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Hydromorphological Literature Reviews for Transitional and Coastal Waters

Integrated Catchment Science programme

Science report: SC060043/SR2

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Steve Killeen

Steve Killeen

Head of Science

Executive summary

This report presents a review of the known direct and indirect linkages between hydro-geomorphology and six core biological elements (phytoplankton, benthic invertebrates, fish, saltmarshes, seagrasses, macroalgae) in transitional and coastal waters. This information is necessary to assess ecological status under the Water Framework Directive (WFD). Searches of the scientific literature were carried out by three groups to form a series of reviews based on the six elements.

The reviews start by examining the known linkages between hydrological (hydrographic) and geomorphological processes and the specific biological factors of WFD interest. Each biological element is related to these processes in succession. This analysis serves to establish the key direct and indirect process relationships between hydro-geomorphology and WFD-relevant biota.

Determining whether and to what degree such inter-relationships exist is especially important to WFD for two reasons. First, it is vital to understand the importance of hydro-geomorphology to underpin good ecological status. Secondly, understanding these relationships is necessary to better measure and predict the effects of hydromorphological pressures and associated mitigation measures (i.e. Programmes of Measures) on WFD-relevant biota.

The reviews then examine the direct and indirect effects of hydromorphological pressures on hydro-geomorphological processes or physico-chemical factors affecting the biotic response as well as direct interactions between hydromorphological pressures and biota.

A number of important observations can be made from both parts of the reviews:

1. Estuarine and coastal systems are complex. Few studies have attempted to tackle the three-way interplay between chemical, biotic and hydro-geomorphological processes at a large spatial or temporal scale. Thus there is limited quantitative material on which to base measures.

2. It is difficult to consider the role of hydro-geomorphological processes in isolation from other processes driving ecosystems such as climate and the physico-chemical factors influenced by hydrographic and geomorphological factors. Managing for pressures in isolation might also exacerbate rather than reduce human pressures on ecosystems.

3. Some biological elements are more sensitive to either hydrographic (e.g. phytoplankton) or geomorphological processes (e.g. saltmarshes), while most are responsive to the combination of hydro-geomorphological processes (e.g. benthic invertebrates) coupled with other environmental and biological forcing factors (e.g. seagrasses, fish).

4. It is often difficult to separate human activities from natural process dynamics, although it is clear that human activities (including hydromorphological pressures) do impact on ecological function of the WFD-relevant biota.

Findings related to each biological element are outlined below in two summary tables grouped into process–biota interactions and pressure–biota interactions where both direct and indirect linkages are outlined. It is noteworthy that ‘indirect relationships’ do not mean they are of less importance or given less priority for WFD considerations. An example helps outline why this is the case.

Phytoplankton, seagrass and macroalgal communities are strongly affected by light availability, a topic that has received considerable attention. One of the dominant controls on light availability is turbidity. Turbidity is caused by a suite of processes such as erosion–accretion cycles and sediment fluxes, which are in turn controlled by hydrographical and geomorphological conditions. To improve ecological quality under WFD it is necessary to improve light availability. To do this, there is a need to:

- understand which human pressures disturb or increase the supply or quality of sediments to systems;
- carry out hydrographic/geomorphic studies to help identify regulatory measures that mitigate major causes of poor light availability.

However, many transitional waters are naturally highly turbid and light regimes in those areas are often poor and difficult to manipulate.

Hydro-geomorphological process: biotic interactions

<u>Phytoplankton:</u> The dominant controls on phytoplankton result from physical and chemical processes that are under the direct control of hydro-geomorphological processes. Thus, the main physico-chemical factors of greatest importance – namely light availability, nutrients and salinity – are determined by hydrographic (e.g. freshwater flows and tidal regime – and thus residence time, stratification and mixing) and geomorphic features and processes. The latter include those explicitly or implicitly detailed in the WFD such as physiography (shape), depth, substratum type, quantity and amount (and thus turbidity levels). The latter relationships are relevant for all the elements covered here.

<u>Benthic invertebrates:</u> The key determinands of benthic community structure are amount and type of substratum, which are determined by hydro-geomorphological processes. Water movement determines the characteristics of both sedimentary substrata (e.g. grain size, stability) and hard substrata (e.g. erosion) directly, thereby determining the availability of suitable habitat for benthic invertebrates. Water movement can also impact feeding (by affecting food supply, especially for filter-feeders) and reproduction (by affecting larval dispersal and settlement). In addition, hydrographic and geomorphic processes impact on benthic invertebrates indirectly by influencing physico-chemical conditions such as salinity, temperature, emersion, nutrients and dissolved oxygen.

<u>Fish:</u> Fish are directly impacted by geomorphological processes and pressures (e.g. substratum condition and availability) as well as some hydrographic factors (e.g. freshwater flow). The physico-chemical factors of greatest importance to fish – namely salinity and temperature – are also influenced strongly by hydrographic factors (e.g. freshwater flows and residence time). Thus the link between hydro-geomorphology and ecology is via alteration of physico-chemical processes.

<u>Saltmarshes:</u> Saltmarshes are directly influenced by hydrographic and geomorphic processes as their spatial dynamics are closely linked to wave action and water movement (also indirectly through suspended sediment loading). Saltmarsh erosion occurs in areas of increased water flow, and seedling survival is highly dependent on exposure to wave action. Supply of allochthonous material also impacts saltmarsh stability – again closely coupled to water movement through the marsh.

<u>Seagrasses:</u> As with phytoplankton and macroalgae, the main factors affecting seagrass beds are mostly physico-chemical (in particular light availability), although most are controlled to varying extent by hydrography and geomorphology. Thus, geomorphology influences turbidity and water depth, which in turn control light availability. Hydrography affects seagrasses indirectly by impacting on salinity (via freshwater flow and mixing), as well as directly by influencing wave action and tidal flow.

Macroalgae: Light is a dominant factor controlling macroalgae distribution, abundance and diversity, and so macroalgae are affected indirectly by those hydrographic and geomorphic processes that affect light availability (as above for phytoplankton, e.g. water depth, suspended sediment load). Other physico-chemical factors (e.g. salinity and temperature) are also strong controlling factors and again these are indirectly controlled by hydromorphology. Direct influences on macroalgal communities include wave action, availability of suitable substratum, current velocity and water circulation patterns – all of which are affected by natural and anthropogenic pressures.

Hydromorphological pressure: biotic interactions*

Direct Pressures

Dredging (bed removal) – primarily fish and benthic communities.

Dredging (bed deposition) – primarily fish and benthic communities.

Boat activity (propeller damage) – primarily seagrass beds, also benthic invertebrates.

Boat activity (wave effects) – primarily macroalgae.

Construction – localised impacts on all biota

Land claim – primarily benthic communities, also vegetation in reclaimed area.

Indirect Pressures

Dredging – May affect sediment supply to saltmarshes. May also affect sediment supply to fauna inhabiting soft substrata, including infaunal invertebrates and demersal fish.

Construction/realignment/bank reinforcement/flood defence measures – any biota affected by flow, in particular macroalgae and benthic invertebrates.

Construction/dredging/other processes that may remobilise contaminants – fish, benthic invertebrates, macroalgae, seagrasses and saltmarshes are all susceptible to contaminants.

Anthropogenic discharge (sewage) – primarily phytoplankton, macroalgae and benthic invertebrates.

Anthropogenic discharge (cooling waters) – phytoplankton, macroalgae and benthic invertebrates.

Anthropogenic discharge (contaminants) – fish, benthic invertebrates, macroalgae, seagrasses and saltmarshes are all susceptible to contaminants.

* Pressure analysis has not been grouped by biota, as it is clear that most human pressures impact on more than one biological quality element. Likewise, it is clear that although a hydromorphological pressure may have a direct impact on one biological quality element, it might indirectly affect another.

What do the review findings mean for the strategic assessment and subsequent work on regulatory measures for TraC hydromorphology?

1. The references on hydromorphological pressure impacts need to be reviewed more thoroughly to:

   - determine the certainty of evidence for creating measures;
   - analyse which sectors are responsible for each pressure–biotic response,
   - identify which pressure–response linkages require further research.

   This is required for both direct and indirect relationships between hydromorphological pressures and biota.

2. Indirect hydro-geomorphological process–biota relationships need to be better understood so that the important role that hydro-geomorphological processes play in wider issues such as eutrophication, diffuse pollution and contamination can be highlighted. Further work is needed to demonstrate the importance of these processes for managing human pressures.

3. These more thorough reviews can be used to highlight the relative paucity of information on hydro-geomorphological processes and pressures. Although the literature search criteria were tightly defined in relation to hydro-geomorphological processes and pressures, most papers focussed more on other factors. This is symptomatic of human interest and concern over the ultimate response (e.g. rates/causes of saltmarsh loss) rather than on understanding the sediment requirements of saltmarshes and what management interventions might be employed to maintain these levels. Thus, this science area has received considerably less attention that others in the past decades and as such, our knowledge is less certain.

4. More work is required before preliminary recommendations on programmes of measures for hydromorphological pressures can be made. In the short-term, further analysis of the human pressure–hydro-geomorphology–biotic response literature is required. In the medium-term, a concerted research programme will be required so that adaptive management measures can be implemented as part of the second and third WFD cycles.

5. Improving the evidence base of both process and pressure links through further analysis of a wider body of literature such as the ESTFISH database at the University of Hull is recommended.

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1 Introduction

1.1 Project background

The Water Framework Directive (WFD) is considered the most substantial piece of EC water legislation to date. It is also a major opportunity to improve the whole water environment and to promote the sustainable use of water for the benefit both of people and wildlife (CEC 2000).

The main objective of the Directive is that all inland, transitional and coastal waters should reach ‘good status’ by 2015. This will be achieved by establishing management plans for River Basin Districts (RBDs) within which demanding environmental objectives will be set, including ecological targets for surface waters.

The WFD requires the creation of a holistic and co-ordinated framework for the sustainable management of water resources based on the introduction of objectives and environmental standards. Hence its implementation requires sound science in developing classification tools/criteria for determining the ecological status of the biological elements. For coastal and transitional waters these include phytoplankton, macroalgae, other macrophytes and benthic fauna together with, for transitional waters only, the fish.

The classification tools/criteria developed to define the ecological quality of the biological elements need to be relevant to the influences of both the natural and the anthropogenic processes affecting water bodies. This requires a clear understanding of the relationships between these tools/criteria and the processes/pressures affecting the ecological status to be measured. It is then necessary to link this understanding with management options for water bodies.

This report identifies:

- the known relationships between hydro-geomorphological pressures and processes;
- the biological elements of the WFD in transitional and coastal (TraC) waters.

It specifically examines:

- the relationships between hydro-geomorphological processes and pressures;
- the WFD biological criteria of:
  - phytoplankton;
  - benthic invertebrates;
  - fish;
  - angiosperms (separated here into seagrasses and saltmarshes);
  - macroalgae.

In order to fulfil the WFD’s aims, it is essential that the criteria for change are related to the ecological sensitivity of waters with respect to changes in hydro-geomorphology. However, many other pressures link only indirectly to hydro-geomorphology (e.g. chemical pollution and the presence of non-native species) and these are not covered in this report.

In addition, the WFD requires any water body deemed to be heavily modified (heavily modified water body; HMWB) from anthropogenic hydro-geomorphological modifications to have a good ecological **potential** rather than good ecological **status** (Freeman *et al.* 2003). Hence, it is important to define the implications of those modifications on the biota and thus the HMWB designation.

Finally, although this report commonly refers to estuaries, these are only one of the types of transitional waters defined by the WFD (see Elliott and McLusky 2002, McLusky and Elliott 2004).

Thus the aim of this project is to:

> 'provide the Environment Agency's Water Framework Directive Programme and ultimately the Department for Environment, Food and Rural Affairs (Defra) with a review of the current state of understanding on the relationships between the biological classification tools/criteria for good ecological status (potential) for transitional and coastal waters to both hydro-geomorphological processes and pressures'.

Defra will ultimately use the Environment Agency's input to the Strategic Review to determine whether new regulatory powers are required to meet the WFD's requirements. This report will inform the Environment Agency's advice to Defra.

The literature cited in this report is an illustrative selection rather than an exhaustive review, although it aims to present the main aspects for each biological component. Each of the biological elements discussed in the report has an extensive literature base which could not be summarised in the time available for the project.

1.2 Basic concepts

An ecosystem can be regarded as the net result of a set of sequential and interlinked components and processes in which physical (i.e. hydrological and geomorphological) and chemical factors play a fundamental role as forcing variables. The ecosystem consists of a set of structural elements or components. The pathways and transfer of material or energy flux between them create the rate processes which constitute ecosystem functioning (Elliott *et al.* 2006). These somewhat abstract concepts are described and illustrated below in Table 1.1 as a set of processes.

Table 1.1 Ecosystem rate processes

Type	**Description**
environment–biology (env.–biol.)	Processes whereby the physico-chemical system (e.g. salinity, temperature, sediment, geomorphology, geology, hydrography, etc.) creates the fundamental niche for colonisation by organisms. This work is often referred to as geobiology, ecogeography and/or biogeomorphology
biology–biology (biol.–biol.)	Processes whereby the resultant community is modified by biological processes and interactions (e.g. predator–prey relationships, competition) and recruitment processes (e.g. propagule supply and settlement).
biology–environment (biol.–env.)	Processes whereby the biology may influence the nature of the physico-chemical system, and the import and export of materials to/from the system. This work is also referred to the study of biogeomorphology and/or biogeochemistry.

These interlinked processes create the observed ecosystem. Anthropogenic change and distortions to the natural system are then superimposed on this set of fundamental relationships.

Figure 1.1 indicates the importance of:

- the hydrological, geomorphological and allied chemical processes in creating the conditions for the biology;
- understanding those hydro-geomorphological variables as a means to understanding the changes to the biota.

In Figure 1.1, the term 'physico-chemical' attributes is taken as shorthand for all hydrological and oceanographic processes.

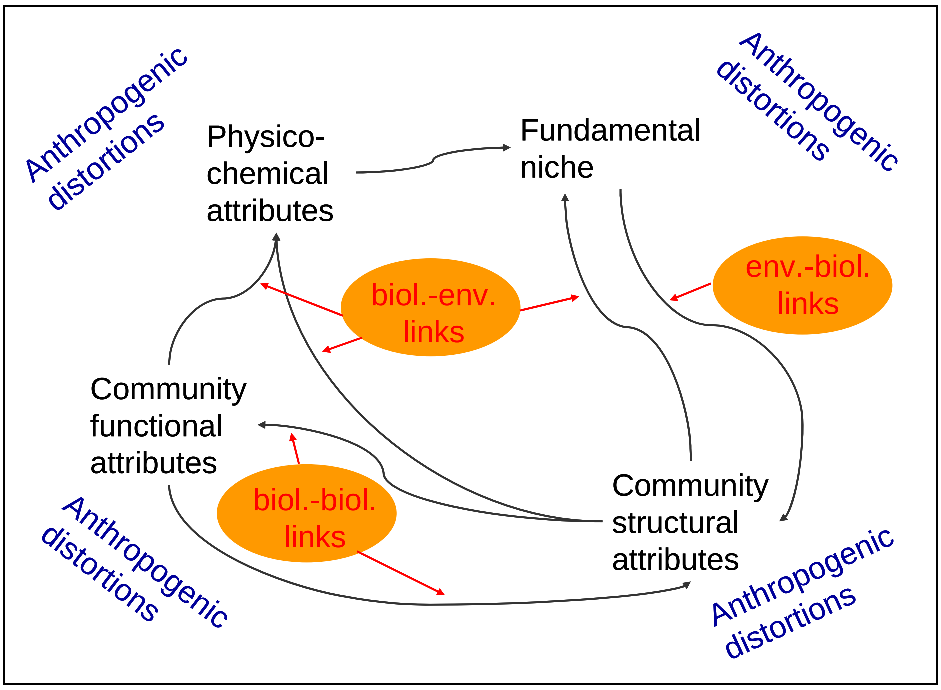

Figure 1.1 Schematic diagram indicating linking and feedback between environmental and biotic marine/estuarine attributes (Elliott *et al.* 2006)

The hydrological, geomorphological and chemical attributes of the marine environment are a set of interlinked regimes that can be loosely grouped to produce, at its most fundamental definition, the water column fundamental niche and the substratum (seabed, intertidal surface) fundamental niche (Figure 1.2). These niches are occupied by organisms.

The red boxes in Figure 1.2 highlight the large number of oceanographic / hydrographic regimes that constitute the marine environment. The white boxes in Figure 1.2 are the factors that create or influence those regimes (e.g. geomorphological processes occurring to create landforms and habitats together with other processes).

These links are complex as shown by Figure 1.2, which indicates the way these marine physical and chemical attributes interact and influence each other and are, in turn, affected by knock-on effects between the variables. An understanding of these regimes is fundamental to interpreting and understanding the ecosystem and human interactions with it.

This report aims to present the relationships between the hydromorphological variables and the biological elements of phytoplankton, benthos, angiosperms (saltmarshes and seagrasses) and macroalgae and, in transitional waters, fish against this conceptual background.

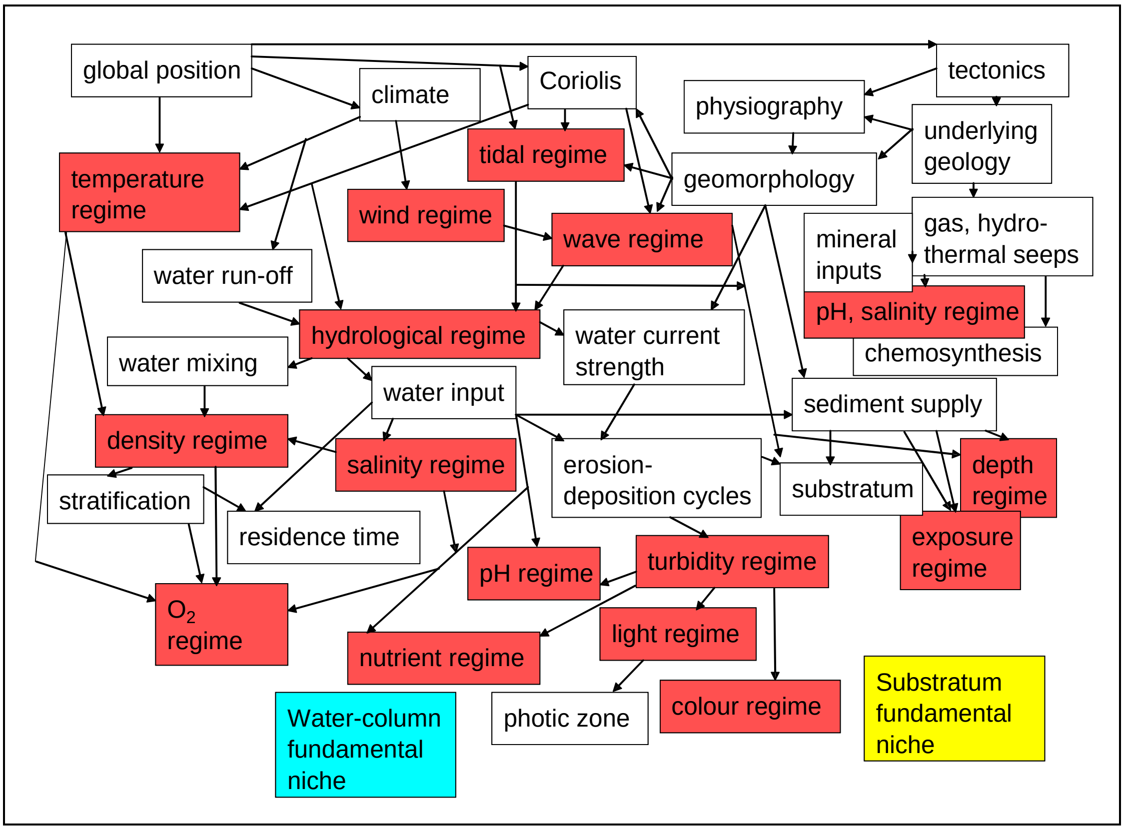

Figure 1.2 Links between the physical (including geophysical and hydromorphological) and chemical attributes resulting in the two main marine fundamental and overarching niches – for the water column and substratum (Elliott *et al.* 2006)

1.3 Methods

Initial literature searches using Web of Science (WoS), [1] Biosis[2] and CAB Abstracts[3] for the six biological elements (fish, phytoplankton, benthic invertebrates, seagrasses, saltmarshes, macroalgae) were undertaken by the Environment Agency for three topics:

- general terms
- hydro-geomorphological processes
- human impacts (pressures).

Appendix 1 gives details of the search strings used for the six biological elements.

The reviews were then completed by specialists around the UK as shown in Table 1.2. Appendix 2 gives the numbers of articles (and percentage of total) referring to particular factors/terms used in the searches.

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[1] See http://scientific.thomson.com/products/wos/
[2] See http://www.biosis.org/
[3] See http://www.cabi.org/datapage.asp?iDocID=165

Table 1.2 Division of work

Organisation	Biological element
Cambridge Coastal Research Unit (CCRU), University of Cambridge	Saltmarshes Seagrasses
Institute of Estuarine and Coastal Studies (IECS), University of Hull	Fish Benthic invertebrates Phytoplankton
Environment Agency	Macroalgae

Initial search methods were consistent between teams, with methods varying slightly due to the amount of material on particular topics. The precise methods used by each group are outlined below. Time and effort limits precluded the analysis of the complete body of literature for each element.

1.3.1 CCRU

The literature search for saltmarshes and seagrasses used only the WoS search facility. While the seagrass search resulted in a representative selection of papers, the saltmarshes search was considered too restrictive (several important articles known to the expert reviewers were not found by the searches) and so an additional search was conducted for major authors (Appendix 1).

With the exception of papers that addressed more generic issues associated with the human pressures on such ecosystems or key linkages not addressed elsewhere, the review focused on studies conducted in saltmarsh/seagrass systems typical of north-west Europe.

The search was initially restricted to articles published in the years 1996-2006 (it was assumed these papers would include fundamental references) but, due to the lack of references found, the seagrasses search had to be expanded to include all years available on WoS (i.e. 1980-2006).

After consulting the abstracts for all articles, a subset of 20 key articles was chosen on the basis of maximum relevance to the WFD topic areas (see above). These 20 articles were consulted in greater detail while, for others, only the abstract was consulted for information.

After completing the literature search, the resulting bibliographies were searched for articles relevant to key factors and process linkages identified in the review.

As the seagrasses search resulted in fewer articles, each article's relevance with regard to particular seagrass species, biogeomorphological and hydromorphological factors was also recorded in a Microsoft® Excel spreadsheet (seagrass_key_parameters.xls).

Conceptual diagrams illustrating linkages between individual hydromorphological factors and the biological elements of seagrasses and saltmarshes are included within each of the review sections.

1.3.2 IECS

IECS adopted a similar approach to CCRU but used its own literature database to supplement the references highlighted in the Environment Agency's search.

Outputs from the searches were used to produce a summary table to establish the main hydrological and geomorphological processes and pressures.

The key literature (limited arbitrarily to around 20 articles per element) was then reviewed for each element and each hydro-geomorphological aspect relevant to the understanding of the relationships between the biological classification tools/criteria for good ecological status (potential) for transitional and coastal waters, and processes and pressures therein.

The marine and estuarine literature is extensive, but the limited time available for the project precluded an exhaustive survey of other literature. Given the fundamental nature of marine and estuarine ecosystems worldwide, literature was not restricted to north-west Europe.

1.3.3 Environment Agency

The Environment Agency used only those references highlighted in the intial search of WoS etc for its review of macroalgae.

The key literature (limited arbitrarily to around 20 articles per element) was then reviewed for each element and each hydro-geomorphological aspect relevant to the understanding of the relationships between the biological classification tools/criteria for good ecological status (potential) for transitional and coastal waters, and processes and pressures therein.

Information from the review was reported for each biological factor under three headings:

- hydro-geomorphological processes;
- general biogeomorphology;
- human impacts.

A limit of 1,000 words was set for each biological factor (inclusive of all three topics).

2 Phytoplankton

2.1 Hydrological and geomorphological processes

Coastal and estuarine areas are among the world's most productive environments; for example, while about 28 per cent of total global primary production takes place in coastal and estuarine areas, their area is only 8 per cent of the Earth's surface (de Jonge and Elliott 2001).

The WFD requires the inclusion of biomass, abundance and composition in the normative definitions for phytoplankton – a biological quality element (BQE) for TRaC waters – to categorise ecological status (Ferreira *et al.* 2005).

Phytoplankton, an integral part of estuarine and coastal ecosystems, consists of microscopic plants including many species of diatoms, microflagellates and dinoflagellates; the relative proportions of the various groups are an indication of ecological status and response to human activities. These organisms are free-floating in the water column and provide primary production in estuarine, coastal and marine food webs. The groups become visible to the naked eye when suitable environmental factors create excessive growth of a population – defined as blooms (or other visible symptoms such as foaming as the result of water movements on the phytoplankton gelatinous matrix). But within dynamic environments, especially transitional waters, microphtyes found in the water column can be resuspended benthic microalgae – also called microphytobenthos (de Jonge and Elliott 2001).

The development of phytoplankton populations and communities is influenced by bottom–up and top–down processes which cover the limiting conditions required to initiate growth and the processes controlling that growth respectively (Chan *et al.* 2002).

In transitional waters, the most important factors controlling phytoplankton are considered to be (de Jonge and Elliott 2001):

- flushing rate (and its corollary, residence time);
- turbidity (as suspended solids concentration) (and its corollaries light regime and the depth of the photic zone);
- nutrient input/concentration gradient.

In general terms, turbidity is determined by the strength of the prevailing currents operating on the bed sediments and keeping material in suspension. More specifically, turbidity in estuaries is a result of the interaction of a number of processes including the tidal range, mixing regime, erosion–deposition cycles, freshwater inflows, substratum and stratification. It results in high concentrations of suspended sediments and particulate organic matter in the water column (e.g. Chan *et al*. 2002; van Raaphorst and de Jonge 2004).

Water column turbidity is the net result of erosion–deposition processes/cycles in water bodies; these are especially notable in estuaries. Erosion of the bed occurs under increased flow conditions, for example:

- during the strongest ebb and flood tide periods;
- during spring tide conditions;
- during other high energy events such as periods of high freshwater run-off.

Deposition occurs during slack high and low water, neap tide periods and seasonal times of poor riverine inputs. Hence erosion–deposition cycles occur on a daily, weekly, monthly and seasonal basis. Bed friction and lateral friction on funnel shaped and inward-shallowing estuaries also contribute to turbidity levels.

Flushing rate (the rate of loss of phytoplankton populations from the estuary) is determined by the relative magnitudes of freshwater inflow and tidal regime (i.e. hydrographic processes). It determines the retention or removal of phytoplankton from the estuary. These processes also determine the salinity, which has an effect through the differing tolerances of different species (Rijstenbil 1991). The relationship between depth, freshwater inflow and tidal range in turn create the conditions for water column stability (e.g. high river flows, a shallow estuary and moderate tidal range create a fully mixed estuary).

The overall physiography, especially the shape of a transitional water body, influences the levels of turbidity and the current dynamics. Coriolis force will deflect currents to one side, thus creating a higher salinity on one shore of an estuary (e.g. the northern shore in an east-facing estuary) because of marine water inflow and a corresponding lower salinity on the opposite shore through freshwater outflow.

Tables 2.1 lists key terms, processes and pressures highlighted in the literature.

Table 2.1 Key terms, processes and pressures highlighted in the phytoplankton literature

Environmental processes	**No. of references (from initial Environment Agency search)**	**Sample references (including from IECS search)**
Biomass (chlorophyll *a*)	51	Ahel *et al.* 1996 Ferreira *et al.* 2005 Moncheva *et al.* 2001
Nutrient concentration/ composition	40	Bode *et al.* 2002 de Jonge and Elliott 2001 Livingston *et al.* 2002 van Beusekom and de Jonge 1998
Salinity	37	Ahel *et al.* 1996 Almeida *et al.* 2002 Bode *et al.* 2002 Moncheva *et al.* 2001
Seasonal variations	28	Almeida *et al.* 2002 Mallin *et al.* 1999
Community composition	27	Cloern and Dufford 2005 Muylaert and Raine 1999
Blooms	25	Cloern 1996 de Jonge and Elliott 2001 Mallin *et al.* 2004 Moncheva *et al.* 2001 Yin *et al.* 2001

Primary production (growth)	22	Almeida *et al.* 2002 Ferreira *et al.* 2005
Hydrological factors (mixing, flushing, tidal range, etc.)	18	de Jonge and Elliott 2001
Zooplankton grazing	16	Muylaert & Raine (1999)
Light/turbidity	14	Ferreira *et al.* 2005 Lemaire *et al.* 2002 Mallin *et al.* 1999 Muylaert and Raine 1999
Temperature	13	Moncheva *et al.* 2001
Abundance	10	Almeida *et al.* 2002 Bode *et al.* 2002
Freshwater input	10	Elliott and de Jonge 2001 van Raaphorst and de Jonge 2004
Modelling	10	Chan *et al*. 2002 Edelvang *et al.* 2005 Ferreira *et al.* 2005
Pigments	7	Lemaire *et al.* 2002 Muylaert and Raine 1999
Population dynamics	6	Cloern and Dufford 2005
Residence time	3	Chan *et al.* 2002 Ferreira *et al.* 2005 Muylaert and Raine 1999
Monitoring (tools)	1	Sagert *et al.* 2005
Anthropogenic pressures	**No. of references (from initial Environment Agency search)**	**Sample references (including from Environment Agency and IECS searches)**
Aquaculture	2	Ahel *et al.* 1996 Camacho *et al.* 1995
Anthropogenic nutrient inputs	2	Cloern 1996 de Jonge and Elliott 2001 Mallin *et al.* 2004 Moncheva *et al.* 2001 Yin *et al.* 2001
Urbanisation	1	Lewitus *et al.* 2004
Deforestation	1	Lewitus *et al.* 2004
Waste water treatment plants	1	Magnien *et al.* 1992
Pulp mill effluents	1	Livingston *et al.* 2002

2.2 General biogeomorphology

There is generally a good qualitative understanding of the ecological processes operating and the changes in community structure, but the quantitative influences on such processes are still not well understood (de Jonge and Elliott 2001). The main hydrophysical processes associated with phytoplankton growth in estuaries are illustrated in Figure 2.1.

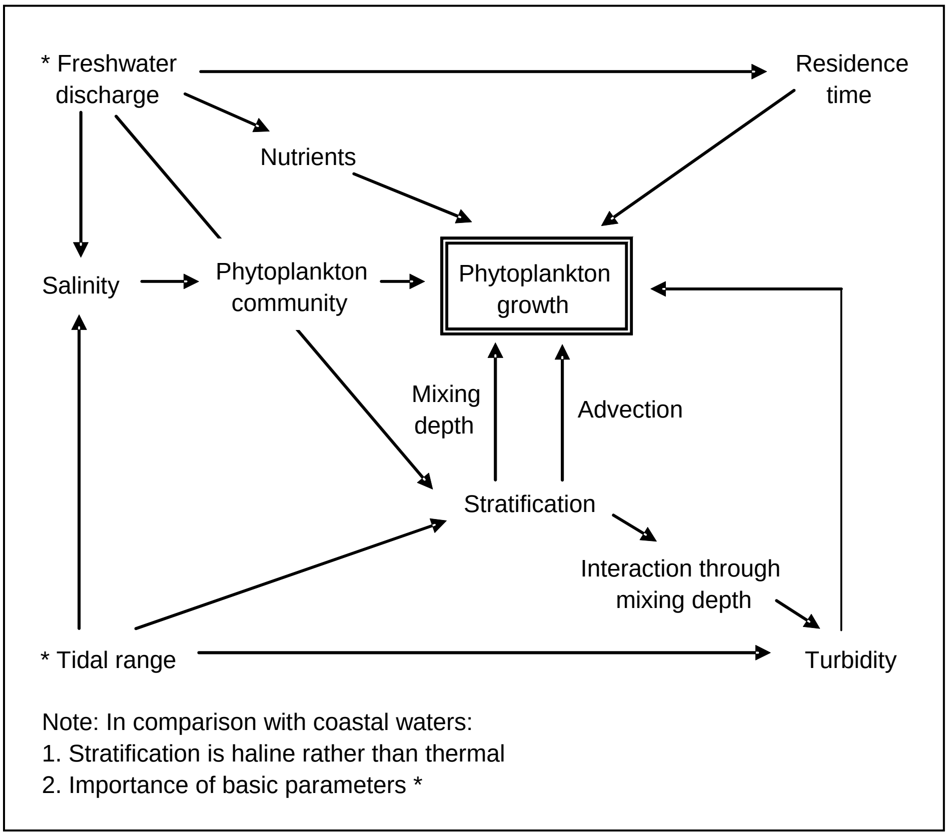


Figure 2.1 Factors affecting phytoplankton growth in estuaries and their interactions (adapted from Professor M Wilkinson, Heriot-Watt University unpublished)

Environmental hydrodynamic factors create adequate conditions for phytoplankton growth but also, under certain circumstances, determine whether an estuarine system has a low or high risk of producing eutrophic symptoms.

Eutrophication is regarded as a set of symptoms of undesirable, anthropogenic disturbance and so includes excessive growth of phytoplankton which causes noxious, nuisance or toxic blooms. The likelihood of these symptoms occurring is related to estuarine and coastal geomorphology and hydrodynamics (Ferreira *et al.* 2005), especially in water bodies or areas with high retention times (e.g. Langstone harbour and Seal Sands on the Tees estuary). Phytoplankton blooms (or other symptoms of eutrophication) can occur as a result of increased nutrient inputs from freshwater inputs, from the atmosphere or from the sea (Cloern 1996).

Due to the highly complex nature of the estuarine and coastal environment, most studies have assessed phytoplankton biomass (as chlorophyll *a*), community composition and/or primary production (as the result of growth). These measurements were often made together with assessments of nutrient concentrations/composition, basic hydrographic features (e.g. salinity and temperature), seasonal variations, and surveys of pelagic and benthic herbivores, which can be used to estimate grazing pressures. In turbid estuaries, however, water column ‘phytoplankton’ (and thus chlorophyll *a* measured in the water column) is more likely to be resuspended microphytobenthos (benthic microalgae) (e.g. de Jonge and van Beusekom 1995).

Light and nutrient limitation controls phytoplankton primary productivity and thus biomass is influenced by the hydrodynamics coupled to inputs (Snow *et al.* 2000). Estuaries are commonly referred to as hypernutrified because high levels of nutrients are present, so the controlling factor for phytoplankton production is usually light availability. Turbidity, in turn, is the major control on light availability and thus primary productivity.

In an estuary, salinity is influenced by the freshwater discharge and tidal range, which dictate the site of the freshwater–seawater interface (FSI), usually in the upper regions (Meire and Vincx 1993). The tolerance of phytoplankton species to changes in salinity will therefore be a dominant factor in the community composition within an estuary (Rijstenbil 1991). For example, freshwater phytoplankton die once they reach the FSI; hence the estuarine phytoplankton community composition will be dominated by euryhaline species. Salinity is more constant in coastal waters and so has a smaller influence on coastal phytoplankton communities, with stenohaline marine species (and possibly euryhaline estuarine species) dominating the assemblage.

The vertical mixing state (stratified or otherwise) of the receiving body and the residence/flushing time of the freshwater and its nutrients in the system determine the sensitivity of systems to developing symptoms of eutrophication (de Jonge and Elliott 2001). In a stratified estuary, the FSI is very efficient in collecting living and detrital particles from the highly productive brackish water layer, thus playing an important role in determining the distribution and fate of organic matter in the estuary. In a well-mixed estuary, river discharges and tidal mixing result in a strong estuarine circulation and an intense exchange between the estuary and coastal waters, thus distributing the organic matter throughout both systems.

In a system with a long residence time (i.e. poorer flushing rate), primary producers have longer to use the excess resources. If residence time is shorter (i.e. high flushing) than the mean growth rate of the phytoplankton, then flushing out of the population will occur; thus, if blooms have not occurred within the estuary they may develop in the lowest reaches of the system or even in adjacent coastal waters. As such, estuaries can be regarded either as a source or sink for nutrients.

In the UK, the susceptibility of waters to enrichment and adverse effects caused by nutrients is interpreted according to their ability as high natural dispersing areas (HNDA). In general this reflects the water body’s assimilative capacity, i.e. capacity to dilute, degrade and assimilate nutrients without adverse consequences (McLusky and Elliott 2004, Elliott and de Jonge 2002).

When comparing phytoplankton blooms over a spatial scale, for example between the Black Sea and the Aegean Sea (Moncheva *et al.* 2001), it has been shown that temperature and salinity are factors contributing to the differences between the ecosystems. However, the differences among the studied sites illustrate the importance of nutrients and their ratios.

Similarly, changes in the geomorphology of a river basin or estuary can also impact on nutrient supply to estuaries and to coastal waters. For example, alterations in the lower part of the Rhine river basin led to a decrease in flushing time of the system and thus a relative increase in the discharge of nutrient loads to the Dutch Wadden Sea (de Jonge and Elliott 2001).

In many cases, changes in the net phytoplankton community and planktonic primary production are the result of the interdependency between nutrient levels, riverine run-off and resuspension (e.g. van Beusekom and de Jonge 1998, Snow *et al.* 2000, van Raaphorst and de Jonge 2004). Seasonality influences most fundamental processes in estuarine and coastal waters. For example, increased precipitation (freshwater input) in the upper watershed may lead to increased flow, turbidity, light attenuation and nutrient loading, and decreased chlorophyll *a* and nutrient limitation potential in an estuary. It is also expected that there will be an influence of the North Atlantic Oscillation in changing riverine run-off, and thus the delivery and dilution of nutrients into estuaries and coastal areas.

2.3 Human pressures (hydrological and geomorphological)

The literature available indicated a lack of information on specific hydrological or morphological pressures on phytoplankton (Table 2.1). The few anthropogenic activities discussed within the literature include:[4]

- water abstraction and flow rate changes;
- anthropogenic nutrient inputs;
- pulp mill effluent discharges;
- urbanisation;
- deforestation;
- aquaculture.

Despite this, wider knowledge indicates that the following anthropogenic activities have the greatest influence on the hydrological and geomorphological process within estuarine and coastal environments (Table 2.2).

In general, hydro-geomorphological pressures result from activities that change:

- the shape of the system in space and time (i.e. the physiography, bathymetry and topography of a water body);
- the water balance and current regimes, the sediment balance and erosion-deposition cycles;
- the natural and anthropogenic water supply.

Each of these has the potential to influence the structure and functioning of phytoplankton communities, but such pressures have a greater influence in restricted water bodies, such as transitional waters (see Table 2.1 for references).

In summary, and as the result of the interactions described above, any hydromorphological pressures that affect the mixing regime, turbidity, salinity and/or residence time/flushing rate will influence the phytoplankton.

Changes to the primary characteristics of water body shape as in HMWBs (i.e. physiography, bathymetry and topography) affect current patterns and thus the response to tidal currents creating turbid conditions. Similarly, anthropogenic pressures such as abstraction influence water supply which, in turn, affects the control of the salinity regime in transitional and near shore areas.

[4] See Table 2.1 for references.

Secondary influences (which are again more important in transitional waters) include the supply of nutrients superimposed on the ability of the area to retain the nutrients (hence residence time and flushing rate) and their use by the phytoplankton.

Measures to prevent changes to the phytoplankton are therefore required to:

- minimise such modifications to shape, water supply and currents;
- control direct and indirect nutrient sources.

Table 2.2 Anthropogenic pressures and their generic impacts on hydrological and morphological processes in transitional and coastal waters (indicative and exemplar references are given)

Activity	Impact on hydrological and morphological processes
Agriculture	Increase in sediment supply (increased turbidity) and nutrients (potential for blooms to develop) have an impact on phytoplankton production in transitional waters (La Jeunesse and Elliott 2004).
Aquaculture	Aquaculture structures (e.g. fish cages and trestles) could have an impact on both the hydrological and geomorphological features of estuaries and coasts by impeding water flow (La Jeunesse and Elliott 2004). Grazing of phytoplankton by filter feeding organisms such as mussels have an impact on phytoplankton populations. Localised, increased organic loading may result in eutrophic symptoms.
Changes to physiography of the system through infrastructure and activities	Changes in the physiography of a river basin or estuary will influence the nutrient supply to estuaries and to coastal waters. For example, alterations in the lower part of the Rhine river basin led to a decrease in flushing time of the system and thus a relative increase in the discharge of nutrient loads to the Dutch Wadden Sea (de Jonge and Elliott 2001).
Changes in water supply/upstream water use	Change in freshwater input (e.g. through abstraction) will influence the supply (loading) and concentrations of nutrients, the location of the FSI (which changes phytoplankton community structure), the residence time (which impacts on nutrient supply in estuarine and coastal zone) and the mixing of the estuary (affecting phytoplankton growth). All these impacts may also have a knock-on effect on phytoplankton production in estuarine and coastal waters.
Construction of harbours, barrages etc	Impact on both hydrological and geomorphological features of estuaries and coastal waters. For example, construction of a storm-surge barrier and two compartment dams were completed in the Oosterschelde, The Netherlands, and resulted in reduced flow velocities, reduced suspended matter content and decreased freshwater loads (Wetsteyn and Bakker 1991).
Dredging/ navigation	Increase in water depth will have an impact on light availability for photosynthesis by phytoplankton. Increase localised turbidity is a limiting factor for phytoplankton production in estuarine ecosystems, which are generally limited by light availability for photosynthesis.
Organic pollution	Increase in nutrients from diffuse (agricultural run-off) and point source discharges (waste water treatment plants) leads to potential for increased phytoplankton production depending on other factors such as light availability, residence time, etc. (La Jeunesse and Elliott 2004).
Urbanisation/ deforestation	Impact on the supply of nutrients into estuarine waters. It has been shown that phytoplankton growth may be iron-limited in deforested areas. This is consistent with the hypothesis that organically bound iron from coastal forests plays an important role in supplying iron for the growth of estuarine phytoplankton (Lewitus *et al.* 2004).

3 Benthic invertebrates

3.1 Hydrological and geomorphological processes

As indicated earlier, substratum features are the result of hydro-geomorphological processes including the hydrological influences on the underlying geology. In high energy conditions, which prevent the accumulation of sediments, the underlying geology produces exposed hard substratum areas.

Given the emphasis in the WFD on the soft substratum benthos (particularly because of its ability to integrate interactions between the hydrography and sediments, the sedimentary accumulation of pollutants and the background knowledge of the benthos), this commentary concentrates on the soft sediment benthos. Any such review cannot reflect the extensive literature on the benthos and the large number of quantitative studies carried out recently (e.g. Eleftheriou and McIntyre 2005).

The hydrophysical regime affecting substratum structure incorporates:

- tidal currents – a function of location, physiography (and shape of estuarine area) and the prevailing tidal regime;
- Coriolis force;
- density-dependent currents – especially in areas where freshwater and seawater mix;
- wind-driven currents and waves – especially in exposed areas.

Once deposited, soft sediments are subject to physical (including hydro-geomorphological), chemical and biological processes (Figure 3.1), which both influence and are influenced by the benthos.

Geomorphological processes (e.g. sediment erosion–deposition cycles that occur on an ebb/flow–slack water, spring–neap or winter–summer basis) influence the nature of the bed sediments and thus the benthic community.

Low energy conditions, as in parts of transitional waters such as estuaries, sea lochs and lagoons, produce fine-grained, organically rich sediments which, with increasing deposition of organic matter, can become anoxic. Diagenesis (post-depositional change) can then lead to toxic levels of hydrogen sulphide and methane below the redox potential discontinuity (RPD). Under very high organic conditions, the RPD can occur at the sediment surface and consequently affect water quality.

Table 3.1 Key terms, processes and pressures highlighted in the benthic invertebrate literature

Environmental factors/processes	No. of references (from initial Environment Agency search)	Sample references (including from IECS search)
Community structure	22	Ysebaet *et al.* 2003
Species abundance	13	Ysebaet *et al.* 2003
Species diversity/heterogeneity	9	Ysebaet *et al.* 2003
Species dominance	9	Ellis *et al*. 2004
Sediment quality/characteristics	8	Ysebaet *et al.* 2003
Substratum	8	Roth and Wilson 1998
Sediment deposition and erosion	7	Hinchy *et al.* 2006
Salinity	7	Ysebaet *et al.* 2003
Recovery rate/ recolonisation/ recruitment	6	Hall and Harding 1997
Species biomass	6	Ysebaet *et al.* 2003
Sediment grain size	6	Mucha *et al.* 2004
Dissolved oxygen	6	Dauer *et al.* 2000
Depth	6	Ysebaet *et al.* 2003
Species numbers	5	Desroy and Retiere 2001
Temperature	5	Harris *et al.* 2005
Hydrodynamics/hydrography	5	Ysebaet *et al.* 2003
Organic matter	4	Pearson and Rosenberg 1978
Population density	3	Lenihan and Oliver 1995
Flow/tidal variations	3	Roth and Wilson 1998
Nutrients	3	Dauer *et al.* 2000
Growth	2	Pearson and Rosenberg 1978
Organic content	2	Pearson and Rosenberg 1978
Pelagic-benthic coupling	2	Cattaneo-Vietti *et al.* 1999
Meteorological conditions (i.e. wind)	2	Ellien *et al.* 2004
Community density	1	Blanchard *et al.* 2004
Filamentous algae blooms	1	Golubkov *et al.* 2003
Life history characteristics	1	Lenihan and Oliver 1995
Microalgal production	1	Posey *et al.* 2006
Organic carbon loading	1	Perez *et al.* 1996
Organic matter decomposition ratio	1	Golubkov *et al.* 2003
Patchiness (spatial variation)	1	Skilleter *et al.* 2005
Primary production	1	Golubkov *et al.* 2003
Reproduction/spawning	1	Cattaneo-Vietti *et al.* 1999
Trophic capacity	1	Cattaneo-Vietti *et al.* 1999
Species size	1	Arsenault *et al.* 2001
Total recoverable metals	1	Mucha *et al.* 2004
Geomorphology	1	Kotta *et al.* 2003
Evenness	1	Estacio *et al.,* 1999
Biodeposition	1	Norkko *et al.* 2001
Oceanographic change (including ELNINO and upwellings)	1	Schiel *et al.* 2004
Pressures	**No. of references (from initial Environment Agency search)**	**Sample references (including from IECS search)**
Commercial fishing	4	Hall and Harding 1997
Anthropogenic contaminants	4	Mucha *et al.* 2004
Silting/sedimentation	3	Desroy and Retiere 2004
Harvesting – various methods	3	Spencer *et al.* 1998
Dredging (various methods)	3	Arseneau *et al.* 2003
Ultraviolet (UV) radiation	2	Wahl *et al.* 2004
Shellfish dredging	2	Hall and Harding 1997

Environmental factors/processes	No. of references (from initial Environment Agency search)	Sample references (including from IECS search)
Sewage	2	Estacio *et al.* 1999
Sea wall construction	2	Ahn and Choi 1998
Pollution	2	Roth and Wilson 1998
Physical perturbation/disturbance	2	Widdicombe and Austen 2001
Nutrient enrichment	2	Posey *et al.* 2006
Manmade submerged habitats	2	Perkol-Finkel *et al.* 2006
Aquaculture	2	Simenstad and Fresh 1995
Heavy metal contamination/ accumulation	1	Ahn and Choi 1998
Turbulence	1	Ellis *et al.* 2005
Trampling	1	Casu *et al.* 2006
Predator exclusion	1	Posey *et al.* 2006
Organic enrichment	1	Widdicombe and Austen 2001
Decrease on mean water level	1	Desroy and Retiere 2004
Cockle hand raking	1	Kaiser *et al.* 2001

3.2 General biogeomorphology

Benthic invertebrates are characterised according to:

- where they live – on the substratum (epifauna) or within the substratum (infauna);
- depth range (intertidal or subtidal);
- mobility (whether mobile, sedentary or sessile);
- feeding type or feeding guild (suspension, deposit, detritus, scavenger or carnivore);
- size (micro-, meio-, macro- or mega-).

Thus the group covers organisms from microscopic foraminiferans through nematodes and polychaete worms to large echinoderms and crustaceans, which may be up to 30 cm long.

The soft sediment benthos constitutes a three-dimensional system in which the organisms modify the surface and deeper features. But while the precise species composition differs with biogeographical regions, the ecological functional groups remain similar (Reise 1991). Each group is limited by the available resources, often space (in the case of suspension feeders such as mussels) or food availability (in the case of deposit feeders such as lugworms). Both the latter structuring features are intimately linked to the hydro-geomorphological characteristics of an area.

For soft sediment macrobenthos, there is:

- a very large body of literature (e.g. Snelgrove and Butman 1994, Eleftheriou and McIntryre 2005);
- an adequate taxonomic knowledge and underlying models of response to anthropogenic features (e.g. the Pearson–Rosenberg and Rhoads–Germano models; Pearson and Rosenberg 1978, Warwick 1986, Diaz and Rosenberg 1995, Warwick and Clarke 1994).

The benthos is intimately linked to changes to the sedimentology and thus the hydrography, and in turn it has the potential to modify the sediment physical and chemical characteristics (e.g. Widdows *et al.* 2006). As the substratum is predominantly affected by all anthropogenic pressures, the soft bottom macrobenthos is the mainstay of environmental quality assessments and thus the main subject of the tools developed for the WFD (e.g. Camus *et al.* 2006, Quintino *et al.* 2006, Borja *et al.* 2007).

While there is continuous change in coastal and estuarine systems, distinctive benthic communities are recognised in relation to the dominant factors of depth and substratum type (Petersen 1915, Thorsen 1957). For example, shallow subtidal sands worldwide have a similar community though the precise species differ with biogeographical regions. Thus the Boreal communities of the north-east Atlantic differ in taxonomic composition, but not functioning, from the Lusitanian communities of the southern European coasts.

The benthos responds to environmental factors and gradients such as temperature, salinity, light, emersion and desiccation, oxygen content, nutrients, currents, and nature of substratum (Jones 1950, McLusky and Elliott 2004). Biotic factors are then superimposed on these, e.g. food supply, supply of colonising larvae, intra- and inter-specific competition and interaction (e.g. Wildish 1977). Gradients in these environmental factors are especially notable in estuaries but also in the shallow coastal areas.

In essence, benthic community structure is created by the interaction between water movements (hydrographic characteristics) and geomorphological processes, leading to sediment structure [particle size, stability, porosity, permeability, organic content, pH, redox potential (Eh), water content, aeration]. Community mediation of the physical environment (bioturbation, irrigation, faeces production, etc.) then occurs (e.g. Elliott *et al.* 1998). Thus, the functioning and composition of benthic invertebrate communities depends to a large degree on the variability and nature of the hydrographic, geomorphological and geological system.

Initial analysis of the benthic invertebrate literature (a total of some 66 papers) highlighted the key processes and pressures – see Table 3.1, which includes example references for each of the environmental factors, processes and pressures.

The environmentally changeable conditions in transitional waters favour a few species which, because of the high allochthonous and autochthonous organic material, often occur in large densities. Hydrodynamically low energy areas (e.g. estuaries) naturally accumulate high levels of organic matter through increased production and reduced breakdown. This affects the redox conditions in the sediment, which impacts on the benthos.

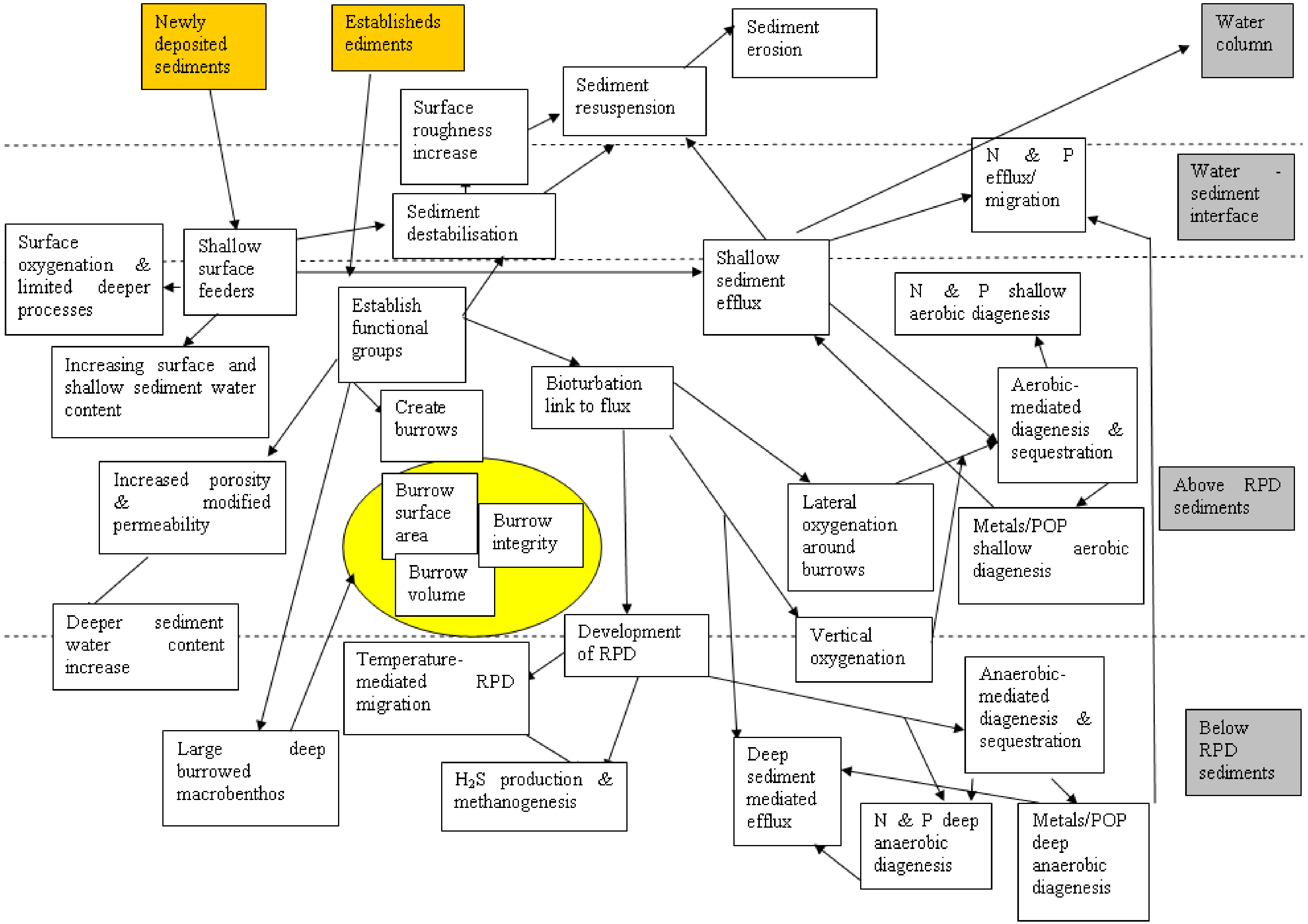
Within estuaries, there are well-defined gradients in diversity, abundance and biomass along the vertical and longitudinal axes (Ysebaert *et al.* 2003). Furthermore, multivariate analyses show a strong relationship between the macrobenthic assemblages and the predominant environmental gradients. Ysebaert *et al.* (2003) found that the most important environmental control was depth, which also reflected the hydrodynamic conditions (current velocities). The salinity gradient was the second most important.

Benthic community structure can be described mathematically and modelled in relation to salinity, depth, current velocities and sediment characteristics (e.g. Elliott and O'Reilly 1991, Ysebaert *et al.* 2003, Rosa-Filho *et al.* 2004), thus producing predictive models valuable for defining reference conditions under the WFD.

Benthic organisms are frequently subjected to natural and anthropogenic disturbance events caused by hydrodynamic processes moving sediment. Erosion–deposition cycles are influenced by storm and tidal events on the coast, as well as river discharge and tides in estuaries (e.g. Attrill *et al.* 1996, Attrill and Power 2000). The communities in muddy estuarine areas and in mobile coastal sand are accustomed to such perturbations (Elliott *et al*. 1998). Hinchy *et al.* (2006) investigated the survival of species once buried and concluded that some benthic species exhibit mechanical and possibly physiological adaptations that may allow them to survive deposition events of the magnitude commonly encountered in estuarine environments.

The biological modification of the substratum takes a number of forms (see Widdows *et al.* 2006, Rosenberg *et al.* 2007):

- Biodeposition occurs from suspension feeders and the production of pseudofaeces, leading to increased sedimentation and the build-up of beds (e.g. *Mytilus*, *Modiolus*).
- Bioturbation is the result of egestion, disturbance and turnover of the bed. This increases the 'surface' layer giving irrigation and increased oxygenation at depth and the creation of habitats suitable for further colonisation (e.g. *Nephrops* and Red Band Fish) (Mazik and Elliott 2000).
- Biomodification or bioerosion is the boring of hard substrata (by, for example, *Polydora*, *Petricola*), thus producing increased erosion and niches.
- Biostabilisation or bioprotection of sediments occurs through infauna (effect of spionid tubes), flora (effect of *Zostera* stems and rhizomes) and by micro-organisms (e.g. the effect of the microphytobenthos and mucopolysaccharide production) (Widdows *et al*. 1998a, Widdows *et al*.1998b, Widdows *et al*. 2000).



N = nitrogen; P = phosphorus; POP = persistent organic pollutant; H_2S = hydrogen sulphide

Figure 3.1 Relationships between physical, chemical and biological processes and their effects in soft sediments

3.3 Human pressures (hydrological and geomorphological)

Most human pressures in coasts and estuaries modify water flow patterns and/or sediment structure. Infrastructure such as bridges, harbours, weirs, etc. impede and modify water currents creating areas of erosion and deposition; dredging and dredged material disposal affect the bathymetry and bed sediments in both near-field and far-field areas. Such modifications are particularly high in transitional waters (McLusky and Elliott 2004).

In addition and also in restricted areas, water abstraction (e.g. for cooling systems) will create erosion areas and abstraction changes in the freshwater region will influence the salinity balance of an estuary. The latter then has a secondary influence on the community composition through the salinity tolerances of the benthos. Water abstraction, and thus the quantity of freshwater entering estuaries, will affect the upstream penetration by marine benthic organisms and the downstream penetration of freshwater and estuarine forms (McLusky *et al.* 1993). Natural patterns such as drought-induced low flows will also modify the estuarine benthic community (Attrill *et al.* 1996, Attrill and Power 2000).

The creation of areas with low hydrodynamic energy will lead to the accumulation of fine sediments, organic matter and contaminants – again special features in transitional waters. The resulting fine materials prevent water movement through the sediments, reducing oxygen and the breakdown of organic matter; this in turn adversely affects the benthic infauna.

Other pressures that affect substratum integrity and thus the benthos include fishing activities, coastal engineering projects and physical disturbance. For example, trawling, mechanical harvesting, mechanical dredging and aggregate extraction have a major impact on the coastal and transitional waters benthic communities (e.g. Hall and Harding 1997, Newell *et al.* 1998, MEMG, 2003, Smith *et al*., 2006).

The intimate links between physiography, hydrography and sediment physical and chemical structure is illustrated by the use of the sediment quality triad (Chapman and Wang 2001). This links sediment quality (as shown by chemical contamination) with the health of, and response by, benthic individuals (as shown by a bioassay) and the health of the community structure (Castro *et al*. 2006).

In water bodies of a high assimilative capacity, pollutants will be degraded, dispersed and assimilated; conversely, there will be an opposite effect in accreting and low energy areas. Hydrodynamically low energy areas such as sea lochs will accumulate organic matter; the consequences are exacerbated by high organic inputs (e.g. from aquaculture) in areas where the organic matter does not degrade. The benthos under these conditions shows a well-defined set of changes:

- loss of large-bodied, long-lived organisms;
- increase in small opportunist and pollution-tolerant forms;
- increased abundance and reduced species richness;
- a well-defined species–abundance–biomass model – these are termed the Pearson–Rosenberg or Rhoads–Germano models (Pearson and Rosenberg 1978, Warwick 1986, Diaz and Rosenberg 1995, Warwick and Clarke 1994).

There may also be a transition from suspension feeding to deposit and detritus feeding forms as shown in the Infaunal Trophic Index, the UK Infaunal Quality Index and the AMBI Biotic Index (e.g. Borja *et al.* 2007).

Paradoxically, the well-defined and understood response of the benthos to organic pollution shows features that are found naturally in the estuarine benthos – the high abundance of a few, small species that are highly tolerant to environmental stressors (McLusky and Elliott 2004). This may be termed the 'estuarine quality paradox' in that all metrics used to define anthropogenically stressed areas (e.g. AMBI, SAB and ABC curves) will indicate estuaries are stressed (e.g. Elliott and Quintino 2007). For example, Mucha *et al.* (2004) found that the macrobenthic community in the lower Douro estuary, Portugal, had low diversity (14 species), was dominated by small size opportunists and seemed to be controlled mainly by natural characteristics such as grain size distribution, metal contents (Al and Fe) and sediment depth.

4 Fish

4.1 Hydrological and geomorphological processes

Fish are one of the biological elements for transitional waters but not for coastal waters. This section therefore refers only to transitional waters as defined by Elliott and McLusky (2002) and McLusky and Elliott (2007).

There is an extensive literature regarding fish in estuaries [e.g. Blaber 2000, Elliott and Hemingway 2002 and the references therein, together with the Fishes in Estuaries Bibliography created by IECS as the result of the EU ESTFISH project).

This literature indicates that estuaries are important as:

- nursery, feeding, spawning and refuge areas;
- migration routes.

Each of these uses is subject to natural and anthropogenic hydro-geomorphological modifications. These dominant uses (Figure 4.1) have given rise to a large body of literature which describes the estuarine fish community in terms of guilds or ecological types based on the habits of the fish. Hence the community can be divided into:

- estuarine residents
- freshwater migrants
- marine juveniles
- other marine migrants
- diadromous species.

Pihl and Wennhage (2002) quantified the range of habitats within estuaries used by fish as:

- tidal freshwater areas;
- reed beds and saltmarsh (intertidal vegetation-dominated habitats);
- intertidal soft and hard substratum (e.g. mudflats and rock platforms);
- subtidal soft and hard substratum;
- intertidal and subtidal seagrass beds (intertidal and subtidal vegetated habitats);
- biogenic reefs (e.g. *Sabellariidae* reefs).

A further habitat – the pelagic part of the water column – can also be considered but is regarded here as a component of all the above habitats.

These habitats provide for fish at varying times during their life-cycle and for several functions which can be thought of as the dominant uses of the habitat.

Estuarine mud and sand flats play an important role as nursery and feeding areas for marine fish (Elliott and Dewailly 1995), with mudflats and saltmarsh habitats also providing important feeding grounds for fish species. The hydrology, geomorphology and biology are thus interlinked in providing habitat for fish (Figures 4.1 and 4.2).

Accordingly, any hydro-geomorphological changes to the river system adjacent to the transitional waters will affect the status of the diadromous species – especially species migrating through the estuary to reach breeding grounds. Thus a central feature of the estuarine fish community is its dependence on processes not only in the estuary but also at sea and in the freshwater systems (Elliott and Hemingway 2002).

The literature provided by the Environment Agency search provides an indication of perceived relevance of both the processes of estuarine and coastal systems and the pressures acting upon these systems (Table 4.1). However, frequency of appearance in the literature does not necessarily confer relative importance as the material reviewed is only a small proportion of scientific work relating to this subject (cf. the ESTFISH database).

Table 4.1 Key terms, processes and pressures highlighted in the fish literature

Environmental factors/ processes	**No. of references (from initial Environment Agency search)**	**Sample references (including from IECS search)**
Salinity	60	Abookire *et al.* 2000 Marshall and Elliott 1998
Temperature	35	Marshall and Elliott 1998
Habitat	28	Elliott and Dewailly 1995
Substratum	18	Claramunt *et al.* 2005
Depth	14	Demestre *et al.* 2000
Dissolved oxygen	13	Chesney *et al.* 2000
Vegetation as habitat	13	Weinstein and Balletto 1999
Oceanographic change (including EL NINO and upwellings)	11	Attrill and Power 2002
Light / turbidity / transparency	8	Able *et al.* 1998
Tidal variations	7	Edgar *et al.* 1999
Water chemistry (i.e. metals, hydrocarbons)	7	Elsdon and Gillanders 2006
pH	5	Singkran and Sudara 2005
Nutrients	5	Adams *et al.* 2003
Relief	4	Carr 1991
Stratification	3	Govoni 1988
Geomorphological characteristics	3	Saintilan 2004
Turbulence	1	Yanez *et al.* 2001
Flooding	1	Adams *et al.* 2003
Zooplankton levels	1	Singkran and Sudara 2005
Trophic sources	1	Islam *et al.* 2006
Pressures	**No. of references (from initial Environment Agency search)**	**Sample references (including from IECS search)**
Fishing (target and non-target organisms) – commercial and recreational	31	Blaber *et al.* 2000 Murawski *et al* 2005
Habitat loss	6	Rothschild *et al.* 1994

Climate change	6	Bailey *et al.* 1995
Coastal construction/ urbanisation	5	Able *et al.* 1998
Dumping and dredging	4	Lenihan *et al.* 2001
Sewage and pollution	4	Ramamurthy 1991
Aquaculture	2	Hartnett 1993
Flood defence measures	2	Zhou and Li 2004
Change in water quality	2	Singh and Raje 1998
Industrial activities	1	Chesney *et al.* 2000
Navigation	1	Chesney *et al.* 2000
Oil exploration	1	Chesney *et al.* 2000
Water abstraction	1	Jennings 1992
Artificial habitat creation	1	Collins *et al.* 1994

4.2 General biogeomorphology

Fish are influenced by environmental factors that produce the essential resources of space, shelter and food (Figure 4.1). Resource availability creates the conditions and niches to be occupied by the community; this is modified by internal functioning such as resource partitioning and competition.

The important environmental factors can be separated into two groups:

- hydrographical factors
- geomorphological factors.

The primary hydrographical factors are those within the water column (e.g. turbidity, stratification and water movements, tidal regime, mixing, wave exposure, freshwater flow), whereas geomorphological factors are those based around the land forms of the estuary and coast (e.g. physical shape, relief and substratum) including their sensitivity and dynamic nature in time and space. These then affect the secondary hydrodynamic and physico-chemical features such as salinity, temperature, dissolved oxygen (DO) and other aspects of the water chemistry of importance to the structuring of the estuarine fish community.

The dominant factors are salinity and temperature. Salinity influences the distribution of fish species in both estuarine (Marshall and Elliott 1998, Jaureguizar *et al.* 2003) and coastal (Abookire *et al.* 2000) environments (Table 4.1).

Salinity is important because it is linked to availability of food as well as the physiological tolerances of the fish species. For example, in Airake Bay, Japan, most of the copepod biomass is from an oligohaline species found in areas of low salinity; thus it is these areas that are believed to support nurseries for fish (Islam *et al.* 2006).

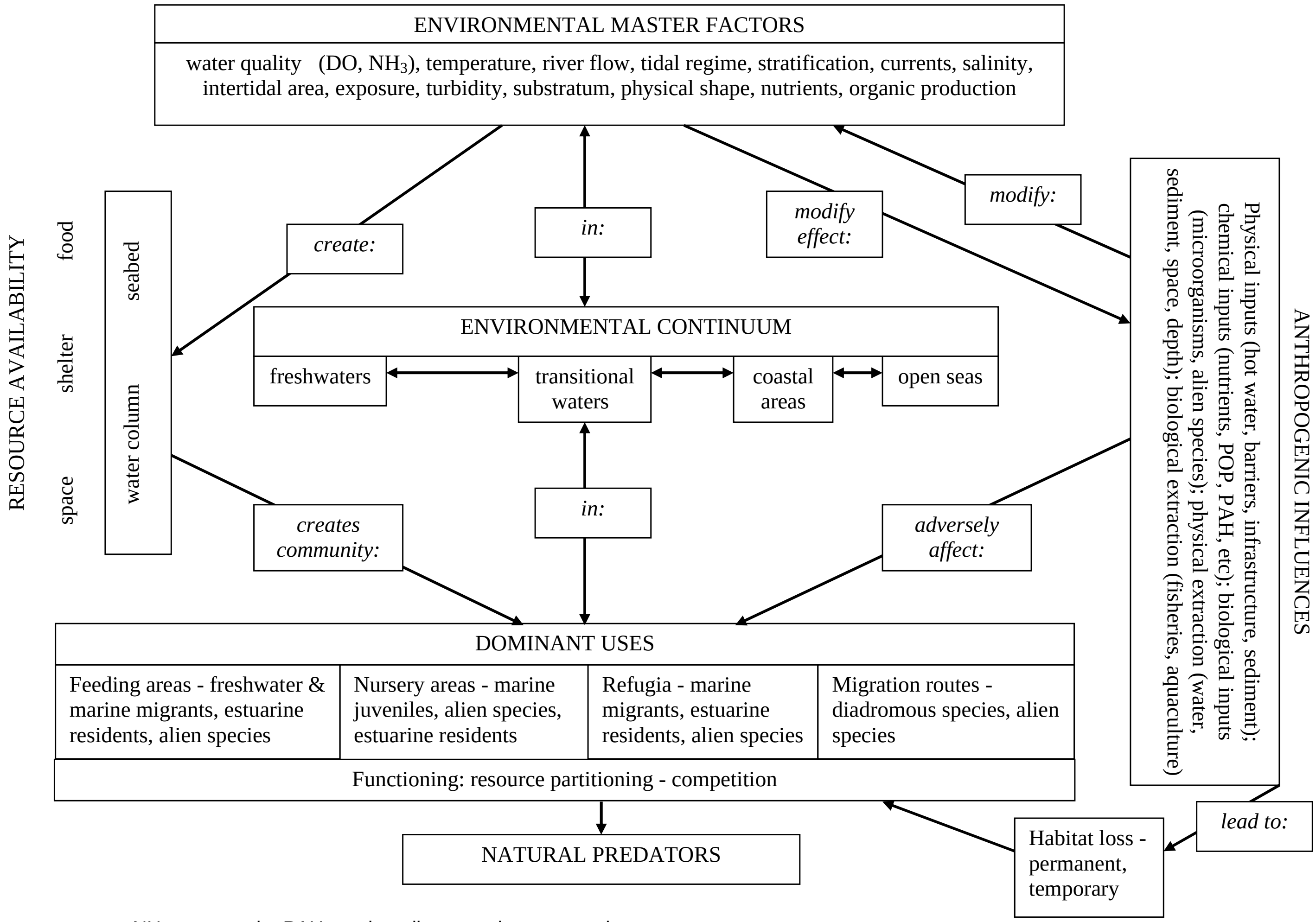
Temperature is also an important factor in the distribution of fish species. For example, in the Humber Estuary, temperature proved to be the best predictor of total abundance, while salinity influenced the species richness and total biomass (Marshall and Elliott 1998).

Geomorphological factors can influence fish diversity and abundance both directly and indirectly via influencing the hydrodynamics (of tidal regime and residence time). The estuarine entrance cross-sectional area, for example, can influence fish abundance as shown in fish landings in Australian New South Wales estuaries. Saintilan (2004) found that estuaries with intermittently open entrances are relatively poor in species diversity and abundance compared with permanently open entrance estuaries. This is because the closure of estuaries reduces opportunities for recruitment; it also causes salinity fluctuations detrimental to survivorship of many species (Pease 1999). This also illustrates the link between geomorphology and hydrology, and their influence on fish distribution.

Tidal regime – linked to the hydromorphological processes that create the overall hydrological regime (see section 3.1) in estuaries – influences the salinity and mixing regimes. However, it also affects the behaviour of fish, particularly the juvenile stages of marine fish. Spawning at sea by marine fish that use the estuary as a nursery area, and by estuarine residents, is followed by larval and post-larval migrations using selective tidal-stream transport (Melville-Smith *et al.* 1981, Jager 1999). Therefore, any disturbance of these current patterns will disrupt the delivery of young fish to the estuary.

The distribution of any species depends on its tolerance to a set of environmental factors, both those acting individually and in combination (e.g. Vorwerk *et al.* 2003). For example, as the result of hydromorphological influences that alter the salinity regime, euryhaline estuarine species such as flounder can tolerate large variability in salinity and so be successful in estuaries. In contrast, stenohaline marine species such as mackerel are restricted to the outer, fully saline part and a freshwater species such as roach will be restricted to the freshwater side of the tidal limit.

Thus, any anthropogenic influences on the hydrological variables will adversely affect the estuarine fish community. Accordingly, any change to the saline balance in the estuary, such as through increased abstraction of the freshwaters, will allow marine species to penetrate further and prevent freshwater species from penetrating into the estuary (McLusky *et al.* 1992, Drake *et al.* 2002, Strydom *et al.* 2002).



NH_3 = ammonia; PAH = polycyclic aromatic compound

Figure 4.1 Key processes affecting fish in estuarine and coastal waters

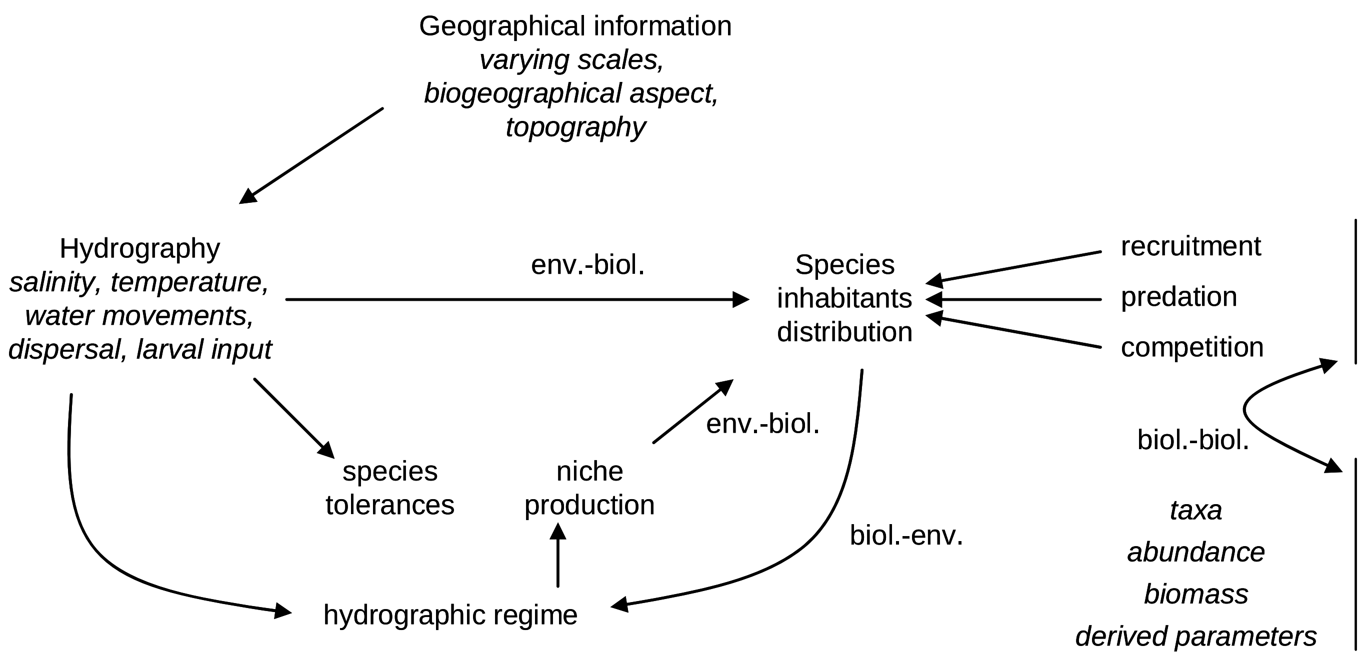


Figure 4.2 Influences of environmental factors on biological structure and features such as predator–prey relationships and competition which further modify that structure

4.3 Human pressures (hydrological and geomorphological)

There are many pressures or 'anthropogenic influences' (see Figure 4.1) that influence fish in transitional waters (Table 4.1). As shown by many texts (e.g. Elliott and Hemingway 2004 and the references therein), the main hydro-geomorphological pressures that influence the estuarine fish are:

- loss of sediment through dredging, which in turn affects the food and space resource;
- input of sediment through activities such as dredged spoil disposal can increase turbidity, thus affecting fish gills, and smother prey and feeding areas as well as liberating pollutants;
- permanent loss of habitat through land claim and building infrastructure, which changes the shape, hydrography and sediment patterns as well as removing feeding (e.g. mudflats) and refugia (e.g. saltmarsh) areas;
- the input and/or extraction of waters (e.g. by cooling systems or for irrigation), which in turn increases the salinity penetration and temperature regime, in turn affecting community structure because of the individual species' tolerances (cooling water extraction also removes fish directly through impingement);
- the presence of permanent barriers (e.g. weirs and storm surge barriers), which control water levels and impede flow as well as impeding diadromous fish migrations;
- the creation of temporary barriers (such as via poor water quality in upper estuarine areas), which will impede diadromous fish migrations and the use of upper areas for feeding and refugia.

Other major activities such as fishing also affect the richness, population structure and biomass of the fish communities, whereby each method of fishing has impacts on ecosystem structure and functioning (Blaber 2000). Some of fishing methods also impact on the hydrogeomorphological features of sediment structure, water quality and current movements. However, the greatest impact is the loss of the biological resource, for example the abundance of fish in estuarine and coastal areas as shown by an apparent decrease in large predatory fish biomass of 90 per cent since the onset of industrialised fishing (Myers and Worm 2003). In addition, even ancillary pressures (e.g. disturbance and sedimentary compaction as a result of bait digging and prawn pumps) affect the integrity of the system (Wynberg and Branch, 1994).

These pressures act to adversely change hydrological and/or geomorphological processes, thereby changing habitat use. Anthropogenic influences also lead to changes in relationships within and between species, which can again disrupt the balance of the habitat (Figure 4.2).

Hence, the creation of either physical barriers (e.g. weirs or land claim) or chemical barriers (e.g. poor oxygen conditions) will affect those links. Low oxygen conditions are created by low current speeds, high turbidity, the input of organic matter from the catchment and also its production *in situ* (see Chapter 2). The effects of these barriers can be to create permanent habitat loss or temporary habitat loss; in the case of the latter, fish usage is impaired by poor habitat (water) quality though this is reduced if the cause of the stressor, such as an organic rich discharge, is removed. In addition, the introduction of physical barriers to hydromorphological processes, such as engineering works, can affect the delivery of spawning populations and/or recruits, thus adversely influencing the population viability.

The effects of permanent and temporary habitat loss (Elliott and Cutts 2004) on estuarine fish occur in all industrialised estuaries. The determination of HMWB status under the WFD has centred on physical changes that prevent good ecological status being attained (Hull *et al.* 2004); in particular, this includes coastal constructions. For example, fish abundance and species richness were found to be lower under large piers than in open water habitats (Able *et al.* 1998). Growth rate comparisons indicated that the under-pier fish were not feeding, possibly due to a lack of suitable prey or light penetration. Thus, this influence transforms the previous habitat via a change in the prey community (a biology–biology shift) or a change in the light regime (a process shift).

As indicated above, temporary habitat loss results from anthropogenic water quality deterioration (pollution) and this affects the estuarine residents as well as migratory salmonids (Pomfret *et al*. 1991). Point source impacts such as sewage plumes can cause significant degradation of adult and larval habitat; for example, a higher amount of deformed larvae were found in waters around Sydney that are influenced by multiple sewage outfalls than those that are not (Kingsford *et al.* 1996). Similarly, Singh and Raje (1998) found that in Versova, Bombay, there were increasing incidents of fish mortality together with a depletion of fish catch in a creek near the sources of organic and industrial pollution. These examples illustrate the influences of water quality barriers as the areas were anoxic, while dissolved oxygen in adjacent areas was up to 4 ml/litre, the pH of the creek was always in the lower range and there was a depressed salinity.

Temporary habitat loss through poor water quality occurs naturally in many estuaries with the production of seasonal dissolved oxygen sags in the upper parts of estuaries, the freshwater–seawater Interfaces and the turbidity maximum zones (Pomfret *et al*. 1991, McLusky and Elliott 2004). However, anthropogenic organic discharges exacerbate those sags, producing areas unsuitable for fish as shown by the removal of the Thames Estuary fish community up to the 1960s. Here, the added influx of freshwater by way of domestic and industrial discharge has changed the hydromorphology of the system, the dilution potential of the area, its carrying capacity and its assimilative capacity, and thus the suitability of this habitat for marine fish.

The interference of river flow and migration routes by dams and weirs is an increasing problem, especially in areas of high water abstraction. The recent papers by Sá *et al.* (2006), Veiga *et al.* (2006) and Chícharo *et al.* (2006) indicate the effects of an upstream dam on fish populations of the Guadiana estuary and adjacent coastline. The community has been adversely affected by the major interference with diadromous migrations and the removal of wetland areas for feeding and breeding.

5 Saltmarshes

5.1 Hydrological and geomorphological processes

Intertidal mudflats frequently show annual and inter-annual variations in surface elevation, reflecting phases of surface erosion and accretion. However, saltmarshes are characterised by more stable surfaces that build up incrementally through the tidal frame.

The dynamic boundary between the two habitats is related to wave climate as wave-induced stresses determine the survival of saltmarsh seedlings; storms may extend mudflat at the expense of saltmarsh with marsh recovery in inter-storm periods. On permanently vegetated surfaces, wave height reductions of up to 50 per cent within the first 20 metres of saltmarsh have been reported (Möller *et al.* 1999, Bouma *et al.* (2005). This is in response not only to the 'roughness' induced by complex vegetation canopies but is also due to the presence of irregular marsh surface topographies punctuated by creeks and surface depressions (or 'saltpans').

However, there must be a threshold where energy dissipation is overcome with excess energy being available for surface erosion and marsh edge retreat; this threshold may be triggered by particular combinations of wave height and water depth. This may help explain phases of saltmarsh erosion (which are not easily explained by rising sea level alone) and may quantify suggestions of links between inter-decadal variations in wind strength and dominant wind direction and switches from saltmarsh stability to areal loss (van der Wal and Pye 2004).

A fundamental control on marsh development is the distinction between allochthonous systems, driven by the trapping of externally derived inorganic sediments, and autochthonous systems, where the primary input is the *in situ* accumulation of organic materials.

In allochthonous systems, sediments are often introduced through bifurcating intertidal channel networks (or 'creeks') and sedimentation patterns on individual tides show strong distance-from-creek relationships (French and Spencer 1993). In meso- to macro-tidal settings, and over annual and longer timescales, sedimentation patterns are strongly controlled by inundation frequencies and there is a strong inverse relationship between substrate elevation and surface height change. In addition, there may be a 'tidal subsidy' of mineral cycling, nutrient transport and waste product removal. All these linkages are less well-developed in micro-tidal settings where non-tidal inundations, storms and extreme events can override these controls (Reed 2002). These relationships are also much less clear in autochthonous systems (Morris et al, 2002) where the environmental controls on surface (and particularly below-ground productivity) are poorly understood.

5.2 General biogeomorphology

Traditionally, geographical variations in saltmarsh vegetation communities, and their variation with elevation, have been used to form the basis for resource inventories and conservation strategies. This recognises their importance in exporting nutrients to sustain nearshore productivity (Dame *et al.* 1991) and their support of *in situ* aquatic food webs.

But in the last decade, such approaches have been balanced by a realisation of the importance of physical controls in determining saltmarsh character and extent. In the context of global environmental change, saltmarshes are now also recognised as being of biogeochemical importance in sequestering carbon (Chmura *et al.* 2003).

At the continental scale, the nature and extent of saltmarshes are determined by climatic, plate tectonic and biogeographical controls (Adam 2002). Marshes are particularly characteristic of temperate latitudes, although they co-exist with mangrove in the Tropics; high latitude marshes are species-poor. On the active, sediment-deficient Pacific plate margin of North America, saltmarsh forms only a fragmented, narrow fringe to estuaries and fjord coastlines whereas on the Atlantic coast passive margin – where sediment availability and accommodation space is high and where shelf hydrodynamics favour a flood-dominated regime and thus onshore sediment transport – marshes are continuous over large distances.

There are similar contrasts between the extensive (prior to human reclamation), sediment-rich marsh systems of the north-west European shelf seas supplied by the reworking of glacial fine sediments and the rocky Mediterranean shoreline where coastal wetlands are restricted to deltaic outlets.

On the eastern seaboard of the USA, saltmarshes sit relatively low within the tidal frame and are characterised by tall stands of *Spartina* grasses, which remain emergent at high tide, whereas many north-west European marshes sit much higher in the tidal frame, are less frequently inundated and comprise either a grass turf or low vegetation canopy which is completely submerged on spring tides (Allen 2000).

Regionally, there are five sets of external controls:

- variations in nearshore suspended sediment concentrations and the nature of fine sediment supply;
- tidal regime;
- wave climate;
- topographic setting;
- sea level history.

When all these controls are favourably aligned, saltmarsh vertical growth and lateral extension can be considerable and rapid. Intrinsic controls include sediment autocompaction, and the sediment trapping and binding role of halophytic vegetation.

At local scales, physical–ecological relationships are mediated by local flooding characteristics (Bockelmann *et al.* 2002) and biogeochemical dynamics including:

- within-marsh variations in nutrient availability (particularly nitrogen);
- soil moisture (Silvestri *et al.* 2005);
- salinity variations (Huckle *et al.* 2000);
- clay mineralogy and its relation to soil chemistry.

These controls are particularly critical on high marshes vegetated by perennial grasses and herbs. Here the addition of inter-specific competition can lead to a mosaicing of species in the vegetation canopy.

Marshes are also characterised by competition between individuals and predators (Sarda et al. 1996, Moon and Stiling 2002) and between plants and microbial communities; these trophic interactions facilitate species diversity. Large herbivores, such as birds and introduced grazers, also impact on the species diversity, structure and vegetation distribution patterns (Esselink *et al.* 2000).

5.3 Human pressures (hydrological and geomorphological)

Sequences of saltmarsh deposits show that saltmarsh development is intimately related to sea level change and many marshes have exhibited persistence in the face of sustained, millennial sea level rise. Mathematical modelling suggests that very high rates of near-future sea level rise will be required to 'drown out' marshes, although the effects of greater water depths over marshes may lead to ill-defined changes in vegetation community structure.

There is, however, a need to give greater consideration to the possible impact on saltmarsh viability of:

- changing tidal conditions (tidal range, frequency of extreme tidal levels);
- changes in wind–wave climate (weather patterns, storminess, storm surge frequency) consequent upon climate change.

Furthermore, marsh response to sea level rise requires adequate sediment supply. Declines in sediment supply from river engineering works and coastal cliff protection have characterised North American and north-west European coasts over the last 200 years – and Mediterranean coast for much longer.

Saltmarsh vegetation is susceptible to increased nutrient inputs and eutrophication (Bertness *et al.* 2002). It is also sensitive to pollutants – particularly heavy metals, hydrocarbons and herbicides.

Many of these impacts are indirect and the effects are wide-ranging and long-lasting. As well as reducing the extent of marshes, land claim in estuaries has resulted in the more rapid passage of the flood tide up-estuary, increasing erosional pressures on remaining marshes, which are unable to retreat landward as they are backed by sea defences. Such processes have been exacerbated by channel dredging and large-scale removal of intertidal clay for industrial use. Where defence lines have breached, marsh redevelopment has often been poor, as a result of poor propagule availability (Wolters *et al.* 2005) and low, poorly-drained surfaces from agricultural use (Portnoy 1999, Williams and Orr 2002).

6 Seagrasses

6.1 Hydrological and geomorphological processes

Figure 6.1 illustrates the key linkages between seagrass beds (i.e. the vegetation itself) and physical, chemical, and biological elements of the surrounding water body.

Seagrass ecosystem presence and 'health' (growth) can be seen as the result of an overcoming potential physical and physiological stressors at sites with suitable hydro-morphological characteristics and water quality. Hydrological and geomorphological process linkages are identified in blue (dark shading) in Figure 6.1.

Although the survival and growth of seagrasses depends on a wide variety of factors, the literature identifies light availability (and thus, indirectly, water depth and turbidity/ suspended sediment concentration) as the main controlling factor (see, for example, Bintz and Nixon 2001, Krause-Jensen *et al.* 2005). Krause-Jensen *et al.* (2005) make the interesting point that the type of water body (e.g. open coast or estuarine) affects the significance of this relationship, i.e. in open water bodies where waters are well-mixed and less turbid, seagrasses are less affected by water depth (light penetration) than in more enclosed and less well-mixed (e.g. estuarine) water bodies.

However, the literature also recognises that the relationship between morphology (water depth, exposure) and seagrass growth/sustainability is affected by secondary factors, in particular salinity (of critical importance in estuarine settings) (Thom *et al.* 2003, van Katwijk *et al.* 1999, Krause-Jensen *et al.* 2005) and wave/tide driven current stress (of greater importance on open coasts) (Fonseca and Bell 1998, Turner *et al.* 1999, van Katwijk and Hermus 2000, Granata *et al.* 2001).

A strong feedback between the biological factors (e.g. species composition, growth forms, density) and hydrodynamic processes (e.g. tidal flow structure, wave energy) exists, with dense seagrass meadows significantly attenuating water flow (Koch and Gust 1999, Peterson *et al.* 2004). This feedback may thus also lead to reduced suspended particle concentrations (due to calmer conditions) inside seagrass meadows (Granata *et al.* 2001), resulting in a positive feedback on vegetation growth. However, the published literature is heavily focused on the study of Eelgrass (*Zostera marina)* and other *Zostera* species of seagrass, which dominate North American and European coasts [52 (i.e. 33 per cent) of all 156 references from the literature search specifically relate to *Zostera* spp.). But the literature search also identified a series of studies on other species, of which only *Halodule wrightii* is found in the North Atlantic region. Others (*Posedonia oceanica and Cymodocea nodosa*) are found in the Mediterranean Sea region, but the remainder (*Syringodium filiforme, Heterozostera Tasmanica, Thalassia testudinum, Halophila ovalis, Amphibolis* spp*.* and *Cymodocea nodosa)* are not typical of European or North American waters. Some key insights into the linkages between seagrasses in general and hydro-morphological factors have, however, been identified through studies of these species and the bibliography thus remains global in scope.

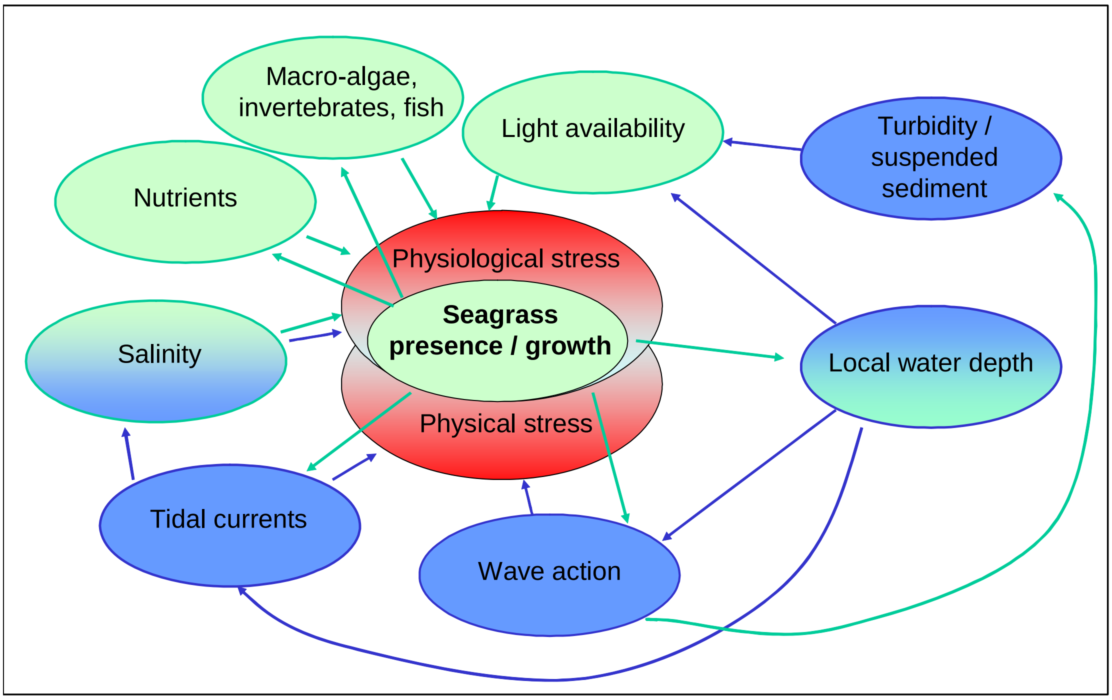


Figure 6.1: Diagram illustrating the key hydro-biogeomorphological linkages in seagrass ecosystems as identified by the literature review

6.2 General biogeomorphology

Seagrass ecosystems are characterised by an intricate web of biogeomorphological relationships as illustrated in Figure 6.1 (biogeomorphological linkages highlighted in green). If light availability is not limited by suspended sediment (turbidity) and physical disturbance does not exist, seagrass growth is closely linked to subtidal geomorphology (as water depth controls light availability in these circumstances) (Fonseca and Bell 1998) and is affected by:

- nutrient concentrations (Jensen and Bell 2001, Deegan *et al.* 2002);
- salinity (van Katwijk *et al.* 1999);
- inter-species competition (Hahn 2001);
- epiphytes, fish and invertebrates (Asmus and Asmus 2000);
- birds (Nacken and Reise 2000).

A detailed study of depth limits of seagrass growth in European waters was conducted by Krause-Jensen *et al.* (2005) and showed an average water depth of 1.0–8.5 m as typical for eelgrass (*Zostera marina*). However, these authors also noted that depth limits have fallen over the past 100 years or so (from 4.3–8.5 m to 1.0–5.4 m), indicating an increase in water turbidity (i.e. a decrease in light penetration due to factors such as increased suspended sediment in the water column).

Important biological functions of seagrasses include their impact on the nutrient budget of the water body itself and on global biogeochemical cycles. Intense nitrogen fixation activity generally takes place in the rhizosphere sediments of seagrasses; a mutualistic or symbiotic association between seagrasses and heterotrophic nitrogen fixers in the rhizosphere is thought to exist, although the literature search revealed little quantitative information on this role (Jensen and Bell (2001).

Seagrasses also affect associated macro-algal communities (Pinckney and Micheli 1998), and their importance as spawning and feeding grounds for fish and invertebrate fauna has also been documented.

The general biogeomorphology of seagrass beds is thus closely linked to the hydrological and geomorphological processes identified above, although not many studies address these highly indirect and complex 'cascading' linkages.

6.3 Human pressures (hydrological and geomorphological)

Given the close linkage between hydrological, geomorphological and biological factors that control seagrass growth, the sustainability of seagrass ecosystems has been brought into question on coasts that are under the influence of both direct and indirect human influences (13 per cent of the articles reviewed made reference to actual or potential anthropogenic pressures or impacts).

Indirect human impacts include climatically induced global sea-level changes (mediated by local and regional land level changes) that may increase water depths and thus reduce light penetration, creating physiological pressures on the vegetation communities (see Figure 6.1).

Changes to estuarine tidal dynamics (e.g. increasing tidal currents and submersion depths), salinity levels and fish populations (and thus the impact of grazing), as well as eutrophication, also reduce growth conditions to sub-optimal levels. The latter (in particular high nitrogen loads in estuarine waters) have been shown to negatively affect the health of seagrass (*Zostera* spp.) indirectly through encouraging algal growth and thus diminishing light levels (Hauxwell *et al.* 2003).

Direct negative human impacts and pressures have been identified in the literature as resulting from:

- marine construction activities (Burdick and Short 1999);
- heavy metal pollution (Schlacher-Hoenlinger and Schlacher 1998);
- pharmaceutical use of seagrass species (Kim *et al.* 2004);
- boat traffic via propeller scarring (Uhrin and Holmquist 2003);
- general physical disturbance on the linkage between infauna, epifauna, and seagrass vegetation.

There is, however, a need to identify thresholds that control recovery and/or continued decline/fragmentation of seagrass beds in response to disturbance and stress. Several authors suggest that the vulnerability of seagrass ecosystems to stress increases markedly with increased fragmentation of seagrass beds (e.g. Turner *et al.* 1999, Jensen and Bell 2001).

7 Macroalgae

7.1 Hydrological and geomorphological processes

Abiotic factors that control the composition, structure and spatial variation among macroalgae communities are well known. They include:

- salinity
- depth
- wave exposure
- emersion.

Most of these influencing factors are closely related to hydromorphology and geomorphology, but not hydromorphological or geomorphological processes *per se*. For example, water depth characteristically causes vertical zonation of macroalgal species because it is the main control of light penetration (e.g. Kautsky, 1993, Goldberg and Kendrick 2004, Eriksson and Bergstrom 2005). Light is essential for photosynthesis, so any factor that limits light availability (e.g. turbidity and canopy cover) affects macroalgal communities (Kautsky 1993, Hurd 2000, Eriksson and Bergstrom 2005, Eriksson *et al*. 2006). But whereas light penetration limits maximum depth of macroalgae, wave action (and other physical disturbance) and emersion usually determine the upper distribution boundary (Kautsky 1993, Hurd 2000, Eriksson and Bergstrom 2005, Eriksson *et al.* 2006).

Macroalgae are usually the main producers in coastal ecosystems, but their production is controlled by a variety of biotic and abiotic factors (see Hurd 2000 and references therein) including:

- light (amount and quality);
- nutrients;
- temperature;
- water movement;
- competition (both inter- and intra-);
- grazing pressures.

In addition to influencing the concentration of suspended material, water motion impacts macroalgae production in other ways. For example, nutrient uptake is negatively affected by increasing current velocity and waves can physically remove herbivores and the algae itself (see Hurd 2000).

In transitional waters, salinity (influenced by freshwater flow) is considered to be the main factor controlling diversity, although availability of suitable substratum for attachment is also important (see Middelboe *et al.* 1998). Salinity can also control macroalgae distribution in seas or coastal areas where species distributions can differ in responses to salinity gradients, e.g. the Baltic Sea (see Malm and Iseus 2005).

Direct effects of hydromorphology include:

- water current speed
- water flow dynamics
- wave exposure.

See for example, Hawes and Smith 1995, Pihl *et al.* 1999, Mistri *et al.* 2002, Jonsson *et al.* 2006).

Unsurprisingly, strong wave action causes physical damage to macroalgae (e.g. Hawes and Smith 1995) and this is magnified in areas where algae are immersed and prone to desiccation (e.g. Haring *et al.* 2002). Flow dynamics can control macroalgal populations; for example the distribution of the free-floating *Ulva* sp. is determined by advective transport (Salomonsen *et al.* 1999). Furthermore, water current impact (usually expressed as shear or shear stress) can determine the stability of macroalgal communities (e.g. Hawes and Smith 1995, Salomonsen *et al.* 1999).

Although a wide range of species have been reported in the literature, the most common species investigated (particularly in terms of European transitional and coastal waters) are from the genera *Fucus*, *Enteromorpha* and *Ulva* (respectively comprising 17, 13 and 11 per cent of the references used for this review).

7.2 General biogeomorphology

Compared with hydrological impacts on macroalgal communities, there are considerably fewer studies describing biogeomorphology. However, the general biogeomorphology of macroalgal communities is closely linked, albeit indirectly, to hydrological and geomorphological processes.

The effect of nutrients is most commonly reported (comprising 22 per cent of the articles reviewed here), although light availability (15 per cent) is clearly also important.

Biological interactions of macroalgae include:

- grazing by herbivores;
- habitat provision for fauna (e.g. amphipods) (e.g. Huang *et al*. 2004);
- use by juvenile fish (e.g. plaice) as nursery grounds (Wennhage and Pihl 1994).

In particular, grazing (by, for example, limpets) can be prolific and determine the spatial distribution of intertidal macroalgae (e.g. Boaventura *et al.* 2002, Jonsson *et al.* 2006).

Another important interaction is inter-specific competition, in particular the shading of smaller species by the larger, canopy forming species (see Eriksson *et al.* 2006 and references therein).

On a global scale, latitude can be important and there is strong research interest in ultraviolet effects in polar species of algae (e.g. Michler *et al.* 2002).

7.3 Human pressures (hydrological and geomorphological)

Essentially, any anthropogenic pressure that influences the hydrology or geomorphology of transitional waters is likely to be a relevant pressure to macroalgal communities. This is because it is likely to impact on several of the variables outlined above that affect such communities.

Hence, flood defence measures that deliberately target water movement can impact on macroalgal communities. For example, an installation of a flood gate in an Italian lagoon disrupted the hydrological regime sufficiently to significantly alter macroalgal cycles.

Similarly, the extra waves created by ferries have been demonstrated to increase *Enteromorpha* growth in rock pools exposed to extra waves (see Ostman and Ronnberg 1991). Furthermore, increased wave action caused by ferries and recreational boating can lead to decreases in macroalgal cover and diversity (Eriksson *et al.* 2004). In addition to increased mechanical damage due to wave exposure, the increase in wave action led to increased turbidity which negatively impacted algae in deeper water (Eriksson *et al.* 2004).

Another anthropogenic hydrological pressure is thermal discharge, usually expelled as cooling water from power stations. In addition, increased localised temperature from such discharges have been shown to allow colonisation by foreign (so-called ‘alien’) species, which may have a competitive advantage over native species (Critchley *et al.* 1997). Almost 25 per cent of the papers reviewed here referred directly to man-made impacts.

Perhaps the most widespread anthropogenic impact affecting macroalgae is pollution, which is again closely linked to those hydromorphic processes that carry the pollutants to the populations in question. Given that many major cities are built on estuaries and that transitional waters act as conduits between the land and the sea, macroalgae can be exposed to a variety of pollutants. For example, trace metals negatively impact macroalgae (e.g. Sawidis *et al.* 2003), whereas sewage – with its associated concentration of nutrients – can lead to increases in macroalgal abundances.

Finally, anthropogenic influence on global climate can impact on macroalgal communities. Most obviously, rising sea levels can affect macroalgal distribution by altering water depth, which affects light penetration as described above. In addition to sea level rise, climate change may lead to increasing frequency of storm events, leading to more frequent exposure of macroalgae to severe wave action.

8 Conclusions/ recommendations

8.1 Interactions between biological elements and hydro-geomorphology

The literature reviews confirmed:

- overlaps between all the biological elements in question;
- the interlinked nature of hydro-geomorphology processes and ecology.

In particular, this reflects the highly dynamic and complex nature of estuarine and coastal environments as well as the bentho-pelagic coupling. For example, although pelagic fish will mainly be affected by pressures in the water column and demersal (bottom-dwelling) fish will mainly be affected by such pressures on the substratum, a reduction in water quality may adversely affect organisms associated with the water column and/or the substratum. Similarly, the impact of trawling will not only have an impact on the demersal target species, but will also have an impact on the benthic invertebrates living within the substratum. Many anthropogenic pressures such as nutrient inputs, dredging and water abstraction will influence phytoplankton, pelagic fish, demersal fish and benthic invertebrates and plants, as well as water and substratum quality.

Ecohydrology is an approach that aims to understand, quantify and explain the relationships between hydrological and biological processes and dynamics throughout the freshwater-estuarine-coastal-open sea continuum (Chícharo and Chícharo 2006).Biogeomorphology aims to understand the two-way interplay between geomorphology and ecology. Together, these two sub-disciplines of earth and ecological sciences will enable us to develop the evidence base for hydro-geomorphology (biological responses for the WFD). Furthermore, hydro-geomorphology aims to increase the ability to manipulate such processes in aquatic systems such that the systems can accommodate human activities.

The brief reviews in this report have taken information from the large body of knowledge available for the relationships between hydro-geomorphology and the six biological quality elements required by the WFD. As shown here, there is a good body of qualitative data but, for some aspects, an insufficient set of quantitative data is available. For example, numerical models of responses by the biota to changes to hydromorphological and other physico-chemical factors are not yet fully quantitative. However, there is:

- confidence in the knowledge of the main underlying processes and the basic ecological structure and functioning;
- a good case history indicating the effects of hydro-geomorphological pressures on the biological elements.

Many of the comments in this report are based on the wider background knowledge and expert opinion of the authors as more time than available was necessary to carry out a more comprehensive literature review. For example, further resources would allow the ESTFISH database to be both brought up to date and interrogated further. Similarly, the wealth of benthic and plankton literature requires a more systematic assessment. For example, a recent issue of *Estuarine Coastal and Shelf Science* (Volume 70, Issues 1-2, October 2006) contains 29 research papers on the ecohydrology/ biogeomorphology approach to the effects of a dam system and other geomorphological changes in estuaries and on coasts.

The review has shown that the severity of impact is determined by:

- the level of anthropogenic influence (e.g. the level of nutrient loading in the freshwater input);
- the hydrology of the area (e.g. the water circulation of an estuary);
- the geomorphology of the area (e.g. the exposure of a coastal area).

It is important to understand, as illustrated in the case evidence here, that these processes, pressures and effects are highly interlinked and therefore require a holistic, ecosystem approach to addressing issues in such an area (Elliott *et al.* 2006). The features of the biological elements responding to the hydromorphological pressures (e.g. species richness, community composition, functional attributes, abundance and the presence of species indicative of stress) are well-understood and well-quantified. Hence the tools developed for determining any deviation from reference conditions for biota are well-founded in the literature.

The regulatory powers required to control those activities responsible for hydromorphological modifications are extensive (Boyes *et al.* 2003), although they cross various legislative instruments (e.g. the Coastal Protection Act 1949, the Water Acts and the Food and Environmental Protection Act 1985). Those measures that do already exist are performed by a number of bodies such as environmental protection agencies, nature conservation bodies, the fisheries bodies, local authorities and governmental organisations. New regulatory powers would need to be considered for many of these sectors for the proper management of hydromorphological pressures.

8.2 Recommendations

What do the review findings mean for the strategic assessment and subsequent work on regulatory measures for TraC hydromorphology?

1. The references on hydromorphological pressure impacts need to be reviewed more thoroughly to:
   - determine the certainty of evidence for creating measures;
   - analyse which sectors are responsible for each pressure–biotic response,
   - identify which pressure–response linkages require further research.

   This is required for both direct and indirect relationships between hydromorphological pressures and biota.
2. Indirect hydro-geomorphological process–biota relationships need to be better understood so that the important role that hydro-geomorphological processes play in wider issues such as eutrophication, diffuse pollution and contamination can be highlighted. Further work is needed to demonstrate the importance of these processes for managing human pressures.
3. These more thorough reviews can be used to highlight the relative paucity of information on hydro-geomorphological processes and pressures. Although the literature search criteria were tightly defined in relation to hydro-geomorphological

processes and pressures, most papers focussed more on other factors. This is symptomatic of human interest and concern over the ultimate response (e.g. rates/causes of saltmarsh loss) rather than on understanding the sediment requirements of saltmarshes and what management interventions might be employed to maintain these levels. Thus, this science area has received considerably less attention that others in the past decades and as such, our knowledge is less certain.

4. More work is required before preliminary recommendations on programmes of measures for hydromorphological pressures can be made. In the short-term, further analysis of the human pressure–hydro-geomorphology–biotic response literature is required. In the medium-term, a concerted research programme will be required so that adaptive management measures can be implemented as part of the second and third WFD cycles.

5. Improving the evidence base of both process and pressure links through further analysis of a wider body of literature such as the ESTFISH database at the University of Hull is recommended.

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List of abbreviations

BQE	biological quality element
CCRU	Cambridge Coastal Research Unit, Cambridge University
Defra	Department for Environment, Food and Rural Affairs
Eh	redox potential
FSI	freshwater–seawater interface
HMWB	heavily modified water body
HNDA	high natural dispersing areas
IECS	Institute of Estuarine and Coastal Studies, University of Hull
RBD	River Basin District
RPD	redox potential discontinuity
TraC	transitional and coastal [waters]
WFD	Water Framework Directive
WoS	Web of Science

Appendix 1 – Search strings used by the Environment Agency

GENERAL BIOGEOMORPHOLOGY			
Biota	**Search String**	**Data-bases*, ****	**No. articles found*****
Phyto-	TI=((phytoplankton) and TS=(intertidal or littoral or coast* or estuar*)) not TS=(freshwater or terrestrial or tropical or lake* or stream*) and TS=(biogeomorph* or ecogeomorph* or hydromorph* or hydro-morph* or hydrogeomorph* or hydro-geomorph* or ecohydrol* or hydroecol* or geomorph* or morphological) not TS=((freshwater or terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff* or histolog* or genetic* or deformit* or molecular* or phylogen*) or TS=((morphol*) same (stasis or deform* or abnormal* or larva* or feed* or body*)))	WOS Biosis CAB	24
Benthic	TI=('benth* invertebrat*' or 'macrobenth* communit*' or 'benth* communit*') not TS=(freshwater or terrestrial or tropical or lake* or stream*) and TS=(biogeomorph* or ecogeomorph* or hydromorph* or hydro-morph* or hydrogeomorph* or hydro-geomorph* or ecohydrol* or hydroecol* or geomorph* or morphological) not TS=((freshwater or terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff* or histolog* or genetic* or deformit* or molecular* or phylogen*) or TS=((morphol*) same (stasis or deform* or abnormal* or larva* or feed* or body*)))	WOS Biosis CAB	4
Fish	TI=((fish*) and TS=(intertidal or littoral or coast* or estuar*)) not TS=(freshwater or terrestrial or tropical or lake* or stream*) and TS=(biogeomorph* or ecogeomorph* or hydromorph* or hydro-morph* or hydrogeomorph* or hydro-geomorph* or ecohydrol* or hydroecol* or geomorph* or morphological) not TS=((freshwater or terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff* or histolog* or genetic* or deformit* or molecular* or phylogen*) or TS=((morphol*) same (stasis or deform* or abnormal* or larva* or feed* or body*)))	WOS Biosis CAB	41
Saltmars	TI=(saltmarsh* or (salt same marsh*) or (coastal same wetland*) or (tidal same wetland*) or salting*) and TS=(biogeomorph* or ecogeomorph* or hydromorph* or hydro-morph* or hydrogeomorph* or hydro-geomorph* or ecohydrol* or hydroecol* or geomorph* or morph* or geoecol* or hydrolog*)	Wos (1996-2006)	172
Seagras	TI=(seagrass* or eelgrass* or zostera or phragmite*) not TS=(freshwater or terrestrial or tropical or lake* or stream*) and TS=(biogeomorph* or ecogeomorph* or hydromorph* or hydro-morph* or hydrogeomorph* or hydro-geomorph* or ecohydrol* or hydroecol* or geomorph* or morphological) not TS=((freshwater or terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff* or histolog* or genetic* or deformit* or molecular* or phylogen*) or TS=((morphol*) same (stasis or deform* or abnormal* or larva* or feed* or body*)))	WOS (1970-2006) Biosis CAB	63

	TI=(seagrass* or eelgrass* or zostera or phragmite*) not KW=(freshwater or terrestrial or tropical or lake* or stream*) and KW=(biogeomorph* or ecogeomorph* or hydromorph* or hydro-morph* or hydrogeomorph* or hydro-geomorph* or ecohydrol* or hydroecol* or geomorph* or morphological) not KW=((freshwater or terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff* or histolog* or genetic* or deformit* or molecular* or phylogen*) or KW=((morphol*) same (stasis or deform* or abnormal* or larva* or feed* or body*)))	CSA	
Macroalgae	TI=(macroalga*) not TS=(freshwater or terrestrial or tropical or lake* or stream*) and TS=(biogeomorph* or ecogeomorph* or hydromorph* or hydro-morph* or hydrogeomorph* or hydro-geomorph* or ecohydrol* or hydroecol* or geomorph* or morphological) not TS=((freshwater or terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff* or histolog* or genetic* or deformit* or molecular* or phylogen*) or TS=((morphol*) same (stasis or deform* or abnormal* or larva* or feed* or body*)))	WOS Biosis CAB	30
	((TI=(macroalga*) not KW=(freshwater or terrestrial or tropical or lake* or stream*) and (KW=(biogeomorph* or ecogeomorph* or hydromorph* or hydro-morph* or hydrogeomorph* or hydro-geomorph* or ecohydrol* or hydroecol* or geomorph* or morphological) not KW=(freshwater or terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff* or histolog* or genetic* or deformit* or molecular* or phylogen*)) NOT (((TI=(morphol*)) WITHIN 15 (TI=(stasis or deform* or abnormal* or larva* or feed* or body*))) or ((AB=(morphol*)) WITHIN 15 (AB=(stasis or deform* or abnormal* or larva* or feed* or body*))))))	CSA	

HYDROMORPHOLOGY			
Biota	**Search String**	**Data-bases*, ****	**No. articles found*****
Phytoplankton	TI=((phytoplankton) and TS=(intertidal or littoral or coast* or estuar*)) not TS=(freshwater or terrestrial or tropical or lake* or stream*) and TS=(estuar* or coast* or marine* or bay) same TS=((tidal same rang*) or salinity or (freshwater same (flow* or input* or abstract* or discharg*)) or 'flow ratio' or 'flow per tide' or 'mixing characteristic' or (current same (direction* or speed*)) or (wave same (exposur* or climat* or action)) or hydrodynam*) not TS=(terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff*) or TS=((substrat* or 'bed sediment type' or 'depth variation' or (habitat or inter*tidal or littoral or subtidal or nearshore or sublittoral or circa*littoral or infra*littoral or 'splash zone' or strandline or geomorph* or morphological or morphology or eco*geomorph* or bio*geomorph* or morphdyn*) same (structur* or condition* or bed* or substrat* or form* or process*)) same (dynamic* or change* or alter* or variab* or stab* or resil* or eros* or erod* or loss* or recover* or adapt*)) not TS=(terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff*)	WOS Biosis CAB	74
Benthic invertebrates	TI=(('benth* invertebrat*' or 'macrobenth* communit*' or 'benth* communit*') and TS=(intertidal or littoral or coast* or estuar*)) not TS=(freshwater or terrestrial or tropical or lake* or stream*) and TS=(estuar* or coast* or marine* or bay) same TS=((tidal same rang*) or salinity or (freshwater same (flow* or input* or abstract* or discharg*)) or 'flow ratio' or 'flow per tide' or 'mixing characteristic' or (current same (direction* or speed*)) or (wave same (exposur* or climat* or action)) or hydrodynam*) not TS=(terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff*) or TS=((substrat* or 'bed sediment type' or 'depth variation' or (habitat or inter*tidal or littoral or subtidal or nearshore or sublittoral or circa*littoral or infra*littoral or 'splash zone' or strandline or geomorph* or morphological or morphology or eco*geomorph* or bio*geomorph* or morphdyn*) same (structur* or condition* or bed* or substrat* or form* or process*)) same (dynamic* or change* or alter* or variab* or stab* or resil* or eros* or erod* or loss* or recover* or adapt*)) not TS=(terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff*)	WOS Biosis CAB	30
Fish	TI=((fish*) and TS=(intertidal or littoral or coast* or estuar*)) not TS=(freshwater or terrestrial or tropical or lake* or stream*) and TS=(estuar* or coast* or marine* or bay) same TS=((tidal same rang*) or salinity or (freshwater same (flow* or input* or abstract* or discharg*)) or 'flow ratio' or 'flow per tide' or 'mixing characteristic' or (current same (direction* or speed*)) or (wave same (exposur* or climat* or action)) or hydrodynam*) not TS=(terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff*) or TS=((substrat* or 'bed sediment type' or 'depth variation' or (habitat or inter*tidal or littoral or subtidal or nearshore or sublittoral or circa*littoral or infra*littoral or 'splash zone' or strandline or geomorph* or morphological or morphology or eco*geomorph* or bio*geomorph* or morphdyn*) same (structur* or condition* or bed* or substrat* or form* or process*)) same (dynamic* or change* or alter* or variab* or stab* or resil* or eros* or erod* or loss* or recover* or adapt*)) not TS=(terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff*)	WOS Biosis CAB	150

Saltmarsh	TI=(saltmarsh* or (salt same marsh*) or (coastal same wetland*) or (tidal same wetland*) or salting*) and TS=(hydr*) and TS=((tidal same rang*) or salinity or flow* or input* or abstract* or discharg* or (current same (direction* or speed*)) or (wave same (exposur* or climat* or action))) and TS=(dynamic* or change* or alter* or variab* or stab* or resil* or eros* or erod* or loss* or recover* or adapt*)	Wos (1996-2006)	74
Seagrasses	TI=(seagrass* or eelgrass* or zostera or phragmite*) not TS=(freshwater or terrestrial or tropical or lake* or stream*) and TS=(estuar* or coast* or marine* or bay) same TS=((tidal same rang*) or salinity or (freshwater same (flow* or input* or abstract* or discharg*)) or 'flow ratio' or 'flow per tide' or 'mixing characteristic' or (current same (direction* or speed*)) or (wave same (exposur* or climat* or action)) or hydrodynam*) not TS=(terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff*) or TS=((substrat* or 'bed sediment type' or 'depth variation' or (habitat or inter*tidal or littoral or subtidal or nearshore or sublittoral or circa*littoral or infra*littoral or 'splash zone' or strandline or geomorph* or morphological or morphology or eco*geomorph* or bio*geomorph* or morphdyn*) same (structur* or condition* or bed* or substrat* or form* or process*)) same (dynamic* or change* or alter* or variab* or stab* or resil* or eros* or erod* or loss* or recover* or adapt*)) not TS=(terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff*)	WOS (1970-2006) Biosis CAB	66
Macroalgae	TI=(macroalga*) not TS=(freshwater or terrestrial or tropical or lake* or stream*) and TS=(estuar* or coast* or marine* or bay) same TS=((tidal same rang*) or salinity or (freshwater same (flow* or input* or abstract* or discharg*)) or 'flow ratio' or 'flow per tide' or 'mixing characteristic' or (current same (direction* or speed*)) or (wave same (exposur* or climat* or action)) or hydrodynam*) not TS=(terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff*) or TS=((substrat* or 'bed sediment type' or 'depth variation' or (habitat or inter*tidal or littoral or subtidal or nearshore or sublittoral or circa*littoral or infra*littoral or 'splash zone' or strandline or geomorph* or morphological or morphology or eco*geomorph* or bio*geomorph* or morphdyn*) same (structur* or condition* or bed* or substrat* or form* or process*)) same (dynamic* or change* or alter* or variab* or stab* or resil* or eros* or erod* or loss* or recover* or adapt*)) not TS=(terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff*)	WOS Biosis CAB	32

HUMAN PRESSURES			
Biota	**Search String**	**Data-bases*, ****	**No. articles found*****
Phytoplankton	TI=((phytoplankton) and TS=(intertidal or littoral or coast* or estuar*)) not TS=(freshwater or terrestrial or tropical or lake* or stream*) and TS=(estuar* or coast* or marine* or bay) same TS=((tidal same rang*) or salinity or (freshwater same (flow* or input* or abstract* or discharg*)) or 'flow ratio' or 'flow per tide' or 'mixing characteristic' or (current same (direction* or speed*)) or (wave same (exposur* or climat* or action)) or hydrodynam*) not TS=(terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff*) or TS=((substrat* or 'bed sediment type' or 'depth variation' or (habitat or inter*tidal or littoral or subtidal or nearshore or sublittoral or circa*littoral or infra*littoral or 'splash zone' or strandline or geomorph* or morphological or morphology or eco*geomorph* or bio*geomorph* or morphdyn*) same (structur* or condition* or bed* or substrat* or form* or process*)) same (dynamic* or change* or alter* or variab* or stab* or resil* or eros* or erod* or loss* or recover* or adapt*)) not TS=(terrestrial or lake* or stream* or pond* or lagoon* or dune* or cliff*)	WOS Biosis CAB	15
Benthic	TI=(('benth* invertebrat*' or 'macrobenth* communit*' or 'benth* communit*') and TS=(intertidal or littoral or coast* or estuar*)) not TS=(freshwater or terrestrial or tropical or lake* or stream*) and TS=((marine or intertidal or subtidal or estuar* or coast* or littoral* or sublittoral*) same ((human* or anthropogenic or man* or fishing* or fisher* or trawler* or 'offshore structur*' or 'coast* defence' or breakwater* or marina or dock* or jetty) same (disturb* or impact* or effect* or harm* or vary* or variab* or respons* or resil* or recover*))) not TS=(freshwater or terrestrial or tropical or infectio* or 'molecular genetics' or parasitology or reproducti* or behavior* or behaviour* or 'population genetics' or dune* or lagoon* or cliff*)	WOS Biosis CAB	32
Fish	TI=((fish*) and TS=(intertidal or littoral or coast* or estuar*)) not TS=(freshwater or terrestrial or tropical or lake* or stream*) and TS=((marine or intertidal or subtidal or estuar* or coast* or littoral* or sublittoral*) same ((human* or anthropogenic or man* or fishing* or fisher* or trawler* or 'offshore structur*' or 'coast* defence' or breakwater* or marina or dock* or jetty) same (disturb* or impact* or effect* or harm* or vary* or variab* or respons* or resil* or recover*))) not TS=(freshwater or terrestrial or tropical or infectio* or 'molecular genetics' or parasitology or reproducti* or behavior* or behaviour* or 'population genetics' or dune* or lagoon* or cliff*)	WOS Biosis CAB	259
Saltmars	TI=(saltmarsh* or (salt same marsh*) or (coastal same wetland*) or (tidal same wetland*) or salting*) and TS=(human or anthro* or man* or engin* or construc*) and TS=(impact*)	Wos (1996-2006)	92

Seagrasses	TI=(seagrass* or eelgrass* or zostera or phragmite*) not TS=(freshwater or terrestrial or tropical or lake* or stream*) and TS=((marine or intertidal or subtidal or estuar* or coast* or littoral* or sublittoral*) same ((human* or anthropogenic or man* or fishing* or fisher* or trawler* or 'offshore structur*' or 'coast* defence' or breakwater* or marina or dock* or jetty) same (disturb* or impact* or effect* or harm* or vary* or variab* or respons* or resil* or recover*))) not TS=(freshwater or terrestrial or tropical or infectio* or 'molecular genetics' or parasitology or reproducti* or behavior* or behaviour* or 'population genetics' or dune* or lagoon* or cliff*)	WOS (1970-2006) Biosis CAB	31
Macroalgae	TI=(macroalga*) not TS=(freshwater or terrestrial or tropical or lake* or stream*) and TS=((marine or intertidal or subtidal or estuar* or coast* or littoral* or sublittoral*) same ((human* or anthropogenic or man* or fishing* or fisher* or trawler* or 'offshore structur*' or 'coast* defence' or breakwater* or marina or dock* or jetty) same (disturb* or impact* or effect* or harm* or vary* or variab* or respons* or resil* or recover*))) not TS=(freshwater or terrestrial or tropical or infectio* or 'molecular genetics' or parasitology or reproducti* or behavior* or behaviour* or 'population genetics' or dune* or lagoon* or cliff*)	WOS Biosis CAB	5

* - Years searched for databases: WOS (1991-2006), Biosis (1998-2006), CAB (1990-2006), CSA (1960-2006) except where stated differently.
** - Specific databases selected: Aqualine (1960-current), ASFA 1 (1971-current), Ecology Abstracts (1982-current), Water Resources Abstracts (1967-current)
*** - Where more than one database was searched, the number of references refers to the de-duplicated list.

AUTHOR			
Biota	**Search String**	**Data-bases**	**No. articles found**
Saltmarshes	TI=(saltmarsh* or (salt same marsh*) or (coastal same wetland*) or (tidal same wetland*) or salting*) and AU=(French JR OR Allen JRL OR French P* OR Pye K OR Pethick JS OR Leonard LA OR Day JW OR Turner RE OR Callaway JC OR DeLaune RD OR Patrick WH OR Dankers N OR Dijkema KS OR Dixon AM OR Eisma D OR Hughes RG OR Mendelssohn I* OR Kelley JT OR Morris JT OR Kjerfve B) or AU=(Shi Z OR Kearney MS OR Titus JG OR Valiela I OR Teal JM OR Zedler JB OR Zeff ML OR Myatt LB OR Wolters M OR Bakker JP OR Esselink P OR Collins M* OR Townend I OR Reed DJ OR Cahoon D* OR Saintilan N*)	WOS (1970-2006)	292

Appendix 2 – Numbers of articles retrieved by topic

The following tables list the numbers of articles (and percentage of total) found by the searches for particular factors/terms.

Table A1 Phytoplankton

Topic	**Factor/term**	**No. of articles**	**Percentage of total**
Methods	Modelling	10	9
	Monitoring (tools)	1	1
General issues	Seasonal variations	28	26
Physico-chemical	Salinity	37	35
	Nutrient concentration/ composition	40	38
	Light/ turbidity	14	13
	Temperature	13	12
Biological/ ecological factors	Population dynamics	6	6
	Abundance	10	9
	Primary production (growth)	22	21
	Blooms	25	24
	Community composition	27	25
	Biomass (Chlorophyll *a*)	51	48
	Zooplankton grazing	16	15
Hydrological/ hydrodynamic factors	Hydrological factors (mixing, flushing, tidal range, etc.)	18	17
	Residence time	3	3
	Freshwater input	10	9
Geomorphological/ sedimentological factors		0	0
Anthropogenic issues	Aquaculture	2	2
	Anthropogenic nutrient inputs	2	2
	Urbanisation	1	1
	Deforestation	1	1
	Waste water treatment plants	1	1
	Pulp mill effluents	1	1
Total number of articles		**106**	

Table A2 Benthic invertebrates

Topic	Factor/term	No. of articles	Percentage of total
General issues	Meteorological conditions (i.e. wind)	2	3
Physico-chemical factors	Salinity	7	11
	Nutrient concentration/ composition	3	5
	Dissolved oxygen	6	9
	Temperature	5	8
Biological/ ecological factors	Community structure	22	33
	Species abundance	13	20
	Species diversity/ heterogeneity	9	14
	Species dominance	9	14
	Species numbers	5	8
	Species biomass	6	9
	Growth	2	3
Hydrological/ hydrodynamic factors	Flow/ tidal variations	3	5
	Hydrodynamics/ hydrography	5	8
	Pelagic-benthic coupling	2	3
	Oceanographic change (including ELNINO and upwellings)	1	2
Geomorphological/ sedimentological factors	Geomorphology	1	2
	Depth	6	9
	Sediment quality/ characteristics	8	12
	Sediment deposition and erosion	7	0
	Sediment grain size	6	11
Anthropogenic issues	Commercial fishing	4	9
	Anthropogenic contaminants	4	6
	Silting/ sedimentation	3	6
	Harvesting – various methods	3	5
	Dredging (various methods)	3	5
	UV radiation	2	5
	Shellfish dredging	2	3
	Sewage	2	3
	Sea wall construction	2	3
	Pollution	2	3
	Physical perturbation/ disturbance	2	3
	Nutrient enrichment	2	3
	Manmade submerged habitats	2	3
	Aquaculture	2	3
	Heavy metal contamination/ accumulation	1	3
	Turbulence	1	2
	Trampling	1	2
	Predator exclusion	1	2
	Organic enrichment	1	2
	Decrease on mean water level	1	2
	Cockle hand raking	1	2
Total number of articles		**66**	

Table A3 Fish

Topic	Factor/ term	No. of articles	Percentage of total
General issues	Climate/ oceanographic change	11	2
	Habitat	28	6
Physico-chemical factors	Salinity	60	13
	Nutrient concentration/ composition	5	1
	Water chemistry (i.e. metals, hydrocarbons)	7	2
	Dissolved oxygen	13	3
	pH	5	1
	Light/ turbidity	8	2
	Temperature	35	8
	Stratification	3	1
Biological/ ecological factors	Vegetation as habitat	13	3
	Zooplankton grazing	1	0
Hydrological/ hydrodynamic factors	Tidal variations	7	2
	Flooding	1	0
	Turbulence	1	0
Geomorphological/ sedimentological factors	Substratum	18	4
	Relief	4	1
	Depth	14	3
	Geomorphological characteristics	3	1
Anthropogenic issues	Fishing (target and non-target organisms) – commercial and recreational	31	7
	Habitat loss	6	1
	Climate change	6	1
	Coastal construction/ urbanisation	5	1
	Dumping and dredging	4	1
	Sewage and pollution	4	1
	Aquaculture	2	0
	Flood defence measures	2	0
	Change in water quality	2	0
	Industrial activities	1	0
	Navigation	1	0
	Oil exploration	1	0
	Water abstraction	1	0
	Artificial habitat creation	1	0
Total number of articles		**448**	

Table A4 Saltmarshes

Topic	Factor/ term	No. of articles	Percentage of total
Approach/ method	Modelling	10	3
	Simulation	3	1
General factors	Biol	52	18
	Geo	34	12
	Loss	7	2
	Growth	7	2
	Mudflat	3	1
Physico-chemical factors	Mineral	3	1
	Phosphorous	3	1
	Nutrient	8	3
	Nitrogen	13	4
	Carbon	6	2
	Geochem	13	4
	Salinity	11	4
Biological/ ecological factors	Vegetation	34	12
	Biogeochem	9	3
	Spartina	12	4
	Herbivore	6	2
	Invertebrate	4	1
	Halophyte	4	1
	Birds	3	1
	Trophic	3	1
	Food web	2	1
Hydrological/ hydrodynamic factors	Tidal	51	18
	Hydrology	13	4
	Flow	8	3
	Creek	7	2
	Sea level	6	2
	Flooding	6	2
	Channel	5	2
	Wave	3	1
	Hydrodynamic	2	1
	Storm	2	1
Morphological/ sedimentological factors	Sediment	41	14
	Elevation	11	4
	Sedimentation	7	2
	Geomorph	6	2
	Deposition	4	1
	Accretion	3	1
	Erosion	3	1
	Sediment supply	2	1
Anthropogenic issues	Restoration	26	9
	Management	17	6
	Pollut	8	3
	Anthro	5	2
	Human	4	1
	Realignment	3	1
	Creation	3	1
	Graz	2	1
Total number of articles		**291**	

Table A5 Seagrasses

Topic	Factor/ term	No. of articles	Percentage of total
Type of article	Methods	9	6
	Review paper	6	4
Species	Various species	33	22
	Zostera	53	36
	Poseidonia oceanica	10	7
	Amphibolis spp.	2	1
	Phragmites	24	16
	Cymodocea nodosa	2	1
	Halodule wrightii	2	1
	Halophila ovalis	2	1
	Syringodium filiforme	1	1
	Heterozostera tasmanica	1	1
	Thalassia testudinum	3	2
General issues	General	12	8
	Temporal dynamics	15	10
	Physical disturbance	10	7
	Water Framework Directive	1	1
Physico-chemical factors	Light	23	16
	Nutrients	36	24
	Water temperature	10	7
	Salinity	10	7
	Methane emissions	1	1
	Climate (air temperature)/ latitude	6	4
Biological/ ecological factors	Fauna	34	23
	Inter-specific effects	7	5
	Fish	16	11
	Physiology/ genetics/ taxonomy	16	11
	Algal blooms	1	1
	Microbial populations	1	1
	Herbivory	1	1
Hydrological/ hydrodynamic factors	Precipitation	3	2
	Water depth	19	13
	Waves	11	7
	Tidal currents	11	7
Morphological/ sedimentological factors	Intertidal morphology	1	1
	Sediment concentration	10	7
	Sediment grain size	6	4
	Sediment organic matter	6	4
	Accretion rates	5	3
	Sediment (general)	7	5
	Erosion	3	2
Anthropogenic issues	Eutrophication	8	5
	Anthropogenic impact	19	13
	Marine construction	1	1
	Boat docks	1	1
	Policy	1	1
	Heavy metals	2	1
	Pharmaceutical use	1	1
	Dredge deposits	1	1
	Propeller scarring	1	1
	Construction use	1	1
Total number of articles		**148**	

Table A6 Macroalgae

Topic	Factor/ term	No. of articles	Percentage of total
Type of article	Methods	1	1
	Review paper	3	3
Species	Various Species	47	53
	Cerarium rubra	1	1
	Ectocarpus siliculosus	1	1
	Enteromorpha sp	11	13
	Fucus sp	7	8
	Gelidium latifolium	1	1
	Macrocystis pyrifera	2	2
	Mastocarpus papillatus	1	1
	Polysiphonia sp.	1	1
	Sargassum muticum	3	3
	Ulva sp	5	6
	Various Species	47	53
	Cerarium rubra	1	1
	Ectocarpus siliculosus	1	1
	Enteromorpha sp	11	13
	Fucus sp	7	8
General issues	Temporal Dynamics	7	8
	Spatial dynamics	20	23
	Diversity	7	8
	General	2	2
	Physical disturbance	8	9
Physico-chemical factors	Light	15	17
	Nutrients	16	18
	Climate (air temperature) / latitude	2	2
Biological/ ecological factors	Fauna	11	13
	Inter-specific effects	6	7
	Fish	1	1
	Physiology/genetics/taxonomy	6	7
	Microbial populations	1	1
	Herbivory	7	8
	Production	17	19
	Morphology	15	17
	Spore dispersal	2	2
	Recruitment	2	2
Hydrological/ hydrodynamic factors	Water Framework Directive	1	1
	Temperature	5	6
	Salinity	11	13
	Chemistry	2	2
	Depth	11	13
	Waves	10	11
	Emersion	2	2
	Sediment Concentration	5	6
	Tidal currents	7	8
Morphological/ sedimentological factors	Sediment organic matter	1	1
	Sediment (general)	3	3
	Intertidal morphology	1	1
	Erosion	2	2
	Sediment organic matter	1	1

Table A6 Macroalgae (contd.)

Anthropogenic issues	Eutrophication	7	8
	Anthropogenic impact	11	13
	Heavy metals	1	1
	Cultivation / harvesting	2	2
	Eutrophication	7	8
Total number of articles		**83**	

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