidity, may be necessary at some SAC sites if no data area available and if these parameters are expected to change due to anthropogenic activities. In general, **available information** will be sufficient although this may be either anecdotal from **local knowledge**, such as fishermen, or from **Admiralty Charts**. A thorough examination of these latter sources should be made prior to collecting primary hydrographic data at the latter is expensive.

Hydrographic exposure will dictate many of the above conditions and especially the nature of intertidal sand and mudflats and the size and formation of subtidal sandbanks. **The exposure index** proposed by Thomas (1986), which is derived from wind velocity, direction, duration and the effective fetch, will be of value as:

- it can be calculated from data readily available on charts and in weather records;
- it integrates a range of conditions occurring rather than just the short-term;
- it can indicate different exposure indices for areas within a transect or site if sufficiently detailed topographic data are available;
- it can be used to detect changing responses to exposure resulting from other environmental variables such as tidal range; and
- it can be used to indicate species responses to exposure.

C. MONITORING OF BIOLOGICAL ATTRIBUTES

Key macrofaunal species which are **indicative** of the area or **rare/sensitive** species should be monitored for changes in presence and/or abundance (see Chapter III for details of the species). Species such as *Capitella capitata* should also be monitored as they are often indicative of organic enrichment. Conversely, other species and assemblages indicative of good water quality should also be monitored.

The estimation of **primary and derived biological parameters** such as total abundance, species richness and diversity will indicate the nature of the community. **Graphical measures** such as Abundance-Biomass-Comparison (ABC), k-dominance and rarefaction curves and trophic measurements such as the Infaunal Trophic Index (UKITI) provide a valuable summary of the large amounts of data obtained from benthic sampling programs (Elliott, 1993). It is emphasised that although these indices involve a loss of information, they allow simple indications of change within a community.

In cases where the above parameters are measured in relation to environmental and biological quality, the use of the **Sediment Quality Triad** approach (Chapman *et al*, 1987) will be required. This provides concurrent assessments of sediment contamination, community structure and the health of an individual species by using a bioassay.

1. Macrofauna

a. Intertidal mud and sandflats

i. Sediment cores

Core sampling is required to obtain and extract the infauna for identification and enumeration and **surface quadrat sampling** will allow surface features to be quantified. These methods have the advantage of providing quantitative data for statistical analysis and a valid comparison of different datasets. However, core sampling is time-consuming and thus costly. Further details are given by Dalkin and Barnett (1998).

ACE surveys allow information to be obtained rapidly and thus are cost-effective (Hiscock 1998b). They also provide sufficiently detailed information on species richness and the presence of rare species or unusual features for comparison with elsewhere. However the results of ACE surveys are not amenable to statistical analysis and the worker variability may be high, hence the need for method standardisation and analytical quality control (see below).

ii. Remote sensing

Remote sensing by **aerial and satellite techniques** is particularly valuable for large intertidal areas and intertidal SACs. It is widely used and, when combined **with false colour spectroscopy**, will give good ground resolution to determine the size and morphology of large intertidal areas such as mudflats and the distribution of topographic and biological features e.g. seagrasses, mussel beds and bird populations. **Digitally-enhanced remote sensing** from satellite or aircraft is useful for determining environmental conditions such as water depth, suspended sediments, temperature and effluent plumes. Wide-scale surveying by techniques such as remote sensing will provide valuable information necessary for the planning of biological surveys by conventional techniques such as core-sampling. More detailed information is given by Baker and Wolff (1987), Curran (1985) and Gierloff-Emden (1982).

b. Subtidal mobile sandbanks

i. Direct sampling

Quantitative substratum samples can be obtained by lowering equipment from vessels. This includes the Van Veen or Day grabs (for less-compacted sediments), Hamon or Shipek grabs (for coarser or compacted sediments), Craib and Knudson cores in soft sediments, or the Reineck box corer, and Forster anchor dredge (for semi quantitative sampling of mobile megafauna). These techniques provide **standardised and quantitative** data for statistical analysis and comparison across surveys although the sample collection and analysis is time consuming. **Diver-operated suction corers** can give undisturbed samples with precise positioning. Site conditions, size of vessel and previous experience will dictate which equipment is most suitable (see Holme & McIntyre 1984; Kramer *et al* 1994; Thomas, 1998).

In areas where the **epifaunal and demersal fish** components are important, small beam trawls fitted with tickler chains can be towed for a fixed time, for example 20 minutes, to give a semi-quantitative estimation. Such samples can be fully analysed on board.

ii. Towed and remote operated video

Still and video photography of the bed, by towed or deployed cameras or by diving, are of limited use in quantifying the fauna of mobile sandbanks as most of the biota are within the substratum. However, the techniques may be valuable in planning a **survey strategy**. Towed and remote operated vehicles, supporting still and video cameras, can visually record large expanses of the seafloor and are not restricted by depth or time as with diving (CEC, 1989). (See Donna, 1998; Service, 1998; Michalapoulos *et al* 1992.)

The techniques can give **semi-quantitative** estimations of faunal abundance as well as providing a permanent visual record of the epifauna and seabed topography. However, the use of the techniques and the analysis of film may be costly. Turbidity, caused by the equipment moving on the sandbank, is less likely to cause difficulties than on softer sediments although the strong tidal currents may affect the use of these systems. The systems require **ground-truthing** using conventional grab and core techniques but they do provide a greater coverage of the biological features of a biotope compared with the very limited coverage given by those conventional sampling techniques.

Sediment profile imaging (SPI) techniques (e.g. REMOTS) have a large use in sediment analysis and can determine the features such as degree of bioturbation, and redox and grain characteristics (Elliott, 1991). They provide a **rapid indication** of these features and thus may be used in survey design. However, the techniques are less suitable for compacted sands (SOAEFD, 1996).

iii. Acoustic survey

Acoustic methods such as **side-scan sonar** and the **RoxAnn**® system have a high value in discriminating the surface features of biotopes. They can be used to survey large areas but require ground-truthing by conventional sampling and photographic techniques (see Rees & Foster Smith, 1998).

2. Meiofauna

The meiobenthic fauna is little-studied but plays an important role in the functioning of the community and is valuable in detecting change. The organisms occur in high densities, hence **sub-sampling** or the use of small sample areas is required, and the community in subtidal sandbanks is likely to be diverse. However, the **taxonomic expertise** for their study is not yet widely available although methods are being developed (SOAEFD, 1996). If meiofauna are to be examined they should be sampled concurrently with the macrofaunal samples if this is feasible.

Meiofaunal sample sizes are smaller than for macrofauna and require cores ranging from 2 to 4 cm diameter, depending on the nature of the sediment. These can be taken intertidally and subtidally either from grab samples or directly using Craib corers which reduces disturbance of the surface sediment. Elutration and centrifugation followed by microscopic examination are required to extract and analyse the samples (Schwinghamer, 1981) and the time-consuming nature dictates that few samples can be analysed in detail. See the methodologies in Holme and McIntyre 1984; Baker and Wolff, 1987; Kramer *et al*; 1994.

3. Birds

The study of bird communities will **indicate maintenance of the integrity** of the many Special Areas of Conservation. This is especially so as both the **intertidal mud and sand flats** and the **subtidal mobile sandbanks** may support nationally or internationally important populations of birds (see Chapters III and VIII). It is necessary to monitor the bird communities, for example using WeBS counts, as they may be characteristic of the biotope complex and will be important in the ecological dynamics and functioning of the biotope complex.

Bird census techniques are detailed in Baker and Wolff (1987) and Bibby *et al* (1992). Such techniques are required to determine the **size of the bird communities** associated with the biotope complexes and thus the **carrying capacities** of those areas.

4. Fish

The continued maintenance of juvenile fish populations over **intertidal sand and mudflats** and **subtidal mobile sandbanks** will indicate the health and integrity of the biotope complexes. Hence it is necessary to identify any nursery areas and areas with sensitive species and trends should be monitored against previous data in order to determine any major changes. Sampling will be primarily by trawls, especially beam trawling, and fixed netting, including traps, and water quality and sediment information will be required to interpret the data produced. In contrast to methods for the other biological components, each fish capture method is species and area specific; details of methodologies required are given in Morris (1983), Baker and Wolff (1987) and Hemmingway and Elliott (in press).

D. QUALITY OF DATA PRODUCED AND QUALITY STANDARDS AND THEIR COMPLIANCE

1. Analytical Quality Control and Quality Assurance (AQC/QA)

The use of Analytical Quality Control and Quality Assurance (AQC/QA) is of great importance in monitoring schemes especially where data from different areas or times require to be compared and centrally collated (Elliott, 1993). Field methodologies require to be standardised to eliminate **worker-variability** (Baker & Wolff, 1987) and to ensure that any changes detected are attributable to **environmental variation** rather than **sampling-induced variation.**

The laboratory analysis of sedimentary faunal samples is required to follow procedures advocated by Rees *et al* (1990) and Elliott (1993) in order to produce valid data from **standardised** and **quality-controlled** methods. Where possible, the analysts should take part in the UK National Marine Biological AQC Scheme which aims to standardise methods and to check the quality of data produced (Elliott & Service, in press). Health and safety guidelines should be followed in all monitoring techniques and appropriately trained staff used.

2. Environmental and Ecological Quality Objectives and Standards (EQO/EQS, EcoQO/EcoQS)

In contrast to surveillance (or condition monitoring), **compliance monitoring** is required to be carried out against pre-determined and agreed numerical **standards and objectives** (Elliott, 1993). Chemical EQS and biological EQO have been used in environmental water quality management for many years and numerical standards for sediment parameters are now being developed (MPMMG/CGSDM unpublished). However, biological or ecological standards are only now being developed for particular stressors such as dredging and sewage-sludge disposal but these require field testing (SOAEFD, 1996).

At present, no **Ecological Quality Standards and Objectives** have been derived for the SAC's nor for the sedimentary biotope complexes considered here. It is now possible to set Ecological Quality Objectives (EcoQS) for SAC's (see Chapter VIII) and after the monitoring of the SACs has been in progress for some time it will be possible to derive EcoQS which take into account natural variations. Compliance monitoring can then be carried out to determine whether such EQS are met after identifying **potential anthropogenic stressors** at the biotope complexes (see Chapter V).

Similarly, the **biological and physical state** of the biotope complexes will have to be **quantified** such that any deviation from the natural state can be determined. Where possible, this will require a **predictive capability** as an aid to management. For example, community based predictive models such as the RIVPACS scheme for freshwater systems (Wright *et al*, 1989) or those based on biological parameters (Elliott & O'Reilly, 1991) indicate change due to anthropogenic stress. These approaches will not be possible in the initial stages of the SAC program but may be of use at a later stage.

E. KEY POINTS FROM CHAPTER VI

- The biotope complexes require sampling and analysis to determine the natural variability (i.e. condition monitoring or surveillance) and to identify departures from that due to anthropogenic impacts (i.e. compliance monitoring). The latter should be further developed to determine whether predefined and agreed standards and objectives (as Ecological Quality Standards and Objectives) have been met.

- In particular the monitoring will determine any interference, especially by human activities, to the physical forcing variables and changes to aspects of conservation value, in invertebrate biota and predators. Furthermore the monitoring has to be sufficient to link biological and environmental variables.

- While surveillance (as condition monitoring) of the biotope complexes may be desirable at 3 or 5 year intervals, the high cost of monitoring may dictate that further surveys, and especially compliance monitoring will be carried out only following changes to the human uses and users of the area or if there is the indication of large-scale natural change.

- The monitoring is required to determine the extent and health of the biotope complexes and the integrity of the physical and biological features. However, it is necessary to emphasise the value of easily-obtained information, such as from large-scale survey techniques, skilled-eye (ACE) surveys and chart information, which can cover large areas, typical of the intertidal sand and mudflats and subtidal sandbanks. Despite this, it is emphasised that ground-truthing by conventional techniques is necessary for remote-sensed data.

- There are well-defined methods for monitoring the sedimentary biotope complexes, their physical and biological attributes although each method is often specific to a component and occasionally a site. In addition, all methods have advantages and disadvantages.

- Finally, as the monitoring of different areas will be carried out by different workers but that the data produced will be centrally collated, it is necessary to emphasise the importance of Analytical Quality Control and Quality Assurance (AQC/QA) in monitoring.

VII. GAPS AND REQUIREMENTS FOR FURTHER RESEARCH

The preceding chapters have indicated the large amount of information available for the biotope complexes **Intertidal Sand and Mudflats** and **Subtidal Mobile Sandbanks**. However, it is concluded that despite this large information, there are many aspects where the knowledge or data are insufficient for understanding the links between the natural processes and the functioning of the physical and biological systems. In addition, the understanding or knowledge base for any one site may be insufficient for the management of the site, especially with respect to temporal variability (changes through time) rather than spatial variability.

The following have been identified as areas in which there is a limited or contradictory knowledge base and therefore which require original or further research or studies. Those denoted (*) have particular relevance to the management of Special Areas of Conservation whereas the remainder will increase the understanding of the habitats. In general, the information gained as the result of these studies can be applied to all areas. However, in certain circumstances (denoted as ‘for each site’) the information is required on a site-specific basis and thus at a scale covering a particular SAC, intertidal mud or sandflat or subtidal mobile sandbank.

A. FUNDAMENTAL KNOWLEDGE OF PHYSICO-CHEMICAL AND BIOLOGICAL ASPECTS

1. The structuring of sediments by the fauna.

2. The precise effects that micro-algae have on the distribution and abundance of sediment faunas in subtidal areas.

3. The precise requirements of individual species. Key species should be established and environmental requirements assessed to provide the range of variation for key environmental attributes (* to derive monitoring standards).

4. The functioning and interdependent relationships between adjacent habitats and biotopes.

5. A clarification of the factors influencing recruitment to benthic communities particularly in subtidal habitats. For example, the influence of long term trends in winter/summer temperatures on community structure.

6. The importance of subtle changes in sediment type or properties of different grain sizes on community structure and function and the impacts on the habitat of small changes in elevation across intertidal areas (*).

B. KNOWLEDGE OF THE BIOLOGY LINKED TO MANAGEMENT

1. The carrying capacity (and spare capacity) should be further defined and measured for both waterfowl and fishes (e.g. for mudflats for birds and sandflats and sandbanks for fishes (and for sandeel-seabird links) (*).

2. The need for long-term datasets to determine stability of benthic communities and the derivation of predictive models for sedimentary communities (*).

3. The movement towards quantitative indicators of change and process-orientated studies rather than structure (*).

C. KNOWLEDGE FOR IMPACT MANAGEMENT

1. The need to produce a matrix collating all uses and users of the habitats and the components of the biological or environmental characteristics which are most likely to change as a result of these uses and users (* for each site).

2. An assessment of cumulative impacts of human activities, in conjunction with natural variability, on predator populations and nursery grounds is required to allow an indication of threshold values for unacceptable loss of habitat (*).

3. The implications of sea level rise and ‘coastal squeeze’ on intertidal habitats and their availability to predator populations (*).

4. The need to derive Ecological Quality Objectives as statements to be achieved for the biotope complexes, and to derive numerical Ecological Quality Standards (*).

5. The need to better quantify the effect of anthropogenic stressors to separate normal from human-induced variability. Following this there is the need to improve the capability to predict the changes to these biotope complexes as the result of natural and human-induced events (*).

D. KNOWLEDGE FOR RESOURCE MANAGEMENT

Biological Resources (*)

1. A study into human activities such as shellfish harvesting, through damaging techniques, and the identification of more sustainable harvesting techniques.

2. The need to assess the effects of commercial fin and shell-fishing on the subtidal mobile sandbanks and on intertidal sand and mud flats (for each site).

3. Competition and impacts between the commercial harvesting of shellfish and the loss of food for birds and fish.

4. The importance of *Ammodytes* in subtidal mobile sandbanks as a main prey species for bird populations

Physical resources (*)

1. Research into the beneficial use of dredge spoil to recharge beaches and mudflats, without causing alteration in the slope and elevation of the flats or the smothering of fauna.

VIII. APPLICATIONS FOR CONSERVATION MANAGEMENT

A. STRATEGIES FOR MANAGEMENT

The previous sections describe the main features and characteristics of the biotope complexes **Intertidal Sand and Mudflats** and **Subtidal Mobile Sandbanks** as well as the links between those features. The **Habitats and Species Directive** dictates that **SAC's** require to be managed to ensure that those characteristics are protected and that they do not change beyond those levels considered usual for the habitats. Where these characteristics are in an **optimal state** can be defined as **Favourable Conditions** for the Biotope Complexes and the natural variation within those characteristics can be defined as being within **Change Levels**; outside those change levels gives cause for concern (Hiscock, pers. comm.). It is of note that defining the maintenance and recovery of Favourable Conditions for marine habitats creates difficulties not encountered for terrestrial habitats.

Marine habitats by their nature exhibit considerable **spatial and temporal variability** within the habitat and there is more influence by features and structures outside the habitat than is shown in terrestrial systems, for example the delivery of food and colonising organisms (see Chapter III). The understanding of that variability is compounded by the non-availability of long term data sets for defining Favourable Conditions and Change Levels, i.e. the natural spatial and temporal variability has not been established (see Chapter VII). Thus there is a **poor quality and quantity of data** on which to base trends and **detection of change** from favourable status.

The definition of Favourable Conditions depends on the **time-scale** in which changes may occur: on diurnal, spring-neap, lunar, seasonal, inter-annual and decadal bases. Similarly, the definition also depends on **spatial scales** which incorporate local patterns, those within a well-defined estuarine or sea-area, those within a coastal area which behaves as a given unit (e.g. sedimentary cells) and other scales up to biogeographic regions. In turn, **required actions and monitoring** have to be related to such temporal and spatial scales.

The most valid assessment of the features of any marine habitat is to define the prevailing hydrographic regime which will create the substratum type and thus the creation of community structure, i.e. a ***bottom-up control***. Once that basic structure has been created, biological interactions (recruitment, competition and predator-prey relationships) will modify it and thus lead to an effect on top predators and the lower trophic levels, i.e. ***top-down processes***.

The aim in any **management** of marine systems should be to **regulate human-induced impacts** and then to let **natural processes operate**. The major difficulty will be if natural processes, such as storm-induced sediment disturbance, lead to significant changes to the habitat. The Habitats Directive implies the maintenance of stability in the systems of concern although the wide variability within marine soft-substrata habitats dictates that such a stability is difficult to quantify.

B. DETERMINATION OF CHANGE

In order to manage these biotope complexes, it is necessary to **determine change** as the result of the action of natural and anthropogenic factors and to **determine the significance** of that change for the **integrity** of the biotope complexes. Following from the description of the main features of these biotope complexes (Chapters II and III), it is possible to create a **priority list** of **Favourable Conditions and attributes**. The over-riding influence of the physical environment (see Chapters II and IV) together with the difficulties and effort required in monitoring (see Chapter VI) dictates that it would be more cost-effective to study the changes in those features rather than in the biology which could not be studied in detail.

The parameters for study can be divided into: **primary parameters**, as the **physical-chemical** attributes that will cause habitat disruption, and **secondary parameters**, the **biological** attributes, that will reflect changes.

The most appropriate **physical features** are:

- **Area**, as the expected size of the habitat, and in certain cases **Shape** of the habitat;

- **Substratum,** as the underlying nature of the bed material;

- **Depth** and/or **Tidal Elevation**, as indicating either the coverage by water for Subtidal Mobile Sandbanks habitats or the extent to which Intertidal Sand and Mudflats are exposed at Low Water; the depth also influences the light regime available to infralittoral plants;

- **Water Characteristics**, as the underlying water chemistry, including salinity, temperature and nutrient regime;

- **Hydrophysical regime**, as the summation of tidal, wind-induced and residual currents which influence the bed nature and the delivery of food and dispersive stages to an area; and

- **Habitat Mosaic**, as an indication of the complexity of the environment created by the physical attributes and thus leading to biological complexity.

The **biological attributes** to be used include important features which describe community structure and functioning. The most appropriate features are:

- **Community Structure**, as the net result of taxa and individuals supported, the diversity of the area and, where necessary, the zonation created by the physical and biological features;

- **Biotopes**, as the number and mixture of representative biological-environment entities and including where possible those listed in site notification, including the quality of biotopes and the maintenance of balance between them;

- **Species**, especially those that are rare and/or included in any site notification, and the dominant species in terms of functioning and support of predators or as predators. The rare species could decline if their niche is removed, the area decreases or the supplying population declines; and

• Community Functioning, as an indication of the overall health of the system and its support for important grazer and/or predator populations.

These **biological attributes** can be divided into **qualitative ones** (e.g. presence of rare species) and **quantitative ones** (e.g. the importance of sediment supporting fish and birds), thus there is the need to determine the carrying capacity to support predators. In addition, in the terms of the Directive, the substratum is regarded as having an intrinsic value (e.g. mudflats as mud) as well as being a resource for (ultimately) supporting higher predators, e.g. waterfowl. While the above list gives general attributes, there is the need ultimately to focus on particular **site-specific cases** with specific features (e.g. species) for use by the manager of a particular site.

The **functioning** of these habitats indicates the importance of physical processes whereby if these are protected, then the biology will be assured, for example a low-energy area will have a typical muddy-substratum faunal community. Although the species composition may change with geographical area, the biotope functioning will remain similar (see Chapter III). Furthermore, there is the need to allow for changes to these most widely-varying environments (e.g. intertidal mudflats in estuaries) as well as those exposed to severe natural events, e.g. the 1 in 50 or 200 year storms on subtidal sand-banks.

Each sedimentary site is likely to consist of a single or very few biotopes although the more **complex marine habitats**, as far as the Directive is concerned, such as estuaries and coastal waters, may be made up of a certain **combination of biotopes** to give it its unique features. Similarly, it may be necessary to separate features dominant at a site from those responsible for its functioning, e.g. over-wintering birds on a mudflat. Within a complex site, the **biotope mosaic** as well as its component parts requires management, thus there is a need to assess each as a structural type which functions in combination with the others.

There are many **potentially damaging human activities** likely to affect the soft substratum habitats (see Chapter V). At present, it is not possible to determine for all sites, key features and all human activities, the quantitative effects of changes to the biological structure and functioning as the result of man-induced changes. The nature of the relationships between the features is well-known, especially for **well-defined stressors** such as sewage disposal or dredged material relocation (Rees *et al*, 1990; MAFF, 1993; SOAEFD, 1996) but the relationships have been rarely and not fully quantified nor given in a predictive, statistical manner (Elliott & O'Reilly, 1991). However, it is necessary to presume that large-scale physical changes will affect the **integrity** of a site.

Because of the nature of the changes, it is suggested that:

- the degree of monitoring should be dictated by the magnitude of the perceived or actual threats;

- recording of human activities should be carried out to indicate a threat to the integrity of the system;

- initial and continued low-level surveillance (using skilled eye surveys and remote sensing) will indicate the possibility of change; and

- the latter will then act as a trigger and require more detailed and quantitative monitoring to indicate the magnitude of the change.

C. PROCEDURE FOR MANAGEMENT

The conceptual model defined in Chapter II concentrated on the sets of relationships required to structure sedimentary habitats (Figures 2.2 and 2.3). The information suitable for defining and understanding those relationships can be obtained from several sources (see Chapter IV, Monitoring Methods), hence the **conceptual diagram** can thus be extended to indicate which information can be derived from existing databases, by measurement and by other, wide-scale survey techniques such as photography (**Figure 8.0**).

It is emphasised that much of the **information** necessary for determining the changes described below can be obtained rapidly by **broad-scale surveys** (P in **Figure 8.0**). These include aerial photography, skilled-eye assessment and Phase 1 surveys of Intertidal Sand and Mudflats, still and video photography and side-scan sonar techniques (such as RoxAnn) for Subtidal Mobile Sandbanks.

The use of the term **database** (D in **Figure 8.0**) implies that information is from **other sources** (published and unpublished) and as such it does not necessarily require to derived for a site. For example, the hydrographic information indicating the current regime over Subtidal Mobile Sandbanks can be derived from Admiralty Charts and the tidal regime influencing Intertidal Sand and Mudflats can be obtained from the published Tide-Tables (Office of HM Hydrographer). Similarly, **biological information** on the reproductive cycles and biology of the dominant faunal species can be derived from the literature, e.g. Rasmussen (1973), Wolff (1973).

The most **cost-effective means of assessing change** in the biotope complexes will be through an annual cataloguing and monitoring of activities at a qualitative and subjective level. This will indicate areas of human-induced change as well as natural but large-scale modifications. This will also indicate the areas and features or components of the system to be monitored in more detail. If there are no **perceived major changes** to the system, then a **quinquenniel survey** should be carried out as a phase 1 (habitat mapping) survey. This should focus on elements at risk of change and lead to a fully quantitative community analysis where change is observed, i.e. outside normal variability.

1. Intertidal Sand and Mudflats

The interaction between the physical and biological **attributes** produces several related features which can be used for **defining the Favourable Condition** of the habitats and **Targets** for their management **Table 8.0**. The **spatial extent**, **tidal regime** and **elevation** of the flats dictates the size of the primary consumer populations, which in turn support the fish and birds. The tidal elevation is required to remain within certain limits, as the major component of the biological community, in terms of abundance and biomass, is located within the mid-tidal zone. A decrease in **tidal height** will force this zone towards the low water mark and thus perhaps expose it to the greater current speeds found close to the low water channels, whereas an increase in tidal height will increase drying periods and thus desiccation of the organisms. The **nature of the substratum**, both as sediment type and slope, is the result of the hydrographical regime, including the tidal, wind-induced and residual water movements, which will influence the water retention properties, the permeability and porosity, retention and degradation of organic matter and thus the sediment oxygen regime and redox characteristics.

With such soft substratum areas, the main assessment will be of change in sediment type and its relationship to **water movements** and, in certain cases, freshwater/land runoff. It is relatively easy to categorise which is regarded as sand or mud but there is still variation. For example, a slight variation in one component of sediment particle distribution can result in a substantial change in sediment type and features, e.g. silt increase affecting porosity.

This **sedimentary regime** reflects whether the zone is a high or low energy flat. This dictates whether the **community** is dominated by detritus and deposit feeders which will be in large abundance in low energy sheltered mudflats, or lower abundances of mobile small crustaceans or sparse suspension feeding bivalves found in higher energy intertidal sandflats. Whereas the former is utilised by waterfowl and some fishes, sandflats are used more as flatfish nursery areas. Because of this, an assessment of **community functioning**, as production supporting vertebrate consumers, is of paramount importance.

Within sand and mudflat areas, the important feature of **community structure** relates more to the abundance and biomass of a restricted set of species than to the presence of rare species. The latter are considered to be of minor importance and unlikely to occur given the homogeneity of the sand and mudflats both physically and biologically and the limited availability of niches.

The community in turn through **biomodification** (biostabilisation, biodeposition and bioturbation) will influence the sediment structure. This is particularly important for large *Lanice*, spionid and *Zostera* beds (biostabilisation), *Macoma* and *Cerastoderma* beds (bioturbation) and mussel beds (biodeposition). Microphytobenthos populations, such as diatoms, euglenoids and flagellates, will also increase the stabilisation of the flats.

Table 8.0 Summary of Favourable Conditions in Intertidal Sand and Mudflats and Targets for their Maintenance.

Attributes	**Indicators of Favourable Conditions**
Area	No decline beyond natural fluctuations but there can be no limit to an increase in the sand or mudflat on condition that other habitats are not adversely affected.
Substratum	Maintain baseline thickness, structure, stability characteristics and particle composition of mudflats or sandflat.
Tidal elevation	The sand or mudflats should be exposed at low tide and there should be no deviation from background levels in tidal elevation or shore slope.
Hydro-graphical regime	Maintain baseline conditions of tidal, wind-induced and residual flow, channel position and, where the sand or mudflats occur in estuaries, freshwater run-off and salinity regime.

(Continued on next page)

Table 8.0 (cont.)

Community structure	Maintain expected community structure given hydrological regime and substratum conditions.
Biotopes	No increase in sand or mudflat area which leads to a decline in other important biotopes, otherwise no generic limits to increase are definable. Remaining areas of the site should continue to be dominated by biotopes representative of the habitat in the region.
Species	Ensure continued presence of nationally scarce or rare species listed in Appendix 1 in Sanderson (1996) or other important species listed in the Site Notification. No upper limits to species abundance except where increase threatens other important species or indicates habitat degradation and/or disruption of the community due to human factors.
Community function	Sand and mudflats should continue to support important predator and/or grazer populations.

a. Frequency of monitoring

These habitats are amongst the simplest to monitor quantitatively although their spatial extent can make monitoring time-consuming. **Remote sensing and skilled-eye surveys** should be used to indicate the **gross features**, with repeat surveys carried out during a similar time period each year. Features to be assessed should include: nature of sediment, extent and shape of area and extent of run-off channels, algal, seagrass and mussel coverage.

An **annual catalogue of human activities** in the area will indicate the likelihood of change either directly or within the hydrographic or sediment cell. The likelihood of large-scale changes should be addressed by a **quantitative survey** of the sediment type, the shore elevation, the macrobenthos (and algae/seagrass where appropriate), the waterfowl population as winter counts, and the juvenile fish populations using the flats. Where their is **no perceived changes** as the result of human activities, a **quinquenniel assessment** of key features is considered suitable. However, this may not be feasible for extensive habitats, such as large estuaries, where an ongoing programme of small scale surveys may be more appropriate.

At present, there exists no quantitative, numerical values for the above attributes against which the compliance monitoring can be carried out (see below). Once these, as monitoring standards, have been developed then the monitoring can test for compliance with such values.

b. Constraints on attributes

The sensitivity of the Intertidal Sand and Mudflats to natural and anthropogenic changes is discussed in Chapters V and VI. Each of the aspects identified thus will constrain the attributes; for example, as a summary:

- nutrient stimulation of the area, as hypernutrification leading to symptoms of eutrophication, will increase the coverage by opportunistic green macroalgae, such as *Enteromorpha*. In turn, this may prevent bird feeding on the flats and create anoxic conditions in the sediment below the mats.

- organic enrichment of the mud and sandflats by sewage and other organic discharges will impair functioning through the development of opportunistic populations and anoxic sediment which affect the palatability of prey. Such changes will also occur as a result of industrial discharges.

- land-claim will remove intertidal flats and thus remove productive areas (McLusky *et al*, 1993), a feature not easily reversed. The change in substratum type and the tidal elevation are the greatest threats to the integrity of the mud and sandflat sites and their carrying capacity in supporting waterfowl and fishes (nursery and adult).

- similarly, a loss of mud and sandflats can occur through an increase in the low water area following channel modification, or upper area through colonisation by pioneer saltmarsh flora. This will lead to a change of habitat and therefore use.

- as the flats are the result of a balance between sediment accretion and erosion, any input of sediment through, for example, hydrographic disruption or dredged-material relocation, will have an effect whose effect depends in size on the nature of the receiving material. For example, an increase of 5% silt and clay in muds will have little effect but the same in sands would have a large effect by preventing percolation and oxygen exchange.

- in addition to any local loss of area, the combined effects of global sea-level rise, isostatic rebound in the southern part of Great Britain and the constraining of the upper tidal region though seawalls will produce the tidal squeeze, again removing productive wetland areas.

2. Subtidal Mobile Sandbanks

Management of the Subtidal Mobile Sandbanks is required to ensure that the Favourable Conditions required for the **protection of their integrity** should be maintained (**Table 8.1**). The **area** of sandbank is the result of: the underlying geology, the hydrographic regime incorporating wave, tidal and residual current patterns, and the supply and removal of sediment (see Chapter II). While the first of these cannot be influenced anthropogenically other than by mineral extraction, which may produce subsidence, the latter two categories require to be protected by preventing any interference or disruption to the water patterns. Given that most colonisation of the habitats is from external sources, there is unlikely to be a critical size for the sandbanks although this is not known (see Chapter VI).

The **depth** of water above the sandbank requires maintenance within natural limits to prevent shallowing leading to exposure on low spring tides, or deepening which would alter the sandbank characteristics, perhaps creating conditions similar to those of the surrounding seabed. In addition, where the bank is dependent on some light penetration, for any algal component of the beds, then any increase in depth will affect that **light regime**. The **hydrographic regime** will also affect the water characteristics in terms of salinity, temperature and dissolved oxygen.

The majority of these sandbanks are marine and any **reduction in salinity** will disturb the marine communities whilst changes to depth and water exchange will affect the temperature and oxygen balance. In addition the upstream addition of **polluting materials** or the on-site increase in **dredging or dredged material disposal** will affect water quality. Similarly, where the banks are at the centre of a gyre, this may increase the delivery and accumulation of polluting materials.

Many sandbanks are the result of conical headland gyres being created either side of headlands by residual currents moving either clockwise or counter-clockwise (see Chapter II). Such gyres require to be protected in order to maintain the sandbanks, for example those found either side of Flamborough Head. This requires control of coastal developments, which may affect changes in the hydrodynamic system, through the terrestrial and offshore planning process.

Table 8.1 Summary of Favourable Conditions in Subtidal Mobile Sandbanks and Targets for their Maintenance.

Attribute	**Indicators of Favourable Conditions**
Area	No reduction in subtidal mobile sandbank beyond natural fluctuations.
Substratum	Predominantly sandy substrata with a low proportion of silt and clay material. Maintenance of baseline thickness, structure, stability characteristics and particle composition of sand bank within natural fluctuations
Depth and tidal range	Sandbank to be covered at all stages of the tidal cycle and with no significant increase in water depth beyond natural fluctuations.
Water characteristics	Maintenance of water characteristics over the subtidal mobile sandbank, in particular salinity.
hydrographical regime	Maintenance of tidal, wind and residual flow baseline conditions with no disruption to patterns which ensure the delivery to the subtidal mobile sandbank of colonising organisms and organic matter as food.
Community structure	Maintenance of community structure, diversity and zonations expected given the subtidal mobile sandbank's hydrophysical environmental regime.
Biotopes	Maintenance of presence and quality of important biotope complexes, including those listed in the Site Notification. The site should continue to be dominated by biotopes representative of the habitat in the region.
Species	Maintenance of presence and viability of important species, including those listed in Appendix 1 in Sanderson (1996) if present and listed in the Site Notification.
Community function	The subtidal mobile sandbank should continue to support important predator populations.

a. Frequency of monitoring

The sand banks can be modified by extreme natural events such as storms as well as anthropogenic interference with the substratum and hydrographic regime. Where there is **no perceived changes** due to human activities, the sites should routinely be assessed qualitatively on a **five-year basis**. However, if there is cause to suspect change has occurred or will occur as the result of human activities such as potential aggregate extraction or modification of the hydrographic regime, then shorter-interval quantitative monitoring should occur. In addition, a **record** should be maintained of **climatic conditions** given that large-scale freshwater inputs and severe storms will have a large effect on the areas and thus these data will be required for any prediction and interpretation of biological changes.

b. Constraints on attributes

The sensitivity of the Subtidal Mobile Sandbanks to natural and anthropogenic changes is discussed in Chapters V and VI. Each of the aspects identified thus will constrain the attributes; for example, as a summary:

- such areas may be in demand for aggregate extraction, depending on the relative mixture of coarse and medium sand material, and this will affect the size, depth and nature of the substratum material.

- interference to the hydrographic patterns by dredging, construction of rigs, jetties and harbours will affect the deposition and erosion processes and the delivery of colonising organisms and organic matter. These activities may also reduce the heterogeneity of the bed and thus the number of niches available for colonisation.

- disruption of the light regime through an increase in turbidity as the result of increased land run-off or bed-disruption by dredging and spoil disposal, will affect any algal and angiosperm flora.

- commercial fishing by beam trawling will disrupt the integrity of the bed and damage the larger benthic fauna, especially the epibenthos. The margins of subtidal sandbanks adjoining rocky areas are likely to support edible crab and lobster populations and thus will be the site of commercial potting and creel fishing.

D. BIODIVERSITY PERSPECTIVES

In general, and because of the extensive nature of these biotope complexes, the soft-sedimentary marine habitats are **unlikely** to have **rare or unusual species or communities**. Because of this, these elements of community structure are of limited value in assessing and defining change, and so it is considered necessary to place emphasis on functioning and thus rate-processes. **Sustainable functioning**, within limits, may be regarded as an indication of the maintenance of integrity of the site, for example whether intertidal mudflats continue to maintain their support for over-wintering waterfowl, or whether subtidal mobile sandbanks support sandeels and juvenile flatfishes. The change of physical or biological attributes is of importance and the rate of that change should be used in decision making; however, it is unlikely that sufficient data exist for this to be determined.

1. Intertidal Sand and Mudflats

It is considered necessary to put **emphasis** on assessing any **decline in well-being** rather than **rarity**. It is further considered necessary to separate a process rather than a structural attribute for monitoring; this is particularly the case where the components of a system may change but not result in a net loss of **ecological function**. For example, in estuarine mudflats, a variation in river flow, and thus salinity, will alter the community structure and components (e.g. change from *Nereis* to *Nephtys* as the dominant polychaete) but its functioning and carrying capacity will remain largely unaffected.

As indicated previously (Chapter III), **rare species** are unlikely to occur given the nature of the areas in general. However, rare species can occur, for example, the anemone, *Nematostella vectensis* and polychaete, *Armandia cirrhosa* - both are **scheduled species** and occur in intertidal areas within the Fleet, Portland Harbour and Poole Harbour (Copeley, *pers. comm.*). The intertidal sand and mud within Portland Harbour supports a diverse assemblage of polychaete worms and molluscs due in part to the extreme conditions imposed by the double low tide. On the lower shore, species occur which are normally considered subtidal and these include a number of rare species or species on the edge of their range.

2. Subtidal Mobile Sandbanks

Similarly, the Subtidal Mobile Sandbanks are **unlikely** to contain **rare species** given the **dispersal mechanisms** of the species and the dynamic nature of the areas. However, in some cases the SAC will be designated because of the presence of rare species. Those species which are rare due the extent of their geographical distribution may be difficult to protect, whereas those which are rare due to a paucity of habitat can be protected more easily. Given the extensive nature of this biotope complex, the latter is unlikely.

Despite this, it is emphasised that the **maintenance of the physical habitats** of the subtidal sandbanks should ensure the protection of even the rare species. However, it is considered of greater relevance that the functioning of the populations of the dominant and/or characterising species is protected as these will support the predators, e.g. the sandeel *Ammodytes* in the case of seabirds, and infaunal amphipods and polychaetes in terms of benthic and demersal fishes. In addition, these dominant species may be required to stabilise the sandbank and thus protect its integrity, e.g. *Lanice* beds and *Zostera* meadows. Any reduction in these will influence the physical stability of the sandbank and perhaps increase levels of erosion.

E. QUANTITATIVE CHANGE LEVELS IN THE MANAGEMENT OF INTERTIDAL SAND AND MUDFLATS AND SUBTIDAL MOBILE SANDBANKS

As indicated in Chapter VI, **surveillance** assesses the state and changes in features of a biotope whereas **monitoring** implies testing against pre-defined and agreed standards or limits (i.e. compliance monitoring). As a trigger to determining whether further action and management decisions are required for Intertidal Sand and Mudflats and Subtidal Mobile Sandbanks, the Country Nature Conservation Agencies have proposed the use of **Change Levels** (Dr K Hiscock, pers. comm.).

Change Levels can be regarded as synonymous with **numerical standards** for which compliance is derived (Elliott, 1996; see Chapter VII). **Environmental Quality Standards** have been long used for chemical and microbiological determinants in quality assessment and the control of human impacts. However, only recently have **Ecological Quality Standards** been proposed for macrobiology, especially community-based features (MAFF, 1993). In essence, these are suggested as a means of defining the standards against which compliance monitoring (as opposed to surveillance) is carried out.

It is considered impractical, because of the wide and undefined variability in the systems (Elliott & O'Reilly, 1991), at present to **derive well-defined and numerical limits** as standards for use in monitoring. If poorly-defined limits are given without adequate testing these will be unsuitable for use by 'non-experienced' monitoring staff to determine quality and the magnitude of anthropogenic changes. Thus, the determination of **action or trigger levels** will require further research.

Despite this, further work is required to give **Environmental and Ecological Quality Objectives** which may be regarded as statements against which any assessments can be carried out (Elliott, 1996). However, the concept of **'naturalness'** of a biotope, as defined by an experienced ecologist, may be the most appropriate means of defining and describing **unacceptable change**. The uncertainty and high degree of variability dictate that exceedence of any level of acceptable change should act as a **trigger** for further study prior to, and/or rather than, management action such as prohibition of an activity suspected of causing the change. In this case, it is not necessary to separate man-induced or natural changes as long as there is some response to change, although such a separation is important for practical and financial management.

F KEY POINTS FROM CHAPTER VIII

1. Management of the biotope complexes Intertidal Sand and Mudflats and Subtidal Mobile Sands will be designed to regulate the effects of human-induced impacts while letting natural processes operate. Because of this, the management should assess and allow for ***Bottom-up controls***, whereby the physical system produces the conditions suitable for biological colonisation, and ensure ***Top-down processes***, such as predators using the sedimentary biota.

2. The information required in managing the biotope complexes can be derived from existing sources such as databases, from rapid-survey techniques such as photography and from more quantitative surveys. An aim is to ensure that cost-effective monitoring is carried out in areas with the possibility of deleterious change. Because of the nature of those changes, it is suggested that:

   - the spatial and temporal degree of monitoring should be dictated by the magnitude of the perceived or actual threats from human activities;

   - recording of human activities and unusual events (e.g. climatic change) should be carried out to indicate any threats to the integrity of the system;

   - initial and continued low-level surveillance (using skilled eye surveys and remote sensing) will indicate the possibility of change;

   - the latter will then act as a trigger and require more detailed and quantitative monitoring to indicate the magnitude of the change.

3. The biodiversity value of the biotope complexes is related more to the protection of their functioning rather than the presence of rare or fragile species. It is unusual for these biotope complexes to have rare or unusual species or communities.

4. In obtaining information for management, the parameters for study can be divided into: primary parameters, as the physical-chemical attributes that will cause habitat disruption, and secondary parameters, the biological attributes, that will reflect changes. The most appropriate physical features are:

   - **Area**, as the expected size of the habitat, and in certain cases **Shape** of the habitat;

   - **Substratum**, as the underlying nature of the bed material;

(Continued on the next page)

- **Depth and/or Tidal Elevation**, as indicating either the coverage by water for Subtidal Mobile Sandbanks habitats or the extent to which Intertidal Sand and Mudflats are exposed at Low Water; the depth also influences the light regime available to infralittoral plants;

- **Water Characteristics**, as the underlying water chemistry, including salinity, temperature and nutrient regime;

- **Hydrophysical regime**, as the summation of tidal, wind-induced and residual currents which influence the bed nature and the delivery of food and dispersive stages to an area;

- **Habitat Mosaic**, as an indication of the complexity of the environment created by the physical attributes and thus leading to biological complexity.

5. The **biological attributes** to be used include important features which describe community structure and functioning. The most appropriate features are:

    - **Community Structure**, as the net result of taxa and individuals supported, the diversity of the area and, where necessary, the zonation created by the physical and biological features;

    - **Biotopes**, as the number and mixture of representative biological-environment entities and including where possible those listed in site notification, including the quality of biotopes and the maintenance of balance between them;

    - **Species**, especially those that are rare and/or included in any site notification, and the dominant species in terms of functioning and support of predators or as predators. The rare species could decline if their niche is removed, the area decreases or the supplying population declines;

    - **Community Functioning**, as an indication of the overall health of the system and its support for important grazer and/or predator populations.

6. These quantifiable features and attributes can be used to define the Favourable Conditions for the maintenance of the integrity of the biotope complexes and, in turn, to indicate the targets for management. Those Favourable Conditions can be linked to Quality Objectives for the sites, to indicate the desired status of the biotope complexes. However, with present knowledge, it is not possible to set quantitative standards for compliance monitoring which covers the impacts of all human-activities in Intertidal Sand and Mudflats and Subtidal Mobile Sandbanks. Although tentative standards have been given for well-defined causes of change in the marine system, these require to be tested and further developed for these biotope complexes. With further study, site-specific trigger points may be identified for use in the monitoring and management.

IX. LITERATURE CITED AND KEY BACKGROUND READING

Ahn, I.Y., Kang, Y.C. & Coi, J.W. (1995). The influence of industrial effluents on intertidal benthic communities in Panweol, Kyeonoggi Bay (Yellow Sea) on the West coast of Korea. *Mar. Poll. Bull.* **30** (3) 200-206.

Allen, P.L. & Moore, J.J. (1987). Invertebrate macrofauna as potential indicators of sandy beach instability. *Estuarine, Coastal and Shelf Science* **24**, 109-125.

Allen, J.H.(in prep) Unpublished Ph.D thesis, University of Hull

Angus, S. (1979). The macrofauna of intertidal sand in the Outer Hebrides. *Proceedings of the Royal Society of Edinburgh* 77B, 155-171.

Ansell, A.D, *et al* (1972). The ecology of two sandy beaches in south-west India. 1. Seasonal changes in physical and chemical factors, and in the macrofauna. *Marine Biology* **17**, 35-62.

Armstrong, M.P. (1997). Seasonal and ontogenic changes in distribution and abundance of smooth flounder, *Pleuronectes putnami* and winter flounder, *Pleuronectes americanus*, along estuarine depth and salinity gradients. *Fisheries Bulletin*. **95** (3) 414-430

Atkins, S.M. (1983). Contrasts in benthic community structure off the North Yorkshire coast (Sandshead Bay and Maw Wyke). *Oceanologica Acta*, Special Volume, p7-10.

Baker J.M. & Wolff, W.J.P. (eds.) (1987). *Biological surveys of estuaries and coasts*. Cambridge University Press, Cambridge.

Barne, J.H., Robson, C.F., Kaznowska, S.S., Doody, J.P & Davidson, N.C. (eds.) (1995). *Coasts and seas of the United Kingdom. Region 5 North-east England: Berwick on Tweed to Filey Bay*. Peterborough, Joint Nature Conservation Committee.

Basford, D., Eleftheriou, A. & Raffaelli, D. (1990). The infauna and epifauna of the northern north-sea. *Netherlands Journal of Sea Research*, **25**, 1-2, 165-173.

Batten, L.A., Bibby, C.J., Clement, P., Elliott, G.D. & Porter, R.F. (eds) (1990). Red Data Birds in Britain, The Nature Conservancy Council and RSPB. T and AD POYSER.

Bibby, C.J., Burgess, N.D. & Hill, D.A. (1992) *Bird Census Techniques.* Published for the British Ornithology and the Royal Society for the Protection of Birds. Academic Press

Blanchard, G. & Guarini, J.M. (1996). Studying the role of mud temperature on the hourly variation of the photosynthetic capacity of microphytobenthos in intertidal areas. *Comptes Rendus de L'academie des Sciences serie III - Sciences de la vie-Life Sciences*. **319** (12) 1153-1158.

Boates, J.S., Forbes, M., Zinck & McNeil, N. (1995). Male amphipods (*Corophium volutator* [Pallas] show flexible behaviour in relation to risk of predation by sandpipers). *Ecoscience* **2** 123-128.

Boesch, D.F. (1973). Classification and community structure of macrobenthos in the Hampton Roads area, Virginia. *Marine Biology* **21** 226-44

Brey, T. (1991) The relative significance of biological and physical disturbance: an example from intertidal and subtidal sandy bottom communities. *Estuarine and Coastal Shelf Science* **33**, 339-60

Brown, B. (1982). Spatial and temporal distribution of a deposit feeding polychaete on a heterogeneous tidal flat. *J. Exp. Mar. Bio. Ecol.* **65**, 213-227.

Brown, A.C. (1983). The ecophysiology of beach animals - a partial review. In: (eds. A. McLachlan & T. Erasmus) *Sandy beaches as ecosystems.* The Hague, The Netherlands: Junk. 575-605.

Brown, B. & Wilson, W. H. (1997). The role of commercial digging of mudflats as an agent for change of infaunal intertidal populations. *J. Exp. Mar. Bio. Ecol.* **218** (1) 49-61.

Brown, J.R., Gowen, R.J. & McLusky, D.S. (1987). The effect of salmon farming on the benthos of a Scottish sea loch. *J. Exp. Mar. Biol. Ecol.* **109**, (1), 39-51.

Brown, R.A. (1989). *Bottom trawling in Strangford Lough: problems and policies*. Proceedings from the North Sea Meeting, Rotterdam.

Bryant, D.M. & Leng, J. (1976). Feeding distribution and behaviour of Shelduck in relation to food supply. *Wildfowl* **27** p20-30

Bryant, D.M. (1979). Effects of prey density and site characteristics on estuary usage by overwintering waders (Charadril). *Estuarine and Coastal Marine Science* **9**: 369-385.

Buchanan, J.B. (1966). The biology of *Echinocardium cordatum* chinodermata (Spatangoidea) from different habitats. *J. Mar. Biol. Ass. U.K.* **46**, 97-114.

Buchanan, J.B. (1984). Sediment analysis. In: . (eds. N.A. Holme & A.D. McIntyre) *Methods for the study of marine benthos* 2nd ed. Blackwell, Oxford, 41-65.

Buchanan, J.B. & Moore, J.J. (1986). A broad review of variability and persistence in the Northumberland benthic fauna – 1971-85. *J. Mar. Biol. Ass. U.K.* **66**, 641-657.

Buekema, J.J. (1992). Expected changes in the Wadden Sea benthos in a warmer world: lessons from the periods with mild winters. *Neth. J. Sea Res.* **30**, 73-79.

Buller & McManus (1979). In: (ed. K.R. Dyer) *Estuarine hydrography and Sedimentation*. Estuarine and Brackish Water Sciences Association. Cambridge University Press.

Burd, F. (1992). Erosion and vegetational change on saltmarshes of Essex and North Kent between 1973 and 1988. *Research and survey in nature conservation* **42.** Nature Conservancy Council, Peterborough.

Burger, J., Niles, L. & Clarke, K.E. (1997). Importance of beach, mudflat and marsh habitats to migrant shorebirds on Delaware Bay. *Biological conservation.* **79** (2-3) pp 283-292.

Carter, R.W.G. (1988). *Coastal Environments. An introduction to the physical, ecological and cultural systems of coastlines.* Academic Press, London.

CEC (1988-91). Cost 647 - Coastal benthic ecology activity report 1988-1991. Compiled by B.F. Keegan

Chapman, G. (1949). The thixotropy and dilatancy of a marine soil. *J. Mar. Biol. Ass. U.K.* **28**, 123-40.

Chapman, P., Dexter, R.N & Long, E.R. (1987). Synoptic measures of sediment contamination, toxicity and infaunal community composition (the sediment quality triad) in San Fransisco Bay. *Mar. Ecol. Prog. Ser.* **37** p75-96

Clark, R.B. (1997). *Marine Pollution* Oxford University Press, Oxford. p60

Commission of the European Communities (1989) CORINE European classification of communities (Corine/Biotopes) listed in the Technical Handbook, *Volume 1,* p73-109,

Connor, D.W., Brazier, D.P., Dalkin, M.J. Hill, T.O., Holt, R.H.F., Northen, K.O., & Sanderson, W.G. (1997). Marine Nature Conservation Review: marine biotopes (two volumes). A classification for Britain and Ireland. Version 97.6. *JNCC Report.*

Costa, M.J. & Elliott, M. (1991). Fish usage and feeding in two industrialised estuaries - the Tagus, Portugal and the Forth, Scotland. In: (eds. M. Elliott & J-P Ducrotoy) *Estuaries and Coasts: Spatial and Temporal Intercomparisons*. Olsed and Olsen, Denmark. 289-297.

Coughlan, J, (1979). Some aspects of reclamation in Southampton Water. In: (eds. B. Knights & A.J. Philips), *Estuarine and Coastal Land Reclamation and Water Storage*. Teakfield, Farnborough and the Estuarine and Brackish Water Sciences Association.

Croker, R.A. & Hatfield, E.B. (1980). Space partitioning and interactions in an intertidal sand burrowing amphipod. *Marine Biology* **61**, 79-88.

Curran, P.J. (1985). *Principles of remote sensing*. Harlow: Longmans.

Dahl, E. (1952). Some aspects of the ecology and zonation of the fauna on sandy beaches. *Oikos* **4** p1-27

Dalkin, M. & Barnett, B. (1998). Procedural guidelines for quantitative sampling of intertidal sediment biotopes and species using cores. In: (ed. K. Hiscock) *Biological monitoring of Marine Special Areas of Conservation: a handbook of methods for detecting change. Part 2. Procedural guidelines*, Peterborough, Joint Nature Conservation Committee.

Davidson, N.C. & Rothwell, P.I. (1993). Human disturbance to waterfowl on estuaries: conservation and coastal management implications of current knowledge. *Wader Study Group Bull.* 68: 97-105

Davidson, N.C., D'A Laffoley, D., Doody, J.P., Way, L.S., Key, R., Drake, C.M., Pienkowski, M.W., Mitchell, R. & Duff, K.L. (1991). Nature Conservation and Estuaries in Great Britain. Nature Conservancy Council.

Department of the Environment for Northern Ireland (1994). *Strangford Lough - proposed marine nature reserve. Guide to designation*. DOE (NI)HMSO.

DeGroot, S.J. (1984). The impact of bottom trawling on benthic fauna of the North Sea. *Ocean Manage* **9**: 177-190.

Dexter, D.M. (1990). The effect of exposure and seasonality on sandy beach community structure in Portugal. *Ciencia Biologica E'Systematica* (Portugal) **10**, 31-50.

Dolphin, T.J., Hume, T.M. & Parnell, K.E. (1995). Oceanographic processes and sediment mixing on a sand flat in an enclosed sea, Manukau Harbor, New Zealand. *Mar. Geol.* **128** (3-4) 169-181.

Donnan, D. (1998). Procedural guidelines for descriptive and quantitative surveys using remote operated vehicles (ROV). In: (ed. K. Hiscock) *Biological monitoring of marine Special Areas of Conservation: a handbook of methods for detecting change. Part 2. Procedural guidelines*. Peterborough, Joint Nature Conservation Committee.

Dyer, K.R. (ed) (1979). *Estuarine hydrography and sedimentation*. Estuarine and Brackish Water Sciences Association. Cambridge University Press.

Dyer, K.R. (1998). *Estuaries - a physical introduction.* 2nd Edition, John Wiley & Son, Chichester

Dyke, P. (1996). *Modelling Marine Processes*. Prentice Hall.

Eagle, G.A. (1983). The chemistry of sandy beach ecosystems - a review. In: (eds. A. McLachan, & T. Erasmus), *Sandy beaches as ecosystems.* The Hague, The Netherlands: Junk. 203-224.

Eagle, R.A. (1973). Benthic studies in the south east of Liverpool Bay. *Estuarine and Coastal Marine Science* **1** p285-99

Eagle, R.A. (1975). Natural fluctuations in a soft bottom benthic community. *J. Mar. Biol. Ass. U.K.* **55**, 865-878.

Eleftheriou, A. & Robertson, M.R. (1992). The effects of experimental scallop dredging on the fauna and physical-environment of a shallow sandy community. *Netherlands Journal of Sea Research* **30**, 289-299.

Eleftheriou, A. & McIntyre, A.D., (1976). The intertidal fauna of sandy beaches-a survey of the Scottish Coast. *SFRR* No 6.

Elliott, M. (1979) Studies on the production ecology of several mollusc species in the estuarine Firth of Forth. Unpublished PhD Thesis, University of Stirling, 2 Vols.

Elliott, M.& Griffiths, A.H. (1988). Contamination and effects of hydrocarbons on the Forth ecosystem. *Proc. Roy. Soc. Edin.*, **93B**, 327-342.

Elliott, M. & Taylor, C.J.L. (1989a). The structure and functioning of an estuarine/marine fish community in the Forth Estuary, Scotland. *Proceedings of the 21st. European Marine Biology Symposium*, Gdansk, September, 1986. Polish Academy of Sciences - Institute of Oceanology, 227-240.

Elliott, M. & Taylor, C.J.L. (1989b). The production ecology of the subtidal benthos of the Forth Estuary, Scotland. *Scient. Mar.* **53** (2-3): 531-541.

Elliott, M., O'Reilly, M.G. & Taylor, C.J.L. (1990). The Forth Estuary: A nursery and overwintering area for North Sea fish species. *Hydrobiologia*, **195**: 89-103.

Elliott, M. (1991). Imaging methods in benthic ecology: summary of discussions, conclusions and recommendations. In: (ed. B.F. Keegan) *COST647 - Coastal Benthic Ecology*. CEC Directorate General; Activity report 1988-1991, p348-351.

Elliott, M. & O’Reilly, M.G. (1991). The variability and prediction of marine benthic community parameters. p231-238. In: (eds. M. Elliott, & J.P. Ducrotoy) *Estuaries and Coasts: spatial and temporal intercomparisons*. Olsen and Olsen, Fredensborg, pp390.

Elliott, M. (1993). The quality of macrobiological data. *Mar. Poll. Bull.* **26** (1) 2-3.

Elliott, M. (1994). The analysis of macrobenthic community data. *Mar. Poll. Bull.* **28** (2) p62-64

Elliott, M. (1996). The derivation and value of ecological quality standards and objectives. *Mar. Poll. Bull.* **32 (11)** p762-763

Elliott, M. & de Jonge V.N. (1996). The need for monitoring the monitors and their monitoring. *Mar. Poll. Bull.* **32, (3)** p248-49

Elliott, M. (1998). Summary of the effects of commercial fisheries on estuarine ecosystems: A European perspective. Unpublished report to SCOR working group 105, Halifax NS, March 1998. p57

Elliott, M. & Service, M. (in press). Analytical quality control and quality assurance in marine benthic studies. Millport, Scotland. Workshop Proceedings p70

Eltringham, S.K. (1971). *Life In Mud And Sand*. The English Universities Press Ltd., St Pauls House, Warwick Lane, London. EC4P 4AH

Erwin, D.G. (1983). The community concept. In: (eds. R. Erwin & D.G. Erwin) *Sublittoral ecology*. *The ecology of the shallow sublittoral benthos.* P144-64. Clarendon Press, Oxford.

Erwin, D.G., Picton, B.E., Connor, D.W., Howson, C.M., Gilleece, P. & Bogues, M.J. (1986). *The Northern Ireland sublittoral survey.* Ulster Museum, Belfast: HMSO.

Evans. P.R. (1996). Improving the accuracy of prediction of the local effects of habitat loss on shorebirds: *Lessons from the Tees and the Orwell Estuary Studies.* In Press.

Fauchald, K. & Jumars, P. (1979). The diet of worms: a study of polychaete feeding guilds. *Oceanography and Marine Biology: Annual Review*. **17,** 193-284.

Fenchel, T.M. & Reidl, R.J. (1970). The sulphide system: a new biotic community underneath the oxidised layer of marine sand bottoms. *Mar. Biol.*, **7,** 255-68.

Fenchel, T (1972). Aspects of decomposer food chains in marine benthos. *Verhandlungen der Deutschen Zoologischen Gellschaft* **65** 14-22

Ferns, P.N. (1983). Sediment mobility in the Severn Estuary and its effect upon the distribution of shorebirds. *Canadian Journal of Fisheries and Aquatic Science,* 40, 331-340.

Fox, A.D., Bell. D.V. & Mudge, G.P. (1993). A preliminary study of the effects of disturbance on feeding Wigeon grazing on Eel-grass Zostera. *Wader Study Group Bull.* **68** (Special Issue).

Fucella, J.E. & Dolan, R. (1996). Magnitude of subaerial beach disturbance during north-east storms. *Journal of Coastal Research* **12**, 420-429.

Gerdol, V. & Hughes, R.G. (1994). Effect of *Corophium volutator* on the abundance of benthic diatoms, bacteria and sediment stability in two estuaries in South-eastern England. *Mar. Ecol. Prog. Ser.* **114** (1-2) 109-115.

GESAMP (1993). Impact of oil and related chemicals and wastes on the marine environment. *GESAMP Reports and Studies No. 50. Joint Group of Experts on the Scientific Aspects of Marine Pollution.*

Gibbons, D.W., Reid, J.B. & Chapman, R.A. (1993*). The New Atlas of Breeding Birds in Britain and Ireland: 1988-1991*. T & A. D. Poyser.

Gibson, R.N., Yin, M.C. & Robb, L. (1995). The behavioural basis of predator-prey size relationships between shrimp (*Crangon crangon*) and juvenile plaice (*Pleuronectes Platessa*). *J. Mar. Biol. Ass. U.K*, **75**, 337-349.

Gibson, R.N. & Robb, L, (1992). The relationship between body size, sediment grain size and the burying ability of juvenile plaice, *Pleuronectes platessa. Journal of Fish Biology* **40 (5)** p771-778.

Gibson, R.N., (1973). The intertidal movements and distribution of young fish on a sandy beach with special reference to the plaice (*Pleuronectes platessa* L.) *J. Exp. Mar. Biol. Ecol.* 12 p79-102.

Giere, O. (1993). *Meiobenthology: the microscopic fauna in aquatic sediments*. Berlin; Springer.

Gierloff-Emden, H.G. (1982). Interest of remote sensing in coastal lagoon research. *Oceanologica Acta 1982: Actes du Symposium International Surles Lagunes Cotieres,* Bordeaux, 8-14 Sept. 1981, ed, P. Laserre and H. Postma, pp 139-49. Paris: Gauthier-Villars.

Glemarec, M. (1973). The benthic communities of the European North Atlantic continental shelf. *Oceanogr. Mar. Biol. Ann. Rev*. **11** p263-289

Goss-Custard, J.D. (1985). Foraging behaviour of wading birds and the carrying capacity of estuaries. In: (eds. R.M. Sibley & R.H. Smith) *Behavioural Ecology*, pp.169-188. Blackwell Scientific Publications, Oxford.

Goss-Custard, J.D. & Ditdurell, S.E.A.L (1990). Bird behaviour and environmental planning: approaches in the study of wader populations. *Ibis*, **132 (2)**, 273-289.

Goss-Custard, J.D. & Yates, M.G. (1992). Towards predicting the effect of salt-marsh reclamation on feeding bird numbers on the Wash. *Journal of Applied Ecology,* **29,** 330-340.

Goss-Custard, J.D, & Verboven, N. (1993). Disturbance and feeding shorebirds on the Exe estuary. *Wader Study Group Bull.* **68** (Special Issue).

Gowen, R.J. & Bradbury, N.B. (1987). The ecological impact of salmonid farming in coastal waters : A Review. *Oceanogr. Mar. Biol. Ann. Rev*. **25**, 563-575

Grant, J. (1984). Sediment microtopography and shorebird foraging. *Marine Ecology Progress Series* **19**, 293-296.

Gray, J.S. (1981). *The Ecology of Marine Sediments*. An introduction to the structure and function of benthic communities. Cambridge University Press.

Green, J. (1968). *The biology of estuarine animals*. Sedgewick and Jackson, London.

Green, R.H. (1979). *Sampling design and statistical methods for environmental biologists*. Wiley, New York.

Hall, S.J. (1994). Physical disturbance and marine benthic communities: Life in unconsolidated sediments. *Ocean. Mar. Biol. Ann. Rev*. **32** 179-239

Hayward, P.J. (1994). *Animals of sandy shores*. England, The Richmond Publishing Company.

Hedgpeth, J.W. (1967). The sense of the meeting, in Lauff (ed) *Estuaries,* AAAS, **83**, 707-712.

Hemingway, K. & Cutts, N.D. (in press) Broad Scale Habitat Mapping of the Solway Firth. *Coastal Zone Topics - Solway Volume.*

Hiscock, K. (1983). Water movement. In: (eds. R. Earll & D.G. Erwin) *Sublittoral ecology: The ecology of the shallow sublittoral benthos.* pp58-96. Clarendon Press, Oxford

Hiscock, K. (1998a). *Biological monitoring of Marine Special Areas of Conservation: a handbook of methods for detecting change. Part 1. Review and description of methods. Consultation draft.* Peterborough, Joint Nature Conservation Committee.

Hiscock, K. (ed.) (1998b). *Biological monitoring of marine Special Areas of Conservation: a handbook of methods for detecting change. Part 2. Procedural guidelines*. Peterborough, Joint Nature Conservation Committee.

Holme, N.A. & McIntyre, A.D. (eds.) (1984). *Methods for study of marine benthos* - 2nd ed. Blackwell Scientific Publications, Oxford.

Iannuzzi, T.J., Weinstein, M.P., Sellner, K.G. & Barrett, J.C. (1996). Habitat disturbance and marina development: An assessment of ecological effects. Changes in primary production due to dredging and marina construction. *Estuaries.* **19**, 257-271.

IECS (1993). *Winter Seabird Survey: Block 41/30 Flamborough Head and Bridlington Bay.* Institute of Estuarine and Coastal Studies, University of Hull.

IECS (1995). Marine environmental baseline survey and assessment, Race Bank, east coast, UK. IECS unpublished report to the Environment Agency.

Jensen, K.T. & Andre, C. (1993). Field and laboratory experiments on interactions among an infaunal polychaete, *Nereis diversicolor,* and two amphipods, *Corophium volutator* and *C. arenarium*: effects on survival, recruitment and migration. *J. Exp. Mar. Biol. Ecol.* **168**. 259-278.

Jones, G. & Candy, S. (1981). Effects of dredging on the macrobenthic infauna of Botany Bay. *Australian Journal of Marine and Freshwater Research*. **32 (3)** p379-98

Jones, J.B. (1992). Environmental impact of trawling on the sea bed: a review. *NZ J Mar Freshwater Res* **26**:59-67

Jones, N.S. (1950). Marine bottom communities. *Biol. Rev*. **25**, 283.

Jones, N.V. & Key, R.S. (1989). The biological value of mudflats in the Humber Estuary (England): Areas proposed for land reclamation. *Proceedings of the International Symposium on Coastal Ecosystems: Planning, Pollution and Productivity.* **2**, 19-32.

Jørgensen, C.B. (1966). Biology of suspension feeding. In: (P.V.R Snelgrove & C.A. Butman) Animal-sediment relationships revisited: Cause versus effect. *Ocean. Mar. Biol. Ann. Rev.* **32** p111-117

Jpfister, C., Harrington, B.A. & Levine, M. (1992). The impact of human disturbance on shorebirds at a migration staging area. *Biol. Cons.* **60**: 115-126.

Kaiser, M.J. (1996). Starfish damage as an indicator of trawling intensity. *Marine Ecology Progress Series* **134**, 303-307.

Kaiser, M.J. & Spencer, B.E. (1996). The effects of beam-trawl disturbance on infaunal communities in different habitats. *Journal of Animal Ecology* **65,** 348-358.

King, C.M. (1975). *Introduction to marine geology and geomorphology,* E. Arnold, London, 370pp.

Kirby, R. & Parker, W.R. (1974). Seabed density measurements related to echo sounder records. *Dock and Harbour Authority*, **54,** 423-4.

Kramer, J.M., Brockman, U.H. & Warwick, R.M. (1994). *Tidal Estuaries: Manual of Sampling and Analytical Procedures*. A.A. Balkema, Rotterdam, Bookfield.

Langslow, D.R. (1981). The conservation of intertidal areas in Britain. *Wader Study Group Bulletin*, **31**, 18-22.

Levinton, J.S. (1979). Deposit-feeders, their resources, and the study of resource limitation. In: (ed. R.J. Livingstone) *Ecological Processes in Coastal and Marine Systems*, 117-41. Plenum Press, New York.

Libes, S.M. (1993). *An introduction to marine biogeochemistry.* John Wiley & Son

Lockwood, S. (1972). *An ecological survey of an O-Group plaice (Pleuronectes platessa L.) population, Filey Bay, Yorkshire.* PhD Thesis, University of East Anglia. A Primer on Methods and Computing. John Wiley and Sons, New York.

Longbottom, M.R. (1970). The distribution of *Arenicola marina* (L.) with particular reference to the effects of particle size and organic matter of the sediments. *Journal of Experimental Marine Biology and Ecology* **5**,138-157.

MAFF, (1993). *Aquatic environmental monitoring report. No.37. Analysis and interpretation of benthic community data at sewage-sludge disposal sites*. Prepared by the Benthos Task Team for the Marine Pollution Monitoring Management Group co-ordinating Sea Disposal Monitoring. Directorate of Fisheries Research Lowestoft 93.

Magorrian, B.H., Service, M. & Clarke, W. (1995). An acoustic bottom classification survey of Strangford Lough, Northern Ireland. *J. Mar. Biol. Ass. U.K.* **75**, 987-992.

Majeed, S.A. (1987). Organic-matter and biotic indexes on the beaches of North Brittany. *Mar. Poll. Bull.* **18 (9)** p490-495

Marshall, S. (1995). *The structure and functioning of the fish assemblage of the Humber Estuary, UK.* PhD thesis, University of Hull.

Marshall, S. & Elliott, M. (1997) A comparison of univariate and multivariate numerical and graphical techniques for determining inter and intraspecifc feeding relationships in estuarine fish. *J. Fish. Biol.* **53(3)** p526-545

McCave, I.N. (1979). In: (ed. K.H. Dyer) *Estuarine hydrography and sedimentation*, p131-185. Cambridge University Press, Cambridge.

McDermott, J.J. (1983). Food web in the surf zone of an exposed sandy beach along the mid-Atlantic coast of the United States. In: (eds. A. McLachlan & T. Erasmus), *Sandy beaches as ecosystems.* The Hague, The Netherlands: Junk. 529-538.

McIntyre, A. D. & Eleftheriou, A. (1968). The bottom fauna of a flatfish nursery ground. *J. Mar. Biol. Ass. U.K.* **48**, 113-42.

McLachlan, A (1983). Sandy beach ecology: a review. In: (eds. A. McLachlan. & T. Erasmus), *Sandy. beaches as ecosystems.* The Hague, The Netherlands: Junk.

McLachlan, A. (1990). Dissipative beaches and macrofauna communities on exposed intertidal sands. *Journal of Coastal Research* **6**, 57-71.

McLachlan, A. & Jaramillo, E. (1993) Sandy beach macrofauna communities and their control by the physical environment: a geographical comparison. *Journal of Coastal Research* 15, 27-38.

McLachlan, A. (1995). Physical factors in benthic ecology: effects of changing sand particle size on beach fauna. Unpublished. *University of Port Elizabeth,* South Africa.

McLachlan, A., Jaramillo, E., Defeo, O., Dugan, J., Deruyck, A. & Coetzee, P. (1995). Adaptations of bivalves to different beach types. *Journal of Experimental Marine Biology and Ecology.* **187 (2)** p147-160.

McLusky, D.S. (1982). The impact of petrochemical effluent on the fauna of an inter-tidal estuarine mudflat. *Estuarine Coastal and Shelf Science*. **14 (5)** p489-99

McLusky, D.S., Anderson, F.E. & Wolfe-Murphy, S. (1983). Distribution and population recovery of *Arenicola marina* and other benthic fauna after bait digging. Mar. Ecol. Prog. Ser. 11 173-179

McLusky, D.S. (1989). *The Estuarine Ecosystem*, 2nd edition. Blackie, USA: Chapman and Hall, New York.

McLusky, D.S. & McCrory, M. (1989). A long-term study of an estuarine mudflat subject to industrial pollution. *Scientia Marina* **53 (2-3)** In: (ed. J.D. Ros) *Topics in marine biology.* Proceedings of the 22nd European Marine Biological Symposium.

McLusky, D.S., Bryant, D.M. & Elliott, M. (1992). The impact of land-claim on macrobenthos, fish and shorebirds on the Forth Estuary, eastern Scotland. *Aquatic Conservation: Marine and Freshwater Ecosystems.* 2 211-222.

Meadows, P.S. & Tait, J. (1989) Modification of sediment permeability and shear strength by two burrowing invertebrates. *Marine Biology* **101**, 75-82. In: Hall .S.J. (1994) Physical disturbance and marine benthic communities: Life in unconsolidated sediments. *Ocean. Mar. Biol. Ann. Rev.* **32** 179-239

Meire, P. (1993). *Wader populations and Macrozoobenthos in a changing estuary: the Oosterschelde, Netherlands.* Institute of Nature Conservation.

Meire, P.M., Seys, J., Buijs, J. & Coosen, J. (1994). Spatial and temporal patterns of intertidal macrobenthic populations in the Oosterschelde: are they influenced by the construction of the storm-surge barrier? *Hydrobiologia* 2821283,157-182.

Michalapoulos, C., Auster, P.J. & Malatesta, R.J. (1992). A comparison of transect and species-time counts for assessing faunal abundance from video surveys. *Marine Technology Society Journal,* **26** 270-30.

Modin, J. & Pihl, L. (1996). Small-scale distribution of juvenile plaice and flounder in relation to predatory shrimp in a shallow Swedish bay. *Journal of Fish Biology* **49**, 1070-1085

Moens, T. & Vincx, M. (1997). Observations on the feeding ecology of estuarine Nematodes. *J. Mar. Biol. Ass. UK.* **77** (1) pp211 - 227

Montagna, P.A., Blanchard, G.F. & Dinet, A. (1995). Effect of production and biomass of intertidal microphytobenthos on meiofaunal grazing rates. *J. Exp. Mar. Biol. Ecol.* **185** (2) pp149-165.

Moreira, F. (1994). Diet, prey size selection and intake rates of Black-Tailed Godwits *Limosa limosa* feeding on mudflats. *IBIS.* **136** (3) pp349-355.

Morris, A.W. (1983). *Practical Procedures for Estuarine Studies.* Institute for Marine Environmental Research, Plymouth.

Mumford, P.A. & Kerney, M.D.M. (1989). An outline of current requirements and techniques in environmental assessment. Chapter 50 In: (eds. R.A Falconer, P. Goodwin & R.G.S. Mathew) *Hydraulic and Environmental Modelling of Coastal, Estuarine and River Waters - Proceedings of the International Conference held at the University of Bradford 19-21 September 1989.* Pub: Gower Technical.

Nedwell, S.F. (1997) Intraspecific variation in the responses to copper by two estuarine invertebrates. Unpublished Ph.D. thesis. University of Hull.

Newell, R.C. (1965). The role of detritus in the nutrition of two marine deposit feeders, the prosobranch *Hydrobia ulvae* and the bivalve *Macoma balthica. Proc, Zool. Soc. Lond.*, **141**, 399-418

Nicol, J.A. (1958) Observations on the luminescence of *Pennatula phosphorea,* with a note on the luminescence of *Virgularia mirailis. J.mar.biol.Ass.U.K.* **37**, 551-563.

Olafsson, E.B., Peterson, C.H. & Ambrose, W.G. (1994). Does recruitment limitation structure populations and communities of macro-invertebrates in soft sediments: the relative significance of pre- and post-settlement processes. *Oceanography and Marine Biology: an Annual Review* **32**, 65-109.

Olive, P.J.W. (1978). Reproduction and annual gametogenic cycle in *Nephtys hombergi* and *N. caeca* (Polychaeta: Nephtyidae). *Marine Biology,* **46**, 83-90.

Olive, P.J.W., Garwood, P.R., Bentley, M.G. & Wright, N. (1981). Reproductive success, relative abundance and population structure of two species of *Nephtys* in an estuarine beach. *Marine Biology,* **63**, 189-196.

Open University, (1989) Oceanography Course Team Waves, tides and shallow-water processes. Milton Keynes, Open University.

Palmer, M.A. (1988). Dispersal of marine meiofauna: a review and conceptual model explaining passive transport and active emergence with implications for recruitment. *Mar. Ecol. Prog. Ser.* **48**, 81-91.

Parslow, J.L.F. (1973). Mercury in waders from the Wash. *Environmental Pollution*, **5**, 295-304.

Parthenaides, E. (1965). Erosion and deposition of cohesive soils. *Proc. Amer. Soc. Civil. Eng.* **91**, HY1, 105-39.

Paterson, D.M. (1989). Short-term changes in the erodibility of intertidal cohesive sediments related to the migratory behaviour of epipelic diatoms. *Limnology and Oceanography* **34**, 223-34

Pearce, F. (1998). Muddy waters - Pollution inspectors miss poisons hidden in sediment. *New Scientist* **158**.(2134). p22

Pearson, T.H. & Rosenberg, R. (1978). Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Oceanogr. Mar. Biol. Ann. Rev.,* 16, 229-311.

Pearson, T.H. & Stanley, S.O. (1979). Comparative measurement of the Redox potential of marine sediments as a rapid means of assessing the effect of organic pollution. *Marine Biology*, **53**, 371-380.

Pearson, T.H. & Eleftheriou, A. (1981). The benthic ecology of Sullum-Voe. *Proceedings of the Royal Society of Edinburgh.* **80 (1-4)**, 241-69.

Pearson, T.H. & Barnett, P.R. (1987). Long-term changes in benthic populations in some west European coastal areas. *Estuaries* **10 (3)**, 220-226.

Peletier, H. (1996). Long term changes in intertidal estuarine diatom assemblages related to reduced input of organic waste. *Mar. Ecol. Prog. Ser.* **137**, (1-3) 265-271.

Penning-Rowsell, E.C., Green, C.H., Thompson, P.M., Coker, M.A., Tunstall, S.M., Richards, C. & Parker, D.J. (1992*). The economics of coastal management - A manual of benefit assessment techniques.* Belhaven Press

Perkins, E.J. (1974). *The Biology of Estuaries and Coastal Waters*. Academic Press, London.

Petersen, C.G.J. (1913). Valuation of the sea. II. The animal communities of the sea bottom and their importance for marine zoogeography. *Report of the Danish Biological Station to the Board of Agriculture*, **25**, 62pp.

Peterson, C.H. (1991). Intertidal zonation of marine invertebrates in sand and mud. *American Scientist* 79, 236-249.

Pethick, J. (1984). *An introduction to coastal geomorphology*. London, Arnold.

Pienkowski, M.W. (1993). The impact of tourism on coastal breeding waders in western and southern Europe: an overview. *Wader Study Group Bull.* **68** (Special Issue).

Pihl, L. (1985). Food selection and consumption of mobile epibenthic fauna in shallow marine areas. *Mar. Ecol. Prog. Ser.* **22**: 169-179.

Pihl, L. (1990). Year-class strength regulation in plaice (*Pleuronectes platessa* L) on the Swedish west coast. *Hydrobiologia* 195: 79-88.

Piriou, J.Y., Menesguen, A. & Salomon, J.C. (1991). Les marees vertes a ulves conditions necessaires, evolution et comparaison de sites. In: (eds. M. Elliott & J.P. Ducrotoy) *Estuaries and coasts:- Spatial and temporal intercomparisons.* ECSA 19. Symposium.

Poiner, I.R. & Kennedy, R. (1984). Complex patterns of change in the macrobenthos of a large sandbank following dredging. *Marine Biology*. 78, 335-352.

Postma, H. (1967). Sediment transport and sedimentation in the estuarine environment. In: (ed. G. H. Lauff) *Estuaries*, Am. Ass. Advmt. Sci. Washington, D.C., Publ. No 83, 158-179

Prater, A.J. (1981). *Estuary birds of Britain and Ireland.* T. & A.D. Poyser, Berkhamsted.

Rasmussen, E. (1973). Systematics and ecology of the Isefjord marine fauna (Denmark). *Ophelia* **11**, 1-507.

Rees, E.I.S., Nicholaidou, a. & Laskaridou, P. (1977). The effects of storms on the dynamics of shallow water associations. In: (eds. B.F. Keegan et al) *Biology of benthic organisms.*

Rees, H.L., Moore, D.C., Pearson, T.H., Elliott, M., Service, M., Pomfret, J. & Johnson, D. (1990). Procedures for the monitoring of marine benthic communities at UK sewage sludge disposal sites. *Scottish Information Pamphlet* No. 18. Department of Agriculture and Fisheries for Scotland.

Rees, H.L., Rowlatt, S.M., Limpenny, D.S., Rees, E.I.S. & Rolfe, M.S. (1992). Benthic studies at dredged material disposal sites in Liverpool Bay. *Aquatic Environment Monitoring Report* No. 28. Directorate of Fisheries Research, Lowestoft.

Rees, I. & Foster Smith, B. (1998). Procedural guidelines for seabed mapping using acoustic ground discrimination interpreted with ground truthing. In: *Biological monitoring of marine Special Areas of Conservation: a handbook of methods for detecting change. Part 2. Procedural guidelines.* Peterborough, Joint Nature Conservation Committee.

Reichelt, A.C. (1991). Environmental effects of meiofaunal burrowing. In: (eds. P.S. Meadows & A. Meadows) The environmental impact of burrowing animals and animal burrows. *Symp. Zool. Soc. Lond.* **63** pp33-50. Clarendon Press, Oxford.

Rhoads, D.C. & Young, D.K. (1970). The influence of deposit feeding organisms on sediment stability and community trophic structure. *J. Mar. Res.* 28 pp150-178.

Rhoads, D.C (1974). Organism-sediment relations on the muddy sea floor *Oceanography and Marine Biology,* Annual Review, 12, 263-300.

Rhoads, D.C. & Boyer, L.F. (1982). The effects of marine benthos on physical properties of sediments. A successional perspective. In: (eds. P.L. McCall & M.J.S. Tevesz). *Topics in geobiology. Vol. 2. Animal-sediment relations. The biogenic alteration of sediments.* pp1-52. Plenum Press. New York.

Robertson, A.I. (1988). Decomposition of mangrove leaf litter in tropical Australia. *J. Exp. Mar. Bio. Ecol.* **116**, 235-247.

Rosenberg (1977). Effects of dredging operations on estuarine benthic macrofauna. *Mar. Poll. Bull.* **8 (5)** p102-104

Russell-Hunter, (1970). *Aquatic productivity - an introduction to some basic aspects of biological oceanography and limnology*

Salvat, B. (1964). Les conditions hydrodynamiques interstitielles de sediments meubles intertidaux et la repartition verticale de la fauna endogee. *C. R. Academie Sciences Paris* **259**, 1576-1579.

Sanders, H.L., (1958). Benthic studies in Buzzards Bay. 1. Animal sediment relationships. *Limnol. Oceanogr*. **5** p138-153.

Sanders, H.L., (1968). Marine benthic diversity: a comparative study. *Am. Natur*., **102** p243-282

Sanderson, W.G. (1996). *Rare marine benthic flora and fauna in Great Britain: the development of criteria for assessment.* JNCC (report no. 240). Peterborough.

Schwinghamer, P. (1981). Extraction of living meiofauna from marine sediments by centrifugation in a silica sol-sorbitol mixture. *Canadian Journal of Fisheries and Aquatic Sciences*. **38**, 476-478.

Scott, C.R., Hemingway, K.L., Elliott, M., de Jonge, V.N., Pethick, J.S., Malcolm, S. & Wilkinson, M. (1997) Impact of Nutrients in Estuaries - Phase 2. Report to the Environment Agency & English Nature. Cambridge Coastal Research Unit, University of Cambridge.

Service, M. (1998). Procedural guidelines of in situ survey of sublittoral epibiota using towed sledge video and still photography. In: *Biological monitoring of Marine Special Areas of Conservation: a handbook of methods for detecting change. Part 2. Procedural guidelines.* Peterborough, Joint Nature Conservation Committee.

Sherman, K.M. & Coull, B.C. (1980). The response of meiofauna to sediment disturbance. *Journal of Experimental Marine Biology and Ecology* **46**, p59-71

Simpson, M.A. (1997). An investigation into the causes, effects and implications of the growth of the green macroalga *Enteromorpha* spp. On Seal Sands, Teesmouth. Unpublished M.Sc. dissertation, University of Hull.

Smit, C.J. & Visser, G.J.M. (1993). Effects of disturbance on shorebirds: a summary of existing knowledge from the Dutch Wadden Sea and Delta area. *Wader Study Group Bull.* 68 (Special Issue)

Snelgrove, P.V. & Butman, C.A. (1994). Animal-sediment relationships revisited: Cause versus effect. *Oceanog. Mar. Biol. Ann. Rev.* 32 p111-177

SOAFD (1996). *Monitoring and assessment of the marine benthos at UK dredged material disposal sites.* Scot. Fish. Inf. Pamph. No. 21, Aberdeen, ISSN 0309 9105 (3rd report of the Biology Task-team, GCSDM/MPMMG/DOE).

Somerfield, P.J., Gee, J.M. & Warwick, R.M. (1994). Soft sedimental meiofaunal community structure in relation to a long term heavy metal gradient in the Fal estuary system. *Mar. Ecol. Prog. Ser*. **105** (1-2) 79-88.

Stephenson, W.S.D., Cook, S.D. & Newlands, S.J. (1978). The macrobenthos of the middle banks area of Moreton bay. *Mem. Qd Mus.* **18**, 185-212.

Strickland, J.D.H. & Parsons, T.R. (1972). 2nd edition. A practical handbook of seawater analysis. *Fish. Res. Bd. Can. Bulletin* **167**, Ottawa, pp.311

Swart, D.H. (1983). Physical aspects of sandy beaches - a review. In: (eds. A. McLachlan & T. Erasmus) *Sandy beaches as ecosystems*. The Hague, The Netherlands: Junk. 5-44.

Tait, R.V. & Dipper, F.A. (1998). *Elements of Marine Ecology*. Fourth edition. Reed Elsevier plc group.

Taylor Smith, D & Li, W.N. (1966). Echo-sounding and sea-floor sediments, *Mar. Geol.* **4**, 353-64.

Thomas, M.L. (1986). A physically derived exposure index for marine shorelines. *Ophelia*, 25 (1) 1-13

Thomas, N.S. (1998). Procedural guidelines for quantitative sampling of sublittoral sediment biotopes and species using remote-operated grabs. In: *Biological monitoring of Marine Special Areas of Conservation: a handbook of methods for detecting change. Part 2. Procedural guidelines*. Peterborough, Joint Nature Conservation Committee.

Thorson, G. (1957). Bottom communities (sublittoral or shallow shelf). *Geological Society of America Memoir* **67**, p461-534.

Thrush, S.F., Pridmore, R.D. & Hewitt, J.E. (1994). Impacts on soft-sediment macrofauna: The effects of spatial variation on temporal trends. *Applied Ecology*. **4** p41

Trimmer, M., Nedwell, D.B, Sivyer, D.B. & Malcolm, S.J. (1998) Nitrogen fluxes through the lower estuary of the river Great Ouse, England: the role of the bottom sediments. *Mar. Ecol. Prog. Ser.* **163** p109-124

Trueman & Ansell (1969). The mechanism of burrowing into soft substrate by marine animals. *Oceanogr. Mar. Biol. Ann. Rev.* **7** p315-366

Tyler, P.A. & Banner, F.T. (1979) The effect of coastal hydrodynamics on the echinoderm distribution in the sublittoral of Oxwich bay, Bristol Channel. *Estuarine and Coastal Marine Science* 5, p293-308.

Underwood, G.J.C. & Paterson, D.M. (1993). Seasonal changes in diatom biomass, sediment stability and biogenic stabilization in the Severn Estuary. *J. Mar. Biol. Ass. U.K.*, 871-887.

Vanosmael, C., Willems, K.A., Claeys, D., Vincx, M. & Heip, C., (1982). Macrobenthos of a sublittoral sandbank in the Southern Bight of the North Sea. *J. Mar. Biol. Ass. U.K.*. **62** p521-534.

Warwick, R.M. & Davies. (1977). The distribution of sublittoral macrofauna communities in the Bristol Channel in relation to the substrate. *Estuarine and Coastal Marine Science*. **5**, 267-288.

Warwick, R.M. & Clarke, K.R. (1994). *Change in marine communities: An approach to statistical analysis and interpretation.* Plymouth Marine Lab.

Whitehouse, U.G., Jeffrey, L.M. & Debbrecht, J.D. (1960). Differential settling tendencies of clay minerals in saline waters. *Proc. 7th Conf. Clays, Clay Min.* 1-79.

Willems, K.A., Vincx, M., Claeys, D., Vanosmael, C. & Heip, C., (1982). Meiobenthos of a sublittoral sandbank in the southern bight of the North Sea. *J. Mar. Biol. Ass. U.K.*. **62** p535-548.

Willems, K.A., Vanosmael,C., Claeys, D., Vincx,M. & Heip, C. (1982a). Benthos of a sublittoral sandbank in the southern bight of the North Sea: General considerations. *J. Mar. Biol. Ass. U.K.*. 62 p549-557.

Wolff, W.J. (1973). The estuary as a habitat. An analysis of data on the soft-bottom macrofauna of the estuarine area of the Rivers Rhine, Meuse and Scheldt. *Zoologische Verhandelingen*, **126** p242

Wood, E.M. (1987). *Subtidal Ecology*. Edward Arnold, London.

Woodin, S.A. (1976). Adult-larval interactions in dense infaunal assemblages: Patterns of abundance. *J. Mar. Res.* **34 (1)** p25-41

Wright, J.F., Armitage, P.D., Furse, M.T. & Moss, D. (1989). Prediction of invertebrate communities using stream measurements. *Regulated Rivers: Research and Management*, **4**: 147-155.

Zwarts, L. & Drent, R.H. (1981). Prey depletion and the regulation of predator density: Oystercatchers (Haematopus ostralegus) feeding on mussels (Mytilus ed.). In: (eds. N.V. Jones & W.J. Wolff) *Feeding and survival strategies of estuarine organisms. Marine Science* **15**. Plenum Press.

APPENDIX I

The biotope complexes covered by this report fall within the Annex I habitats defined under the European Directive. This Appendix gives the definitions of those habitats.

Biotope Complex: Intertidal Mudflats and Sandflats - 'Mudflats and sandflats not covered by seawater at low tide'

In the context of the Habitats Directive Annex I (code 14) classification, this biotope complex is included in the habitat defined as '**Mudflats and sandflats not covered by seawater at low tide**' - *sands and muds of the coasts, their connected seas and associated lagoons, not covered by sea water at low tide, devoid of vascular plants, usually coated by blue/green algae and diatoms.*

Biotope Complex: Subtidal Mobile Sandbanks - 'Sandbanks which are slightly covered by sea water all the time'

In the context of the Habitats Directive Annex I (code 11.25) classification, this biotope complex will be included in the broad category habitat of '**Sandbanks which are slightly covered by sea water all the time**' - *sublittoral sandbanks, permanently submerged, with water depth seldom more than 20m below Chart Datum and including non-vegetated sandbanks or sandbanks with vegetation belonging to the Zosteretum marinae and Cymodeceion nodosae.*

Estuaries

The EU Manual definition of estuaries is that *they are the downstream part of a river valley, subject to the tide and extending from the limit of brackish waters. River estuaries are coastal inlets where, unlike 'large shallow inlets and bays' there is generally a substantial freshwater influence. The mixing of freshwater and sea water and the reduced current flows in the shelter of the estuary lead to deposition of fine sediments, often forming extensive intertidal sand and mud flats. Where the tidal currents are faster than flood tides, most sediments deposit to form a delta at the mouth of the estuary.*

Large shallow inlets and bays

These are indicated by the EU Manual definition *as large indentations of the coast where, in contrast to estuaries, the influence of freshwater is generally limited. These shallow indentations are generally sheltered from wave action and contain a great diversity of sediments and substrata with a well developed zonation of benthic communities. These communities generally have a high biodiversity. The limit of shallow water is sometimes defined by the distribution of the Zosteretea and Potametea associations. Several physiographic types may be included under this category providing that the water is shallow over a major part of the area: embayments, fjords, rias and voes*

APPENDIX II

Table 1.0. Biotopes typical of intertidal mud and sandflats.

Biotope definition and code	**Environmental Characteristics**	**Characterising species**
Hediste (Nereis) diversicolor and *Macoma balthica* in sandy mud shores (**LMU.HedMac**) Subtypes of this biotope are: **LMU.HedMac.Are** - least sheltered, abundant *Arenicola marina* and frequent *Cerastoderma edule;* **LMU.HedMac.Pyg** - contains less *A. marina;* **LMU.HedMac.Mare** - contains *Mya arenaria* in high densities	Full-Variable salinity Sheltered, Very sheltered, Extremely sheltered Sandy mud-Mud Eulittoral Mid shore, Lower shore Anoxic layer present	• Polychaetes, typically *Hediste (Nereis) diversicolor* • Other smaller polychaetes include *Eteone longa and Nephtys hombergii, Tharyx marioni, Pygospio elegans, Arenicola marina* and *Manayunkia aestuarina.* •Oligochaete worms include *Tubificoides* spp. •Amphipod, *Corophium volutator* •Mud snail, *Hydrobia ulvae* •Bivalves include *Macoma balthica* •Green algae, e.g. *Enteromorpha*
Hediste diversicolor and *Scrobicularia plana* in reduced salinity mud shores (**LMU.HedScr**)	Variable-Reduced/Low salinity Sheltered, Very sheltered, Extremely sheltered Mud-Sandy mud Eulittoral Upper shore, Mid shore, Lower shore Anoxic layer present	•Hediste (*Nereis) diversicolor* and the bivalve *Scrobicularia plana* are abundant •Other polychaetes include *Eteone longa* •Oligochaete, *Tubificoides benedeni* •Isopod, *Cyathura carinata* •Other bivalves include *Macoma balthica* and *Cerastoderma edule*
Hediste (Nereis) diversicolor and *Streblospio shrubsolii* in sandy mud or soft mud shores (**LMU.HedStr**)	Variable-Low salinity Very sheltered-Extremely sheltered Mud-Sandy mud Eulittoral Mid shore, Lower shore Black, possibly nutrient enriched	•*Streblospio shrubsolii, Tharyx killariensis* and *Manayunkia aestuarina* •*Hediste (Nereis) diversicolor, Nephtys hombergii, Pygospio elegans* •*Corophium volutator, Hydrobia ulvae, Macoma balthica* and *Abra tenuis* •*Tubificoides* spp.

Hediste (Nereis) diversicolor and oligochaetes in low salinity mud shores (**LMU.HedOl**)	Reduced-Low salinity Extremely sheltered Mud-Sandy mud Littoral fringe, Eulittoral Upper shore, Mid shore, Lower shore	•Oligochaetes, including *Tubificoides* spp. and *Hediste (Nereis) diversicolor* are abundant •*Corophium volutator* •Reduced polychaetes and absence of bivalves
Barren coarse sands (**LGS.BarSnd**)	Full salinity Exposed-mod. Exposed Coarse-medium sand Supralittoral, Eulittoral Strandline, Upper shore, Mid shore, Lower shore	•Sparse macrofauna •Low abundances of burrowing amphipods *Bathyporeia* spp. or *Pontocrates* spp. and *Eurydice pulchra*
Burrowing amphipods and *Eurydice pulchra* in well drained clean sand shores (**LGS.AEur)**	Full salinity Exposed-Moderately exposed Medium sand Eulittoral Upper shore, Mid shore, Lower shore	•Burrowing amphipods •*Eurydice pulchra* •Impoverished polychaetes only *Scolelepis squamata*
Burrowing amphipods and polychaetes in clean sand shores (**LGS.AP**) Sub biotopes are (**LGS.AP.P**.) and (**LGS.AP.Pon**), depending on the amphipod to polychaete ratio	Full salinity Exposed, Mod. Exposed, Sheltered Medium-Fine sand Eulittoral Mid shore, Lower shore	•Burrowing amphipods and polychaetes includes *Pontocrates* and *Bathyporeia* spp. and *Nephtys cirrosa, Scolelepis squamata, Paraonis fulgens* and *Arenicola marina.* •Occasional bivalves e.g. *Angulus tenuis* •Isopod, *Eurydice pulchra*
Dense *Lanice conchilega* in tide-swept lower shore sand (**LGS.Lan**)	Full-variable salinity Moderately exposed Sheltered, Very sheltered Strong-Moderately strong tidal streams Medium sand-fine sand Eulittoral Mid shore, Lower shore	•Dense populations of *Lanice conchilega* •Other polychaetes include *Nephtys cirrus, Nephtys hombergii* and *Pygospio elegans* •Few crustaceans •Bivalve cockles, *Cerastoderma edule*

Bathyporeia pilosa and *Corophium* spp. in upper shore slightly muddy fine sand shores (**LMS.BatCor**)	Variable salinity Mod. exposed, Sheltered, Very sheltered Muddy fine sand Eulittoral Upper shore, Mid shore	•Amphipods, *Bathyporeia pilosa, Corophium arenarium* and *Corophium volutator* •Polychaetes and bivalves (with the exception of *Macoma balthica*) are limited in their abundance and variety.
Polychaetes and *Cerastoderma edule* in fine sand or muddy and shores (**LMS.PCer**)	Full salinity Moderately exposed-Sheltered Fine sand or muddy sand Eulittoral Mid shore, Lower shore	•*Cerastoderma edule* and other bivalves •Reduced amphipod populations, *Bathyporeia sarsi* •Polychaetes, *Nephtys hombergii, Scoloplos armiger, Pygospio elegans, Spio filicornis* and *Capitella capitata* •Oligochaetes
Macoma balthica and *Arenicola marina* in muddy sand shores (**LMS.MacAre**)	Full-Variable salinity Mod.exposed, Sheltered, Very sheltered, Extremely sheltered Fine sand or muddy sand Eulittoral Upper shore, Mid shore, Lower shore Anoxic layer present	•*Arenicola marina* and *Scoloplos armiger* •*Macoma balthica* and *Cerastoderma edule* •*Corophium volutator* can be common

Table 1.1. Biotopes typical of subtidal mobile sandbanks

Biotope definition and code	**Environmental Characteristics**	**Characterising species**
Sparse fauna in infralittoral mobile clean sand (**IGS.Mob**)	Full salinity Very exposed- Exposed Moderately strong-weak tidal stream Coarse sand Infralittoral 0-10m depth range	•Sparse infauna •Opportunistic amphipods •Sandeel *Ammodytes* spp. •Epifauna e.g. *Asterias rubens*

Nephtys cirrosa and *Bathyporeia* spp. in infralittoral sand (**IGS.NcirBat**)	Full salinity Very exposed-Sheltered Strong-weak tidal stream Medium-fine sand Infralittoral 0-30m depth range	•*Nephtys cirrosa* •*Bathyporeia* spp. •*Pontocrates* spp. (occasionally) • Sandeel *Ammodytes* spp.
Dense *Lanice conchilega* and other polychaetes in tide swept infralittoral sand (**IGS.Lcon**)	Full salinity Sheltered-extremely sheltered Strong-moderately strong tidal stream Coarse sand Infralittoral 0-20m	•*Lanice conchilega* •*Scoloplos conchilega* •*Chaetozone setosa* •*Arenicola marina*
Fabulina fabula and *Magelona mirabilis* with venerid bivalves in infralittoral compacted fine sand (**IGS.FabMag**)	Full salinity Moderately exposed-sheltered Weak tidal streams Stable fine sands Infralittoral 0-30m depth	•*Fabulina fabula* •*Magelona mirabilis* •*Ensis* spp. •Less stable community (IGS.Sell) *Spisula elliptica*
Nephtys cirrosa and fluctuating salinity-tolerant fauna in reduced salinity infralittoral mobile sand (**IGS.Ncir**)	Reduced/low salinity Moderately exposed-sheltered Strong-moderately strong tidal stream Sand (medium fine) Infralittoral 0-10m	•*Nephtys cirrosa* •*Scoloplos armiger* •*Bathyporeia* spp.
Neomysis integer and *Gammarus* spp. in low salinity infralittoral mobile sand (**IGS.NeoGam**)	Reduced-low salinity Very sheltered-extm.sheltered Strong-mod.strong Sand Infralittoral 0-10m Fluctuating low salinity: high biochemical oxygen demand	•*Neomysis integer* •*Gammarus* spp.

Sparse fauna in reduced salinity infralittoral mobile sand (**IGSMobRS**)	Reduced/low salinity Sheltered-extremely sheltered Very strong-moderately strong tidal stream Very fine sand Infralittoral 0-10m	•Sparse fauna •*Bathyporeia* spp. •*Haustorius arenarius*

APPENDIX III

This Appendix details particular and illustrative features of the methods of monitoring characteristics of the biotope complexes. Further details can be found in the references cited within the Appendix or within the main body of text of Chapter VI.

1. MONITORING OF ENVIRONMENTAL ATTRIBUTES

1.1 Substratum

a. Sampling methods

i. Intertidal sediments

For sediment analysis the size of the sample is not of great importance as long as sufficient material is collected for analysis. A core of approximately 8cm diameter is generally sufficient and at least the top 2 cm of sediment will be representative for analysis of the physico-chemical characteristics. In sediments that are inhomogenous sub-samples may be taken which can be pooled and thoroughly homogenised. Core samples allow an undisturbed sample to be taken and this allows an inspection of the sediment structure. This may be important if for example if the substratum is characterised by a layer of silt overlying coarser sandy material. Information on other features such as the depth of the anoxic layer should also be noted.

ii. Subtidal sandbanks

Subtidal monitoring of the substratum will require the use of large box corers if possible, as they take an undisturbed sample of sediment from which cores can be taken in a similar fashion to that used in intertidal areas. The other possibility is the use of grabs e.g. Day or Van Veen grab (Rees *et al*, 1990). The grab should take a sample such that disturbance to the sediment structure is minimised and samples which have low quantities of sediment or have lost sediment in transit are rejected. The use of Flow-through corers, e.g. the Craib corer, will prevent surface material being removed by any bow-wave created by the largest sampling devices. A small corer can be used to take the sediment sample and detailed methodologies for sampling subtidal areas are given in Kramer *et al* (1994) and Holme and McIntyre (1984). Subtidal sandbanks can be heterogeneous and remote operated video (ROV) equipment is useful to visually inspect the nature of the substratum as described above. If sediment samples are collected during biological sampling it is more reliable to take the samples from each biological sample rather than from a separate grab. However, a strict methodology for subsampling the grab must be employed to ensure that the biological sample is uniformly affected.

The use of grabs or corers to sample subtidal areas is somewhat limited and, as mentioned, ROV equipment can greatly enhance the coverage and knowledge of areas where turbidity is not a problem. Other tools include acoustic ground discrimination equipment (Hiscock, 1998b) as described above e.g. RoxAnn^{TM} or side scan sonar. Ground-truthing should be carried out by grab sampling. This is probably the most effective means at present to gain sufficient coverage of offshore areas and these methods are extremely useful in initial site characterisation of the substratum and consequent monitoring of change.

b. Particle analysis and distribution

Particle size analysis can be carried out by several methods. These are dry sieving (Buchanan, 1984), pipette analysis, Coulter counter analysis, and laser granulometry techniques. Laser and pipette/sieve techniques tend to be the most widely used; the former are quick and accurate but costly. In addition, laser techniques cannot however analyse coarser (>2mm) material so are limited to areas of fine sands and silts e.g. intertidal mud and sand flats. Coarser sediments, as often found on more exposed beaches and on offshore sandbanks in areas of higher currents, will require dry sieving which is a time consuming process although it is possible to split samples and use laser techniques on the finer material.

Results of particle size analysis should be shown graphically as percentage per size class and features such as bimodality of sediments noted. Summary statistics e.g. Mean/median grain size, sorting coefficient, skewness and % silt, sand and gravel should also be calculated. Sediment trigons may also be constructed based on the quantity of silt, sand and gravel from which samples can be classified, for example,. sand, muddy sand and muddy gravel. Details of the derivation of these and other parameters are given in Dyer (1979) and Buchanan (1984). These summary statistics provide an easily interpretable analysis of the nature of the substratum although it must be remembered that traditional methods of sedimentary petrography do not take into account the structure of the sediment and in fact tend to destroy aggregated material to allow total dispersion.

Other features which may be examined include porosity which will relate to the water content of the sediment. This is a difficult property to measure with accuracy but is of importance on intertidal mud and sand flats and will influence the abundance of meiofauna. Porosity can be measured gravimetrically (Holme & McIntyre, 1984) and by sonograph interpretation (Taylor *et al*, 1966). This feature will also be related to the other characteristics of the sediment such as grain size and sorting and due to the difficulties in obtaining an accurate value it is not often measured. Qualitative estimates of the porosity or water content of the intertidal areas may be just as useful.

c. Organic content

The organic content of the samples should be analysed. Several methods exist and these are described by Dyer (1979), Holme & McIntyre (1984) and Kramer *et al* (1994). The most common technique is by loss on ignition (LOI) at 600°C but other techniques e.g. by CHN analyser can be used to determine levels of organic carbon and nitrogen and derive C/N ratios. Chlorophyll levels (as an indicator of phytoplankton biomass) measured by spectrophotometric or fluorimetric techniques and particulate organic phosphorous measured by wet digestion and spectrophotometric analysis can also be measured. The quantity of organic matter is particularly important in determining the food availability for benthic communities and increased organic enrichment can lead to a deterioration in the health of the benthic population (Pearson & Rosenburg, 1978). This parameter is particularly important in intertidal mudflats. In areas of coarser material e.g. subtidal sandbanks, levels of organic material may be of less importance where levels are very low.

d. Redox potential

Measurements of the redox potential of the sediment can be done using hand held redox probes either directly into the sediment intertidally or into the contents of the grab subtidally if the sediment is relatively undisturbed. Details of determining the redox potential are given by Morris (1983), and Pearson & Stanley (1979). This parameter is useful in identifying the electrochemical regime of the sediment, oxygenation of the sediment and assessing levels of organic enrichment. High levels of microbial activity may be expected in reducing sediments though this should if necessary be determined using more specialised methods e.g. by C14 tracing (Strickland & Parsons, 1972; Dyer, 1979). The redox potential is of more use in intertidal silts than in well oxygenated substrata such as well sorted sands.

e. Trace metal and other persistent contaminants determination

An extensive literature exists on this topic and is considered outside the scope of this review. For example, if it is suspected that the areas to be studied may be subject to influxes of particulate trace metals particularly in finer substratum such as intertidal mudflats. Sediment samples can be totally or partially digested with acid followed by instrumental analysis, Kramer *et al* (1994) provides detailed methodologies. It should be emphasised that contamination should be kept to a minimum with no metal components used in sampling. If metallic equipment is used e.g. when grab sampling then stainless steel grabs should be used and the sample taken from the centre of the grab away from contact with the grab.

Other contaminants which can be measured from sediments include particulate polycyclic aromatic hydrocarbons (PAHs) measured by fluorescence and UV absorption or gas chromatography, particulate polychlorobiphenyls (PCBs) measured by gas chromatography with mass-spectrometric detection. Precise details of the sampling and analysis are not given in the present report but details are given in Kramer *et al* (1994) and it is of paramount importance with these techniques that contamination is avoided.

1.2 Hydrological Regime

If necessary measurements of current strength/direction, residual flow circulation patterns etc. can be determined with simple drifters or drogues at surface and depth. Eulerian techniques can also be employed using direct reading current meters or recording current meters if long term measurements are necessary. If a SAC may be affected by a potential discharge dye tracer techniques e.g. with Rhodamine B dye may also be utilised to track the direction and extent of the dispersal of the effluent. These techniques utilise fluorimeters e.g. the Chelsea systems Aquapack to measure the concentration of dye. This equipment can be towed either at surface or as a series of transects at various depths depending on the buoyancy of the effluent. A known quantity of the dye should be mixed with saline or fresh water to obtain the correct density and deployed at the depth at which the effluent will be released either directly from a boat or via the discharge installation. Several deployments should be made so that dispersion can be monitored at slack, ebb and flood conditions. Positional data from DGPS can also be linked to output from the fluorimeter and the results logged onto a PC for further processing.

The results of current data profiles and dye tracking may be used with recent computer software to describe circulation patterns, dispersion and to derive peak stress and tidally averaged stress levels on the sea bed. Detailed methodologies for this type of survey are given by Morris (1983) and Dyer (1979). Areas of subtidal sand banks are often subject to considerable stress from tidal currents and this is one of the most important factors controlling the sedimentary and biological environment (Warwick & Davies, 1977) and a detailed knowledge of natural patterns in tidal dynamics is essential in differentiating between natural fluctuations and severe disturbance.

Salinity temperature depth probes can be employed where data are unavailable in order to monitor long term changes in these variables. Turbidity levels should be monitored preferably with transmitometers or nephelometers (McCave, 1979) to assess changes in levels of suspended sediment. The equipment used to for dye tracing mentioned above can often measure a whole suite of parameters simultaneously (for example, temperature, salinity, depth, turbidity, chlorophyll, dissolved oxygen and pH) and can be towed to provide a continuous set of data across an area or deployed throughout the water column at specified sites. Many survey vessels e.g. those employed by the Environment Agency have continuous recording equipment for these parameters. This equipment could be employed whilst carrying out routine monitoring of the subtidal communities as required. Other parameters e.g. dissolved metals, inorganic and organic nutrients etc should be measured when necessary. This will normally involve the use of specialised water samplers which allow water samples to be taken at specified depths without contamination from other parts of the water column. The laboratory procedures required for the analysis of these parameters are complex and details are given in Kramer *et al* (1994).

2. MONITORING OF BIOLOGICAL ATTRIBUTES

2.1 Macrofauna

a. Intertidal mud and sandflats

i. Sediment cores

On intertidal areas core samples using a 0.01m² corer can be used to take quantitative samples of the sediment. Generally five replicates are recommended for statistical analysis. Samples should be taken up to 5m either side of the site location but not up or down the shore. Each sample should be placed in a sealable plastic bag which is clearly labelled with a waterproof marker. The samples should be washed through a 0.5mm mesh within 24 hours and fixed in a 10% buffered saline formalin solution for storage after which the samples can be sorted aided by an illuminated magnifier or low power binocular microscope and the animals identified with high power compound microscopes and up to date taxonomic literature. In coarser sediments an additional five $0.01m^2$ cores or three $0.1m^2$ box cores should be taken depending on the level of silt present. If data is to be collected on the abundance of specific species then prior knowledge on the density and aggregation of the species is necessary to determine the number of samples required. Additional information on the condition of the sediment, anoxic layer and surficial features should be noted. A $1m^2$quadrat should also be used at the site to record numbers of worm casts and algal cover and the area dug over to within 20-30 cm depth to record larger species. $1m^2$ quadrats can also be used as part of an ACE survey to determine abundance scales of conspicuous species and epifauna noted over a $10m^2$ area followed by site photographs. Species which cannot be identified in the field can be taken for subsequent identification. Information should be noted on an MNCR recording form. Site positions can be recorded using shore transit mark or DGPS as appropriate.

ii. Remote sampling

This technique generally involves all equipment lowered from a boat to take a quantitative sample of the sediment. Samples are taken by grabs e.g. the Van Veen or Day grab. Other equipment includes the Reineck box corer, Knudsen corer (particularly in softer sediments), Hamon or Shipek grabs (in coarser sediments) and Forster anchor dredge (for semi quantitative sampling of mobile megafauna). Site conditions, size of vessel and previous experience will dictate which equipment is most suitable. Details on these and other models are given in Holme (1971). Samples are generally $0.1m^2$ and sieved through 0.5 or 1mm mesh depending on substratum and between five and ten replicates should be taken. Notes on the sediment sample should be taken backed up by photographs if possible. For Day and Van veen grabs samples should be at least 7 cm deep in finer sediments and 5cm in sands. After sieving samples should be fixed in a 10% saline formalin solution. Site positions should be recorded by DGPS.

b. Subtidal mobile sandbanks

i. Towed and remote operated video

The cameras are generally mounted at 45 degrees with video lights and flash strobes pointed vertically downwards. With ROV systems the cameras are mounted on a submersible vehicle which is controlled by a surface operator via an umbilical cable. Towed systems require a vessel which can maintain steerage at low speeds of around 1 to 1.5 knots and the water depth needs to be monitored and the length of cable checked accordingly.

Both systems usually operate along predefined transects along which the seabed characteristics are recorded and the benthic animals counted, still photographs may be taken of interesting features. With towed systems the ships DGPS can give the precise location of the equipment but this is more problematical with remote systems though in some areas it is possible to lay a marked transect line onto the seabed with marker buoys at the surface. ROV systems are hampered by having to remain within a certain radius of the ship but have the advantage that they may hover over a particular area or retrace its path and avoid obstructions, some models can also take benthic samples.

The recording of animals with towed systems usually involve time series counts by which the length of video recording is broken into segments of equal times and either the presence of animals in each segment noted (rapid visual count) or the total number of animals counted (visual fast count). ROV systems may also operate in this fashion or if reliable knowledge on the size of the video frame and a straight transect is possible (allowing the total distance travelled to be calculated) then the number of target species in a known area can be calculated. Problems in the quantification of animals with ROVs may arise because the ROV may not always be a fixed distance from the substratum so the field of view may change.

ii. Acoustic survey

The underlying principle behind these methods is based on the fact that acoustic energy is reflected off the sea floor and the amount of reflection depends on the density of the bed material and the angle of incidence at which the acoustic waves meet the sea floor. It should be remembered that these systems measure the acoustic properties of the sea bed not other properties such as grain size although these are related. The most widely used system available is the RoxAnn® system. This utilises commercial echosounders set at frequencies of 200 KHz in waters shallower than 60m or in deeper waters frequencies of 50-120 KHz. The first and second echoes (E1 and E2) are used with E1 used as a measure of roughness i.e. topographic irregularities and E2 as a measure of hardness which is related to substratum type.

Transects across the study area are made at moderate speeds with the data logged as an average over a set time e.g. 5-10 seconds. The two parameters are plotted against each other to derive sediment type and this information together with depth and positional information from DGPS allow a 3 dimensional representation of the seabed to built up and the main substratum types determined. The differences in acoustic properties of the sea floor are related to factors such as grain size which is itself an important factor in determining benthic communities and as such these methods can give an idea of biotope. The benthos itself affects the substratum e.g. through bioturbation, tube building etc so the system can also detect biological features such as *Modiolus* beds, seagrass, *Nephrops* burrows, *Sabellaria* reefs etc. The information gathered from these systems needs to be ground-truthed either by grab sample or towed or remote operated video and post processing of the data may be required to recalibrate the system to get the most accurate representation. Successful studies of candidate SACs have been made using RoxAnn™ e.g. Strangford Lough (Magorrian *et al*, 1995).

The advantages of systems such as RoxAnn™ is that they can map extremely large areas of substratum fairly quickly with no depth constraints in coastal areas. Other factors such as turbidity are unimportant. With accurate ground-truthing a much more representative idea of the main substratum types in a SAC can be gained than from spot grab samples and the information can be used stratify other direct sampling regimes for an area and reduce the cost and time spent undertaking these surveys. At large areas acoustic methods are probably the only way to effectively map the main biotope complexes. However the system is an indirect representation of the substratum and detailed ground-truthing is required as no direct information is produced on the sediment type or of the detailed composition of the community. The equipment is also expensive an needs a skilled operator to derive accurate results. Care should be taken not to interpret the data at too higher a level of precision as the results may be misleading and the differences between the echosounders and frequencies used may mean that results from different surveys may not be entirely comparable.

2.2 Birds

WeBS counts are probably the most effective method. Current WeBS counts are carried out by volunteers and cover the majority of UK wetland sites including estuaries and some open coastal areas. A very large dataset over the last 30 years has been built up for many areas so there is a large amount of existing data available. These counts can be made on a monthly or yearly basis (in the winter) depending on the size of the area, although in extremely large areas e.g. the Wash it may not be possible for financial reasons to sample this regularly.

Bird counts on the intertidal areas are made around high water (usually ± 2 hours depending on location) with the area divided into sectors and counted separately. These counts give a good indication of usage in general and counting is easy as the birds are pushed to the top of the shore. High water counts are also inexpensive. However depending on the topography of the site and tidal conditions birds can be pushed off sites into different areas at high water and give misleading usage. Low water counts may be used in smaller areas and these give a good indication of preferred feeding areas on the flats not just general usage and identifies which species are using the site as predators rather than roosting. However there is a shorter historical dataset and the method is difficult over large areas. Goss Custard (1985) showed that there was often a good correlation between high and low water counts although this is not true in all areas. In large areas remote sensing techniques although costly can provide useful information on habitat usage and may give initial information on the changes in feeding distribution reflecting changes in sediment type.

2.3 Fish

A quantitative survey of the juvenile fish populations using the intertidal areas can be carried out with push nets. Small beam trawls should also be made of the subtidal sand banks whilst minimising any damage to the epibenthic population. The beam trawl will usually be around 2m diameter with tickler chains across the front of the net to disturb fish buried in the substratum. Transects of around 20 minute duration can be made with positions fixed by DGPS. Demersal fish are rarely evenly distributed throughout an area so a random sampling method is usually applicable. With beam trawls it is fairly easy to calculate the absolute abundance per area using the width of the trawl and the distance trawled to determine the area trawled, a catchability component may also be included.

Seasonal components should be taken into account in the sampling strategy and analysis of production and age classes (cohort analysis) carried out. Analysis of the stomach content of the fish population may also prove useful and may dispense with the need to sample the infauna.

3. CHARACTERISATION OF THE BIOTOPES.

A thorough baseline survey should be carried out particularly where existing information is scarce. In intertidal areas ACE studies will be useful in characterising the biotopes particularly in large areas where time and cost considerations may preclude a full quantitative survey. However localised core samples should also be taken at representative sites usually on transects down the shore to give a more detailed representation of the community and allow statistical analysis of the areas SACs and determine levels of change. Bird surveys (WeBS counts) may also be necessary in some areas. Subtidally grab samples in the habitats defined by acoustic survey or by reference to bathymetric charts. Towed or remote operated video and epibenthic tows may also be employed where appropriate.

The high costs and labour intensive nature of remote sampling (and video work) should be taken into account and the number of samples and replicates taken will reflect this. Information from existing data, remote sensing, acoustic surveys, bathymetric charts will be useful to determine the location of monitoring sites and a stratified random sampling strategy for quantitative sampling of the fauna will usually be employed on the basis of this information. It may be necessary to store some samples to reduce laboratory analysis which can be examined at a later date if necessary. A full account of survey design for remote sampling is given in Hiscock (1998a), Baker & Wolff (1987), Holmes & McIntyre (1984) and Rees *et al* (1990).

It is recommended that sediment samples should be taken at all sites for particle size analysis, other parameters such as organic content, redox potential etc is also recommended and in specific cases other information such as measurements of hydrocarbons, trace metals etc may also be necessary. Where possible the biological communities should be classified according to the MNCR biotope classification system although it is understood that the MNCR system is not complete particularly in subtidal sediments. Multivariate analysis of the data with techniques such as MDS, TWINSPAN etc will also be useful in classifying communities and relating them to the environmental conditions. Input of data into GIS systems is also encouraged.

4. MONITORING CHANGE

In general terms as mentioned above the macro infauna will provide the best indicator to the health of the systems. Reference to baseline data should be made to define a set of stations for routine monitoring the numbers of which will be dictated by financial and time considerations. In intertidal areas core samples on transects taken down the intertidal zone should be taken. There is no clearly defined time of year for sampling as summer months which provide ample daylight and amenable weather conditions are subject to ephemeral populations of invertebrates and recruitment of juveniles. Established winter populations may fluctuate due to storm events, heavy rainfall and freezing, the limited hours of daylight is also a problem.

If samples are to be compared over time it is important that the sample time must not vary from year to year and major weather events noted (Dalkin & Barnett, 1998). Subtidally at representative stations grab sampling should be undertaken. In areas where the epifaunal component is important use of trawls and towed or remote operated video along set transects may be necessary. Subtidally the time of sampling is best carried out around May as weather conditions are generally best from May to September and recruitment generally occurs from February to May (Thomas, 1998). However weather conditions may preclude this but it is important that samples are taken at as close to the same time of year as possible.

The high cost of benthic sampling may mean that it is more practical to only work up a reduced number of replicates or stations with the remainder being carried out to allow full statistical analysis if some change is evident.

The frequency of monitoring will be largely determined by financial and time constraints. Hiscock (1998a) recommends following a six year cycle for statutory sites with a proportion of the sites e.g. those which have a particular scientific or conservation interest monitored more regularly at least every three years. These guidelines seem reasonable for the monitoring of the intertidal and subtidal SACs dealt with here but this will depend on the size of the areas involved.

The characterisation of the community structure will involve separation of the main trends within a multivariate data set. Each species and each physico-chemical parameter constitutes a variable within the statistical analysis. It is often possible to rationalise the species list to around ten important species which control the dynamics of the community particularly if manipulation experiments are feasible or have been carried out (Gray, 1981). Multivariate analysis of sites within the SACs e.g. techniques such as TWINSPAN (Gauch, 1982) or the MDS and SIMPER routine in the PRIMER package (Warwick & Clarke, 1994) identify groups of sites with similar composition and the indicator species which are particularly well correlated to the assemblages found within the SAC. Replicate samples will usually be required to allow detailed statistical analysis and significance testing.