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ENVIRONMENT AGENCY

Development of Type-Specific Reference Conditions

Development of Hydromorphological Reference Conditions and Draft Classification Scheme For Transitional and Coastal Waters

Work Packages 1-4: Final Report

Reference number/code SC040037

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Environment Agency
Rio House
Waterside Drive, Aztec West
Almondsbury, Bristol BS32 4UD
Tel: 0870 8506506
Email: enquiries@environment-agency.gov.uk
www.environment-agency.gov.uk

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Author(s):

Cooper N, Freeman S, Frost N, Hinton C, Hull S (ABPmer)
Brampton A, Hutchings C, Spearman J, Whitehouse R (HR Wallingford)

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Research Contractors:

ABP Marine Environmental Research Ltd (ABPmer)
Pathfinder House, Maritime Way, SO14 3AE
Tel: 023 8033 8100

HR Wallingford (HRW)
Howbery Park, Wallingford, Oxon., OX10 8 BA
Tel: 01491 835381

Institute of Estuarine and Coastal Studies (IECS)
University of Hull, Cottingham Road, Hull, HU6 7RX
Tel: 01482 465503

Centre for Environment, Fisheries and Aquaculture Science (CEFAS)
Pakefield Road, Lowestoft, Suffolk, NR33 0HT
Tel: 01502 562244

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Development of Hydromorphological Reference Conditions and Draft Classification Scheme For Transitional and Coastal Waters

Environment Agency's Project Manager:

Andrew Richman, Rivers House, Lower Bristol Road, Bath. BA2 9ES.

Collaborator(s):

CEFAS, DEFRA, EHS (NI), FRS (Marine Lab), SEPA, SNIFFER.

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A Richman Environment Agency Project Manger

Contents

1. Background to Study

A consortium involving ABPmer, HR Wallingford, CEFAS and IECS is undertaking a study to develop hydromorphological reference conditions and a draft classification scheme for transitional and coastal waters (TRaC Waters), compatible with the achievement of high and good ecological status as required under Article V of the Water Framework Directive. The project is being undertaken on behalf of the Environment Agency and SNIFFER and is being managed by a Project Board (Appendix A).

The project will establish present understanding of the inter-relationships between hydrology, geomorphology and ecology to develop a conceptual framework upon which the consideration of hydromorphological reference conditions and classification schemes will be based.

Using this conceptual framework, type-specific reference conditions will be defined and an initial classification scheme developed and tested for subsequent review.

Products from the study will include a comprehensive literature review, a conceptual framework, derivation of type-specific reference conditions and development and initial pilot testing of a draft classification scheme.

The project is being broken down into eight discrete work packages, as indicated in Table 1. Work within each work package will build on the findings of preceding packages.

Table 1 Study Work Packages

Work Package	Title
1	Literature review, consultation and conceptual framework
2	Development of draft reference conditions
3	Workshop
4	Development of type-specific reference conditions
5	Development of a decision-making framework for managing alterations to the morphology of TRaC waters
6	Development, testing and refinement of a hydromorphological classification scheme
7	Identification and collation of supporting datasets
8	Finalisation of outputs

The main body of this report represents the output from Work Package 4 and it is supported by Appendices B to C, detailing the output from Work Packages 1 to 3, respectively.

2. Aims and Objectives

The aim of Work Package 4 is to define type-specific reference conditions (hydrological and morphological) for all UK transitional and coastal water body types for the purpose of defining ‘high status’ or unimpacted status as defined in Annex V of the Water Framework Directive. It is recognised that the output will be a first step in the process and may be revised over the lifetime of the Directive as knowledge improves and in response to improved understanding of natural dynamics and change. Specific objectives included:

- To ensure the proposed reference conditions take due account of the findings of Work Packages 1-3, particularly in relation to the key recommendations arising from the Workshop held on 7th and 8th December 2004;
- To develop a draft report defining a set of type-specific reference conditions (hydrological and morphological) for all UK transitional and coastal water body types (this document);
- To discuss the content of the draft report at the Project Board Meeting on 10th February 2005; and
- Finalise the report based on the feedback from the Project Board Meeting.

3. Methods

Throughout Work Packages 1-3, potential methods for establishing hydrological and morphological reference conditions have been considered. Work Package 1 (Appendix B) reviewed available scientific literature and applied specialist knowledge to provide a conceptual basis for the development of later stages of the study. Work Package 2 (Appendix C) specifically tested three potential approaches that were then discussed in considerable detail at the Workshop. These methods sought to provide both reference conditions and a basis for hydromorphological classification. Whilst some of these approaches found some favour and were considered worthy of further consideration, perhaps in a modified manner for the later stages of the study, there was a recommendation made at the Workshop that given the timescales within which output was required and the complexities of these possible methods, a considerably more simplified approach to defining type-specific reference conditions should be adopted. The method used in this element of the study has, therefore, been to develop further some of the ideas for a more simplified approach that were initially proposed at the Workshop (these are reported in full in Appendix D and are summarised throughout Section 4 of this report). It should also be noted that it has been essential in preparing this report to ensure compatibility with previous work undertaken on defining the typology of TRaC waters (e.g. Rogers *et al*., 2003; UKTAG, 2003) and the requirements of the Directive.

4. Type-Specific Reference Conditions

4.1 Workshop Recommendations

At the Project Workshop on 7th-8th December 2004, recommendations were made for a relatively simple approach to defining hydromorphological reference conditions that could be produced within the tight deadlines of this work package of the study. It was stated that this could be best focused on a broad, generalised baseline of the parameters that were used in the typological classification of different TRaC water bodies. The simplified approach could then, potentially, be further developed in later stages of the study (i.e. in Work Packages 6-8). This staged approach was considered to be compatible with the approach presently being adopted by the teams developing biological reference conditions. It was, however, recognised at the workshop that there would be limitations with this approach, particularly that the approach does not incorporate a spatial context and that the reference conditions would be relatively insensitive to change (i.e. only very major alterations to the existing hydrological or morphological parameters that have been used to define the water body typologies would take a water body outside the range of its reference condition).

4.2 UK TRaC Water Body Types

The UK TRaC water body types are defined in accordance with 'System B' of Annex 2 of the Water Framework Directive and are presented in a UKTAG Guidance Document (UKTAG, 2003). UK typology of coastal waters has been based on a number of mandatory factors, such as 'latitude and longitude', 'mean tidal range' and 'salinity', and optional factors such as 'wave exposure', to yield the following coastal water body types:

CW1 Exposed, Macro-tidal;
CW2 Exposed, Meso-tidal;
CW3 Exposed, Micro-tidal;
CW4 Moderately exposed, Macro-tidal;
CW5 Moderately exposed, Meso-tidal;
CW6 Moderately exposed, Micro-tidal;
CW7 Sheltered, Macro-tidal;
CW8 Sheltered, Meso-tidal;
CW9 Sheltered, Micro-tidal;
CW10 Coastal Lagoons;
CW11 Shallow Sea Lochs; and
CW12 Deep Sea Lochs.

For transitional waters, further optional factors have been considered, such as 'dominant substrate' and 'extent of inter-tidal area' to yield the following transitional water body types:

TW1 Partly mixed or stratified, meso or polyhaline, macrotidal, intertidal or shallow subtidal, predominately sand and mud;
TW2 Partly mixed or stratified, meso or polyhaline, mesotidal, intertidal or shallow subtidal, predominately sand and mud;
TW3 Fully mixed, polyhaline, macrotidal, sand or mud substratum, extensive intertidal areas;
TW4 Fully mixed, polyhaline, mesotidal, sand or mud substratum, extensive intertidal areas;
TW5 Transitional Sea Lochs; and
TW6 Transitional Lagoons.

4.3 Hydrological Reference Conditions

Given the need to ensure compatibility with previous typology work and the requirements of the Water Framework Directive, the definition of hydrological reference conditions has been based largely on the content of available documentation on UK typology (e.g. Rogers *et al*., 2003; UKTAG, 2003). Such documentation already provides a quantitative means of defining water body types for 'mean tidal range' and 'salinity' (for both transitional and coastal waters) and qualitative or semi-quantitative means for 'wave exposure' and 'mixing characteristics'. Given this, the hydrological reference conditions (or ranges) are, by default, the parameters and values used in these previous studies.

4.3.1 Coastal Waters

Since all coastal water body types are defined as being 'euhaline' (salinity >30ppt), the relevant discriminating hydrological parameters listed in the UK TAG Guidance (2003) are 'mean tidal range' and 'wave exposure'.

Table 2 presents how these parameters were initially proposed to be considered at the Workshop.

Table 2 Workshop Proposals for Hydrological Reference Conditions for Coastal Waters

			Tidal Range		
			Micro-tidal	**Meso-tidal**	**Macro-tidal**
			<1m	**1m-5.0m**	**>5.0m**
Exposure	**Significant wave height, H_s**	**Low**	CW9	CW8	CW7
		Medium	CW6	CW5	CW4
		High	CW3	CW2	CW1
			all salinity > 30		

Note:
There is a need to further consider how CW 10-12 may be incorporated.

In considering the incorporation of CW10-12 during the present stage of the study, Table 2 has been re-structured as Table 3.

Table 3 Proposed Hydrological Reference Conditions for Coastal Water Bodies

	Wave Exposure (#)			Mean Tidal Range				Salinity
	Exposed (> 500km)	Semi-exposed (50-500km)	Protected (<50km)	Macro-tidal (>5.0m)	Meso-tidal (1.0m-5.0m)	Micro-tidal (<1.0m)	Non-tidal (0.0m)	Euhaline (>30ppt)
CW1	X			X				X
CW2	X				X			X
CW3	X					X		X
CW4		X		X				X
CW5		X			X			X
CW6		X				X		X
CW7			X	X				X
CW8			X		X			X
CW9			X			X		X
CW10			X				X	X
CW11			X		X			X
CW12			X		X			X

Wave exposure is commonly classified through wave fetch distances. The numbers given in the table refer to the value of the maximum wave fetch distance from the predominant direction of approach, but alternative approaches based on a combination of fetch, aspect and water depth within certain proximity of the shoreline could also be used. The difficulty with using a 'significant wave height' value, as proposed at the workshop, is that this varies so greatly both spatially across a water body and temporally, whereas the other reference conditions are more 'fixed' and therefore more easily measurable.

Note 1: Although UK TAG (2003) states that 'mean tidal range' is not applicable for CW10, it may be best to class it as '<1.0m' since some may have a very minor tidal component.

For a coastal water body type CW1 to remain at high hydrological status, it must have a tidal range in excess of 5.0m and must be exposed to waves with a maximum fetch of 500km (i.e. ascribe to the reference conditions). Any alteration to these hydrological parameters, for example through the construction of a barrage or large offshore breakwaters, could alter the wave exposure and/or mean tidal range within the water body, thus potentially changing its hydromorphological status from the reference condition (i.e. changing from macro-tidal to meso-tidal environment), depending on the scale and/or location of intervention.

4.3.2 Transitional Waters

At the Workshop, it was proposed that Table 1 (now re-structured and expanded as Table 2) could be developed for transitional waters to additionally include the following hydrological parameters:

- Tidal range;
- Salinity;
- Freshwater flow.

In further consideration of relevant hydrological parameters for transitional waters, it is noted that in the UK TAG Guidance (2003) all transitional water body types are defined as being 'sheltered' (in terms of wave exposure). Therefore, the relevant discriminating hydrological parameters used by UK TAG are 'mean tidal range', 'salinity' and 'mixing characteristics'. Consequently, Table 4 demonstrates how hydrological reference conditions can be ascribed for transitional water body types.

Table 4 **Proposed Hydrological Reference Conditions for Transitional Water Bodies**

<table>
<tr><th rowspan="2"></th><th colspan="3">Mixing Characteristics (#)</th><th colspan="5">Salinity</th><th colspan="4">Mean Tidal Range</th><th>Wave Exposure</th></tr>
<tr><th>Fully mixed F<0.1</th><th>Partly mixed 0.1<F<1.0</th><th>Stratified F>1.0</th><th>Freshwater (<0.5ppt)</th><th>Oligihaline (0.5-<5ppt)</th><th>Mesohaline (5-<18ppt)</th><th>Polyhaline (18-<30ppt)</th><th>Euhaline (30-<40ppt)</th><th>Macro-tidal (>5.0m)</th><th>Meso-tidal (1.0m-5.0m)</th><th>Micro-tidal (<1.0m)</th><th>Non-tidal (0.0m)</th><th>Protected (<50km)</th></tr>
<tr><td>TW1</td><td></td><td colspan="2">X</td><td></td><td></td><td colspan="2">X</td><td></td><td>X</td><td></td><td></td><td></td><td>X</td></tr>
<tr><td>TW2</td><td></td><td colspan="2">X</td><td></td><td></td><td colspan="2">X</td><td></td><td></td><td>X</td><td></td><td></td><td>X</td></tr>
<tr><td>TW3</td><td>X</td><td></td><td></td><td></td><td></td><td></td><td>X</td><td></td><td>X</td><td></td><td></td><td></td><td>X</td></tr>
<tr><td>TW4</td><td>X</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">X</td><td></td><td>X</td><td></td><td></td><td>X</td></tr>
<tr><td>TW5</td><td></td><td></td><td></td><td></td><td></td><td></td><td>X</td><td></td><td></td><td>X</td><td></td><td></td><td>X</td></tr>
<tr><td>TW6</td><td></td><td colspan="2">X</td><td></td><td colspan="3">X</td><td></td><td></td><td></td><td></td><td>X</td><td>X</td></tr>
</table>

F represents the flow ratio, expressed as the river flow per tide, divided by the tidal prism, as recommended by Dyer in Futurecoast (Defra, 2002). It should be noted that this may need to be further developed since it is a reference condition that can vary considerably temporally (i.e. dependent on river flow per tide) and some average or peak condition may need to be applied.

Note 1: No information is provided in UK TAG (2003) on the mixing characteristics of TW5.
Note 2: Although UK TAG (2003) states that 'mean tidal range ' is not applicable for TW6, it may be best to class it as '<1.0m' since some may have a very minor tidal component.

Whilst freshwater flow can also be considered as a hydrological element in its own right, it is suggested that it is incorporated, if proven relevant, within the more detailed hydromorphological classification scheme to be prepared as part of Work Package 6, rather than as a separate type-specific reference condition.

4.4 Morphological Reference Conditions

Relatively few morphological reference conditions are listed in the UK TAG Guidance (2003), as described separately below for coastal and transitional waters, making their consideration more complex than for hydrological reference conditions. Furthermore, the approaches proposed at the Workshop for coastal (Table 5) and transitional waters (Table 6) do not ascribe reference conditions to specific water body types, but instead simply state the EUNIS Level 3 habitats anticipated at different depth zones for a given predominant 'substrate' (i.e. bed sediment type).

Table 5 **Workshop Proposals for Morphological Reference Conditions for Coastal Waters**

Substrate	Depth			
	>10m	2-10m	LWMT-2m	HAT-LWMT
Rock	CR	CR	IR	LR
Gravel/Sand	SCS	SCS	SCS	LCS
Muddy Sand	SSa	SSa	SSa	LSa
Muddy Gravel	SMx	SMx	SMx	LMx

Table 6 Workshop Proposals for Morphological Reference Conditions for Transitional Waters

Substrate	Depth			
	>10m	**2-10m**	**HWMT-2m**	**HAT-HWMT**
Rock	CR	IR	IR	LR
Gravel	SMx	SMx	LMx	LMx
Mud	SMu	SMu	LMu	LMu
Sand	SSa	SSa	LSa	LSa

Definitions of reference types for Tables 4 and 5: CR (Circalittoral Rock), IR (Infralittoral Rock), LR (Littoral Rock), SCS (Sublittoral Coarse Sediment), LCS (Littoral Coarse Sediment), SSa (Sublittoral Sand), LSa (Littoral Sand) , SMx (Sublittoral Mixed Sediment), LMx (Littoral Mixed Sediment), SMu (Sublittoral Mud) LMu (Littoral Mud).

Consequently, in order to determine whether a potentially valid means of considering reference conditions could be identified, it has been necessary to consider what predominant bed sediment one might expect to be present for each of the twelve coastal and six transitional water body types, as reported in following sections. If the results indicated no difference between water bodies, then the approach of using predominant bed type as a discriminating reference condition would not be valid. This issue has been considered for each water body type at three different ‘depth zones’ within the water body, namely: (i) circa-littoral zone (nearshore deeper and offshore subtidal, -13m to -80m depth); (ii) infra-littoral zone (shallow sub-tidal, +1m to –13m depth); and (iii) littoral zone (splash zone, strandline, intertidal, +8m to +1m depth). Note: The depth ranges stated are from Connor *et al* (2003, as modified from Hiscock, 1996).

The predominant bed sediments that have been considered are those that were adopted by Rogers *et al* (2003) and are based upon existing BGS data. These are given in Table 7.

Table 7 Types of Predominant Bed Sediment

No.	Category	Description
1	Rock platform (with rocks, boulders and cobbles)	Hard rock substratum including chalk and soft rock substrata of consolidated mud and diamictons (i.e. glacial till and London Clay)
2	Gravel	Including the Folk Classifications of: Gravel (G), sandy Gravel (sG) and gravely Sand (gS)
3	Sand	Including the Folk Classifications of: slightly gravely Sand ((g)S), Sand (S); muddy Sand (mS); slightly gravely muddy Sand ((g)mS)
4	Mud	Including the Folk Classifications of: Mud (M); slightly gravely Mud ((g)M); sandy Mud (sM); slightly gravely sandy Mud ((g)sM)
5	Mixed sediment	Including the Folk Classifications of: Gravely Mud (gM); gravely muddy Sand (gmS); muddy Gravel (mG); muddy sandy Gravel (msG)
6	Mosaic	Areas of the sea floor in which no single category was dominant

4.4.1 Coastal Waters

The UK TAG Guidance (2003) does not explicitly list any morphological parameter, either obligatory or optional, for use in defining the typology of coastal water bodies. However, in clarification of the meaning of two coastal water body types (namely CW11 and CW12), depth is used to differentiate between ‘shallow’ (i.e. <30m) and ‘deep’ (i.e. >30m) sea lochs. Additionally, sea lochs are defined as being ‘narrow in relation to their length’, which is a plan form morphological relationship (UKTAG, 2003).

These parameters are considered to be of limited use in defining morphological reference conditions. Consequently, an initial assessment of the likely predominant bed sediments anticipated for each water body type has been made and is presented in Table 8.

Table 8 Likely Predominant Bed Sediments for Coastal Waters

		Depths		
		Circa-littoral	**Infra-littoral**	**Littoral**
Coastal	**CW1**	1, 2, 3	1, 2, 3	1, 2, 3
	CW2	1, 2, 3	1, 2, 3	1, 2, 3
	CW3	1, 2, 3	1, 2, 3	1, 2, 3
	CW4	2, 3, 5	2, 3, 5	2, 3, 5
	CW5	2, 3, 4	2, 3, 4	2, 3, 4
	CW6	2, 3, 4	2, 3, 4	2, 3, 4
	CW7	3, 4	3, 4	3, 4
	CW8	3, 4	3, 4	3, 4
	CW9	3, 4	3, 4	3, 4
	CW10	n/a	4	4
	CW11	1	1	1
	CW12	1	1	1

The above predominant sediment types could be translated into EUNIS Level 3 habitats in accordance with Table 9.

Table 9 Likely Predominant EUNIS Level 3 Habitats for Coastal Waters

		Depths		
		Circa-littoral	**Infra-littoral**	**Littoral**
Coastal	**CW1**	CR, SCS, SSa	IR, SCS, SSa	LR, LCS, LSa
	CW2	CR, SCS, SSa	IR, SCS, SSa	LR, LCS, LSa
	CW3	CR, SCS, SSa	IR, SCS, SSa	LR, LCS, LSa
	CW4	SCS, SSa, SMx	SCS, SSa, SMx	LCS, LSa, LMx
	CW5	SCS, SSa, SMx	SCS, SSa, SMx	LCS, LSa, LMx
	CW6	SCS, SSa, SMx	SCS, SSa, SMx	LCS, LSa, LMx
	CW7	SSa, SMu	SSa, SMu	LSa, LMu
	CW8	SSa, SMu	SSa, SMu	LSa, LMu
	CW9	SSa, SMu	SSa, SMu	LSa, LMu
	CW10	n/a	SMu	LMu
	CW11	CR	IR	LR
	CW12	CR	IR	LR

Where: CR (Circalittoral Rock), IR (Infralittoral Rock), LR (Littoral Rock), SCS (Sublittoral Coarse Sediment), LCS (Littoral Coarse Sediment), SSa (Sublittoral Sand), LSa (Littoral Sand) , SMx (Sublittoral Mixed Sediment), LMx (Littoral Mixed Sediment), SMu (Sublittoral Mud) LMu (Littoral Mud).

It is proposed that the likely predominant habitats presented in Table 8 be used as a measurable reference condition from which the predominant bed sediments can be inferred and used as a morphological reference condition for coastal water bodies.

4.4.2 *Transitional Waters*

The UK TAG Guidance (2003) lists only two morphological parameters that are to be used in the definition of transitional waters; (i) 'mean substratum composition'; and (ii) 'depth'. Table 10 demonstrates how these morphological reference conditions could be ascribed for transitional water body types.

Table 10 Morphological Parameters Used as Typological Characteristics in Transitional Water Bodies

	Mean Substratum Composition				Depth		
	Sand	Sand or mud	Sand and mud	Mud	Inter-tidal/ shallow sub-tidal estuaries	Shallow	Extensive inter-tidal areas
TW1			X		X		
TW2			X		X		
TW3		X					X
TW4		X					X
TW5							
TW6				X		X	

The parameters in Table 10 appear somewhat overlapping and are considered to be of limited use in defining morphological reference conditions. Consequently, an initial assessment of the likely predominant bed sediments anticipated for each water body type has been made and is presented in Table 10.

Table 11 Likely Predominant Bed Sediments for Transitional Waters

		Depths		
		Circa-littoral	Infra-littoral	Littoral
Transitional	**TW1**	n/a	3, 4	3, 4
	TW2	n/a	3, 4	3, 4
	TW3	n/a	3	3, 5
	TW4	n/a	2, 3, 4, 5	2, 3, 4, 5
	TW5	1, 2	1, 2	1, 2
	TW6	n/a	4	4

The above predominant sediment types could be translated into EUNIS Level 3 habitats in accordance with Table 12.

Table 12 Likely Predominant EUNIS Level 3 Habitats for Coastal Waters

		Depths		
		Circa-littoral	**Infra-littoral**	**Littoral**
Transitional	**TW1**	n/a	SSa, SMu	LSa, LMu
	TW2	n/a	SSa, SMu	LSa, LMu
	TW3	n/a	SSa	LSa, LMx
	TW4	n/a	SCS, SSa, SMu, SMx	LCS, LSa, LMu, LMx
	TW5	CR, SCS	IR, SIS	LR, SLS
	TW6	n/a	SMu	LMu

Where: CR (Circalittoral Rock), IR (Infralittoral Rock), LR (Littoral Rock), SCS (Sublittoral Coarse Sediment), LCS (Littoral Coarse Sediment), SSa (Sublittoral Sand), LSa (Littoral Sand) , SMx (Sublittoral Mixed Sediment), LMx (Littoral Mixed Sediment), SMu (Sublittoral Mud) LMu (Littoral Mud).

It is proposed that the likely predominant habitats presented in Table 11 be used as a measurable reference condition from which the predominant bed sediments can be inferred and used as a morphological reference condition for transitional water bodies.

5. Discussion

In pursuance of hydromorphological reference conditions that are applicable at the scale of a water body-type, it is apparent that such reference conditions are difficult to prescribe. This is principally because while there exists a range of hydrological and morphological parameters that potentially can be used as reference conditions, these vary both spatially across any water body area and temporally. Consequently, at the scale of the water body type, the reference conditions presented here are extremely broad and, through necessity of ensuring compatibility with existing typological classifications, largely are defined by default in accordance with the criteria that have been used to establish the typology. This perhaps presents something of a circularity of argument. It also means that the reference conditions proposed here are relatively insensitive to changes in hydromorphological parameters and will only detect notable changes (e.g. reduction in tidal range due to the construction of a barrage or massive reclamation) that may result in a re-classification of water body type. To derive more specific reference conditions, if desired, requires either:

(a) water body-specific assessments (i.e. looking at each individual water body around the UK in detail); or

(b) more detailed consideration of the individual morphological elements from which each water body type may be composed.

The problem with the latter approach, however, is that whilst reference conditions may be derived for certain features (e.g. as presented at the Workshop by Larissa Naylor of the Environment Agency for saltmarshes) they need to be combined within the context of the water body. There exists a vast potential combination of different landform elements within any water body type and there are few, if any, morphological features that are exclusive to one water body type only.

At the Workshop, a further idea of considering the ‘physical stress’ (due to wave and tidal action) within different depth zones of coastal or transitional waters was briefly discussed (see Appendix D for further details). Upon further examination, it is considered that this approach duplicates the existing hydrological parameters which already contain elements of 'mean tidal range' and 'wave exposure' and therefore implicitly capture the range of physical stresses from 'low' to 'high'.

Similarly, the concept of 'sediment stress' within a coastal or transitional water body was raised during discussion at the Workshop. This was proposed as a potential means of identifying whether a water body has a surplus, balance or deficit of sediment. However, it is not possible, at the generic of assessment, to differentiate in this manner between different water body types. Even within one water body type, a coastal or transitional water may have a naturally positive, neutral or negative sediment budget. More detailed consideration of such matters would only be possible at the water body specific level of investigation, where sufficient data and information exists relating to sediment inputs, transportation pathways, sediment stores and sinks and morphological changes.

Some Workshop delegates also raised the issue of natural variability and dynamics within transitional and coastal water body systems. It was generally felt that this was a valid comment but that the approaches proposed for defining reference conditions (i.e. as broad ranges) should accommodate such natural variability.

A final point raised at the Workshop was whether 'degree of modification' could be used to assist in defining reference conditions. Members of the project team have been further considering this issue as part of the ongoing Work Package 5. Whilst it is possible to quantify the extent of physical pressures on TRaC water bodies, for example as already has been done for the morphological pressures risk assessment (Freeman *et al*, 2004), it is difficult to express these pressures in morphological terms. This is because the way in which individual pressures may manifest themselves in morphological condition is very much a site specific determination and the cumulative effect of multiple pressures can only be estimated using advanced modelling techniques. Even following such analyses, it is very difficult to condense such information into a single metric, particularly given the limited range of metrics that the Water Framework Directive permits for consideration. It is therefore not considered practicable at this time to establish reference conditions on the basis of the extent of physical pressures.

At the Project Board Meeting on 10th February 2005 in London, the proposed hydrological and morphological reference conditions contained within this report were presented and thoroughly discussed. Attendees generally felt comfortable with the approach that was presented, agreeing that at the scale of the water body type this was in line with what was expected to be achievable. It was further stated by SEPA/SNIFFER that when working on the original typology study, it was found that at this scale, there could not be precise reference conditions prescribed but rather a relatively wide range of conditions that the water body type sits within. It was stated that it was reassuring that the Project Team for the present study had come to the same view after considering the issue so thoroughly.

The Environment Agency and SEPA/SNIFFER also considered that the approach of linking morphological reference conditions, based on predominant sea bed sediment, to EUNIS Level 3 habitats set-up a means of further developing ecologically-relevant approaches in Work Package 6 of the study.

Appendix A

Project Board Membership

TraC Hydromorphology Project Board			
Board Members:			
Name	**Organisation and Role**	**Telephone**	**Email**
Andrew Richman	Environement Agency Science Group – Technology. Project Manager	01225 487622	Andrew.richman@environment-agency.gov.uk
Dave Jowett	Environment Agency - Policy Advisor Monitoring. WFD UK TAG Lead - Marine Task Team	01454 284414	Dave.jowett@environment-agency.gov.uk
Roger Proudfoot	Environment Agency - National Marine Service WFD Marine Policy Advisor	01733 464113	Roger.proudfoot@environment-agency.gov.uk
Anton Edwards	Scottish Environment Protection Agency SNIFFER representative	01738 627989	Anton.Edwards@SEPA.org.uk
Mark Williams	Scottish Environment Protection Agency Marine Morphologist	**0131 449 7309**	Mark.Williams@sepa.org.uk
Mark Charlesworth	Environment and Heritage Service (NI) Marine Resources-Water Management Unit	02890 254779	Mark.Charlesworth@doeni.gov.uk
James Mckie	Fisheries Research Services (Marine Lab) WFD Programme of Measures Hydromorphology.		j.c.mckie@marlab.ac.uk
Jane Rawson	Environment Agency – HO Policy	-	-
Larissa Naylor	Environment Agency – Science Group Biogeomorphologist	01491 828545	Larissa.naylor@environment-agency.gov.uk

Corresponding members:

Name	Organisation and Role	Telephone	Email
Mike Best	Environment Agency – WFD Marine Plants Project	01733 464556	Mike.best@environment-agency.gov.uk
Mark Diamond	Environment Agency – WFD Programme of Measures Hydromorphology	01925 542701	Mark.diamond@environment-agency.gov.uk
Steve Colclough	Environment Agency – WFD Transitional Fish Project	020 8310 5500	Steve.colclough@environment-agency.gov.uk
Steve Coates	Environment Agency – Estuarine Fish Scientist - WFD R&D Programme	020 8310 5500	steve.coates@environment-agency.gov.uk
Alison Miles	Environment Agency – WFD Benthic Invertebrates Project	01733 464138	**Alison.miles@environment-agency.gov.uk**
Andrew Mackenny-Jeffs	Environment Agency – Water Resources WFD Policy Advisor	0118 9535231	Andrew.mackennyjeffs@environment-agency.gov.uk

Appendix B

Work Package 1: Literature Review, Consultation and Conceptual Framework

1. Aims and Objectives of Work Package

The aim of Work Package 1 is to establish a conceptual framework from which the development of hydromorphological reference conditions and classification schemes will be based.

The project brief states the objectives of the above exercises are as follows:

- Assess present knowledge of dynamic hydrological and geomorphological processes (hydromorphology) and their relationship with ecological function for transitional and coastal waters of the UK;

- Identify and review other hydromorphological classification schemes, particularly those that aim to define reference conditions and assess hydromorphological condition and quality classes;

- Review and integrate with ongoing work to define the reference conditions and classification schemes for the biological quality elements (benthic invertebrates, fish and plants);

- Ensure broad consistency with the equivalent project for classifying river and lake systems; and

- Ensure that the requirements of the Directive are considered and adhered to, with particular attention paid to the hydromorphological elements identified in Annex V (Tables 1.2.3 and 1.2.4) of the Directive.

2. Methods

To achieve the aims and objectives stated above, a variety of methods have been adopted. These are listed below:

- Discussions with EA Technical Science Advisor and the Project Board;
- Detailed literature review to provide scientific basis for the conceptual framework;
- Consultation and advice gathering from independent experts;
- Liaison with biological task teams.

These methods are described further in the following sections.

2.1 Discussions with Environment Agency's Technical Advisor and the Project Board

Considerable discussion was facilitated between the contractor Project Team and both the Environment Agency's Technical Advisor (Larissa Naylor) and the client Project Board concerning a number of key aspects of the study. This involved a series of telephone conversations, email communications, provision of relevant documentation and advice and a formal Project Board Meeting on 5th October 2004. The key issues discussed at this meeting are summarised in Annex A.

2.2 Literature Review

A comprehensive literature review was undertaken to: (i) highlight present understanding of hydromorphological (hydrological and morphological) processes; (ii) understand their interactions over different spatial and time scales; (iii) identify the relationships between hydromorphology and ecology; and (iv) identify relevant classification schemes that are in existence and may be of use in this study.

The literature review was undertaken by specialists with key skills in hydraulics, geomorphology and ecology, so that a relatively high level of expertise and understanding was already available to the project team. This meant that the review could focus on available scientific papers, documents related to other aspects of the Water Framework Directive, and other recent or ongoing studies that are also attempting to use hydromorphology as a foundation for delivering their specific project aims and objectives. Many references included in the review were kindly provided by the Environment Agency, other Project Board members and various external experts.

2.3 Consultation with Individual Experts

A number of key individuals were identified as potentially being able to contribute relevant references and suggest conceptual approaches to be considered in the study. Key individuals included client Project Board members (including the Environment Agency's Technical Advisor) and various external experts, as listed below:

Project Board Members (meetings and workshop):

- Dave Jowett - Environment Agency
- Andrew Richman – Environment Agency
- Roger Proudfoot – Environment Agency
- Larrisa Naylor - Environment Agency
- Jane Rawson – Environment Agency
- Chris Vivian – CEFAS
- Mark Charlesworth – EHS
- Anton Edwards / Dave Ross / Mark Williams – SEPA
- John Maslin – DEFRA
- James Mckie - FRS Marine Lab
- Steve Colclough – Environment Agency
- Mark Diamond – Environment Agency
- Jean Erbacher – SNIFFER
- Gina Martin - SNIFFER

External Experts (telephone conversations and/or email communications and/or workshop):

- Daniel Leggett - Royal Haskoning
- John Pethick – independent
- Keith Dyer - University of Plymouth
- John Widdows - PML
- Hubert Rees / Stefan Bolan – CEFAS
- Piers Larcombe – CEFAS
- Donald McLusky - University of Stirling
- Mark Charlesworth – EHS
- Phil Elliott – EHS
- Dierdory Quinn – EHS
- Michale Coyle / Roger Morris – EN
- Rob Hughes - QML University
- Marjolein Van Wijngaarden - RIZA
- Andrew Black – University of Dundee
- George Lees - SNH
- David Connor – JNCC
- John Rees – BGS
- Chris Frid – University of Newcastle
- Marcel Stive – Delft Technical University
- Dave Rafaelli – University of York
- Victor de Jonge - University of Groningen
- Tom Spencer - University of Cambridge

2.4 Liaison with Biological Task Team

Two members of the Project Team are directly involved with the ongoing work of the Biological Task Team. Specifically, Mike Elliott (IECS) is Chair of the Marine Benthic

Invertebrates Task Team and Stuart Rogers (CEFAS) is involved with the Fish and Marine Plants Task Team. Information from the various Biological Task Teams will continue to be collated throughout the study and used as a link between their work and the present project.

3. Key Findings

The following sections present key findings from the work undertaken in Work Package 1, using a variety of methods, under the categories of: (i) hydromorphological processes and their inter-relationships; (ii) relationships between hydromorphological processes and ecological function; and (iii) existing classification tools and classification schemes. Further detail derived from the literature review is presented in Annex B.

3.1 Hydromorphological Processes and their Inter-relationships

3.1.1 Background

Coastal and estuarine environments are complex physical systems that are subject to change over a range of spatial and time scales. These physical systems comprise three main internal components, namely:

(i) the forces that are generated and imposed;
(ii) the sediments that can become mobilised and transported; and
(iii) the morphology, which can change as a result of sediment movement.

Anthropogenic intervention, for example in the form of dredging or construction of marine structures, can be an external influence on any coastal or estuarine system but in a natural context the three internal components are each inter-linked by a complex combination of physical processes. Important feedback interactions occur between these components such that whilst an imposed force may lead to sediment mobilisation and transportation and hence cause morphological change, that very morphological change may, in turn, have an effect (either positive or negative) on the applied force. Additionally, further complications arise when considering the timescales and spatial horizons over which changes occur. For example, an individual sediment particle may be in almost constant motion throughout a tidal cycle of a few hours but this may not necessarily lead to notable change in morphology over the short-term. In contrast, a whole coastal system or estuary may take centuries to fully respond to large scale changes, such as substantial reduction in, or cessation of, sediment supply or alternatively large-scale land reclamation.

Notwithstanding these complexities, a large amount of information is known about various physical processes and morphological responses. In essence, coastal or estuarine change will only occur when the forces acting on a system, or sub-components of a system, exceed certain thresholds for motion of particular sediments, or when significant changes like reduction in sediment supply occur. The constant seeking of a balance between the forces, sediments and morphology within such systems is the dynamism that drives coastal change.

3.1.2 Forces

The physical forces that are imposed within a coastal system include:

- Waves
- Tides
  which have direct loading impacts and also generate currents;
- Winds - which can both influence waves and tidal levels, and act directly on sand particles;
- Atmospheric pressure - which influences tidal levels;
- Sea level rise/fall - which influences tidal levels;
- Rainfall - which influences run-off through the catchment, freshwater discharge through the estuary and sea cliff behaviour (e.g. can be a trigger for landsliding events);
- Salinity
- Temperature which can drive circulation flows in estuaries.

Sometimes these are thought of as energy flows, or the ability to do work, which have been linked with physical processes and developed into an estuary cause-consequence model by Townend (2004).

3.1.3 Sediments

The strength of the sediments upon which the forces are imposed dictates their response to those forces. Where the shear stresses caused by the forces exceeds the shear strength of the material, sediments will become mobilised and transported. Sediment transport of individual particles can occur as bed load transport (for non-cohesive sediments such as sands and gravels) and as suspended load transport (for fine sands or cohesive silts and clays). The strength of sediments also plays and important role in controlling the large scale evolution of coastal and estuarine systems since morphological features composed of sediments of different geology (e.g. hard rock versus soft rock) and structure (e.g. the presence of faulting, which can weaken rocks) exhibit different rates and types of behaviour. For example, hard rock cliffs may experience relatively low rates of recession even in very hostile forcing environments, whereas clay cliffs may be subject to large-scale land sliding events involving tens or even hundreds of metres of recession in a single event.

3.1.4 Morphology

The morphology (or shape and features) of coastal and estuarine systems can alter in response to imposed forcing or sediment movements over the full range of spatial and time scales. For example, individual features, such as ripples, can be formed or eroded almost instantaneously, whilst larger scale coastal embayments may take centuries to fully evolve.

Any coastal or estuarine system can be considered to comprise a number of inter-connected geomorphological landforms. These include:

- banks and shoals;
- channels;
- beaches;
- barriers;
- mudflats;
- saltmarshes;
- spits;
- tidal deltas;
- sea cliffs;
- sand dunes;
- shore platforms;
- flood plain;
- drainage basin.

It is important to understand how each of these landforms interacts with others within the context of a functioning physical system. For example, in the cross-shore sense, there is an intrinsic relationship between cliffs and shore platforms whereby the rate of cliff recession is controlled by the rate of platform lowering. In a wider spatial context, cliff recession also releases sediment into the coastal system and this sediment can be transported along the coast to feed other landforms, such as beaches or spits, which are remote from the cliff. Often such wider-scale interactions are viewed in the context of a sediment budgetary approach in which various inputs, transport pathways, stores and sinks of sediment can be identified.

3.1.5 Relevant Studies

Various recent or ongoing studies have attempted to incorporate consideration of hydrological processes and morphological responses, as observed over a range of spatial and time scales, in order to achieve certain aims and objectives. Relevant studies include:

- *Mapping of littoral cells* - based on non-cohesive sediment transport along the open coast and provided the framework for 'first generation' shoreline management plans (SMPs) in England, Wales and Scotland;

- *EMPHASYS* (Estuary Morphology and Processes Holistic Assessment System) - aimed at collating available tools for assessing processes and morphology in estuaries, ranging from 'bottom-up' methods (such as short-term numerical process-based models) through to 'top-down' methods (longer term geomorphological tools) and including hybrids of the two. The study recommended the synthesis of results from a range of approaches, suited to different spatial and time scales, as a means of better understanding estuarine systems;

- *Futurecoast* - aimed at improving understanding of coastal systems and their component landforms, as a means of predicting future behavioural tendencies over the next century. This involved the preparation of 'behavioural statements' for individual landform components and consideration of how these components interact within the context of different types of coastal system (e.g. barrier-inlet coasts, source-pathway-sink coasts, etc.). The project also brought in the local knowledge of a number of recognised coastal experts so that the precise subtleties and behaviours of all sections of English and Welsh coast could be considered;

- *Procedural Guidance for SMP2* - which involved a development of the Futurecoast methodology to envisage future coastal behaviour under different shoreline management policies across three future epochs. This study also involved a review of existing estuary classification schemes as a precursor to proposing procedural guidance to determine the extent of process interaction between a particular estuary and the adjacent open coast;

- *EstProc* (Estuary Processes Research Project) - which has produced improved understanding of the hydro-biosedimentary processes in estuaries. The final project report presents a wide range of algorithms for physical processes, these cover hydrodynamics - waves and currents, sediment transport - sands, muds and mixtures of these, and biological processes - including interactions of biology with flows and sediments. These algorithms can be implemented in analytical studies and computational models of estuary processes and morphology, increasing the range of physical parameters that can be represented and reducing uncertainty on some of the key processes.

- *F-ECTS* - This study recognises that coastal resources cannot be sectorially managed and instead the interactions that occur between adjacent sectors must be fully considered within an holistic management approach. This has created a need for powerful tools for decision-making, effective management, protection and development of the coastal zone. The project provides an information tool for decision makers to give efficient answers for the development of operational and integrated coastal zone management. The concepts upon which this tool is founded include: phytobenthos communities; hydrodynamics; nutrient cycling; and sediment transport. The study involved the provision of a specific background for selective generation of new field data, modelling activities to set up linked modules for simulation of feed-back loops between physical processes (hydrodynamics and sediment transport) and phytobenthic habitats, and the merging of data into a Geographical Information System (GIS).

- Estuary Research Programme Phase 2: *Geomorphological Tools* - aimed at providing a consistent and formalised approach to the application of existing geomorphological tools (e.g. regime theory, entropy, estuarine 'roll-over', etc) within estuarine studies. As part of this project over 125 references were reviewed as a means of establishing the scientific basis for entropy approaches alone;

- Estuary Research Programme Phase 2: *EstSim* - which adopted a conceptual systems-based approach similar to the Futurecoast methodology but for estuaries. This involved the preparation of 'behavioural statements' for individual landform components and consideration of how these components interact within the context of different types of estuary system (e.g. fjards, rias, spit-enclosed, embayments, tidal inlets, etc);

- *Capturing Geomorphological Change for the Coastal Simulator* - this Tyndall Centre project again further developed the Futurecoast-type approach and is considering the trend likelihoods for cross-shore change within a range of profile typologies (e.g. cliff face - foreshore - offshore) in response to changes in sea level and sediment supply. Cross-shore trend likelihoods are then reviewed in the context of the long-shore setting within which the cross-shore profile is set (i.e. identifying any constraints on identified cross-shore response imposed by landforms to the updrift and downdrift of the profile).

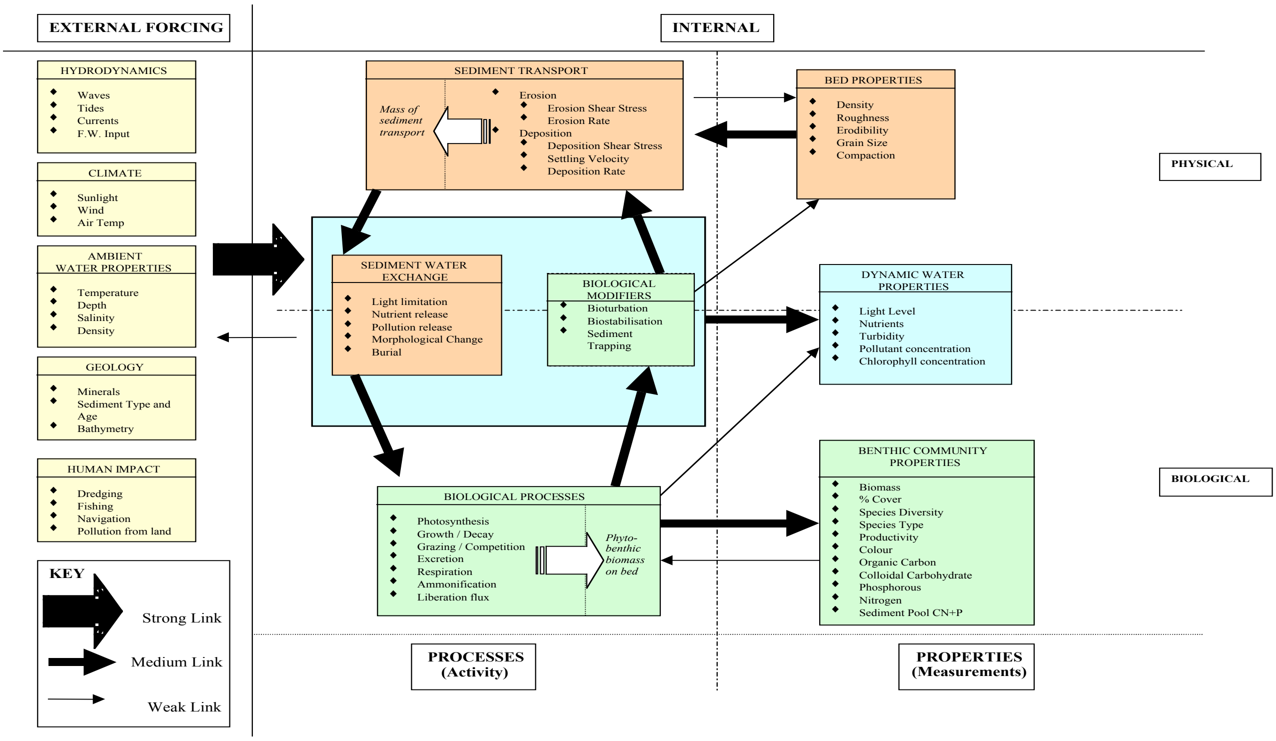
A common theme emerging from each of the aforementioned studies is that even 'simplified' approaches to considering morphological response and process interactions are extremely complex because whilst there exists a finite number of processes or general factors that can cause or influence change, they coalesce in an infinite combination of magnitudes and frequencies. Even in studies where numerical models are used to quantify short-term changes, gross assumptions are necessarily made and only a small range of events generally are considered. When attempting to assess longer-term or larger-scale interactions and responses, more qualitative geomorphological approaches are adopted. These generally have involved understanding specific landform behaviour and viewing this within the context of the functioning of the controls, interactions and feedback mechanisms that exist within a wider-scale coastal or estuarine system.

3.2 Relationships between Hydromorphological Processes and Ecological Function

3.2.1 Background

Coastal and estuarine systems are highly complex due to feedback which exists between the various physical, chemical and biological processes (see Figure 1). The observed distribution of broad habitat types and species assemblages associated with these habitats is therefore the result of a complex suite of interactions between these various elements.

Figure 1. Feedbacks and interactions between various physical processes (source: F-ECTS Project)



This review is designed to highlight the links that exist between the hydromorphologcial parameters and ecological components of a system. The review covers a number of biological entities which are derived from the Biological Quality Elements defined under the Water Framework Directive. The elements comprise:

- Benthic invertebrates
- Macroalgae
- Angiosperms
- Fish in transitional waters
- Phytoplankton

The marine habitat classification (Connor *et al* 2004) and EUNIS (http://eunis.eea.eu.int/index.jsp) provides a hierarchical classification of UK marine habitat types ranging from descriptions of broad physical habitats (Levels 2 and 3) to more detailed descriptions of species assemblages (Levels 4 to 6). The classification provides a firm basis for the conduction of relationships between habitats and the physical parameters that govern their distribution. A primary distinction in the classification is between rocky and sedimentary habitat types and this distinction has therefore been applied in considering factors governing the distribution of benthic invertebrate quality element, below.

3.2.2 *Benthic Invertebrates*

Sediment habitats

The substratum - Sediment grain size is a key physical factor controlling the distribution and occurrence of benthic organisms (e.g. Gray, 1974; Goss-Custard & Yates, 1992 & Warwick & Davies, 1977). Sediment grain size preferences relate largely to the behavioural and feeding methods of invertebrates.

Zonation - In intertidal locations the degree of wetting and drying caused by the tides will have physiological consequences for the species inhabiting this environment. Stresses resulting from the periodic wetting and drying of intertidal areas include fluctuations in temperature, salinity, desiccation and UV radiation. In subtidal environments water depth can influence the resulting community structure (e.g. Freeman & Rogers, 2003). The importance of water depth on benthic communities has also been emphasised by Buchanan (1963).

Exposure to wave action - Waves and tidal currents have a large role in determining the sedimentary characteristics of an area and can be considered as the ultimate cause of the broad scale community patterns observed on intertidal areas (Hall, 1994; OU, 1989; Elliott *et al* 1998).

Hydrodynamic regime & tidal currents - Tidal currents and bed stress, contribute to determining sediment grain size and hence influence community structure in this way (e.g. Warwick & Uncles, 1980; ABPmer, 2003). Tides and currents will not only affect erosion and disturbance thresholds but has the potential to impact on food supply and larval dispersal (Wildish, 1977; Wildish & Kristmanson, 1979).

Topography, geology & aspect - The geology and aspect of a location are typically considered as irrelevant in the shaping of sediment based communities. The relative slope of the shore does, however, have the potential to impact on the period of emersion and influence the degree of wave exposure to which the invertebrates are exposed.

Accretion & erosion - From the intertidal zone to the subtidal, sands, silts and clays these sediments are inhabited by a variety of marine benthic organisms which display a range of adaptations to deposition and erosion of the bed (Miller *et al* 2002).

Salinity, sediment & water quality - All chemical processes that occur within the sediments will affect distribution patterns. Organic content, pH, redox potential, oxygen availability and drainage, for example, can all affect distribution patterns. Salinity is a particularly important factor affecting ecological distributions (Attrill & Rundle, 2002; Little, 2000).

Biotic factors - When examining the relationship between hydromorphological and ecological parameters it is important not to ignore the biological interactions that operate in the environment such as competition and predation. The complex relationships between the relative importance of sediment characteristics and biological interactions in shaping observed community patterns has also been examined (Reise, 2002).

Rocky habitats

Substratum - Rock types are important in affecting species diversity and community composition as they provide different micro-habitats. The larvae of most benthic invertebrates are highly selective in their choice of habitat and actively search out suitable surfaces on which to settle (Crisp, 1984).

Zonation - Rocky shores for many years have been described in terms of their zonation patterns (Stephenson & Stephenson, 1949; Southward, 1958; Lewis, 1964).

Higher on the shore there is a greater variability and hence unpredictability in physical factors such as salinity, oxygen, humidity, temperature, light penetration and availability of food and nutrients (Hawkins & Jones, 1992; Raffaelli & Hawkins, 1996). This results in patterns of zonation along this dimension, which in general are related to tidal level and exposure to wave action. Subtidal communities are vertically zoned but the zones are generally broader and less pronounced than intertidal communities.

Exposure to wave action - The gradient of differing wave exposure influences the species present at a particular location and can modify the tidal height at which they are found. It is not only the relative distribution of species that changes under differing wave climates but also the actual species that occur under such environmental conditions. Species capable of existing across a spectrum of wave exposures may exhibit different forms depending on the degree of exposure they experience (Newell, 1979).

Hydrographic regime & tidal currents - Tides and water circulation patterns affect larval dispersal and hence colonisation patterns. Animals and plants attached to hard surfaces frequently demonstrate phenotypic adaptations to maintain their position in locations of strong water movements (Koehl, 1982).

Topography, geology & aspect - The aspect of a shore is an important factor in determining the upper limits at which intertidal animals can live. Sheltered shores with a shallow gradient have a relatively wide littoral zone which allows an upward extension of the sublittoral fringe organisms. Conversely where the shore is steep, the whole of the littoral zone may be condensed to a relatively narrow band. Under exposed conditions the topography of the shore plays an important part in modifying the effects of wave action.

Accretion & erosion – this is largely irrelevant in rocky shore habitats.

Salinity, sediment & water quality - All key rocky shore species are typically able to tolerate a range of salinities. The key species are also thought to be moderately tolerant of temperature changes although sudden and extreme changes in temperature can result in death. Species are typically considered as being tolerant of elevated turbidity.

Biotic factors - Biological interactions such as competition for space and food, predation and grazing will also affect the distribution of species (Hawkins & Hartnoll, 1985; Jenkins *et al*, 1990; Noda, 1999).

3.2.3 Macroalgae

Substratum - Macroalgae need to remain attached to hard substrates and have adaptive mechanisms to allow them to do so. The relative stability of the substratum will have implications for the growth and subsequent survival of the inhabiting plants. Macroalgae are therefore generally associated with rocky shores, although a number of chlorophyceae (green algae) occur in sedimentary environments.

Zonation - Macroalage are subject to the same environmental conditions as those described for the invertebrate species. There is considerable evidence from direct observations that upper limits of plant species can be set by physical factors (Hawkins & Jones, 1992). The upper limit of some mid and low shore species may, however, be set by biological interactions. Similarly the lower limits of a number of plants species are thought to be affected by both physical and biological factors. The depth of light penetration will also limit the lower limit of subtidal algal species.

Wave action - Algal growth tends to be greatest in sheltered environments where they are not as frequently removed from the substratum by strong wave action. Wave exposure plays a key role in affecting the balance between fucoids, limpets and barnacles observed on rocky shores (Hawkins & Hartnoll, 1983). For intertidal species it is frequently observed that plants growing on exposed shores are usually, tougher, shorter, narrower and often have stronger attachment structures than those growing in calmer conditions (e.g. Price, 1978; Russell, 1978; Steffenson, 1976).

Hydrographic regime & tidal currents - The tidal range will have implications for the width of each of the zones that occur on rocky substrata. This is associated with the duration of emersion periods and associated physiological stresses experienced by the macroalgal species (Hawkins & Jones, 1992). Water motion has been attributed with influencing the morphology of seaweeds, the composition of seaweed communities (Sundene, 1953) and the relative biomass of seaweeds (Conover, 1968).

Topography, geology & aspect - The aspect of the shore will influence the amount of desiccation experienced by macroalgae when they are emersed. Locations which are shaded and remain damp for longer may result in an upward extension of some species. The shallower the gradient of a shore the greater the potential width of each of the intertidal zones.
Accretion & erosion - largely irrelevant in rocky shore habitats.

Salinity, sediment & water quality - Most rocky shore species are relatively tolerant to salinity changes and can tolerate long term reductions in salinity within their normal tolerance range although growth rates and fecundity are likely to be impaired. Similarly most species of macroalgae can occur across a range of temperatures. Schonbeck & Norton (1979) demonstrated that fucoids can increase tolerance in response to gradual temperature change in a process known as 'drought hardening'. However, fucoids are more intolerant of sudden changes in temperature. Temperature can affect the distribution and reproductive timings of a number of algal species (Lobban & Wynne, 1981).

Biotic factors - Biotic interactions between plants and animals, particularly competition and grazing play a key role in determining species distribution. The outcome of such interactions is, however, subject to environmental conditions.

3.2.4 Angiosperms

Saltmarsh

Substratum - Most saltmarsh plants are not limited by sediment types and textures that occur on natural saltmarshes, and are found on various marine sediments from coarse sands to heavy clays (Adam, 1990). However, sediment grain size composition and porosity affect drainage characteristics and organic content, and can influence the elevation of species colonisation and the outcome of competition.

Zonation - Typically saltmarshes occur between mean high water neaps to high water spring tides. Within a saltmarsh habitat complex, halophytic plant species and communities display a transition, from marine to terrestrial habitat (Grey *et al*, 1995). There is general agreement that the main factors affecting the zonation relate to frequency of tidal inundation and associated effects of salinity and tidal scouring. Each species has a different tolerance to tidal flooding and therefore a different, although often overlapping, vertical range.

Wave action - Saltmarshes tend to form in sheltered environments (Adam, 1990).

Hydrographic regime & tidal currents - Tides are important in influencing patterns of zonation. Patterns of water movement may also influence the dispersal and subsequent establishment of propagules (CEFAS, 2004).

Topography, geology & aspect - Where an area is gently sloping this provides a greater opportunity for a full range of saltmarsh types to establish. The surface gradient does, however, need to be sufficient to allow adequate drainage as prolonged waterlogging can result in the death of vegetation (Adam, 1990). Creeks are also considered important for supplying the marsh surface with sediment and nutrients and dissipating tidal energy, and for draining the marsh during the ebb tide. In addition the size of an estuary influences the elevational limits of saltmarsh species.

Accretion & erosion - A sufficient sediment supply is required to sustain the surface elevation at a suitable height for continued vegetation survival (CEFAS, 2004). Excessive accretion at levels suitable for marsh colonisation may result in burial of seedlings and vegetation, although saltmarsh plants are tolerant of quite high levels of accretion.

Salinity, sediment & water quality - Salinity, along an estuarine gradient for example, affects the species that occur at a particular location. Most saltmarsh plants can grow well in non-saline soils but show poor competitive ability with terrestrial and brackish marsh plants. Major freshwater inputs to saltmarshes will therefore have implications for the species composition. Nitrogen and phosphate can be limiting to some saltmarsh plant growth (Adam, 1990), although excessive nutrients can also introduce problems. In addition the chemistry of the sediment, such as the pH and redox potential, can also affect nutrient uptake and affect other biological processes.

Biotic factors - Biotic interactions between plants, particularly interspecific competition, also determine species distribution. The outcome of such competition is, however, subject to environmental conditions. Competition is thought to determine the upper limit of a number of species.

Eelgrass

Substratum - The substratum of eelgrass beds ranges from soft mud to a mixture of sandy gravel.

Zonation - *Zostera* spp. tend to inhabit lower regions of the intertidal down to subtidal depths. Light is the limiting factor of eelgrass growth in deeper water, and its upper limits are typically attributed to its susceptibility to desiccation.

Wave action - All three species require shelter from strong tides, currents and wave exposure. Dense swards tend to develop in sheltered inlets, bays, estuaries and saline lagoons, but in more exposed sites the beds are usually smaller, patchier and more susceptible to storm damage.

Hydrographic regime & tidal currents - Water movement affects seagrass biomass and habitat structure (Short *et al* 2001), for example, within limits biomass and height may increase with increasing velocity. Water movement is also for important for pollination.

Accretion & erosion - *Zostera* spp. cannot tolerate excessive sedimentation, which can smother plans, or high turbidity, which inhibits growth by reducing light penetration for photosynthesis (Giesen *et al* 1990).

Salinity, sediment & water quality - *Zostera* spp. tends to prefer fully saline conditions. The optimum temperature range for growth and germination of UK species is reported as between 10-15 °C, although plants can tolerate sea temperatures between 5-30°C (Davison & Hughes, 1998). Nitrogen is typically the limiting nutrient for plant growth. However, excessive inputs may be harmful. A variety of toxic contaminants have the potential to cause harmful effects.

Biotic Factors - Eelgrasses provide shelter, nursery areas and food web support for a number of organisms. The root networks increase sediment stability, reducing erosion (Fonseca & Fisher, 1986), while the canopy buffers water movement, reducing current flow and trapping suspended sediments and organic particles.

3.2.5 *Fish in transitional waters*

The number and types of species found within a particular system will depend on many factors including:

- Habitat diversity;
- Estuary size and shape;
- Structural complexity;
- Tidal amplitude; and
- Freshwater runoff.

Mudflats and saltmarsh habitats provide important feeding grounds for fish species. As substrate is very important in determining benthic communities this can influence the distribution of a number of fish species. Saltmarsh habitats can be extremely productive and in combination with creek systems are considered especially valuable for small adult fishes and fry (Rozas & Minello, 1997; Hettler, 1989; West & King, 1996). Lower saltmarsh communities improve habitat heterogeneity and structural complexity, and as such influence fish habitat selection (Grenouillet & Pont, 2001). They also provide food sources and offer some form of protection from strong currents and fish predators (Little, 2000). Such habitats are also important nursery grounds for a number of fish species.

Estuarine fish show some tolerance of high turbidity, temperature extremes, and a wide range of salinities and dissolved oxygen levels; the distribution of species in an estuary is largely determined by their tolerance to each of these parameters (ABP Research, 1998).

The strength of the tidal flow affects the movement of fish and the freshwater draining into the upper end of the estuary will influence the suitability of the ecosystem as a habitat for fishes (ABP Research, 1998). Climatic conditions also alter habitat conditions, for example, strong winter rains or snow melts in northern latitudes can flush out the maritime influence.

3.2.6 *Phytoplankton*

The distribution of phytoplankton species and productivity on a small scale is both spatially and temporally patchy in nature. Several processes appear to shape these patterns including physical, reproductive and feeding. The availability of nutrients, amount of vertical mixing, salinity, density, temperature, and depth of water affect phytoplankton growth rates (Harris, 1986).

In estuarine systems it is not typically nutrient availability that limits the phytoplankton populations, there are other factors limiting growth. Of most importance in estuaries are the relatively high turbidity levels that are characteristic of temperate systems. In addition the growth rates of phytoplankton may be less than the flushing time of the estuary (McClusky, 1989).

In shallow water and on intertidal areas diatoms are an important food source for surface feeders. In addition mats of diatoms on the surface of the sediment act to stabilise the sediment. Diatoms and other benthic microalgae also play an important role in developing and maintaining an oxygenated zone on the surface of intertidal estuarine sediments.

3.2.7 *Summary*

As already stressed the review focuses on the hydromorphological parameters that influence the ecological components of a system. It is important to remember that chemical and biological parameters and their interactions will also affect the distribution and form of the ecological components of a system. In examining the distribution patterns of habitats and species careful interpretation is required in the analysis of all community types and the associated physical parameters. It is important to remember that correlations are not necessarily evidence of cause and effect relationships between particular environmental variables and faunal distributions, they are merely indicative of the presence of gradients of environmental variables within systems that may be influencing the composition of communities (Morrisey *et al* 2003).

3.3 Existing Classification Tools and Classification Schemes

3.3.1 Background

A number of literature sources contain details of existing hydromorphological classification tools and classification schemes. These have been reviewed to determine whether any available coastal or estuarine schemes can be applied, either directly or in an adapted form, in the present study. Furthermore, existing river classification schemes have been reviewed to determine whether any approaches adopted to consideration of these physical environments can be generically applied. The review has also considered available Biological Task Team classification schemes.

3.3.2 Coastal Classification

Most coastal classification schemes are based upon typology, for example the European Union for Coastal Conservation (1998) define five coastal types:

- hard rock, cliffed coasts;
- hard rock coastal plains;
- soft rock coasts;
- tide-dominated sediment plains; and
- wave-dominated sediment plains.

Definition of the coastal type in this manner is on such a broad-scale that these schemes can be considered simplistic. Often, such classifications do not consider the interactions that occur within these environments for example between the morphology and hydrodynamics. In addition, ecological parameters are rarely, if at all, used. An additional drawback is that many schemes do not include all the littoral, nearshore and offshore areas of the coastal environment.

The majority of studies that have attempted to incorporate hydromorphology have not relied upon classifications *per se*, but instead have attempted to define sediment budgets, or synthesise a combination of information on sediment type, tidal processes and wave action in order to understand coastal *behaviour*.

3.3.3 Estuary Classification

Similar to coastal environments, most previous estuary classification schemes have essentially been typological classifications that do not necessarily yield much useful information about hydromorphological status. For example, Hayes (1975) defined three categories of estuary according to tidal range, which is useful to some extent in identifying the gross scale of hydromorphological pressure due to this process but does not consider the interactions between tidal range and other processes or their combined effect on hydromorphological quality. Typically, the parameters or processes that have been used in most classification schemes to date include:

- physiography - mode of origin;
- hydrography - tidal range;
- hydrography - stratification (salinity gradient);
- sedimentation - mode of infilling;
- ecosystem energetics - Arctic, tropical, etc.

Hume and Herdendorf (1988) attempted to combine many of the above factors in their classification scheme. This first grouped estuaries according to the primary process that shaped their basins (i.e. before modification by Holocene processes) and then sub-divided these five classes into 16 specific types, based on geomorphic and oceanographic characteristics, such as the presence or absence of features (e.g. barriers) and the relative magnitude of certain processes (e.g. high or low wave energy).

Hume and Herdendorf were then able to identify that different groupings of certain estuary types exhibited similar characteristics (at a broad scale) in certain factors (Table 2).

Table 2. Generalisation of Behaviour of Different Estuary Types

Factor	Magnitude	Estuary Types
Channel stability	Low	Funnel-shaped estuary Headland enclosed estuary Barrier enclosed estuaries (all types) River mouth estuaries (all types except straight banked) Coastal embayment
	High	River mouth – Straight banked Tectonic Volcanic Glacial activity
Inlet stability	Low	Funnel-shaped estuary Barrier enclosed estuaries (all types) River mouth estuaries (all types except straight banked) Coastal embayment
	High	Headland enclosed estuary River mouth – Straight banked Tectonic Volcanic Glacial activity
Sediment infilling	Moderate	Funnel-shaped estuary Headland enclosed estuary River mouth – spit lagoon Fault-defined embayment Volcanic embayment
	High	Barrier-enclosed estuaries River mouth –Spit lagoon River mouth –Deltaic

Hume *et al*. (2003) further developed the estuarine classification system into an approach termed the 'Estuary Environment Classification'. This is based upon a hierarchal model that describes the physical characteristics of an estuary as a result of related physical processes. This was applied over three classification levels, or scales: (i) global; (ii) regional - which was further sub-divided into two classes of controlling forces (hydrodynamics and catchment); and (iii) estuary. These levels were then further sub-divided into different physical processes, for example climate, oceanic forcing and tidal currents, respectively. This is best summarised in Figure 2.

Figure 2. Summary of 'Estuary Environment Classification'

CLASSIFICATION LEVEL	CONTROLLING FACTORS	PROCESSES	TYPICAL SIZE (km^2)	PHYSICAL CHARACTERISTICS
global	climate; water mass	heating, solar radiation	10^4 macro	temperature & stratification regimes
regional (between estuaries)	(hydrodynamic) basin morphometry; oceanic forcing; river forcing	whole estuary hydrodynamic processes influencing mixing, circulation & flushing	10^4 10^3	flushing, salinity & percentage of intertidal area
	(catchment) topography; geology; land cover	catchment processes supplying freshwater, sediment & water chemistry constituents	meso 10	turbidity, sediment fluxes & other water column constituents
estuary (within an estuary)	ocean swell; tidal currents; wind waves; depth	local hydraulic forces influencing deposition & erosion	1 micro 0.1	patterns of sediment facies

Dyer (in Defra, 2002) developed a modified version of Hume and Herdendorf's system and populated it with basic data on certain processes or parameters as provided by Davidson *et al* (1991). This system and database has been incorporated within ongoing work for both Work Package 2 of the present study and, in a modified form, within EstSim (ABPmer, 2004).

In addition, several authors have attempted to group estuaries according to relationships empirically observed between different morphological parameters. The most commonly applied approach is the O'Brien Rule (1931) in which the cross-sectional area of an inlet entrance (at mean tide level), A, is related to the spring tidal prism, P, in the form:

$A = cP^n$ where c and n are empirical coefficients.

Townend (in press) has had some success in grouping estuaries according to the above relationship in accordance with their maturity in a Holocene context.

3.3.4 River Classification

Fluvial geomorphology arguably is a more developed science than estuarine or coastal geomorphology, possibly because the range of physical processes and process-interactions is smaller (i.e. no wave or tidal process or salinity effects). Fluvial processes and geomorphology have long been studied (Richards, 1982; Leopold, 1964) and several classification schemes have been developed (Rosgen, 1994; 1996; Thorne, 1997). This review focuses on the practical application of such schemes for specific purposes that are akin to the aims and objectives of the present study.

Rosgen (1994, 1996) developed a river classification system that comprised assessments of channel characteristics (e.g. entrenchment ratio, width-depth ratio, sinuosity and gradient) and predominant bed material. Modified versions of this have proven to be practically useful in assisting in assessments of the geomorphological impacts of certain structures placed in river channels (Cooper and Hooke, 1998) and in developing a geomorphologically-derived framework for examining river rehabilitation potential in Australia (Brierley and Fryirs, 2000).

Independently of any river classification approach, Entec (2004) has undertaken work to establish hydrological (rather than hydromorphological) reference conditions for rivers and lakes. They recommended the adoption of a threshold based on the total influence of abstraction, discharge and impoundment being less than 1% of Qn95 (the natural 95th percentile flow) for high status in rivers.

3.3.5 Biological Classifications

Links with the classification work of the Biological Task Teams is ongoing throughout the course of the study, and further comments will be incorporated in subsequent working papers and discussed at the Workshop.

3.3.6 Summary

Most coastal, estuarine and river classification systems can essentially be considered as typologies that do not necessarily yield much information about hydromorphological status. They are generally based on processes or parameters such as:

- mode of origin (estuaries);
- degree of infilling (estuaries);
- landforms (coasts);
- tidal range (estuaries);
- salinity/stratigraphy (estuaries);

- channel characteristics (rivers);
- bed sediment (rivers).

Where work has been undertaken to establish hydromorphological reference conditions, this has been based on the establishment of a threshold that represents 'nearly totally undisturbed' hydrological conditions, with the threshold verified against water bodies considered to be at high ecological status (see Entec, 2004 for examples in river water bodies).

4. Conceptual Framework

4.1 Hydromorphological Status

The review of available hydromorphological literature has revealed little in the way of listings of physical parameters that are important for defining the 'quality' of coastal and estuarine systems. However, following the provision of expert advice from both within the project team and external consultees, the following physical parameters have been identified as being potentially important in defining the hydromorphological status of estuaries, coasts and nearshore seabeds/waters:

Geological

- Seabed (surface) sediment type – e.g. mud, gravel, sand or various mixtures
- Substrate type (hardness, permeability, rock type/chemistry)
- Texture (roughness, vegetation cover)
- Broad-scale erosion/deposition (i.e. source/sink) behaviour

Topography of seabed/beaches and sediment transport

- Level (relative to Chart Datum – above or below)
- Gradient
- Bed forms (e.g. sand waves) and features (e.g. rock outcrops)

Hydrodynamics

- Water levels (tidal range, % distribution, exceptional levels)
- Wave energy/disturbance
- Currents - mainly tidal (energy, residual direction)
- Flushing/exchange rates
- Fluvial and other discharge rates (leading to mixing/stratification, etc.)

Water characteristics

- Turbidity/suspended sediment concentrations
- Salinity (density-driven currents)
- Temperature

Environmental parameters

- Wind (beach sand interchange to dunes)
- Rainfall (coastal cliff landsliding)

Anthropogenic disturbances

- Land claim
- Shoreline reinforcement
- Navigation dredging
- Aggregate dredging
- Disposal of dredged material
- Shellfisheries
- Fisheries
- Impoundments
- Flow manipulation

In general, all of the above will vary both spatially, i.e. in location and extent, and over time, i.e. over time-scales ranging from days (e.g. storm response), months (e.g. seasonally) and longer-term (e.g. long-term trends such as shoreline erosion). These variations complicate both the initial establishment of 'baseline' conditions and the subsequent monitoring and interpretation of conditions. The list is also undoubtedly too large to form a schedule for monitoring; measuring each of these parameters over the large water body areas defined would be much too onerous.

4.2 Influence of Hydromorphological Factors on Ecological Status

From the review of the links between hydromorphology and ecology, a number of factors have been identified that can influence ecological status. These are summarised in Table 3 for benthic invertebrates (sediment habitat and rocky habitat), macroalgae and angiosperms (saltmarshes and eelgrass). The distribution of fish and phytoplankton are to some extent dependent on habitats and substratum type (Rozas & Minello, 1997; Hettler, 1989; West & King, 1996; Colclough *et al*, 2004), but are also governed by the hydrodynamic regime (Harris, 1986; McClusky, 1989; ABP Research, 1998) and factors such as salinity (Harris, 1986; ABP Research, 1998); they have not yet been included in the table.

4.3 Proposed Conceptual Framework

It is necessary to propose a conceptual framework that is intended as a basis for the progression of the study. In particular, this framework is needed to provide the scientific basis that underpins the development of the classification scheme and reference conditions. The conceptual framework proposed herewith is essentially a collation of the factors presented in Sections 5.1 and 5.2.

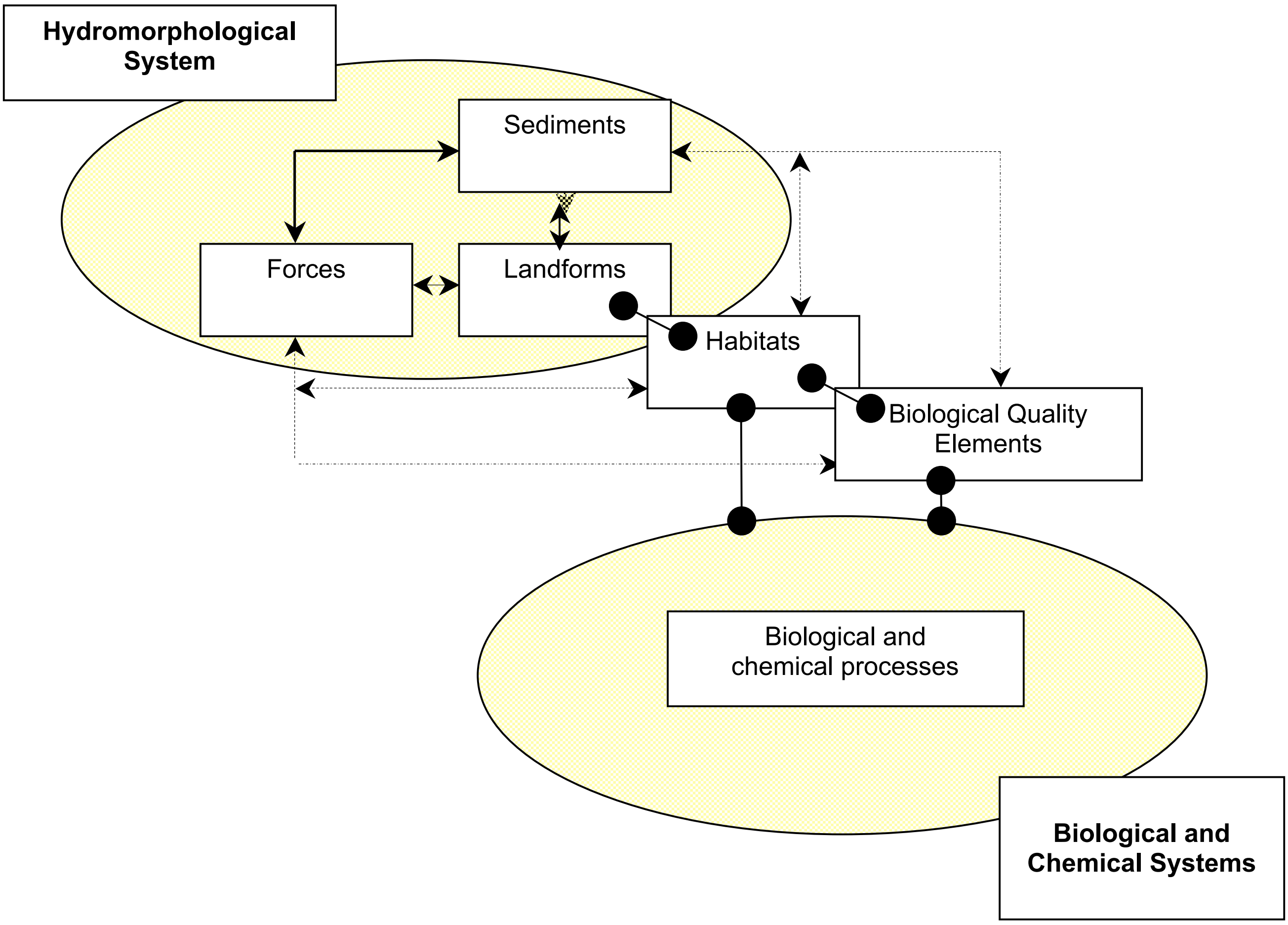
It is proposed that the framework (Figure 3) is founded on the concept that the landform is the principal integrator of hydromorphological pressures and ecological function. The benefit of this approach is that is presents an overlap between hydromorphology and ecology (i.e. any hydromorphological parameters to be considered are ecologically relevant). It is also a valid approach since:

- hydromorphological processes/parameters act upon or influence/are influenced by landforms (e.g. wave-induced currents or wind stresses enable the transportation of sediments and, ultimately, landform response); and

- specific landforms sustain specific habitats and, in turn, these sustain characteristic species.

It is also important to recognise that some hydromorphological processes can have direct and/or indirect effects on hydromorphological and ecological status. For example, freshwater flow can affect the salinity profile in an estuary. This can have a direct effect on ecology (e.g. influence the zones in which different habitats or species can survive) but can in turn also have an 'indirect' effect through the creation of density-driven currents that may cause morphological change (e.g. erosion or deposition) that could also influence particular habitats or species.

Figure 3. The proposed conceptual framework



Notes:

The framework recognises that forces, for example, play an important role in the hydromorphological system in: (i) impacting directly on landforms (e.g. causing erosion of inter-tidal zones); and (ii) impacting directly on sediments (e.g. causing their mobilisation, transportation and deposition). The solid arrows in the above figure depict these types of interactions.

However, the forces can also interact directly with specific habitats, or *vice versa* (e.g. wave attenuation by saltmarsh vegetation) and specific species (defines physical zones or niches which may or may not be tolerated by certain species). The dashed arrows in the above figure depict these types of interactions.

In addition, it is important to note that the biological quality is not only influenced by hydromorphological processes and pressures, but also by chemical and biological factors, which are also indicated in the above figure.

Table 3. Parameters that influence benthic invertebrates, macroalgae and angiosperms

Factor	Benthic Invertebrates		Macroalgae	Angiosperms	
	Sediment Habitats	**Rocky Habitats**		**Saltmarsh**	**Eelgrass**
Substratum	Sediment grain size is a key factor controlling the distribution and occurrence of benthic species. Species distributions relate to behavioural and feeding methods. Example references: Gray, 1974; Peterson, 1991; Elliott *et al* 1998, 2001; ABP Research, 1998	Rock types affect distribution patterns along with smaller scale topographic variation. Example references: Lewis, 1977; Hayward & Ryland, 1995	Generally require a hard substrate on which to attach. Example references: Hawkins & Jones, 1992	Most saltmarsh plants are not limited by particle size. Example references: Adam, 1990	Ranges from sloppy mud to a mixture of sandy gravel. Example references: Rodwell, 2000
Zonation	Stresses associated with periodic wetting and drying of intertidal habitats: • Temperature • Salinity • Desiccation • UV radiation Water depth in more subtidal locations. Example references: Boaden & Seed, 1985, Buchanan, 1963	Exposure time of intertidal organisms is a crucial factor in shaping distribution patterns. Considered physiologically more stressful at the upper limits. Example references: Southaward, 1958; Lewis, 1964; Newell, 1979; Raffaelli & Hawkins, 1996	Exposure time of macroalgae is a crucial factor in shaping distribution patterns. Desiccation is a key limiting factor. Example references: Schonbeck & Norton, 1978; Hawkins & Hartnoll, 1985; Hawkins & Jones, 1992	Typically saltmarshes occur between mean high water neaps to high water springs. Zonation of species apparent between this zone. Example references: Toft & Maddrell, 1995; Gray *et al.,* 1995; ABPmer, 2003	Stresses associated with periodic wetting and drying of intertidal habitats. Upper limits set by desiccation and lower limits set by light penetration. Example references: Short *et al*, 2001; Duarte, 1991

Factor	Benthic Invertebrates		Macroalgae	Angiosperms	
	Sediment Habitats	**Rocky Habitats**		**Saltmarsh**	**Eelgrass**
Wave Action	Has biggest influence by affecting sediment grain size. Example references: Hall, 1994, Elliott *et al* 1998	Affects zonation patterns. Can raise upper limit by spray. Affects species distribution and form. Example references: Ballantine, 1961; Lewis, 1964; Newell, 1979	Affects zonation patterns. Can raise upper limit by spray. Algal growth is typically greatest on sheltered shores. Affects species distribution and form. Example references: Ballantine, 1961; Lewis, 1964; Newell, 1979	Saltmarshs tend to form in sheltered environments. Example references: Adam, 1990	Requires shelter from wave exposure. Example references: Short *et al*, 2001
Hydrographic Regime/ Tidal Currents	Has biggest influence by affecting sediment grain size. Disturbance events. Larval and food supply. Example references: Warwick & Uncles, 1980, Ansell *et al*, 1972	Larval and food supply. Affects species morphology. Example references: Newell, 1979; Koehl, 1982	Affects propagule release and distribution. Affects species morphology. Example references: Conover, 1968; Gordon & Brawley, 2004	Will influence zonation patterns and seed dispersal. Example references: CEFAS, 2004	Water movement affects biomass and plant structure. Important for pollination. Example references: Short *et al*, 2001
Topography, Geology & Aspect	Geology and aspect relatively irrelevant. Slope will effect width of intertidal band and consequently zonation. Example references: Boaden & Seed, 1985	The aspect can affect the degree of shading. The gradient will affect the widths of the different tidal zones. Example references: Lewis, 1954; Evans, 1974	The aspect can affect the degree of shading. The gradient will affect the widths of the different tidal zones. Example references: Lewis, 1954; Evans, 1974	Gentler slope provides a greater opportunity for full range of saltmarsh types. Gradient must be sufficient for adequate drainage. Example references: Zedler, 1984	Not applicable

<table>
<tr><th rowspan="2">Factor</th><th colspan="2">Benthic Invertebrates</th><th rowspan="2">Macroalgae</th><th colspan="2">Angiosperms</th></tr>
<tr><th>Sediment Habitats</th><th>Rocky Habitats</th><th>Saltmarsh</th><th>Eelgrass</th></tr>
<tr><td>Accretion & Erosion</td><td>Can result in smothering and direct removal of species through erosion of the supporting substratum.

Example references:
Miller et al, 2002; Nelson, 1989</td><td>Not typically an issue in hard substrate environments.</td><td>Not typically an issue in hard substrate environments.</td><td>Require a sufficient sediment supply to sustain the surface at a suitable elevation for continued vegetation survival.
Excessive sedimentation can result in burial of seedlings and vegetation.

Example references:
CEFAS, 2004</td><td>Cannot tolerate excessive sedimentation.

Example references:
Giesen et al, 1990</td></tr>
<tr><td>Salinity, sediment & water quality</td><td>Salinity is particularly important.
Chemical processes will affect species distributions and interactions.

Example references:
Attrill & Rundle, 2002; Little, 2000</td><td>Communities found in rocky shore environments are fairly resistant to changes in salinity and temperature.

Example references:
http://www.marlin.ac.uk/biotopes/Bio_Sensexp_MLR.BF.htm/</td><td>Communities found in rocky shore environments are fairly resistant to changes in salinity and temperature.

Example references:
http://www.marlin.ac.uk/biotopes/Bio_Sensexp_MLR.BF.htm/</td><td>Salinity affects competitive ability of saltmarsh plants. Will affect species distribution patterns.
Nutrients can be a limiting factor.
Excessive nutrients can result in algal mats and smothering.

Example references:
Hellings and Gallagher, 1992; Adam, 1990</td><td>Prefers fully saline conditions.

Example references:
Davison & Hughes, 1988</td></tr>
</table>

Factor	Benthic Invertebrates		Macroalgae	Angiosperms	
	Sediment Habitats	Rocky Habitats		Saltmarsh	Eelgrass
Biological Interactions	Competition, predation and other biotic relationships will also determine species distributions. Biology can also influence sediments by stabilising and destabilising the substratum. Example references: Reise, 2002; Widdows & Brinsley, 2002; Lawton, 1994	Competition, predation and other biotic relationships will also determine species distributions. Example references: Stephenson & Stephenson, 1949; Lewis, 1964	Competition, grazing and other biotic relationships will also determine species distributions. Example references: Hawkins & Jones, 1992; Hawkins & Hartnoll, 1983	Competition is thought to be important in setting the upper limits of species. Example references: Gray, 1992	Provides shelter and increases sediment stability. Example references: Fonseca & Fisher, 1986

ANNEX A KEY ISSUES DISCUSSED WITH PROJECT BOARD

Several key issues were discussed between the contractor Project Team and the client Project Board at a meeting on 5th October 2004. A summary of these is presented below.

Hydromorphological issues that may affect ecological status – several issues were identified and discussed, such as how current speeds or bathymetric changes can affect ecological status, either directly or indirectly (i.e. by changes in current speeds altering stratification which then affects ecological status, or by changes in bathymetry altering current speeds). The importance to ecological status/changes of underlying geology and thickness of surface sediment deposits was also identified.

Pressures and cumulative pressures – it was widely agreed that the issue of cumulative pressures from several schemes/activities was, in many cases, of more concern than pressures arising from any one scheme/activity. However, it was recognised that the approach to assessing pressures very much depended on where they acted in the water body and also that cumulative pressures can, in the context of the WFD, act in different directions. The matrix approach to exemplifying how pressures manifest themselves, as proposed by ABPmer in the HMWB study, was considered to be useful. The importance of freshwater flows to estuaries arose at several times during the meeting and will be included in the study.

Overall approach – the general consensus from the meeting was that the overall approach should initially be a top-down approach, with more detail in terms of quantification coming in WP6-8 (e.g. use of Lidar/CASI to map water bodies, or important sub-areas of water bodies). However, the Project Team mentioned that it may be difficult to 'plug-in' more bottom-up methods/details into a top-down approach. The issue of scale was also raised and discussed. Concern was raised that whatever is developed is kept simplistic enough to use at the regulators' required scale (along with consideration for resource implications). How WFD regulators will use the recommendations should always be kept in mind. In order to gain maximum value from the Workshop, and due to the lack of a single immediately obvious approach to achieving the study aims and objectives, it was suggested that a small number of different approaches will be put to workshop delegates as potential methods. The relative strengths/limitations of each will then be discussed.

Starting point in time for reference conditions – a key issue was whether the reference condition should be the present situation, or some antecedent situation prior to human intervention, and if the latter what point in time should be taken. Environment Agency stated that the HMWB project is considering the starting point to be prior to human intervention, but it was acknowledged that this would be different for different water bodies.

Quantification of deviation from reference condition - Environment Agency stated that whilst they agreed there were complex areas and scientific challenges on the study, some quantitative means of enabling deviation from reference conditions was still needed. Project Team replied that this may need to be an 'administrative' decision as a hydromorphological decision may not be possible at the generic level.

How to consider long-term change in defining reference conditions – SNIFFER advised that for the CIS guidance, it was decided to revisit the reference conditions every 6-10 years and, if necessary, redefine conditions to account for long-term changes. This approach was discussed and consensus was reached that this was a pragmatic solution to an extremely complex issue.

Classification Scheme(s) – The Project Team asked the Project Board whether separate hydrological and morphological classification schemes should be developed or whether a single hydromorphological scheme would be better. Environment

Agency's Technical Advisor had, in a telephone call prior to the meeting, discussed this issue and suggested a hydromorphological scheme would be needed, with hydrological parameters necessarily incorporated within it. SNIFFER replied that both schemes may still be needed, running in parallel, so that if criteria are not met for one or other scheme, then the whole water body fails. This was considered important because the morphology of a water body could remain unaffected, but the hydrological regime be affected. If judged on morphology alone, the classification scheme would indicate no quality change. The example of the complete diversion of a freshwater flow into a new river channel was given, whereby the morphology of the original channel remained unaffected, but now contained no flow and hence the ecological status would be significantly affected. SNIFFER commented that the requirement is to produce reference conditions and deviations from those conditions (which is not a classification system *per se* and there is no requirement to produce a 'number'). Environment Agency stated that some means of monitoring is required. It was decided that further clarity on this issue would arise following further work during WP1.

<u>Annex V tables</u> – ABPmer asked the project board what latitude, if any, existed to modify the Annex V tables, particularly in view of the fact that wave action is stated in the accompanying text but absent from the tables, and that freshwater flow is likely to be insignificant to coastal water bodies. Those elements in the tables were considered to only partially explain ecological distributions. Environment Agency initially stated that there probably was no latitude for amendment but instead alternative means of considering issues should be investigated. Examples given included using certain elements that are present in the tables as surrogates for other parameters such as waves, or using the typology of the water body as a means of inferring information on waves. However, considerable further debate on this issue ensued and ultimately the consensus amongst Project Board members was that some latitude should exist and that waves were an important element to consider. Environment Agency offered to seek further clarification on this issue.

ANNEX B LITERATURE REVIEW

B.1 Hydromorphological Processes and their Inter-relationships

The aim of this component of the literature review is to identify hydrological and geomorphological (hydromorphological) processes and their inter-relationship and application over different time and space scales. The review is based on literature provided to the Project Team by both the Project Board and various consultees and also as identified through internal literature searches.

Numerous classic textbooks exist that each describes hydrological processes and/or geomorphological forms of transitional and coastal waters in exhaustive detail. Examples include:

- Masselink, G. and Hughes, M.G. (2003). *Introduction to Coastal Processes and Geomorphology*. Hodder Arnold, London, 354p.
- Woodroffe, C.D. (2003) *Coasts: process and evolution*. Cambridge University Press. 623p.
- Davis, R A and Fitzgerald, J R (2002) *Beaches and Coasts*.
- Bird E C F (2000) *Coastal Geomorphology: An Introduction*, John Wiley.
- Carter R W G (1988) *Coastal Environments*, Academic Press.
- Komar P (1998, 2nd Edition) *Beach Processes and Sedimentation*, Prentice-Hall.
- Dyer KR (1997) *Estuaries: A physical introduction*. 2nd Edition. John Wiley & Sons.
- Trenhaile A S (1997) *Coastal Dynamic and Landforms*, Oxford University Press.
- French P W (1997) *Coastal and Estuarine Management*. London, Routledge.
- Viles H and Spencer T (1995) *Coastal Problems*, Edward Arnold, London.
- Hansom J D (1989) *Coasts*.
- Dyer K R (1986) *Coastal and Estuarine Sediment Dynamics*, John Wiley & Sons.
- Pethick J (1984) *An Introduction to Coastal Geomorphology*, Edward Arnold.
- Clayton K M (1981) *Coastal Geomorphology*.
- Davies J L (1980, 2nd Edition) *Geographical Variation of Coastal Development*.
- Davis R A (ed) (1978) *Coastal Sedimentary Environments*.
- King C A M (1972) *Beaches and Coasts*.
- Steers J A (ed) (1971) *Introduction to Coastal Geomorphology*.

It was not the intention of this literature review to repeat the content of these text books verbatim, but rather to identify other literature sources that have utilised the content to develop methods and approaches to assessing the inter-relationships that exist between such hydromorphological processes over a range of time and space scales. Usually this has been for the specific purpose of developing suitable methods to adopt in various research and development projects (see Sections B1.2 to B1.7).

However, prior to that, it is useful to set out the context of hydromorphological processes and their interactions over various spatial and time scales, as described in various published papers and reported in Section B1.1.

B1.1 Time and Space Scales

Temporal and spatial scales are interlinked, and it is within this framework that physical processes and morphological responses interact. The type, frequency and magnitude of morphological response is dependent on the balance between the forces applied (imposed by processes such as wave and tidal action or wind stresses) and the resistance of the receptor (e.g. shoreline or sea bed sediments) to these forces. Typically, rocky and carbonate systems have slower rates of change than soft sediment systems due to the relatively greater resistance provided to the forcing conditions. Within this falls another generalisation in that younger soft sediment systems, for example young marshes, tend to be more susceptible to erosion than more developed systems as a consequence of low bed shear stresses.

This is described in the assumption of the 'primary-scale relationship' (De Vriend, 1991). Here a process of a certain scale will be in dynamic interaction with coastal / estuarine behaviour of a similar scale; that same process will be an extrinsic condition for coastal behaviour on a smaller scale and will be noise for behaviour on a larger scale. This implies that for each scale, a specific morphodynamic system can be identified (Figure 1; taken from De Vriend, 1991). Within this system water motion induces a net sediment transport which in turn causes morphological change (Figure 2; taken from Wijnberg, 1996).).

Figure 1. Scales of Interaction

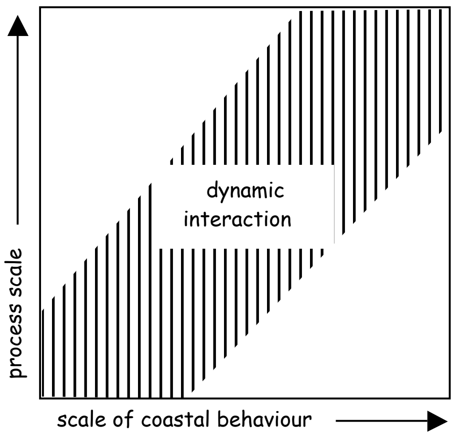
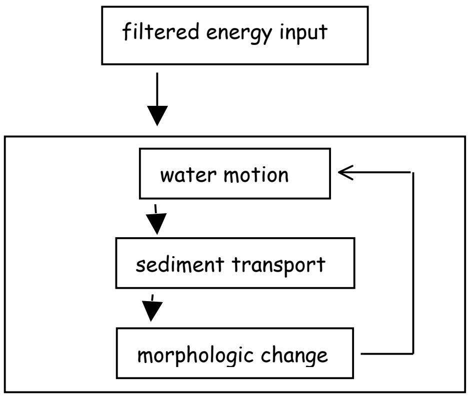


Figure 2. Morphological change



This concept has been taken further to define the morphological types and processes over the different scales. An example is given by Cowell and Thom (1994) where morphological features are grouped into four scales, namely: (i) instantaneous time (single forcing event, i.e. tidal cycle); (ii) event time (single event i.e. storm); (iii) historical time (multiple events or sequences); and (iv) geological time. This is demonstrated in Figure 3. Some examples of morphodynamic processes which fall into these categories are given in Table 1.

Figure 3. **Definition of spatial and temporal scales involved in coastal evolution, with typical classes of sedimentary features**

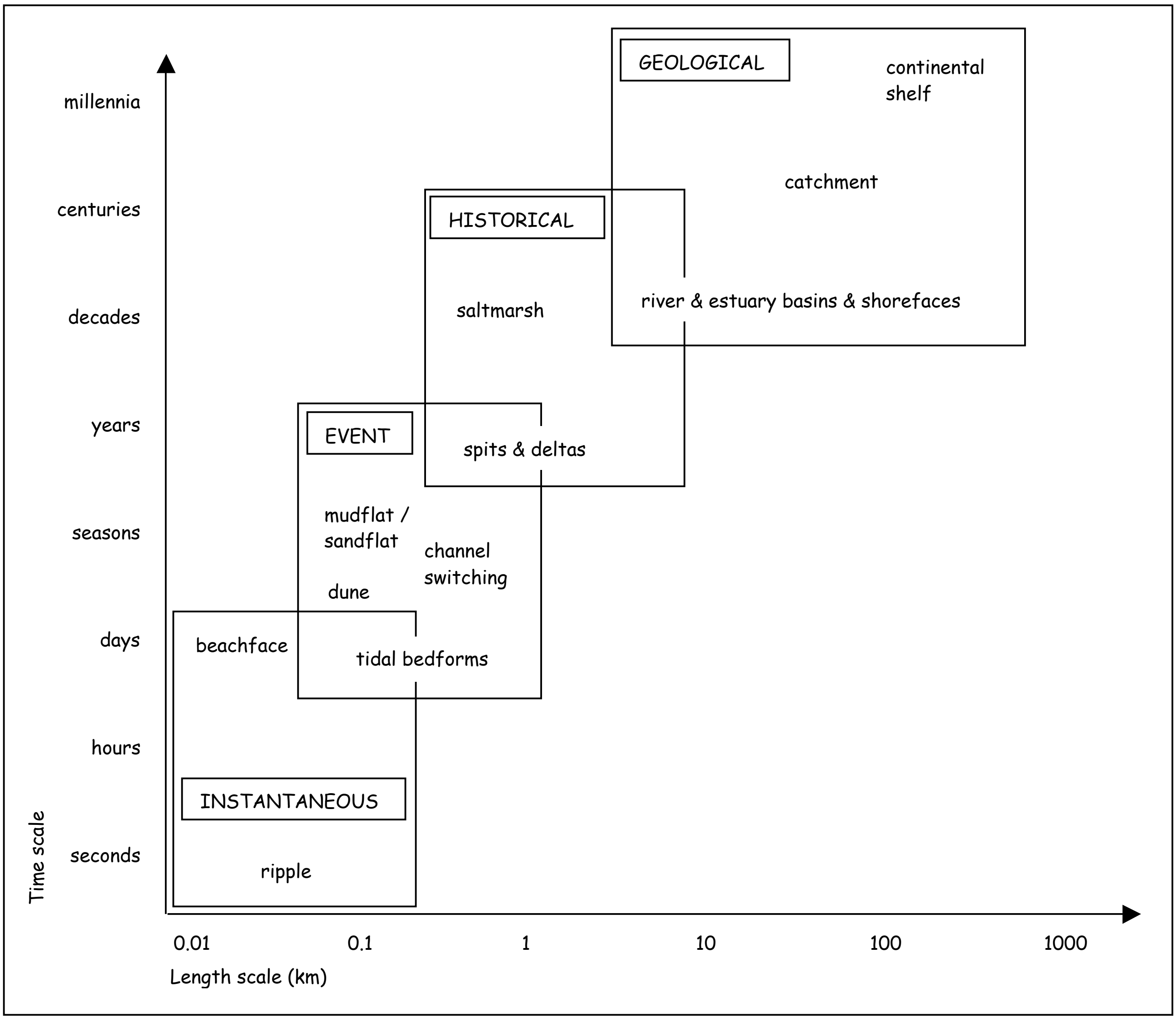


Table 1. Examples of morphodynamic processes over different scales.

PROPERTY	INSTANT-ANEOUS	EVENT	HISTORICAL	GEOLOGICAL
Self regulation	Edge waves and beach cusps	Plan form adjustment to wave direction change	Equilibrium profile, regime discharge	Basin infilling in response to sea-level rise
Threshold to self regulatory regimes	Wave breaking, bed form transitions, onset of transport	Beach transition from reflective to dissipative, breaching of barrier beaches, switching of channels due to flood events	Barrier to tidal delta transformation	On–set of ice age, tectonic eruption
Self organisation	Beach cusps	Beach-dune interaction during storms, meander to braid switches	Ebb tide shoals, shore parallel sand bars	Holocene evolution to infill basin during still stand

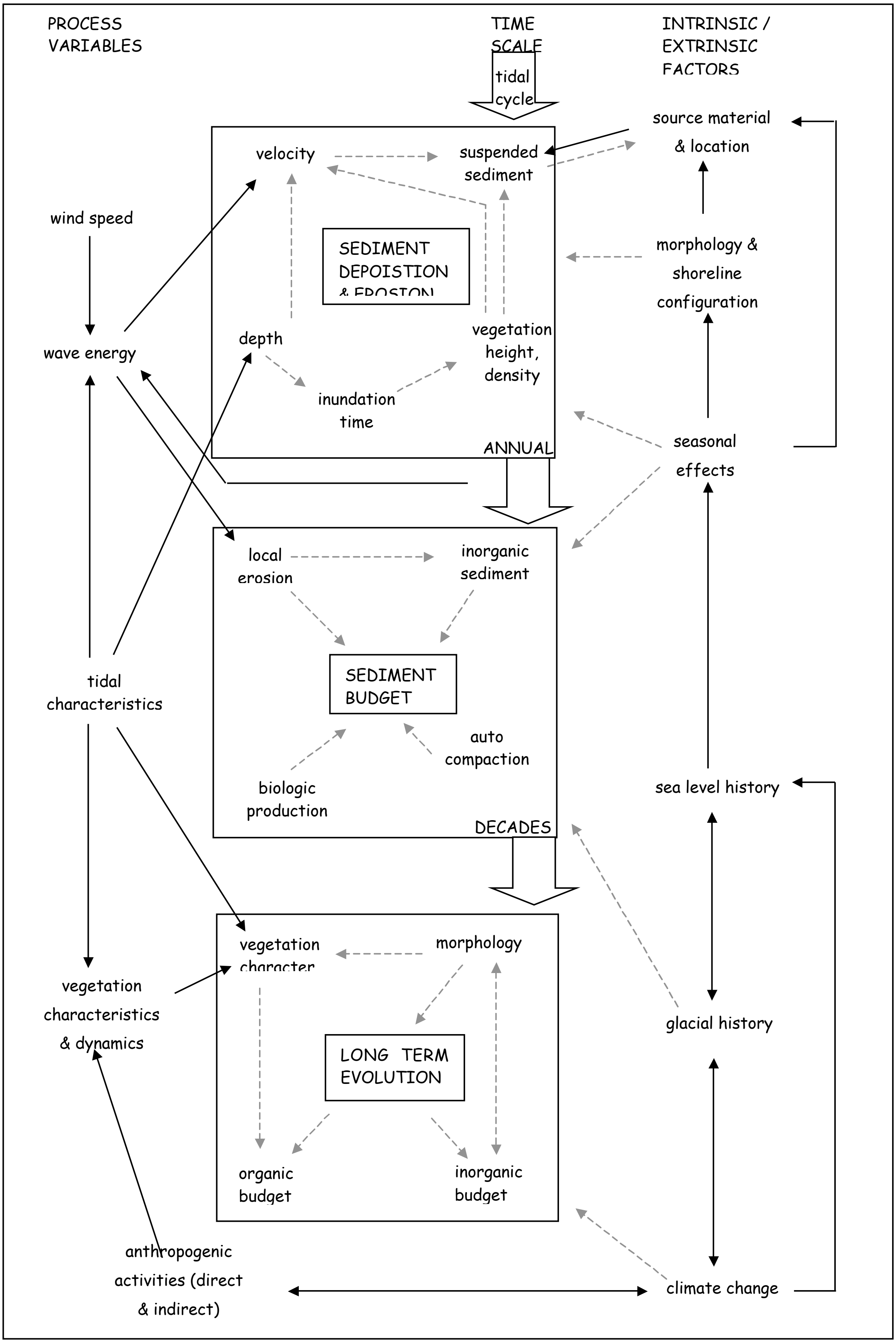
Time and space scales have also been classified into a hierarchical theory that divides process and responses into similar scales. These scales interact with higher and lower levels in a systematic way with each level interacting with higher levels as constraints/boundary conditions and the lower levels as noise (as detailed in De Vriend, 1991). This hierarchy is termed the ‘Coastal Tract Cascade’ (Cowell *et al.*, 2003a and 2003b) and is given in Table 2.

Table 2. The Coastal Tract Cascade

SYSTEM	SYSTEM - SCALE	TIME - SCALE	SPACE - SCALE	EXAMPLE (using the coastal system)
zero order	meta	quaternary period (> 10^4 years)	tract environment	
first order	mega	holocene approach (10^2 – 10^4 years)	coastal tract	entire coast system
second order	macro	late Holocene age (10 – 10^3 years)	morphological complex	shoreface
third order	meso	years to decades	morphological unit	surf zone
fourth order	meso	seasons to years	morphological element	surf zone bars
fifth order	micro	days to seasons	sub-grid phenomenon	ripples
> fifth order	micro	seconds to days	sub-grid phenomenon	grain - grain movement

The scales proposed above can be applied to particular systems and sub-systems with the example in Figure 4 (from Davidson-Arnott *et al*, 2002) demonstrating saltmarsh sedimentation over different scales.

Figure 4. **Schematic diagram of factors controlling saltmarsh sedimentation at three time scales**



Review of the literature specifically provided by the Environment Agency has revealed the following important processes or interactions operating at different time and spatial scales:

Wave Behaviour
Modification to offshore waves occurs such that the wave energy reaching the shoreline typically is reduced. These changes are induced by, amongst others, the following parameters and their interaction:

- shoreface morphology;
- shoreface slope;
- shoreline morphology;
- water depth;
- interaction with longshore currents;
- wave frequency; and
- angle of approach.

Offshore waves can also enter an estuary, but the degree to which they do so depend upon the orientation of the estuary mouth, angle of wave approach and the wave energy. For example in the Ribble Estuary there are moderate waves in the outer and middle sections of the estuary, with minimal waves in the inner estuary (van der Wal and Pye, 2002). However in the Crouch Estuary waves are able to enter the estuary but are quickly dissipated along the intertidal zone in the outer estuary.

Internally generated waves are also an important process that should be considered, particularly in the larger estuaries. These waves are greatly influenced by the local wind regime.

A change in storm conditions will result in modifications to the sediment transport regime, for example in the Ribble there is an increase in onshore sediment transport during storm events (van der Wal and Pye, 2002). Such a relationship has also been observed in the Humber where an increase in the import of finer marine material occurs during storms (Townend and Whitehead, 2003). Increased hydrodynamic activity also has the consequence of releasing more material at other coastal locations for inclusion in sediment transport pathways, which may consequently introduce more material into the estuary system. However the periods over which this increased transport potential occurs will typically be over the short-term.

Interactions between Waves & Morphology: Rocky Shores
Bedrock changes, for example flutes, result from high velocity flows that can be expected from both tidal- and wave-induced processes. It has been suggested that very extreme infrequent events, such as tsunamis, will create these features over the short-scale whilst infrequent, but less extreme, storm induced processes will result in the development of these features over longer temporal periods (Felton and Crook, 2003). The more extreme events are also more likely to create these features in harder substrates than those that produce lower velocities.

Other consequences of these processes are the movement of free-standing boulders; such a process has been observed in Australia (Felton and Crook, 2003). Whilst restrained to those locations which have such characteristics, a parallel could be drawn to other geomorphological features. The type of movement of this material size, as with any, is a function of the energy introduced into the system. The classifications which are associated with sediment movement are: (i) surface creep; (ii) saltation and (iii) suspension (Inman, 1949).

Severe events may result in the episodic movement of rocks, again consider this a parallel to other material, which is otherwise in equilibrium with the long-term hydrodynamic climate.

Severe events could move rocks considerable distances, for example very large storms have been shown to move rocks up to 35m above sea-level in the North and West of Scotland (Hansom, 2001).

Interactions Between Waves & Morphology: Saltmarsh

Low wave energy and a relatively high roughness will enhance sediment deposition whilst a higher wave climate will induce sediment erosion and transport; for example periods of rapid erosion within the Thames estuaries have been attributed to the occurrences of higher magnitude waves (van der Wal and Pyel, 2004). High energy wave climates are generally not associated with saltmarsh environments (Davidson-Arnott et al, 2002).

Tides

Changes in tidal range will alter the ability of the waves to enter and propagate within an estuary or reach a shoreline (van der Wal and Pyel, 2004). In addition, the tidal discharge at a particular point in the estuary is directly related to the channel morphology and frictional losses (Dunn and Townend, 1997).

A reduction in the tidal channel and associated currents, through for example land reclamation, will lead to an increased capacity for sediment deposition (van der Wal and Pye, 2004). This in turn will result in the reduction of the tidal prism. However this cause and response behavioural pattern is dependant upon an adequate sediment supply.

Bathymetric changes, induced by either anthropogenic or natural processes, will result in an immediate alteration in tidal propagation. Changes in the bed roughness also induce a change, albeit a less direct one. Resultant asymmetries in the ebb and flood sediment fluxes will adjust until an equilibrium state is restored (Dronkers, 1998).

A change in the flow regime within a system may also lead to a change in the sediment population. This has been observed in the Ribble where a reduction in energy has lead to an increase and reduction in the mud and sand fraction, respectively (van der Wal and Pye, 2002).

The tidal range will limit the vertical growth of a saltmarsh sub-system, assuming a constant sea-level. The saltmarsh vegetation in turn exerts a strong influence upon suspended sediment concentrations and deposition rates through increasing bed roughness by increasing shear stresses and reducing flow turbulence.

Sea Level Rise

It has been suggested that, in the Thames, it is the increases in high and extreme water levels rather than the secular increases in sea level rise that have contributed most significantly to changes in coastal and estuarine systems (van der Wal and Pyel, 2004).

Freshwater Flow

It is only significantly different (higher) river discharges to the normal that will effect the tidal propagation within an estuary (Lane, 2004). As previously stated, it is the changes in bathymetry and sediment type (thus bed roughness) that will have the greatest effect. The river discharge rates are a consequence of the rainfall and catchment characteristics rather than the channel shape (Dunn and Townend, 1997).

Changes in the freshwater flow will influence the salinity of the water within the estuary. This in turn will result in changes to the density driven circulation within the estuary (Dunn and Townend, 1997).

Sediments

The sediment source and volume of supply will influence morphological development and therefore the type of habitats, for example saltmarsh, that exist.

Anthropogenic Influences
Changes within the natural estuarine and coastal systems will induce responses from existing processes over a range of scales. Presently, human intervention is investigated and installed to a scale that is not intended to cause change greater than the natural variation within a system. However, historic changes were not as well mediated and thus have been shown to cause larger scale changes but have led to an improved understanding of the effect of such influences.

Embankment construction and reclamation practises can lead to reductions in the tidal prism, intertidal area and current velocities. Historic channel training and dredging activities within the Ribble have been shown to concentrate ebb flows and increase scour along bank edges (van der Wal and Pye, 2002). Increasing velocities and the proportion of the total discharge through the main channel is likely to lead to the reduction of velocities and bed shear stresses over intertidal flats (van der Wal and Pye, 2004). An additional potential effect of dredging is the progressive net movement of sediment from the intertidal areas into the channels through processes such as slumping (van der Wal and Pye, 2004). This has been observed in the Thames and in the Tees. An over deepened area may result in a sediment sink. Changes to the channel form may result in changes to the propagation of the tidal wave within the system.

B1.2 Mapping of Littoral Cells

The mapping of littoral cells was a study that has fundamentally altered the way in which the coastline of England, Wales and Scotland is being managed because it provided the foundation for the development of Shoreline Management Plans (SMPs), which now form a key component of the DEFRA strategy for flood and coastal erosion risk management in England and Wales (Cooper and Hutchison, 2002).

The preparation by co-operative groupings of flood and coastal defence operating authorities, such as maritime local authorities and the Environment Agency, of SMPs involves large-scale and long-term strategic planning in order to reduce risks to people and the developed and natural environments from coastal flooding and erosion. The SMP approach necessarily requires an understanding of:

- natural coastal processes;
- coastal defence needs;
- environmental considerations;
- planning issues and current and future land uses.

The SMP considers the above issues and proposes sustainable coastal defence policies, in broad-level terms, for the future management of coastlines within distinct physical units. These units are normally relatively self-contained coastal sediment cells and sub-cells defined by transport pathways of non-cohesive sediments. The boundaries of littoral cells generally coincide with prominent headlands or estuaries and were identified by Motyka and Brampton (1993) to facilitate SMP production in England and Wales. The approach has more recently been applied to certain sections of coastline in Scotland (Hansom *et al*, 2000).

B1.3 EMPHASYS

EMPHASYS (Estuary Morphology and Processes Holistic Assessment System) was a research programme aimed at collating available tools for assessing processes and morphology in estuaries. It included ‘bottom-up’ methods (such as short-term numerical process-based models), ‘top-down’ methods (longer term geomorphological tools) and hybrids of the two (EMPHASYS Consortium, 2000). Many of the geomorphological and hybrid tools are presently being developed further under the Estuary Research Programme Phase II (see Section B1.7).

B1.4 Futurecoast

A review of the first generation of Shoreline Management Plans around England and Wales (Cooper et al, 2002) concluded that there was relatively little vision presented of how the coast is likely to evolve over a timeframe of 50 to 100^{+} years. In response, MAFF (now part of DEFRA) commissioned a consortium (involving Halcrow, British Geological Survey, ABP Research, Risk and Policy Analysts and various university and industry experts) to undertake an innovative research project to improve understanding of the major natural influences upon evolution, over the next century, of the open coastline of England and Wales (Burgess *et al*, 2001).

Unlike previous assessments of this coast, which have primarily focused upon contemporary hydrodynamic and sediment transport processes alone, the methodology adopted in the Futurecoast project developed an alternative geomorphological approach, based upon an improved understanding of larger-scale coastal behaviour, based upon key controls, influences and linkages. This approach involved the identification of different elements that make up the coastal structure and developing an understanding of how these elements can interact over different spatial and temporal scales (Cooper and Jay, 2002).

The methodology involved the establishment of large-scale Coastal Behaviour Systems, within which the sediments, morphology and forces across the offshore, nearshore, foreshore, backshore and hinterland interact. As such, analysis of Coastal Behaviour Systems incorporated an understanding of Holocene and recent historic evolution, geological and topographic controls (strength, structure and relief), sedimentary linkages, contemporary processes, the interactions between the coast and estuaries and the role of offshore or nearshore bathymetry (e.g. banks, channels, ebb tidal deltas) in influencing large-scale system evolution. Within this, a series of Shoreline Behaviour Units were identified, examples of which include: embayment developed between rock headlands; drift- and swash-aligned shores, source-pathway-sink units, and barrier islands and tidal inlets. In turn, each of these comprised a series of Geomorphic Units, such as sea cliffs, coastal dunes, tidal flats, beaches, etc over discrete and identifiable lengths.

Key challenges to the study were:

- Ensuring that the interactions between various hydrological processes and landform response was understood (e.g. influence of wave action on beach, or rainfall on a clayey cliff);
- Ensuring that the linkages between individual Geomorphic Units were properly understood (e.g. interactions between beaches and dunes);
- Using knowledge of coastal evolution over a range of space and time scales to anticipate future changes.
- Understanding feedback mechanisms operating within the system.

Whilst the first two aspects are relatively well known interactions, the last two points are more complex because various forcing factors, influences controls or constraints can change over time or vary in different locations along the coast. Examples include:

- Changes in geological controls (e.g. emergence of headlands within eroding cliffs, recession of existing headlands, exacerbation of embayment curvature);
- Hydrological forcing (changes in sea level, wave conditions, rainfall intensity);
- Changes in sediment supply or transport (possibly leading to changes in shoreline orientation as swash-alignment in sought);

- Human intervention (cessation of sediment supply due to cliff protection or groynes along beaches);

- Erosion in one part of a system releasing material that can assist in the stabilisation of another part of the system.

The Futurecoast study adopted the view that despite the complications associated with understanding coastal systems and their constituent components and predicting or estimating their future evolutionary trends and tendency, sufficient information is presently known about certain coastal geomorphological features to enable statements to be made describing how, in theory, they form and evolve. Based upon this information, it is also possible to identify theoretical responses of various coastal elements to changes in certain controlling parameters.

However, it was recognised that in order to be able to state more precise (and quantitative) responses, it is necessary to quantify **thresholds** of change. This is not possible at the generic level, and remains extremely difficult at the site-specific level, due to the need for quantified data relating to all potential parameters which may influence change, and considerable historic information concerning previous coastal response to these parameters. Despite being unable to generically quantify the thresholds for change, the Futurecoast study adopted the approach of generically determining relative **sensitivities** of different systems to changes in fundamental controlling factors.

It was envisaged that gaining an understanding of the relative sensitivities of different systems would lead to identification of the potential for one (or possibly more) of a number of particular generic behavioural responses in shoreline position, as listed below and described in more detail in Table 3.

- No change;
- Retreat (erosional or depositional);
- Advance (erosional or depositional);
- Breakdown.

Table 3. Generic Geomorphic Responses

No	Resp-onse	Shoreline "State"	Dominant Processes and Landform Changes	Examples	Present Causative Scenarios	Future Causative Scenarios
1a	No change	Resistance	Landforms resistant to change due to their lithology and structure	• Hard rock cliff	• Resistance of geology > forces applied (i.e. strength of material > applied stress)	
1b		No net advance or retreat of shoreline	Cyclic changes with a balanced sediment budget	• Seasonal cut and fill cycles on a sandy beach; • Berm building and flattening on a static gravel beach.	• Sediment supply = demand	• Sediment supply < demand and reduction in forcing conditions • Sediment supply > demand and increase in forcing conditions (aggradation)
1c		No net advance or retreat because evolution is constrained	Static or restrained shoreline in which the landform(s) are reducing in mass and in their capacity to dissipate energy and protect the backshore.	• Erosion of debris/lowering of beach levels at a cliff base • Saltmarsh undergoing coastal squeeze due to a constraining backshore topography	• Sediment supply < demand and evolution is constrained by backshore topography / resistance	• Sediment supply = demand and increase in forcing conditions AND • Backshore constraint

No	Resp-onse	Shoreline "State"	Dominant Processes and Landform Changes	Examples	Present Causative Scenarios	Future Causative Scenarios
2	Net Advance	Regression	Accreting shoreline; seaward migration of a shoreline	• Prograding saltmarsh; • Dune building resulting in seaward movement of the shoreline; • Sediment accumulation updrfit of a longshore transport "constraint" (e.g. inlet, structure, ness) or in areas exposed to low forcing conditions	• Sediment supply > demand	• Sediment supply ≤ demand and decrease in forcing conditions (erosional regression) • Sediment supply > demand (dominant process) and decrease/no change/ increase in forcing conditions (depositional regression)
3	Net Retreat	Transgressi on	Transgessing shoreline; landward migration of a shoreline which nevertheless maintains the characteristic form and function of its landforms	• Retreating cliff coast /beach-dune system; • Retreating barrier beach or spit; • Landward migrating saltmarsh or tidal flat.	• Sediment supply = demand and increase in water level OR • Sediment supply < demand and evolution is not constrained by backshore	• Sediment supply ≤ demand and increase in forcing conditions (erosional transgression) • Sediment supply > demand and (dominant) increase in forcing conditions (depositional transgression)

No	Resp-onse	Shoreline "State"	Dominant Processes and Landform Changes	Examples	Present Causative Scenarios	Future Causative Scenarios
4	Breakdown	Variable trend	Transient (short-lived) change towards a new characteristic form	• Reactivation of landsliding on a relic cliff or other major change in style and rate of cliff behaviour; • Breaching and/or fragmentation of a barrier or spit; • Deterioration or removal of a constraint leading to permanent tidal inundation of the backshore	• Sediment supply<<demand • Sediment supply>>demand • Significant change in sediment composition • Significant increase in forcing conditions which cannot be accommodated by existing morphology • Removal/breaching/inundation of backshore constraint • Reduction in material shear strength due to other factors (e.g. increased groundwater pressure within a cliff, chemical pollution breaking biological cohesion in a mudflat)	

By considering van Rijn's (1998) review of shoreline evolution concepts, it could be seen in the study that the fundamental factors influencing shoreline evolution are:

- Shoreline orientation;
- Shoreface topography;
- Wave and tidal current vectors;
- Mean sea level; and
- Sediment supply.

The range of possible shoreline responses to sea level change, given certain known information about the sediment budget, were identified by van Rijn (1998) to be transgression, regression or aggredation (Table 4).

Table 4. Shoreline response to changing sea levels

Shoreline Position Response	Behaviour	Sea Level Change	Sediment Budget	Net Lateral Movement	Models
Trans-gression	Erosional	Rise	Balance	Landward	Bruun response
	Depositional	Rise (dominant)	Positive		Barrier island washover
Reg-ression	Erosional	Fall (dominant)	Negative	Seaward	Beach ridges
	Depositional	Fall	Positive+ (dominant)		
		Rise			
Aggredation	Depositional	Rise	Positive+	None (although vertical movement)	Barrier up-building

Where sediment budget categories represent:
Balance; sediment input = sediment output
Negative; sediment input < sediment output
Positive; sediment input > sediment output
Positive+; sediment input >> sediment output

Output from the Futurecoast study has provided a long-term, qualitative picture of future coastal evolutionary tendency, in terms of characteristic change in the morphological elements and trends of shoreline movement. This is based upon an improved understanding of coastal behaviour within a longer-term and wider scale framework as facilitated by an understanding of how specific Geomorphic Units function, both generically and within the wider context of a coastal system.

This is a major project that will be applied to underpin the next generation of SMPs and thus assist in future coastal management decisions. A further important output from this research is the improved understanding that coastal engineers and planners will have of larger-scale coastal behaviour and geomorphological evolution of natural features. This will assist in raising awareness now of key geomorphological issues that are relevant beyond the time horizon of existing plans and the design life of existing flood and coastal defence structures, in an attempt to avoid tying future generations into inflexible and inappropriate coastal management decisions.

Summary: Whilst this study presents a useful methodology for understanding the interactions between different coastal landforms and their interactions over a range of space and time scales, it does not consider the relationship between such changes and the ecological response, nor does it consider transitional waters, or extend its focus beyond England and Wales.

B1.5 Procedural Guidance for SMP2 Development

Defra published procedural guidance for the development of second generation Shoreline Management Plans (hereafter referred to as SMP2) in 2003. This involved methods for assessing shoreline changes over various time scales (defined as three different 'epochs') and methods for determining the scale of interaction between an estuary and the adjacent open coast.

The methods for assessing future shoreline changes was largely founded on the concepts developed and applied in Futurecoast and consequently do not require repetition here. Consequently, this section focuses on the estuarine guidance that was developed.

ABPmer (2003) undertook a review of estuary types, influences and classification tools as part of their procedural guidance to assist in the determination of whether a particular estuary should be included in the predominantly open coast-focused SMP process. Although this was considered to be an interesting and necessary task to meet one of the specific objectives of the study, it alone did not provide information relating to the 'influence' of different estuary types on the coast (and *vice versa*). Indeed, there was considered to be a general absence of such information from the scientific literature, suggesting that classification of different estuarine types is a relatively academic exercise.

In addressing the issue of 'degree of influence' (in the context of a Shoreline Management Plan), Dyer (in Defra, 2002) suggested that there are two principal interactions that need consideration:

- Estuaries can be a source of, or a sink for sediment, either contributing river- or estuarine-derived sediment to the coastal sediment budget, or removing coastal sediment and trapping it within the estuary.

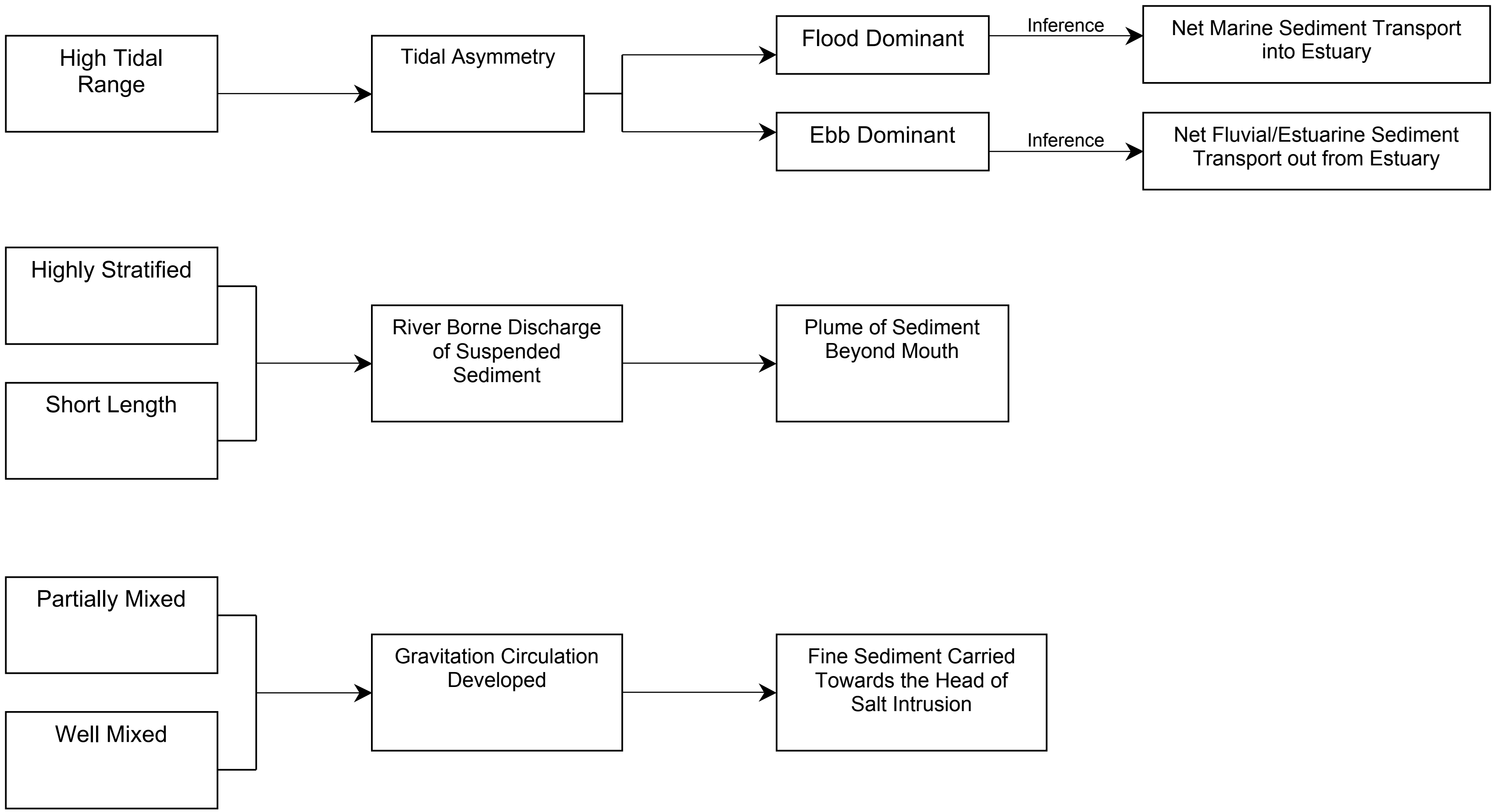
- During periods of river spate, the hydraulic forcing of the river flow can act as an effective means of transferring nearshore sediment further offshore, normal to the coastline.

In relation to these issues, Dyer suggested that generally, highly stratified, short and ebb-dominated estuaries are likely to be sources of riverine sediment to the coast. Conversely, partially mixed, longer and flood dominated estuaries are likely to be sinks for coastal sediment. The former are likely to be dominated by river flow, whilst the latter are likely to be dominated by tidal motion. Further general relationships suggested by Dyer are simplified in Figure 5.

In addition to the typical influences of estuaries on the open coast described above, it should be remembered that it is the mouth of the estuary and its sub-tidal and inter-tidal morphology that are the key regulators of hydraulic processes within the estuary. Should these factors be altered through either anthropogenic (e.g. reclamation or re-alignment, barrages, etc.) or natural factors (e.g. mouth widening to accommodate sea level rise, ‘squeeze’ of inter-tidal areas against rising ground, etc.) then the estuary processes will alter, possibly also leading to alteration of the influences of the estuary upon the open coast.

Additionally, an estuary, whilst possessing identifiable components and identifiable processes, functions as a complex integral whole which can influence, and can be influenced by, the open coastal processes and management (MAFF, 1998). This means that management intervention along a particular section of open coast can influence the processes within an estuary or at its mouth. Conversely, management intervention within one section of an estuary can potentially not only influence the entire estuary system, but also the adjacent open coast. Some examples of these interactions are described further in Box A.

Figure 5. Simplified relationships suggested by Dyer (after Defra, 2002)



Box A – Potential interactions between estuaries and the open coast

- The open coast can provide sediment to the estuary or its mouth through processes of shoreline erosion from a near or remote 'updrift' source and subsequent longshore transport of sediment to the estuary. The volume of sediment erosion or transport (and hence input to the estuary) can vary according to different management practices along the open coast. For example, seawalls can reduce or stop the erosion of soft cliffs and as a consequence reduce the volume of sediment reaching the estuary. It is important to note that an estuary can be an important sink for both cohesive and non-cohesive marine sediment transported from the coast.

- The flow of water through an estuary mouth can partially or fully block the longshore transport of coastal sediments across the mouth of the estuary, enabling sediment to accrete in spits.

- Periods of particularly high river spate can push sediment drifting along the shoreline further offshore as a plume from the estuary mouth. Such sediment may then be lost from the littoral system rather than returning to the shoreline.

- In many estuaries, the transport of sediments across the estuary mouth is achieved through a more complex transport pathway. Sediment can pass into the estuary where it is temporarily stored within flood tide deltas before being transported back out of the estuary to reach the 'downdrift' shoreline of the open coast.

- Changes to the tidal prism of an estuary, caused for example by a significant change in management practice (reclamation would reduce, and re-alignment would increase the tidal prism of the estuary), can alter tidal asymmetry and/or flow velocities of the estuary. This could potentially lead to changes in existing erosion/deposition patterns and/or to changes in present nett tendencies for sediment to either enter or leave an estuary (e.g. if the tide becomes more ebb-dominated due to the management intervention, then estuarine sediments may be more likely to be transported out of the estuary to the open coast).

- Ebb tidal deltas form at the mouths of many estuaries and their associated sand bars provide important natural coastal defence features to both the estuary mouth and the adjacent open coasts. The size of the delta depends on the tidal prism of the estuary and consequently the degree of natural protection can change as the prism changes through differing estuary management techniques.

- Predictive models used in the EMPHASYS programme indicate that sea level rise will result in the progressive landward migration ('roll-over') of the entire morphological form in many estuaries. This process is achieved through erosion of the outer estuary (often located within the Schedule IV boundary) and deposition of eroded sediments towards the head of the estuary (often beyond the Schedule IV boundary). In order to fully incorporate such interactions, the entire estuary needs to be considered as a whole, not just a short length at or close to the estuary mouth.

As existing sediment cell and sub-cell boundaries were defined according to non-cohesive sediment transport processes, many estuaries around England and Wales have been used as an existing SMP boundary (e.g. Humber, Wash, Thames, Solway). This means that often some highly important processes and interactions between either bank of the estuary and/or between the estuary and the open coast may not have been dealt with in a consistent and 'strategic' manner in the first generation of SMPs.

The review also identified a range of tools that exist to assist in identification of the nature and extent of influence between an estuary and the open coast. These are outlined below:

Desk-based Tools
Reviews of scientific and professional literature and analysis of existing field measurements can be undertaken to develop a 'conceptual understanding' of the process and morphological linkages between the open coast and an estuary (and indeed those operating within an estuary). This can involve identifying:

- sediment linkages (e.g. sources from the open coast and within the estuary, stores at the estuary mouth, and sinks within both the inter-tidal and sub-tidal areas of the estuaries); and
- hydrodynamic linkages (e.g. tidal prism, flows and water levels, extent and magnitude of wave influence, etc.).

Such approaches are relatively cost-effective and quick to undertake, but are dependent upon the quality and availability of existing literature sources.

Various empirical and theoretical relationships can be applied to the estuary parameters to determine the present 'condition' of an estuary relative to a theoretical goal, and its role as a source or sink of sediment. These approaches require certain parameters of an estuary to be defined and available, but are useful in identifying the general role that the estuary plays in influencing, or being influenced by, the open coast.

Field-based Tools
Direct measurements can be undertaken to capture information relating to flow velocities, water levels, wave heights, suspended sediment concentrations, sediment transport and erosion/accretion rates. Such information can then be interpreted to assist in identifying the extent of influence (e.g. coastal sediments may be entering the estuary to be deposited on the inter-tidal areas, may be stored in deltas at its mouth, or alternatively may bypass the estuary mouth or be flushed offshore by river spates). The disadvantage of this approach is that the natural system is highly variable and the measurements taken may not be representative of 'normal' or 'extreme' conditions. Furthermore, gaining a sufficient spatial spread of measurements over an appropriate time period to characterise key interactions would be both difficult and cost-prohibitive. Consequently, field-based studies may be undertaken in specific locations to address issues, data gaps or uncertainties that have been identified following a broader-level desk-based approach.

Numerical Model-based Tools
Numerical modelling of tidal flows, waves, sediment transport pathways and morphological change can be undertaken to characterise the existing regimes and determine the extent to which open coast and estuarine systems interact through water and sediment exchanges. The disadvantages of this approach are the cost, timescale and input data requirements, and the fact that such models can only characterise the short- to medium-term process and morphological changes. The advantages, however, are that once set-up, a numerical model can investigate the relative effects of changes in particular processes or morphological conditions on the entire coastal-estuarine system for particular developments or 'what-if' scenarios.

Such models can be adopted to characterise:

- Tidal levels at different locations in the estuary / along the open coast at various stages of the tidal cycle;
- Corresponding flow velocities (speed and direction) and bed shear stresses to determine the tendency for material transport, deposition or erosion;
- Preferential transport directions of sediments (although different techniques are required for suspended-load and bed-load transport);

- Extent of wave propagation into the estuary and, in wide or long estuaries, the generation of wind-waves within the estuary.

B1.6 EstProc

The Estuary Processes Research Project, or EstProc, (www.estproc.net) has produced improved understanding of the hydro-biosedimentary processes in estuaries. The final project report presents a wide range of algorithms for physical processes, these cover hydrodynamics - waves and currents, sediment transport - sands, muds and mixtures of these, and biological processes - including interactions of biology with flows and sediments. These algorithms can be implemented in analytical studies and computational models of estuary processes and morphology, increasing the range of physical parameters that can be represented and reducing uncertainty on some of the key processes.

B1.7 Estuary Research Programme Phase 2

This research programme comprises three ongoing studies, two of which are of direct relevance to the present study, namely: (i) FD2116 Review and formalisation of geomorphological concepts and approaches for estuaries; and (ii) FD2117 Development and Demonstration of Systems Based Estuary Simulators (EstSim).

FD2116 is being undertaken by HR Wallingford, ABPmer and Professor John Pethick and the project has the following objectives:

- To review critically the current geomorphological understanding and concepts related to the medium (month-year) to long term (decadal) behaviour of estuaries.

- Through formalisation of Expert Geomorphological Assessment and Historic Trend Analysis, to provide a resource for the end user so that he/she can substantially increase the quality of their analysis.

The benefits arising from this project are that a consistent and formalised approach to the use of geomorphology in estuarine prediction will be established. This will improve the quality and effectiveness of studies associated with flood defence and estuarine impact.

The work being undertaken at present involves the development of a framework within which specific geomorphological tools can be applied. In order to facilitate increased use of the tools themselves, specific guidance is being developed in the application of the following methods:

- Historic Trend Analysis;
- Regime theory;
- Rollover model;
- Entropy-based relationships;
- Asymmetry relationships;
- Sediment budget modelling;
- Geological methods for estuarine studies;
- Intertidal form.

Although this 1-year study remains in progress and has not yet reported, the Project Team can directly transfer key matters arising from FD2116 to the present study, since several staff members from ABPmer and HR Wallingford are active on both. In particular, a comprehensive literature review has been undertaken of each of the above tools in order to review and develop further the scientific base upon which the concepts have been founded.

Similarly, whilst EstSim (FD2117) remains an ongoing 3-year study, it is being undertaken by a team led by ABPmer and key matters arising can be transferred directly to the present study through a commonality of key staff input. The overall aim of EstSim is to extend the ability to simulate estuarine response to change. This will be achieved through the delivery of research into the systems-based approach as an alternative yet complimentary methodology to those research lines being undertaken within the other ERP Phase 2 projects (morphological concepts, bottom-up, top-down and hybrid methods). EstSim will also explore the simulation process in order to facilitate knowledge exchange between the systems-based tools and estuary managers.

The systems-based approach can be considered as a qualitative method that seeks to express the behaviour of a system. The concept, as described by Capobianco et al. (1999) is to develop an understanding of the behaviour of a coastal system and map it onto a simple mathematical model, which exhibits the same behaviour although this need not necessarily have any relationship to the underlying physical processes. Capobianco refers to the Bruun Rule (Bruun, 1962) as an example where the behaviour of a sandy shoreline is described by a geometric concept rather than a formulation of sediment transport. Townend (2003) also cites a number of examples including, estuary transgression (or rollover) and estuary development as a consequence of tidal asymmetry as examples of capturing systems behaviour.

Within the whole estuary context what is sought is an expression of the behaviour between morphological elements (e.g. cliff, beach, spit, mudflats, saltmarsh, tidal creek, etc.) and forcing functions so that key components the estuary system can be simulated and the likely response to change established. The interactions between system elements may be expressed in many ways including both qualitative and quantitative approaches.

A behavioural model enables a representation of the interactions between physical processes (forcing factors) and geomorphological elements. It seeks to capture the response of the system to changes in forcing or imposed constraints. The system response over different scales may be accompanied by alternative (simplified) models that represent the critical interactions to the relevant time frame.

A behavioural model may be set up through application of behavioural statements and systems diagrams with development into a full behavioural model occurring after the formalisation of the cause-effect relationships/rules (Figure 6)

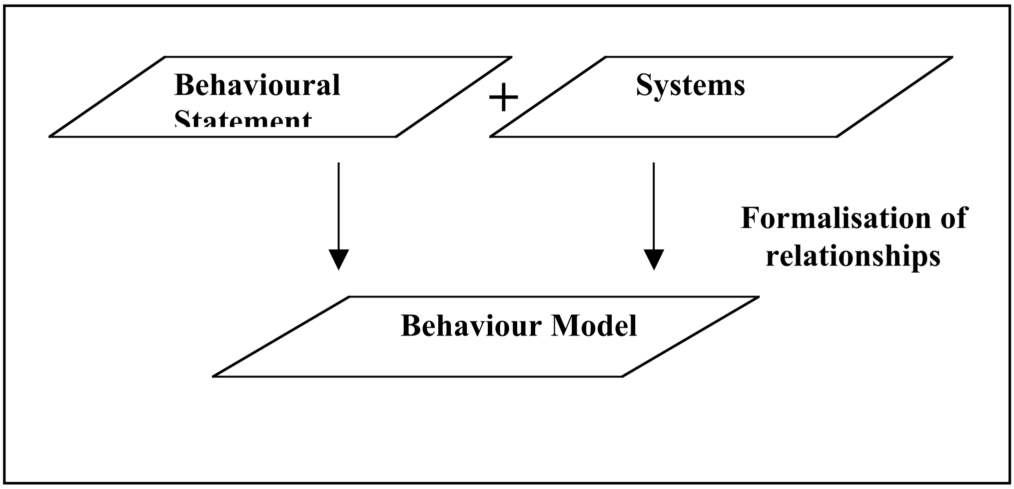


Figure 6. Elements of systems-based approach

The 'Behavioural Statement' is a textural description of the interactions and relationships within a system. The system components for an estuary may comprise different geomorphological elements such as a saltmarsh and intertidal mudflat with the behavioural statement capturing a description of the range of forcing factors and their influence on the geomorphological element. A behavioural statement may capture the nature of relationships between system components and discuss the evolution of the system over time.

The 'Systems Diagram' is a formal flow chart representation of the interactions between system components. Systems diagrams may capture the relationship between components (such as directionality and relative importance/dominance) and may be integrated to capture critical elements over different time scales.

The 'Behaviour Model' is an extension of systems diagrams and behavioural statements that includes formalisation of the system interactions (behaviour). Formalisation may be in the form of existing models and morphological concepts or rules or through qualitative statements.

B1.8 Capturing Geomorphological Change for the Coastal Simulator

During the course of the present study, a member from the Project Team and a member of the client's Project Board, were invited to attend an Expert Workshop in London for the above Tyndall Centre project. This was a useful exercise since the workshop not only explained the work of the Coastal Simulator project (Brown, 2004), but also brought together a number of geomorphological experts from around the UK and enabled wide ranging discussions to take place relating to the development of approaches to capturing geomorphological change. The proposed approach involved assessing the trend likelihoods for cross-shore change within individual profile types in response to differing combinations of sea level rise and sediment supply drivers. This was based largely on expert judgement and reported in a standard format using a number of matrices. Typical cross-shore profile types included a cliff face-foreshore-offshore unit, and a low-lying hinterland-barrier-foreshore-offshore unit, amongst others. Cross-shore trend likelihoods were then review in the light of differing long-shore combinations of features (e.g. cliff-barrier-cliff) to determine whether the envisaged cross-shore trends would be altered when considered in a long-shore context also.

Initial feeling amongst many workshop delegates was that the approach was over-simplified and did not capture true aspects of coastal system dynamics. However, when the methodology was applied in a practical example, the complexities of even this seemingly simplified approach became immediately apparent. Ultimately, the workshop attendees concurred that whilst the approach had weaknesses (in a pure scientific context), its greatest strength was that it was a practical and achievable means of delivering a required output.

B.2 Relationships between Hydromorphological Processes and Ecological Function

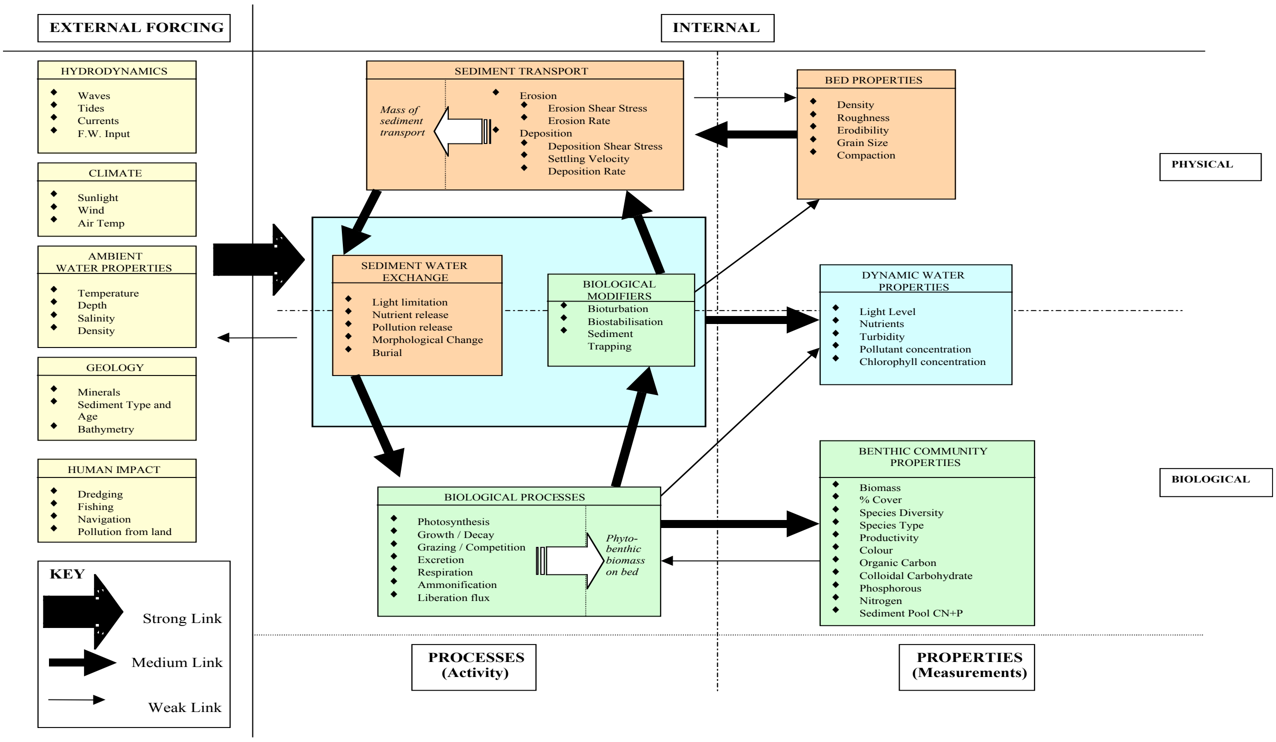
B2.1 Introduction

Coastal and estuarine systems are highly complex due to feedback which exists between the various physical, chemical and biological processes (see Figure B1). The observed distribution of broad habitat types and species assemblages associated with these habitats is therefore the result of a complex suite of interactions between these various elements.

Figure 1. Feedbacks and interactions between various physical processes (source: F-ECTS Project)

This review is designed to highlight the links that exist between the hydromorphologcial parameters and ecological components of a system. The review covers a number of biological entities which are derived from the Biological Quality Elements defined under the Water Framework Directive. The elements comprise:

- Benthic invertebrates
- Macroalgae



- Angiosperms
- Fish in transitional waters
- Phytoplankton

The marine habitat classification (Connor *et al* 2004) and EUNIS (http://eunis.eea.eu.int/index.jsp) provides a hierarchical classification of UK marine habitat types ranging from descriptions of broad physical habitats (Levels 2 and 3) to more detailed descriptions of species assemblages (Levels 4 to 6). The classification provides a firm basis for the conduction of relationships between habitats and the physical parameters that govern their distribution. A primary distinction in the classification is between rocky and sedimentary habitat types and this distinction has therefore been applied in considering factors governing the distribution of benthic invertebrate quality element, below.

B2.2 Distribution patterns

The patterns of distribution of a particular species can be defined across a wide range of scales. At the broadest scale each species can occupy a particular geographical range, which depending on its mode of life can be either very extensive or very limited. Within the broad limits of its geographical range, each species occurs in a particular habitat, defined by the particular, optimum conditions for its growth and reproduction. Bordering each area of optimum habitat may be a zone of suboptimal habitat in which the species is able to exist, but in which it does not achieve maximum growth or longevity or is able to achieve maximum reproductive output, or is at a competitive disadvantage to other species. The optimum habitat may be limited by physical, chemical and / or biological factors (Hayward & Ryland, 1995)

In examining the distribution patterns of habitats and species careful interpretation is required in the analysis of all community types and the associated physical parameters. It is important to remember that correlations are not necessarily evidence of cause and effect relationships between particular environmental variables and faunal distributions, they are merely indicative of the presence of gradients of environmental variables within systems that may be influencing the composition of communities (Morrisey *et al* 2003). In addition to facilitate understanding the key geomorphological parameters under review have been divided into a number of subcategories. In reality it is impossible to wholly consider each of the parameters independently due to the strong linkages and inter-relating processes in operation. When using predictive models, for example, the inclusion of more than one factor frequently provides a better prediction of species distributions (Freeman & Rogers, 2003).

B2.3 Benthic Invertebrates

B2.3.1 Sediment habitats

The substratum of sediment varies quite considerably in particle size, ranging from shingle and gravels to very soft mud. The substratum can be defined by the size range of its constituent particles, and may be classified by the Wentworth scale which is then transformed into the Phi scale where $\varnothing = -\log_2$ diameter (mm) (Dyer, 1986). Sediment grain size and composition varies according to hydrodynamic conditions and along the shore profile.

Table 5. Grain size scales for sediments (adapted from Dyer, 1986 & Elliott *et al*, 2001).

Wentworth 1922	∅	Grain size (mm)	Grain size (μm)
Boulder	-8	256	
Cobble	-7	128	
Cobble	-6	64	
Pebble	-4	16	
Pebble	-2	4	
Granule	-1	2	
Very coarse sand	0	1	
Coarse sand	1	0.5	
Medium sand	2	0.25	
Fine sand	3	0.125	125
Very fine sand	4		62.5
Coarse silt	5		31.3
Medium silt	6		15.6
Fine silt	7		7.81
Very fine silt	8		3.9
Coarse clay	9		1.95
Medium clay	10		0.98
Fine clay	11		0.49
Very fine clay	12		0.24

The distribution of invertebrate fauna that inhabit intertidal and subtidal flats is largely controlled by the tolerance of the various species to the physiological stress, predation, competition and disturbance which are influenced by physical factors, such as tidal inundation, salinity, sediment composition and structure, exposure, wave action and elevation. Recently work has been undertaken to quantify the strength of the association between the distribution of benthic fauna and the physical factors of their habitat such as substratum, bathymetry and near-bed hydrodynamics (e.g. Freeman & Rogers, 2003). Physical parameters such as these are important in structuring the habitat of bottom dwelling organisms and provide useful parameters for predicting patterns in their spatial distribution (Freeman, 2001; Rosenberg, 1995; Warwick & Uncles, 1980).

(a) Substrate

Sediment grain size is a key physical factor controlling the distribution and occurrence of benthic organisms (e.g. Gray, 1974). Investigations of the intertidal invertebrates in the Wash (Goss-Custard & Yates, 1992) and Morecambe Bay (Anderson, 1972), for example, demonstrated that typical invertebrate species vary according to two key environmental factors; elevation of the shore level and sediment particle size. Warwick & Davies (1977) investigated the relationship between subtidal communities and the nature of the substratum in the Bristol Channel and observed that community types can occupy a wide range of substrates. In the Bristol Channel, however, subgroupings can be recognised within each community which have more closely been defined. An additional detailed survey of the Severn Estuary was conducted during a 1988 survey by Mettam *et al* (1994). The results strongly associated the intertidal and subtidal faunal groupings with the large scale distribution of sedimentary characteristics within the estuary.

Sediment grain size preferences relate to behavioural and feeding methods of the invertebrates. Sediment grain size has implications for drainage, chemical processes and organic content. In general, sand composed of larger grain sizes will not hold much water, detritus or nutrients, and many of the finer particles will be drained away or deposited in deeper layers (Burchett & Dando, 1996). This makes coarser sediments relatively unsuitable environments for many infaunal species, whereas fine sediments such as muds which have grains tightly packed together often have poor water circulation and restrict the presence of interstitial fauna (Elliott *et al*, 2001). Fine and medium sands generally have abundant macro and meiofauna, although densities are often much greater in mud substrata due to high organic matter content (Gray, 1981). In addition, organic matter degrades less quickly in poorly oxygenated muds and the greater relative surface area of those sediment particles allows a greater build up of organic matter. Detailed descriptions of community structure in relation to sediment type are provided elsewhere (e.g. Connor *et al* 1997; Peterson, 1991; Eleftheriou & McIntyre, 1976; Wolff, 1973; Jones, 1950; Elliott *et al*, 1998).

(b) *Zonation*

In intertidal locations the degree of wetting and drying caused by the tides will have physiological consequences for the species inhabiting this environment. Stresses resulting from the periodic wetting and drying of intertidal areas include fluctuations in temperature, salinity, desiccation and UV radiation. As a result species that inhabit higher tidal elevations tend to burrow down into the sediments to avoid such stresses. Alternatively, tube dwelling (amphipods and worms) and shell-bearing (molluscs and gastropods) invertebrates are typically more tolerant to stress which enables them to inhabit sediment at higher elevations. Depending on the particular location the relative stability of the sediments will also differ at different elevations. The relative severity of each of these parameters on the associated fauna will be influenced by the hydrodynamic, wave and sediment regimes. Biological interactions, such as competition and predation will also affect the elevations at which species can occur.

In subtidal environments water depth can influence the resulting community structure (e.g. Freeman & Rogers, 2003). The importance of water depth on benthic communities has also been emphasised by Buchanan (1963).

(c) *Exposure to wave action*

Wave action has its strongest influence on the species inhabiting a particular location by influencing the particle size distribution of the sediments (Section 2.1.1). Waves and tidal currents have a large role in determining the sedimentary characteristics of an area and can be considered as the ultimate cause of the broad scale community patterns observed on intertidal areas (Hall, 1994; OU, 1989; Elliott *et al* 1998).

(d) *Hydrographic Regime & Tidal Currents*

It is relatively difficult to correlate hydrodynamics with observed macrofaunal assemblages. Tidal currents and bed stress, like wave action contribute to determining sediment grain size and hence influence community structure in this way (e.g. Warwick & Uncles, 1980). Warwick and Uncles (1980) found that community type in the Severn Estuary and Bristol Channel were correlated with tidal stress that was derived from a hydrodynamic model.

Disturbance in any form can alter community structure (Begon *et al* 1990); the frequency and magnitude with which such disturbance events occur can therefore play an important role in shaping community structure. Frequent disturbance of high intensity by hydrodynamic factors, can generally lead to impoverished communities dominated by amphipods e.g. haustoriids and Pontocrates *spp.* mysids and polycheates such as *Scolelepis squamata.* During severe storm events there is the potential to impact on the infaunal community of an area. Impacts on the community will depend on the erosion potential of the sediment type and the depth to which the waves disturb the sediment. Species can be removed altogether and the interactions between species may also change affecting competitive relationships etc. Due to frequent storm events, regular cycles of habitat creation and destruction can occur (Dauvin *et al.,* 1993*).* In contrast in more sandy environments there is little evidence of persistent effects of storm events on the sand-beach fauna (e.g. Keith & Hullings, 1965; Ansell *et al.,* 1972*).*

Tides and currents will not only affect erosion and disturbance thresholds but has the potential to impact on food supply and larval dispersal (Wildish, 1977; Wildish & Kristmanson, 1979).

(e) *Topography, Geology & Aspect*

The geology and aspect of a location are typically considered as irrelevant in the shaping of sediment based communities. The relative slope of the shore does, however, have the potential to impact on the period of emersion and influence the degree of wave exposure to which the invertebrates are exposed. The period of emersion will affect the observed zonation patterns (Section 2.1.2.).

(f) *Accretion and erosion*

Invertebrates live at different depths of sediment, which will influence the degree of accretion/ erosion that they can withstand. From the intertidal zone to the subtidal, sands, silts and clays these sediments are inhabited by a variety of marine benthic organisms which display a range of adaptations to deposition and erosion of the bed (Miller *et al* 2002). The amphipod *Corophium* and the cockle (*Cerastoderma*) live at relatively shallow depths as they have short siphons. Species found slightly deeper in intertidal sediments include bivalves such as *Tellina* and *Macoma* and deeper burrowers include the bivalves *Mya, Ensis, Solen, Scrobicularia* and the lugworm *Arenicola.* In areas that experience high rates of accretion smothering can result if the species present are unable to respond to the change in sediment level. However, deposition rates on natural mudflats tends to be highly variable, at sites on the Humber Estuary, for example, elevations have demonstrated fluctuations of 5cm per year (Brown *et al* 1998). Some species can tolerate instantaneous burial by up to 10cm of sediment (Nelson, 1989), although mortality rates are dependent on sediment grain size and species (Nelson, 1989).

(g) *Salinity, Temperature, Chemical Fluctuations, Water Quality*

All chemical processes that occur within the sediments will affect distribution patterns. Organic content, oxygen availability and drainage, for example, all of which will be affected by the parameters that have been discussed above can affect distribution patterns. Excessive nutrient levels can also result in algal mats which can reduced the diversity and biomass of some mud-dwelling invertebrates (e.g. Raffaelli, 2000). Turbidity can affect species distributions as it can interfere with feeding and respiratory apparatus of a number of intertidal organisms. Salinity is a particularly important factor affecting ecological distributions.

The daily variations in salinity of estuarine water affects the abundance and diversity of the species within intertidal habitats and tidal channels (Attrill & Rundle, 2002). Estuarine / marine invertebrate diversity declines with decreasing salinity within an estuarine gradient and are gradually replaced by freshwater species (Little, 2000). In the US there is a general trend that the abundance of most marine species in estuaries decreases with extended periods of salinity of less than 1/3 that of seawater. The size of marine organisms such as bivalves and lugworms also decrease along a salinity gradient (Remane, in Little, 2000; Mettam, 1980), which may be due to a direct effect of salinity or to other factors such as biotic interactions, food availability, or age structure of the population (Little, 2000). Evidence from routine subtidal surveys on the Humber Estuary conducted by the Environment Agency have also highlighted he importance of salinity in shaping intertidal communities (Barr *et al*, 1990). In the Forth Estuary salinity has also been described as the primary source of variation in the faunal data and sedimentary variables exerted a secondary control (Elliott & Kingston, 1987).

(h) Biotic Factors

When examining the relationship between hydromorphological and ecological parameters it is important not to ignore the biological interactions that operate in the environment such as competition and predation. The relative mobility of different species can also affect how susceptible they are to each of the morphological or hydrodynamic parameters.

The complex relationships between the relative importance of sediment characteristics and biological interactions in shaping observed community patterns has also been examined (Reise, 2002). The effect of certain organisms such as mussel beds on the erodability of the sediments, for example, has been investigated (Widdows & Brinsley, 2002). Jones *et al* (1994) and Lawton (1994) introduced the concept of organisms as ecosystem engineers, altering the physical state of the habitat with effects on other species. Some species are known as biostabilisers (e.g microphytobenthos, *Enteromorpha* spp. & *Cladophora rupestris*) and bio-destabilisers (such as *Macoma balthica*, *Hydrobia ulvae*).

B2.3.2 Rocky Shores & Subtidal Rock

(a) Substratum

Depending on local geology rocky habitats can range from steep overhanging cliffs to wide, gently shelving platforms, from smooth uniform slopes to highly dissected, irregular masses or even extensive boulder beaches (Lewis, 1977). Rock types are important; limestones are the most richly colonised rocks, being sufficiently resistant to erosion to enable populations to persist, yet eroding sufficiently along bedding or jointing planes to provide crevices, gullies and pools, thus increasing the diversity of local habitat. Softer limestones, shales and marls will have a different fauna of boring organisms, but fewer encrusting species. Hard igneous and metamorphic rock provide the least diversity of habitat (Hayward & Ryland, 1995). The larvae of most benthic invertebrates are highly selective in their choice of habitat and actively search out suitable surfaces on which to settle (Crisp, 1984).

(b) Zonation

Rocky shores for many years have been described in terms of their zonation patterns (Stephenson & Stephenson, 1949; Southward, 1958; Lewis, 1964). Biologically the intertidal is essentially a marine province: it is inhabited principally by marine organisms and a few terrestrial species tolerant of short periods of tidal submersion (Southward, 1958; Lewis, 1964; Connell, 172; Raffaelli & Hawkins, 1996). Consequently the vertical dimension of the shore is generally regarded as a unidirectional stress gradient associated with the twice daily ebb and flood of the tide (Connell, 1972). As a consequence higher on the shore there is a greater variability and hence unpredictability in physical factors such as salinity, oxygen, humidity, temperature, light penetration and availability of food and nutrients (Hawkins & Jones, 1992; Raffaelli & Hawkins, 1996). The shift in physical conditions along the vertical dimension of the shore results in patterns of zonation along this dimension, which in general are related to tidal level and exposure to wave action.

Subtidal communities are vertically zoned but the zones are generally broader and less pronounced than intertidal communities. Desiccation is clearly unimportant here and zonation is determined by light, water movement and biotic factors (Boaden & Seed, 1985).

Table 6. Principal zones which are universal occurrence on rocky shores (Based on Lewis 1961 & Newell, 1979).

<table>
<tr><th>Tidal Level</th><th colspan="2">Zone</th><th>Indicator Organisms</th></tr>
<tr><td rowspan="4">Extreme high water of Spring tides

Extreme low water of Spring tides</td><td colspan="2">Maritime Zone</td><td>Terrestrial vegetation
Orange and green lichens</td></tr>
<tr><td rowspan="2">Littoral zone</td><td>Littoral Fringe</td><td>Upper limit of Littorinids
Littorina neritoides, Ligia, Petobius, Verrucaria etc.</td></tr>
<tr><td>Eulittoral zone</td><td>Upper limit of barnacles
Barnacles
Mussels
Limpets
Fucoids
(many others)</td></tr>
<tr><td colspan="2">Sublittoral zone</td><td>Upper limit of Laminarians
Rhodophyceae
Asciidians
(many others)</td></tr>
</table>

Secondary effects caused by the ebb and flow of the tide are numerous and include time available to feed, temperature variation and oxygen availability (Newell, 1979). The limit of distribution may be set by the level at which sufficient food can be obtained for growth and reproduction. Similarly the period of immersion to air limits the time during which animals of the upper shore may pass oxygenated water over the surface of the body. The differing abilities of intertidal animals to undertake either aerial respiration or anaerobic respiration may play an important part in determining the level on the shore at which they can survive.

The temperature of the upper sublittoral zone approximates to the sea temperature throughout the year, where as the higher shore levels approach the air temperature or may even exceed this on bare rock surfaces exposed to the sun. Equally in winter these areas may be exposed to extremely low temperatures. Shelter afforded by crevices and algal cover (e.g. Bourget *et* al, 2004) may reduce the thermal stress in some instances. The humidity of the upper intertidal zone varies too in a general way with shore level, being at a maximum at the sublittoral fringe and a minimum on bare rock surfaces at the top of the shore. While some mobile animals may be able to avoid such stresses dessication may play an important part in limiting the distribution of both sessile and motile species in the upper part of the littoral zone.

(c) Exposure to wave action

Many open coasts are continuously exposed to oceanic swell and extreme wave action, whilst deeply indented coastlines may be largely calm. The existing gradient of differing wave exposure also influences the species present at a particular location and can modify the tidal height at which they are found. The effect of wave exposure was reviewed extensively by Ballantine (1961) and Lewis (1964). Exposure to wave action tends to increase the amount of water reaching the upper tidal levels either by wave splash or spray. This effectively increases the period of submersion and creates an upward extension of the distribution of intertidal species.

It is not only the relative distribution of species that changes under differing wave climates but also the actual species that occur under such environmental conditions. These differences may in part be due to the differing susceptibilities of organisms to mechanical damage by wave action and by material such as sand and rocks which may be hurled against the rocks by waves. Other key contributing factors are thought to include larval recruitment, competition for space between species such as barnacles and fucoids, the presence of organic debris and silt in more sheltered environments, as well as the interdependence of the fauna and flora. Species capable of existing across a spectrum of wave exposures may exhibit different forms depending on the degree of exposure they experience (Newell, 1979).

(d) Hydrographic Regime & Tidal Currents

Tides and water circulation patterns affect larval dispersal and hence colonisation patterns. Animals and plants attached to hard surfaces frequently demonstrate phenotypic adaptations to maintain their position in locations of strong water movements (Koehl, 1982).

(e) Topography, Geology & Aspect

Further factors such as topography, nature of the substratum and aspect affect distribution patterns of observed species. On a broader scale there are gentle but overriding gradients associated with latitude and climate. The aspect of a shore is an important factor in determining the upper limits at which intertidal animals can live. Shaded positions to some extent offset the rigours of desiccation and thermal stress, and when coupled with exposure to wave action allow a great upshore extension of the sublittoral organisms (e.g. Lewis, 1954). The limpet *Patella vulgata* for example can occur at higher levels on the shore in shaded conditions and this effect is even more pronounced on shore with exposure to wave action (Evans 1974).

Sheltered shores with a shallow gradient have a relatively wide littoral zone which allows an upward extension of the sublittoral fringe organisms. Conversely where the shore is steep, as on cliffs or man-made structures such as jetties and piers, the whole of the littoral zone may be condensed to a relatively narrow band corresponding to the height of the tidal rise and fall. Under exposed conditions the topography of the shore plays an important part in modifying the effects of wave action.

(f) Salinity, Temperature, Chemical Fluctuations

All key rocky shore species are able to tolerate lower salinity estuarine waters, down to about 20psu and can tolerate long term reductions in salinity within their normal tolerance range although growth rates and fecundity are likely to be impaired. Barnacle and fucoid shores, for example, are able to tolerate short term variations in salinity because the littoral zone is regularly exposed to precipitation. However, some of the other species found on rocky substrata may be highly intolerant of changes in salinity resulting in a loss of diversity. However most species have planktonic larvae so recolonization and recovery should be high.

Rocky shore communities occur in warmer and colder parts of Britain and Ireland and similar assemblages of species are known to occur in Norway, Canada and Brittany so that long-term temperature change is unlikely to cause a change in biotope.

All key species are considered moderately tolerant of temperature changes although larvae and juvenile individuals are likely to be more intolerant of changes in temperature than adults. Changes in the numbers of the key structuring species are likely to have profound effects on community structure.

Intolerance to turbidity is typically low because the key species found on rocky shores are rarely subjected to such conditions. An increase in turbidity may reduce algal growth rates because of increased light attenuation although because photosynthesis also occurs during emersion the effect may not be significant. There may also be some clogging of suspension feeding apparatus in some species.

(g) *Biological Interactions*

Biological interactions such as competition for space and food, predation and grazing will also affect the distribution of species (Hawkins & Hartnoll, 1985; Jenkins *et al*, 1990; Noda, 1999). The composition of shore communities is therefore determined by a suite of interacting factors.

B2.4 Macroalgae

Marine algae vary enormously in size and complexity and this review is focused on macroalgal species. Alga are mainly classified according to the photosynthetic pigments they contain and broadly fall into three groups: the Chlorophyta or green algae, the Heterokontophyta or brown algae and the Rhodophyta or red algae (Gibson *et al*, 2001).

(a) *Substratum*

Macroalgae need to remain attached to hard substrates and have adaptive mechanisms to allow them to do so. The substratum on which they can survive ranges from boulder shores to extensive cliffs and man-made structures. The relative stability of the substratum will have implications for the growth and subsequent survival of the inhabiting plants. Macroalgae are therefore generally associated with rocky shores, although a number of chlorophyceae (green algae) occur in sedimentary environments. There is a general relationship between the size of the plants and their substratum, with only smaller plants growing on unstable substratum except in very still water (Lobban &Wynne, 1981).

(b) *Zonation*

The zones of rocky substratum have already been described for the benthic invertebrates (Section B.2.3.2.). Macroalage are subject to the same environmental conditions as those described for the invertebrate species. There is considerable evidence from direct observations that upper limits can be set by physical factors (Hawkins & Jones, 1992). Some macroalgae are better adapted to withstand desiccation and they will be able to colonise further up the shore. Those better adapted to dry conditions may, however, require long periods of light for photosynthesis. Algal species that are less well adapted to withstand long periods of emersion may be better adapted to photosynthesise using wavelengths that are available underwater.

The upper limit of some mid and low shore species may, however, be set by biological interactions. *Fucus vesiculosus* and *Fucus serratus* for example, have not been shown to die at their upper limit, even during extremely hot weather when some high shore species are being badly affected (Schonbeck & Norton, 1978; Hawkins & Hartnoll, 1985). Competition or grazing pressures may modify the upper limits in these instances. Similarly the lower limits of a number of plants species are thought to be affected by both physical and biological factors. The depth of light penetration will also limit the lower limit of subtidal algal species.

(c) Wave Action

Algal growth tends to be greatest in sheltered environments where they are not as frequently removed from the substratum by strong wave action. This is particularly true in locations which do not provide secure anchorage or in young plants which are not as well established (Hawkins & Jones, 1992). On sheltered shores the algal canopy can inhibit the settlement of key grazers such as limpets and macroalgae can therefore continue to thrive. Wave exposure plays a key role in affecting the balance between fucoids, limpets and barnacles observed on rocky shores (Hawkins & Hartnoll, 1983).

For intertidal species it is frequently observed that plants growing on exposed shores are usually, tougher, shorter, narrower and often have stronger attachment structures than those growing in calmer conditions (e.g. Price, 1978; Russell, 1978; Steffenson, 1976).

(d) Tidal Range and Hydrodynamics

The tidal range will have implications for the width of each of the zones that occur on rocky substrata. This is associated with the duration of emersion periods and associated physiological stresses experienced by the macroalgal species (Hawkins & Jones, 1992).

Water motion has been attributed with influencing the morphology of seaweeds, the composition of seaweed communities (Sundene, 1953) and the relative biomass of seaweeds (Conover, 1968). Water movements also play a role in the transfer of propagules and as such will affect overall distribution patterns. In addition water movements may affect the release of propagules from plants into the water column (Gordon & Brawley, 2004)

(e) Topography, Geology & Aspect

The influence of shore aspect on zonation has been discussed by Stephenson & Stephenson (1949) and Lewis (1964) who refer to the effects of desiccation and atmospheric humidity on community structure. The aspect of the shore will influence the amount of desiccation experienced by macroalgae when they are emersed. Locations which are shaded and remain damp for longer may result in an upward extension of some species. The shallower the gradient of a shore the greater the potential width of each of the intertidal zones.

(f) Salinity, Temperature, Chemical Fluctuations, Water Quality

Most rocky shore species are relatively tolerant to salinity changes and can tolerate long term reductions in salinity within their normal tolerance range although growth rates and fecundity are likely to be impaired. Barnacle and fucoid shores, for example, are able to tolerate short term variations in salinity because the littoral zone is regularly exposed to precipitation.

Similarly most species of macroalgae can occur across a range of temperatures. Schonbeck & Norton (1979) demonstrated that fucoids can increase tolerance in response to gradual temperature change in a process known as 'drought hardening'. However, fucoids are more intolerant of sudden changes in temperature and relative humidity with field observations of bleaching and death of plants during periods of hot weather (Hawkins & Hartnoll, 1985). Temperature can affect the distribution and reproductive timings of a number of algal species (Lobban & Wynne, 1981).

(g) *Biological Interactions*

Biological interactions plays a key role in determining and modifying the distribution patterns of a number of macroalgal species. Grazing by invertebrates such as limpets, for example, has a big impact on the survival of algal germlings and seedlings (Hawkins & Hartnoll, 1983). Competition between plant species can also affect the upper and lower limits of macroalgal species. The outcome of such competition is, however, subject to environmental conditions.

B2.5 Angiosperms

B2.5.1 Saltmarsh

Coastal saltmarshes may be defined as areas, vegetated by herbs, grasses or low shrubs, bordering saline water bodies (Adam, 1990). Saltmarshes form in low energy or sheltered environments with shallow water, such as estuaries, behind spits and barrier islands and in protected bays where there is a supply of suspended sediment that can accrete. The rate of formation of salt marshes depends upon the degree of protection, the topography of the near shore sea-bed, and the supply of suspended sediment (Long & Mason, 1983). At managed realignment schemes such as at Tollesbury in the UK, colonisation rates of saltmarsh plants have been more successful where elevations are raised (Garbutt *et al in submission*).

(a) *Substratum*

Most saltmarsh plants are not limited by sediment types and textures that occur on natural saltmarshes, and are found on various marine sediments from coarse sands to heavy clays (Adam, 1990). However, sediment grain size composition and porosity affect drainage characteristics and organic content, and can influence the elevation of species colonisation and the outcome of competition.

(b) *Zonation*

Typically saltmarshes occur between mean high water neaps to high water spring tides. Therefore the higher the tidal range the larger the vertical range of any saltmarsh habitat. In terms of tidal inundations, sites with elevations that will experience less than about 450 tidal inundations would be expected to develop saltmarsh, whereas mudflat will develop at levels that experience greater that 500 inundations per year (Burd, 1995).

Within a saltmarsh habitat complex, halophytic plant species and communities display a transition, from marine to terrestrial habitat. There is general agreement that the main factors affecting the zonation of halophytic plant species within a saltmarsh habitat relate to frequency of tidal inundation and associated effects of salinity and tidal scouring. Each species has a different tolerance to tidal flooding and therefore a different, although often overlapping, vertical range. Different communities are therefore apparent at different tidal elevations, a summary of which is presented in Table 7:

Table 7. Typical plant species observed in each of the major saltmarsh plant communities (Adapted: CEFAS, 2004).

Zone	Tidal Elevations	Dominant species
Transitional Marsh	Around and above Highest Astronomical Tides	Transitions e.g. to reed swamp, freshwater marsh, grazing marsh
Driftline	Around Extreme High Water Springs	*Elymus pycnanthus* (sea couch) Sueda vera (Shrubby seablite)
Mid-upper marsh.	Approx. from Mean High Water to Extreme High Water Springs	*Puccinellia maritima* (saltmarsh grass), *Limonium vulgare* (Sea lavender), *Armeria maritima* (sea thrift), *Festuca rubra* (red fescue), *Juncus gerardii* (saltmarsh rush), *Juncus maritimus* (sea rush)
Low to Mid Marsh	Up to Mean High Water	*Puccinellia maritima* (saltmarsh grass), *Atriplex portulacoides* (sea purslane)
Pioneer marsh	Most seaward zone, down to aprox Mean High Water Neaps.	*Spartina anglica* (cord grass), *Salicornia* (annual glasswort), *Sueda maritima* (seablite) *Aster tripolium* (sea aster)

It is widely accepted that the lower limits of saltmarsh plants is set by tolerance to tide related factors while biotic factors such as competition are important at the upper limits (eg Gray, 1992). Studies conducted by the Institute of Terrestrial Ecology (ITE) now Centre for Ecology and Hydrology (CEH), developed regression equations relating the lower limit of *Spartina anglica* to simple tidal parameters and environmental characteristics (Gray *et al* 1989; Gray *et al*, 1995, Clarke & Brown, 2002). Gray demonstrated that 90% of the variation in lower limits could be explained by a multiple regression model using a set of physical variables including:

- Tidal range;
- Submergence times;
- Submergence during daylight hours;
- Fetch;
- Estuary area; and
- Latitude

(c) Wave Action

Saltmarshes tend to form in sheltered environments (Adam, 1990).

(d) Tidal Range and Hydrodynamics

The importance of tides influencing zonation patterns has been discussed in Section 3.1.2. Patterns of water movement may also influence the dispersal and subsequent establishment of propagules (CEFAS, 2004).

(e) Topography, Geology & Aspect

As described above saltmarsh can establish and persist across a broad spectrum of tidal ranges. Where the area is gently sloping this provides a greater opportunity for a full range of saltmarsh types to establish. The surface gradient does, however, need to be sufficient to allow adequate drainage as prolonged waterlogging can result in the death of vegetation (Adam, 1990). Drainage characteristics are important as they influence the times that tidal waters stand on the marsh surface, sediment stability and velocities of currents. A relatively flat intertidal topography that slopes gradually toward the intertidal channels provides the most suitable location for saltmarsh development (Zedler, 1984). Creeks are also considered important for supplying the marsh surface with sediment and nutrients and dissipating tidal energy, and for draining the marsh during the ebb tide.

The size of an estuary influences the elevational limits of saltmarsh species. The lower limits of saltmarsh plants are typically at higher elevations in larger estuaries, possibly due to the greater degree of exposure to wind and wave action (CEFAS, 2004).

(f) *Accretion and erosion*

A sufficient sediment supply is required to sustain the surface elevation at a suitable height for continued vegetation survival, providing it is sufficient to offset the predicted sea level rise in the area of coastline under review (CEFAS, 2004).

Excessive accretion at levels suitable for marsh colonisation may result in burial of seedlings and vegetation, although saltmarsh plants are tolerant of quite high levels of accretion.

(g) *Salinity, Temperature, Chemical Fluctuations, Water Quality*

Salinity, along an estuarine gradient for example, affects the species that occur at a particular location. In upper estuaries low marsh zones may have low soil salinities and brackish water species such as the common reed *Phragmites australis*, can be abundant. *Phragmites* typically tolerates salinities between 2-12ppt (Hellings and Gallagher, 1992).

Saltmarsh plants are essentially terrestrial species that are tolerant of saline conditions (Halophytes). Most saltmarsh plants can grow well in non-saline soils but show poor competitive ability with terrestrial and brackish marsh plants. Freshwater inputs into an area can introduce greater diversity of species, but in excessive may have an adverse impact on salt tolerant plants as they may be unable to compete with terrestrial and brackish water species. Major freshwater inputs to saltmarshes will therefore have implications for the species composition.

Nitrogen and phosphate can be limiting to some saltmarsh plant growth (Adam, 1990). Nutrient addition can cause shifts in plant zonation and the outcome of plant competition. High levels of nutrients can also cause problems by encouraging excessive algal growth and large algal mats washed up can result in smothering and subsequent death of saltmarsh plants. In addition the chemistry of the sediment, such as the pH and redox potential, can also affect nutrient uptake and affect other biological processes.

(h) *Biological Interactions*

Biotic interactions between plants, particularly interspecific competition, also determine species distribution. The outcome of such competition is, however, subject to environmental conditions. Competition is thought to determine the upper limit of a number of species.

B2.5.2 *Eelgrass beds*

Eelgrasses are marine flowering plants of sheltered environments anchored to shallow subtidal and intertidal sands and muds by a rhizome and root system. There are three species of *Zostera* in the UK, common eelgrass *Z.marina, Z. angustifolia* and dwarf eelgrass, *Z. noltii.* Information on eelgrass beds has largely been derived from CEFAS (2004) and Short *et al* (2001).

(a) *Substratum*

Zostera marina is essentially a sublittoral species, growing in the subtidal zone, on a firm relatively coarse substrate of sand or sandy mud, sometimes with a mixture of fine gravel. Similarly the substrate on which *Z. angustifolia* grows can range from sloppy mud to quite firm containing some fine gravel (Rodwell, 2000). *Z. noltii* is typically found in sheltered estuaries and harbours on mixed substrates of sand and mud of varying consistencies from very soft to quite firm mud, often in pools or runnels on the shore (Rodwell, 2000).

(b) *Zonation*

Z. marina occurs in areas protected from full exposure, from slightly above Low Water Spring Tides (LWST) to a depth of about 4m below LWST in Britain.

Z. angustifolia also grows on sheltered tidal mudflats, in estuaries and coastal lagoons, but typically higher on the shore than Z. marina. Z. angustifolia grows between mid and low tide marks, extending to well above low water of neap tides, sometimes to high water of neap tides.

Light is the limiting factor of eelgrass growth in deeper water, and its upper limits are typically attributed to its susceptibility to desiccation. Of the three species *Z. noltii* is better adapted to exposure to air than the other two species and as a result can colonise higher up the shore. In general the minimum light requirement is considered to be around 10-20% of surface light (Duarte, 1991). A short period of exposure to air on a sunny or windy day is sufficient to kill the flowers, and may be sufficient to kill the base of the shoot.

(c) *Wave action*

All three species require shelter from strong tides, currents and wave exposure. Dense swards tend to develop in sheltered inlets, bays, estuaries and saline lagoons, but in more exposed sites the beds are usually smaller, patchier and more susceptible to storm damage.

(d) *Tidal Range and Hydrodynamics*

Water movement affects seagrass biomass and habitat structure (Short *et al* 2001), for example, within limits biomass and height may increase with increasing velocity. Water movement is also for important for pollination.

(e) *Accretion and erosion*

Zostera spp. cannot tolerate excessive sedimentation, which can smother plans, or high turbidity, which inhibits growth by reducing light penetration for photosynthesis (Giesen *et al* 1990).

(f) *Salinity/ Chemistry / water quality*

Information on the salinity preferences for *Zostera* spp. are conflicting. *Z. marina* in the UK is reported to be found in bays, sea lochs and estuaries with little land drainage (Tutin, 1942), and lagoons, preferring marine conditions with salinities not much below 35. This view is also supported by Stewart *et al* (1994) who claim that British *Z. marina* prefers saline conditions and avoids brackish waters. In contrast data from field and laboratory studies indicated that germination occurs over a wide range of salinities and temperatures (Davison & Hughes, 1988). It is acknowledged by Davison & Hughes (1988), however, that in the UK *Z. marina* occurs almost exclusively in fully saline condition. *Z. angustifolia* can tolerate variable salinities but optimal salinity is considered between 25-34 (Proctor, 1980) and *Z. noltii* has been reported to occur in full to variable (8-10) salinities (Connor *et al* 1997).

The optimum temperature range for growth and germination of UK species is reported as between 10-15 °C, although plants can tolerate sea temperatures between 5-30°C (Davison & Hughes, 1998). Nitrogen is typically the limiting nutrient for plant growth, however, excessive inputs may be harmful, resulting in blooms of algae that may smother plants. In addition high levels of nitrate may cause metabolic imbalances in *Zostera* (Davison & Hughes, 1998). A variety of toxic contaminants have the potential to cause harmful effects, including herbicide run off, heavy metals, antifoulants, oil pollution and dispersants, and excessive nutrient inputs.

(g) Biological Interactions

Eelgrasses provide shelter, nursery areas and food web support for a number of organisms. The root networks increase sediment stability, reducing erosion (Fonseca & Fisher, 1986), while the canopy buffers water movement, reducing current flow and trapping suspended sediments and organic particles.

B2.6 Fish in Transitional Waters

The number and types of species found within a particular system will depend on many factors including:

- Habitat diversity;
- Estuary size and shape;
- Structural complexity;
- Tidal amplitude; and
- Freshwater runoff.

In the US, large scale efforts are underway to gather information on the habitat requirements of fish at various stages in their life history, and this has highlighted the lack of knowledge concerning the habitat use of many fish species (Schmidt, 1998).

(a) Substratum/Habitat types

Mudflats and saltmarsh habitats provide important feeding grounds for fish species. As previously described the substrate is very important in determining benthic communities and as such can therefore influence the distribution of a number of fish species. An experiment in France, for example, found that when sand and gravel were removed from an area, a hard-ground fauna developed which was of less food value to demersal fish species than the previous soft bottom fauna (ICES, 1992).

Saltmarsh habitats can be extremely productive and in combination with creek systems are considered especially valuable for small adult fishes and fry (Rozas & Minello, 1997; Hettler, 1989; West & King, 1996). Lower saltmarsh communities improve habitat heterogeneity and structural complexity, and as such influence fish habitat selection (Grenouillet & Pont, 2001). They also provide food sources and offer some form of protection from strong currents and fish predators (Little, 2000). This has been demonstrated in a number of systems where macrophyte removal resulted in reduced recruitment of 0+ fish in the Great Ouse (Mann & Bass, 1997) and reduced food availability (Mann *et al*, 1997).

Foraging fish regularly move from tidal creeks onto vegetated saltmarsh during rising tides, preferentially using permanent creek channels with shallow sloping profiles or areas with abundant submerged aquatic vegetation, such as seagrass (Rozas *et al*, 1988). There is evidence that dense vegetation inhibits the foraging efficiency of some piscivores and that topological features of the marsh, such as rivulets, facilitate the use of vegetated wetland surface for foraging by juvenile fish (Havens *et al*, 1995). Fish utilisation of a creek system may be affected by the sinuosity of the creek, channel depth, bank stability and the adjacent vegetated marsh surface (McIvor and Odum, 1988). As such research into the potential benefit of managed realignment sites is being undertaken (Colclough *et al*, 2004).

(b) *Nursery Areas*

Tidal marshes and creeks have been shown to be important habitats for the juvenile and larval stages of marine and estuarine fish (Clark and Hannon, 1969). Within the eastern English Channel and southern North sea, sole have been found to spawn predominantly within inshore waters and over offshore sandbanks at depths of <30m (Borremans, 1987; Land, 1991; ICES, 1992; Grioche, 1998). Investigations using mathematical equations and GIS procedures has demonstrated that spatial variations in sole egg density were found to be limited by depth, temperature, salinity and sediment type, with highest densities found in shallower regions over sediments consisting of <30% gravel (Eastwood *et al*, 2001).

The estuarine resource provides nursery areas for juvenile fishes, including sole, plaice, sprat, cod, dab, flounder, bass, herring and other species. Estuaries are particularly important to sea bass as spawning and nursery grounds. The late postlarvae bass appear to congregate around the saltwater/freshwater boundary at the top end of many estuaries (Davidson *et al*, 1991). Juvenile Dover sole have been observed to use the mudflats of the Tamar Estuary as a nursery area. During their time in the estuary individual fish appear to restrict themselves to a single mudflat with only limited movement of fish between adjacent mudflat areas. These populations are thus very susceptible to localised disturbance or the destruction of mudflat areas.

(c) *Water Quality*

Estuarine fish show some tolerance of high turbidity, temperature extremes, and a wide range of salinities and dissolved oxygen levels; the distribution of species in an estuary is largely determined by their tolerance to each of these parameters (ABP Research, 1998). Chemical reactivity, tidal movement and freshwater discharge interact to produce complex conditions that vary between one estuary and another, and also within any particular estuary on an hourly, monthly or annual basis due to tidal cycles, climatic conditions and so on. Water movement, critical for the distribution and dispersal of suspended matter and pollutants, is affected by the tidal amplitude and geomorphology of an estuary. The number of variables illustrates the problem in defining water quality and relating it to the distribution of fish species within an estuary. The most serious impact of water quality in estuarine fish habitats results from the deoxygenation of the water, which kills fish communities and the invertebrates upon which they feed.

(d) *Hydrodynamics*

The strength of the tidal flow affects the movement of fish and the freshwater draining into the upper end of the estuary will influence the suitability of the ecosystem as a habitat for fishes (ABP Research, 1998). Climatic conditions also alter habitat conditions, for example, strong winter rains or snow melts in northern latitudes can flush out the maritime influence.

B2.7 Phytoplankton

Phytoplankton are photosynthetic organisms that live suspended in seawater and are generally incapable of moving against water currents. Two forms of phytoplankton, dinoflagellates and diatoms are particularly important as founders in the planktonic food webs because most of the animal life in the oceans depend on these. The dinoflagellates are usually found in warmer waters, and the diatoms are usually more abundant in cooler waters. The distribution of phytoplankton species and productivity on a small scale is both spatially and temporally patchy in nature. Spatially the scale of patchiness can range in the order of millimetres down to a few decimetres. Several processes appear to shape these patterns including physical, reproductive and feeding.
The availability of nutrients, amount of vertical mixing, salinity, density, temperature, and depth of water affect phytoplankton growth rates (Harris, 1986).

In estuarine systems it is not typically nutrient availability that limits the phytoplankton populations, there are other factors limiting growth. Of most importance in estuaries are the relatively high turbidity levels that are characteristic of temperate systems. In addition the growth rates of phytoplankton may be less than the flushing time of the estuary (McClusky, 1989).

In shallow water and on intertidal areas, however, diatoms are an important food source for surface feeders. Diatoms are microscopic single celled plants encased in a siliceous structure. Diatoms are able to migrate within the upper layers of sediment, tending to move down into the sediment when intertidal areas are covered with water to prevent them from being washed away and moving up to the sediment surface when the mud is uncovered in order to photosynthesise. Under certain conditions, a golden brown film of diatoms can often be seen on the surface of intertidal mudflats. Whether they are present within the sediment, adsorbed onto the surface of sediment particles or present on the surface of the mud, diatoms can constitute an important feeding resource for benthic invertebrate communities.

In addition to providing a feeding resource, mats of diatoms on the surface of the sediment act to stabilise the sediment. In certain situations, where diatom density reaches sufficiently high levels, this can reduce the rate of erosion of intertidal muds, although the extent to which this occurs will depend on the hydrodynamic conditions.

Diatoms and other benthic microalgae also play an important role in developing and maintaining an oxygenated zone on the surface of intertidal estuarine sediments. Along with tidal action which supplies a source of oxygen from the water column to intertidal sediments, benthic microalgae may be the main source of oxygen for the sediment surface through the process of photosynthesis (McLusky, 1989).

B2.8 Impacts of Change

Dynamic ecosystem response to natural and/or anthropogenically induced change is a product of a number of complex physical, physiochemical and biological interactions. In order to adequately model the cross linkages between the parameters a number of factors need to be considered (derived from Cascade Consulting, 2002):

- Changes to physiographic character (e.g. basin shape, topography, bathymetry) which in turn will alter hydrodynamic function leading to variation in water flows, velocities and levels;
- Consequent implications for sediment transport and changes to erosional/ depositional/ accreting character;

- Potential impacts on habitat stability through for example direct effects of changes in flow character or substratum availability or indirect changes through water quality effects;
- Consequent changes due to hydrographic alteration causing a change in food supply and/or the recruitment of colonising organisms; and
- Acute or chronic impacts on communities and species reliant on the ecosystem, ranging from macroalgae and benthos to birds, fish and possibly mammals.

B.3 Existing Classification Tools and Classification Schemes

B.3.1 Coastal classification

Most coastal classification schemes are based upon typology, for example the European Union for Coastal Conservation (1998) define five coastal types:

- hard rock, cliffed coasts;
- hard rock coastal plains;
- soft rock coasts;
- tide-dominated sediment plains; and
- wave-dominated sediment plains.

Definition of the coastal type in this manner is on such a broad-scale that such schemes can be considered simplistic. Often, such classifications do not consider the interactions which occur within such environments for example between the morphology and hydrodynamics. In addition, ecological parameters are rarely, if at all, used. An additional drawback is that many schemes do not include all the littoral, nearshore and offshore areas of the coastal environment.

The classification system used in the South African National Wetland Inventory (Dini *et al.*, 1998) is very top-level and provides little detail on the physical factors used to support the classification. There are however tentative links to the ecology that one could expect in the different classes.

The proposed classification is devised for different wetland systems and sub-systems:

- marine system;
- estuarine system;
- riverine system;
- lacustrine system;
- palustrine system;
- endorheic system; and
- wetland classes.

With respect to the marine system, the following classification (Figure 7) is used:

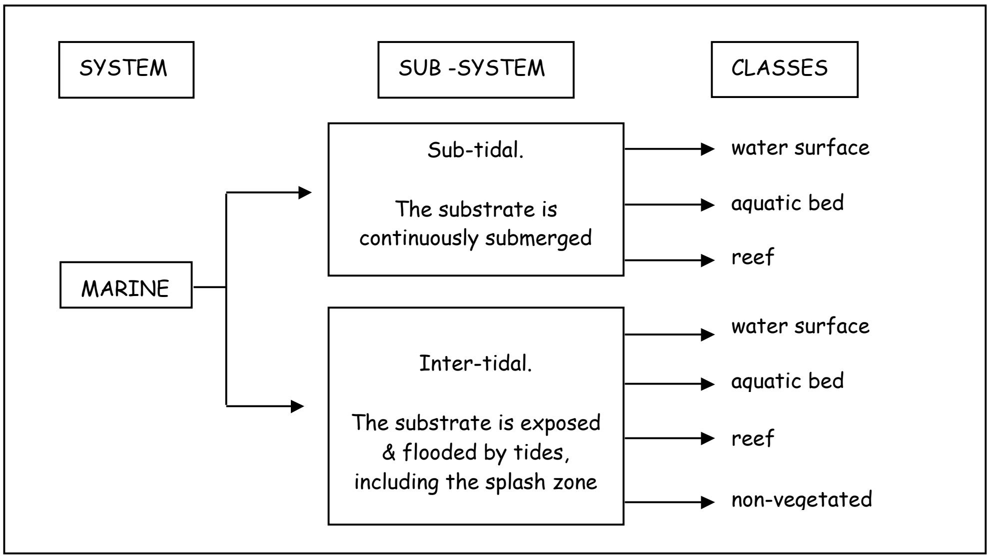
Definition : the open ocean overlying the continental shelf and its associated exposed coastline.

Description : marine habitats are exposed to the waves and currents of the open ocean and the water regimes are determined primarily by the ebb and flow of oceanic tides. Shallow coastal indentations or bays without appreciable freshwater inflow are also considered part of the marine system because they generally support typical marine biota.

Boundaries : the system extends landward from the outer edge of the continental shelf to one of the following:

- the landward limit of tidal inundation (extreme high water of spring tides);
- the seaward limit of wetland emergents, trees or shrubs;
- the seaward limit of the estuarine system, where this limit is determined by factors other than vegetation

Figure 7. The marine system



The classification system used by the European Union for Coastal Conservation (1998) has been designed for application to the open coasts of Europe. Three main parameters were used to classify the coasts, as shown in Table 8.

Table 8. Classes used in the identification of coastal types

CLASS	RATIONALE	SUB-CLASS	
		PARAMETER	DESCRIPTION
Predominant substrate in the littoral zone	This is a vital condition for the development of a whole range of coastal systems and habitats	hard rocks	rocks which are extremely resistant to erosion (mostly supplying almost no sedimentary material to the littoral zone, apart from river sediment)
		soft rocks	rocks with a lower resistance to erosion (mostly supplying moderate amounts of clastic and sedimentary material to the littoral zone)
		recent sediments	loose soils consisting of small particles with a low resistance to erosion (mostly supplying relatively large amounts of sediments in the littoral zone)
Slope of the coastal zone	This indicates the space available for the development of intertidal and supratidal systems and habitats.	high and cliffed coasts	reaching over 100 m above sea level in the first 5 km from high water mark
		coastal plains	providing ample room for the development of sedimentary and aeolian systems
Tidal regime	The formation and evolution of coastal landscapes and habitats depend on the relative impact of tidal regime, longshore drift, wave climate or river flow in the littoral zone.	tide-dominated	tidal range above 2m
		wave-dominated	tidal range below 2m

The application of this classification scheme resulted in the identification of five coastal types, as listed in Table 9.

Table 9. Provisional 1st level Coastal Typology for Europe

COASTAL TYPE	COMPONENT
hard rock, cliffed coasts	sea cliffs, cliff islands, archipelagos, fjords and sea lochs, rias, rocky shores with caves, bay and pocket dunes, river mouths and small estuaries and embayments
hard rock coastal plains	skerry coasts, fjards, river mouths, Arctic tidal plains, and Karstic shores
soft rock coasts	soft rock glacial cliffs tidal bedrock plains, other friable sea cliffs with e.g. shale and sandstone. Soft rock coastal bedrock plains
tide-dominated sediment plains	barrier shingle/dune coasts, sea lagoons, barrier shingle/dune islands, estuaries, freshwater tidal deltas and dune-wetland coasts
wave-dominated sediment plains	lagoons, Black Sea limans, river deltas, dune coasts, Baltic barrier-half-delta coasts, German Baltic bodden coast

Whilst of benefit to coastal studies, this and similar classifications of coastlines includes features that are probably outside the scope of the Water Framework Directive, for example dunes, bluffs and cliffs. In addition, the nearshore seabed is rarely considered.

In the UK, a high-level generic classification is provided in the Coastal Cells review for England and Wales (Motyka and Brampton, 1993), and in a similar review for Scotland. These are essentially based on the definition of units (or 'cells') within which sediment movement is relatively self-contained. The cells are defined according to non-cohesive sediment transport processes and their boundaries usually coincide with prominent headlands or estuaries.

Some of the work on classifying open coastlines can be extended seawards, but extensions may be required. For example, BGS publishes maps of seabed sediment distribution using combinations of Mud, Sand and Gravel (Folk classification) and bedrock, but these maps are often lacking in detail close to the coast (where there may be significant temporal as well as spatial variations in sediment cover).

Another distinct feature of interest in nearshore waters is the amount of suspended sediment, which will affect water clarity and hence biology, e.g. photosynthesis in marine flora.

This leads on to another possible starting point for classification of coastal waters is to define 'habitats' e.g. the classification offered by the JNCC for ecological habitats on the seabed/shoreline is:

1. sheltered rocky;
2. exposed rocky;
3. sheltered sandy;
4. exposed sandy; and
5. soft sediments.

Their classification system also features five sediment types:

1. mud;
2. muddy Sand;
3. sand ;
4. muddy Gravel; and
5. Gravel.

In addition, the following habitats are described in terms of community structure:

1. shell sand and gravel;
2. muddy sand and gravel;
3. shallow muddy sand ;
4. silt/clay; and
5. littoral sand (either sediments with a high shell content or finer sand).

As with many of the classification schemes, this approach does not mention factors such as vegetation cover or important bathymetric features.

Finkl (2004) presents an up-to-date and extremely comprehensive review of coastal classification schemes. Key issues arising from his review are:

- Since modern scientific investigations of the coast began in the early 1800s, the classification of coasts has been problematic.

- No mutually satisfactory or complete solution has yet been found because philosophies of coastal classification are guided by existing knowledge and pragmatic circumstances that seek to study coastal features for their own special purposes.

- Coastal researchers are still attempting to understand process relationships between form, function, time and space that occur in a very dynamic environment.

- It is difficult to classify the coast because of time-(in)dependent forms that compound upon one another at all scales.

- The geological framework on which the overlapping terrestrial, coastal and marine processes operate is important to establish.

- Coasts represent spatially and temporally transient manifestations that are locations of unique assemblages of erosional and depositional processes.

- Coastline evolution occurs over different time scales and spatial scales, leading to small- and large-scale behaviour.

- Coastal forms successively overprint younger morphologies.

- Some general morphological classification schemes for particular features (e.g. dunes, spits, banks, reefs, beaches, rock cliffs and platforms) but comprehensive approaches that organise individual landforms into a universal hierarchy are yet to be devised.

- Geomorphological systems can potentially provide the framework or underpinning for other types of classifications.

Finkl then attempted to formulate a unified, multi-purpose, comprehensive and universal scheme for coastal classification (based on geomorphic zones and features) that in turn can be used as underpinnings to biologically-based systems. However, he recognised that his approach was an open-ended approximation that can subsequently be modified. Nonetheless, this approach represents one of the most up-to-date and comprehensive attempts at organising coastal landforms within a classification scheme and was contributed to be numerous internationally recognised experts. Despite this, it has limited applicability for the purposes of the present study as it is essentially a typology approach that does not consider hydromorphological status.

B.3.2 Estuarine Classification

A number of previous estuary classification systems have been developed and presented in the scientific literature. These generally have been biased towards one particular aspect (i.e. geomorphology, hydrography, salinity, sedimentology, or ecosystems). A small number of examples of these are summarised in Table 10.

Table 10. Examples of existing estuary classification schemes

Focus	Author	Date	Description
Geomorphology and physiography	Pritchard	1967	▪ Drowned river valleys (coastal plain estuaries) ▪ Lagoon type bar-built estuary ▪ Fjord ▪ Tectonically-produced
Hydrography	Pritchard	1955	▪ Salt-wedge estuary, highly stratified ▪ Partially-mixed estuary, moderately stratified ▪ Vertically homogeneous estuary, with lateral salinity gradient ▪ Sectionally homogeneous estuary, with longitudinal salinity gradient
Tidal characteristics	Hayes	1975	▪ Micro-tidal (tidal range of 0-2m, sediments of tidal and river deltas) ▪ Meso-tidal (tidal range of 2-4m, sediments deposited largely by tidal currents) ▪ Macro-tidal (tidal range of >4m, completely tidally-dominated)
Sedimentation	Rusnak	1967	▪ Positive filled (entirely filled with river sediment) ▪ Inverse filled (filled by marine sediments by the flood tide) ▪ Neutral filled (in equilibrium with no basin volume change)
Ecosystem energetics	Odum and Copeland	1974	▪ Natural stressed systems of wide latitudinal range ▪ Natural tropical ecosystems of high diversity ▪ Natural temperate ecosystems with seasonal programming ▪ Natural Arctic ecosystems with ice stresses ▪ Emerging new systems associated with man ▪ Migrating sub-systems that organise areas.

As can be seen from this table, most of these classifications are of limited value to this study since they are either too general or require detailed field measurements (e.g. of salinity profiles). Hume and Herdendorf (1988) developed a more comprehensive classification scheme for estuaries, reflecting their origin and the dominant hydraulic, sedimentological and ecological processes operating. The purpose of this system was to aid recognition of different estuary types, thereby simplifying their description and enabling the transfer of knowledge between estuaries of the same type. The classification scheme led to the grouping of estuaries in New Zealand on a regional basis, using geological and topographic mapping data, complemented by aerial photographs and site visits.

Initially, Hume and Herdendorf (1988) grouped estuaries into five classes based on the primary process that shaped the basin, before it was modified by sedimentary processes associated with the Holocene. These classes are (from Hume and Herdendorf, 1988):

1) **Fluvial erosion**. These are estuaries where the depositional basin was originally cut by river action, commonly when sea level was lower than present. The landform has since been drowned by a rise in sea level, and modified by sediment deposition of both fluvial and marine origin.

2) **Marine erosion**: These are small coastal embayments that have been shaped by a combination of stream erosion, wave attack and sub-aerial weathering. They have small catchments and very little fluvial input.

3) **Tectonics**: These are flooded basins of tectonic original, for example fault-defined basins.

4) **Volcanics**: These are drowned explosion craters that have been breached by the sea and partially infilled with sediment.

5) **Glacial activity**: These are represented by fjords and are elongate, with steep parallel shores.

Within these 5 classes, there was a further sub-division of 16 specific types, based on the geomorphic and oceanographic characteristics of the estuary, as described in Table 11.

Table 11. Hume and Herdendorf Classification Scheme
(after: Hume and Herdendorf, 1988)

Mode of Basin Origin	Estuary Type	Description
Fluvial erosion	1 – Funnel-shaped	Simple or branched drowned-valley systems with funnel-shaped inlets. No barrier features or deltas at inlets. Low wave energy shores. Little fluvial sediment. Well-mixed.
	2 – Headland enclosed	Inlets constricted by rock headlands, with a deep throat maintained by strong currents. Inside of mouth constriction, the estuary widens significantly.
	3 – Barrier enclosed (double spit)	Drowned river valleys and embayments whose inlet is formed by spit, tombolo, island or beach landforms. These barriers are formed from sediment transported onshore and/or by littoral drift. Tidally-dominated and well mixed. Typically wide inter-tidal areas.
	4 – Barrier enclosed (single spit)	
	5 – Barrier enclosed (tombolo)	
	6 - Barrier enclosed (island)	
	7 - Barrier enclosed (beach)	
	8 – River mouth (straight-banked)	River dominated hydrology and large fluvial input.
Fluvial erosion	9 – River mouth (spit lagoon #1)	
	10 – River mouth (spit lagoon #2)	
	11 – River mouth (deltaic)	
Marine erosion	12 – Coastal embayment	Small coastal embayments that have been shaped by a combination of stream erosion, wave attack and sub-aerial weathering. Small catchments and very little fluvial input.
Marine erosion or Tectonics	13 – Fault-defined embayment	These are flooded basins of tectonic original.
Tectonics	14 – Diastrophic embayment	
Volcanics	15 – Volcanic embayment	Drowned explosion craters that have been breached by the sea and partially infilled with sediment.
Glacial activity	16 – Glacial embayment	Elongate, with steep parallel shores.

A re-arrangement of the characteristic properties of various classes, or sub-classess, of estuaries revealed that certain generalisations could be defined (Table 12).

Table 12. Generalisation of Behaviour of Different Estuary Types

Factor	Magnitude	Estuary Types
Channel stability	Low	Funnel-shaped estuary Headland enclosed estuary Barrier enclosed estuaries (all types) River mouth estuaries (all types except straight banked) Coastal embayment
	High	River mouth – Straight banked Tectonic Volcanic Glacial activity
Inlet stability	Low	Funnel-shaped estuary Barrier enclosed estuaries (all types) River mouth estuaries (all types except straight banked) Coastal embayment
	High	Headland enclosed estuary River mouth – Straight banked Tectonic Volcanic Glacial activity
Sediment infilling	Moderate	Funnel-shaped estuary Headland enclosed estuary River mouth – spit lagoon Fault-defined embayment Volcanic embayment
	High	Barrier-enclosed estuaries River mouth –Spit lagoon River mouth –Deltaic

A similar classification scheme was used by Dyer during Defra's *Futurecoast* study (Defra, 2002). This was a modified version of the system developed by Hume and Herdendorf (1988), extended to incorporate a qualitative assessment of important processes and geomorphological features. It was principally focused on simple dimensional relationships, since there is a general paucity of basic data on water flow and salinity characteristics. Dyer's classification is listed in Table 13 and described in more detail in Box B.

Table 13. Dyer's *Futurecoast* classification system

Origin	Type	Sub-type
Glaciated valley	Fjord (1)	With spits (1a)
		No spits (1b)
	Fjard (2)	With spits (2a)
		No spits (2b)
Drowned river valley	Ria (3)	With spits (3a)
		No spits (3b)
	Spit-enclosed (4)	Single spit (4a)
		Double spit (4b)
		Filled valley (4c)
	Funnel-shaped (5)	-
	Embayment (6)	-
Drowned coastal plain	Tidal inlet (7)	Symmetrical (7a)
		Asymmetrical (7b)

Dyer applied this classification system to the ninety-six estuaries around England and Wales during the *Futurecoast* study (Defra, 2002). Table 14 shows specifically which estuaries fall into which class.

Box B – Description of Dyer's Different Estuary Types (source: Defra, 2002)

Fjords and ***fjards*** are present in glaciated areas, the former created in more resistant rock than the latter. Both are likely to have small, but seasonally very variable river flow. Fjords (Type 1) often have mouths that have been overdeepened, and despite a rock sill at their mouths, normally do not have sufficient coastal erosion to provide enough sediment to create spits. Fjards (Type 2), on the other hand, tend to be shallower and more likely to support spits.

Drowned river valleys are defined in periglacial areas, where the original valley was produced by fluvial processes. ***Rias*** (Type 3) are present in hard rock. They have steep relief, often with much exposed rock. They have other characteristics of river valleys, with a meandering form, a triangular cross-sectional shape and deep areas on the bends.
Other drowned river valleys occur where the rocks are in general relatively soft. Therefore the relief is subdued, and cliffs are of small vertical extent. ***Spit enclosed*** *t*ypes (Type 4) have distinctive spits restricting their mouths. These tend to limit high tidal velocities to the mouths, and wave action within the estuary is relatively small. At low water salinity in the estuary can be very low. Double spits occur in situations where there are coastal sources of sediment on both sides of the mouth, and the wave climate produces significant littoral drift in both directions, converging at the estuary mouth. Single spits occur when there is one predominant direction of littoral drift. In this case the growth of the spit can be terminated by hard rock outcrops and a small cliff. A feature of spit enclosed estuaries are large flood and ebb deltas. When there has been sufficient sedimentation to fill the estuary, there is no low water channel and the water surface forms a continuation of the river, with the flood current starting well after low water on the adjacent coast.

Funnel shaped estuaries (Type 5) are a distinctive group which may be close to the classical definition of equilibrium form, where the cross-sectional area of the mouth is related to the active tidal volume (tidal prism) of the estuary. They do not possess spits, which implies strong tidal motion and relatively weak sources for littoral drift. One distinctive feature of this type is elongated linear sandbanks within the estuary mouth that are aligned with the current flow direction. However, because of the regular expansion at the mouth, it is difficult to define the mouth as anything other than a zone in which there is interaction with the sea and complicated sediment circulation patterns.

Embayments (Type 6) often form where several rivers converge, with their joint valleys creating a wide mouth area open to large wave and weather effects. They have large inter-tidal areas, and the salinity is high throughout the embayment over high water.

Inlets (Type 7) are produced where the sea level rise has occurred over an extremely low relief coastal plain. These are characterised by narrow mouth areas backed by extensive tidal lagoons, and barrier beaches. They have many similarities to spit enclosed types, except that the backing lagoons are large enough for weather effects to be significant. Symmetrical and asymmetrical types mirror the double and single spit enclosed drowned river valleys. Davis and Hayes (1984) have categorised inlets in terms of the ambient tidal range and wave conditions. This illustrates that there can be a wide temporal range of different relative strengths of the two dominant processes. However, most inlets average mainly tide or wave-dominated mixed energy types. It is assumed here that the former creates symmetrical inlets and the latter, asymmetric. In the symmetric type the inlet channel is directed almost straight out to sea, with spits that are approximately aligned with each other. Sand bypassing is then by migration of shoals, outer channel shifting or deflection of the littoral sand transport (Fitzgerald et al, 2001). These are likely to be tide-dominated mixed energy inlets. The asymmetric inlets have spits that overlap such that the channel is oblique to the coastline. They are characterised by more frequent channel shifts, and are likely to be more wave-dominated. The sand bypassing mechanisms are then by breaching of the spit or tidal delta.

Table 14. Dyer's Classification of Estuaries in England and Wales

Fjard		Ria		Spit-enclosed			Funnel	Embayment	Tidal inlet	
2a	**2b**	**3a**	**3b**	**4a**	**4b**	**4c**	**5**	**6**	**7a**	**7b**
Pwllheli	Alaw	Wear	Tweed	Coquet	Aln	Cuckmere	Thames	Wash	Pagham H.	Foryd Bay
		Christchurch	Tyne	Wansbeck	Tees	Wootton	Ribble		Chichester H.	Traeth Melynog
		Aberystwyth	Esk	Blyth	Deben	Newtown	Solway		Langstone H.	
		Dovey	Medina	Humber	Hamford Water	Yar			Portsmouth H.	
		Mawddach	Dart	Yare	Colne	Lymington			Afan	
		Glaslyn	Kingsbridge	Waveney	Rother				Artro	
		Traeth Dulas	Avon	Blyth	Bembridge	Axe				
		Conwy	Erme	Ore/Alde	Poole	Otter				
			Yealm	Harwich	West Bay	Parrett				
			Plymouth	Blackwater	Hayle	Neath				
			Looe	Crouch	Taw-Torridge	Tawe				
			Fowey	Medway	Lougher	Nyfer				
			Falmouth	Swale	Carmarthen	Teifi				
			Helford	Stour/Pegwell	Clwyd					
			Gannel	Ouse	Morecambe					
			Camel	Adur	Duddon					
			Severn	Arun	Esk					
			Milford Haven	So'ton Water						
			Cefni	Beaulieu						
			Mersey	Weymouth						
				Exe						
				Teign						
				Ogmore						
				Dysynni						
				Dee						

The degree of stratification within estuaries has also been used to classify these systems. Stratification results from mixing between the tidally pumped seawater and the freshwater flow. The salt-freshwater mixing in an estuary can have a significant effect on the hydrodynamics and therefore is of interest with regard to the net residual transport of sediment.

Measures of circulation and stratification have been derived by Pritchard (1955) using two parameters (Hansen and Rattray, 1965 and 1966). On the basis of these parameters seven estuary types were developed, each representing a different estuarine mixing type. However, this approach was later criticised by Fischer (1979) as it was considered to ignore the effect of lateral mixing. A simpler classification was then suggested based upon:

$$R = \frac{\Delta \rho g Q_f}{\rho W u^3}$$

where __ = difference in density between seawater (__+_) and river water (_);
W = channel width;
Qf = freshwater discharge; and
u = rms tidal velocity.

Observations showed that the transition from a well mixed to a strongly stratified estuary occurs for 0.08 < R < 0.8.

A simpler classification parameter was derived by Schultz and Simmons (reported in Dennis and Spearman, 1993):

$$E = \frac{Q_f T}{V}$$

where T = tidal period; and
V = tidal prism.

The transition from a well mixed to a strongly stratified estuary is judged to be 0.1 < E < 1.

Most UK estuaries are tidally-dominated and well-mixed but some, e.g. Southampton Water, Tamar (the Hamioaze), Mersey (the Narrows) exhibit partially mixed behaviour. For many estuaries the existence of stratification is well documented and the simple Pritchard classification sufficient. Where information is lacking, application of latter parameters (Fischer *et al.*, 1979; Dennis and Spearman, 1993) ought to give an indication of the overall mixing until deployment of salinity profiling can be undertaken. Note, however, that on a habitat by habitat basis considerations of the mixing of seawater and freshwater are not important and the focus should be on the absolute values of salinity experienced.

Roy (1984) considered that most existing estuary classification schemes have focused on geomorphic and/or hydrologic conditions without considering their effect on habitat types and ecology, and very few have included any reference to the evolutionary stage (or maturity) of estuaries which influences both estuarine hydrology and ecology.

The classification system used in the South African National Wetland Inventory (Dini *et al.*, 1998) is very top-level and provides little detail on the physical factors used to support the classification. There are however tentative links to the ecology one could expect in the different classes. The proposed classification is devised for difference wetland systems and sub-systems:

- marine system;
- estuarine system;
- riverine system;
- lacustrine system;
- palustrine system;
- endorheic system; and
- wetland classes.

With respect to estuaries, the following classification (Figure 8) is used:

Definition : consists of tidal wetlands usually semi-enclosed by land but have open, partly obstructed or sporadic access to the open ocean, and in which ocean water is at least occasionally diluted by freshwater runoff from the land.

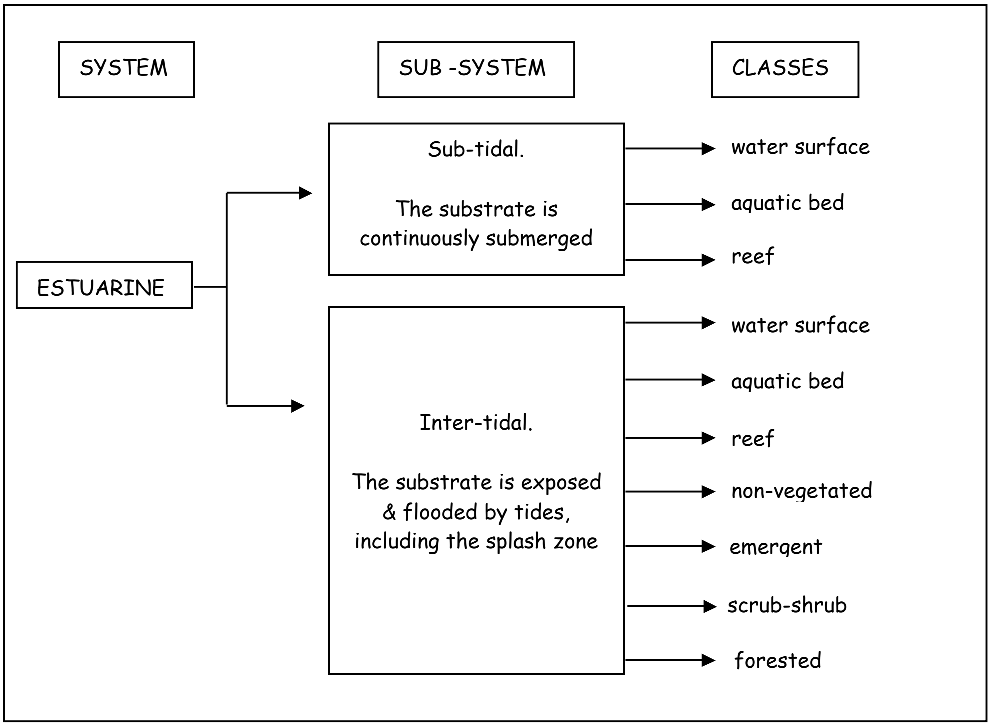
Description : includes both estuaries and lagoons, and is more strongly influenced by its association with land than is the marine system. In terms of wave action, estuaries are generally considered to be low energy systems. Salinity and temperature regimes tend to be highly variable, and salinities may periodically be increased above that of the sea by evaporation. Estuarine systems are often highly turbid and contain distinctive fauna. Features include salt marshes and mud and sand flats.

Boundaries : the system extends:

- upstream and landward to where ocean-derived salinity measures less than 0.5g/l during the annual average low flow;
- downstream, in the absence of salinity data, to an imaginary line closing the mouth of a river, bay or sound;
- to the seaward limit of wetland emergents, trees or shrubs where they are not included within the imaginary line.

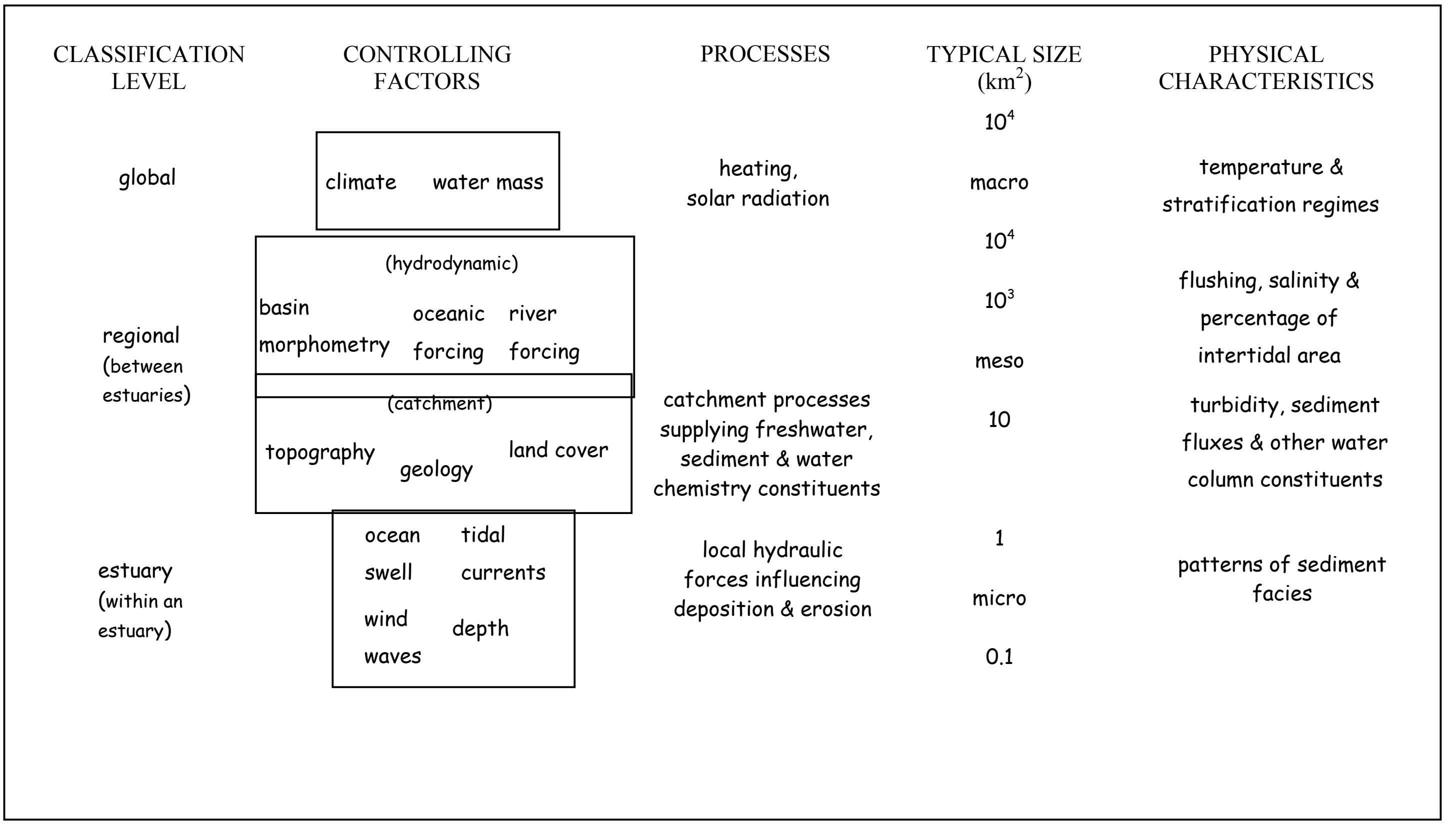
The system also includes offshore areas of continuously diluted sea water.

Figure 8. The estuarine system



A classification system, the ‘Estuary Environment Classification’ has been proposed based upon a hierarchal model describing the physical characteristics of an estuary as a result of related physical processes (Hume et al, 2003). This processes are in turn controlled by factors such as climate change and riverine forcing. The EEC takes an estuary definition of: ‘*a partially enclosed coastal body of water that is either permanently or periodically open to the sea in which the aquatic / ecology environment is affected by the physical and chemical characteristics of both runoff from the land and inflow from the sea’*. The Estuary Environment Classification is demonstrated in Figure 9.

Figure 9. A model describing the Estuary Environment Classification



In further detail:

Global Scale: using the very general classes of climate and water mass. An example is given in Hume et al (2003) of the application of Bailey's 1995 classification which would lead to the division of New Zealand's estuaries into the two region of sub-tropical and sub-Antarctic waters.

Regional Scale: Hydrodynamic Level. This is based upon the assumption that under conditions of a similar climate and oceanic water mass, the differences in physical characteristics within a group of estuaries primarily result from hydrodynamic processes. Eight categories are proposed within this level, as given in Table 15.

Catchment Level: This is based upon the assumption that catchment processes control the freshwater input regime and fluxes of terrestrial sediment and chemical constituents. Three categories are proposed within this level, as given in Table 16. These categories are further divided into a total of eight sub-categories.

Estuary Scale: It is at this scale that estuary systems are further divided into morphological sub-systems. Examples are bays and intertidal areas. These sub-systems are designed to de-lineate patterns within estuaries according to ocean swell, tidal currents, wind waves and depth.

Table 15. Description of categories at the hydrodynamic level of the EEC

HYDRODYNAMIC CATEGORY	GEOMORPHOLOGICAL CATEGORY	DESCRIPTION
A	hapua	Small elongate very shallow basin with constricted entrance to the sea. Occurrence restricted to mixed sands gravel coasts. River dominated hydrodynamics and river volume in a tidal cycle is large compared to the total estuary volume. Tidal influence restricted to backwater effect. Excellent flushing. Salinity close to zero. Entrances bar off for short periods of time when river flow low ad insufficient to flush wave driven littoral sands from the entrance.
B	coastal lake	Very shallow basin. Entrance to sea barred off for most of time because small freshwater inflow is insufficient to flush wave driven littoral sediment from entrance (therefore no tidal influence). Episodic flood events open entrance for short periods. Wind generated 2-D circulation and mixing, and wave suspension of bottom sediments important in the larger systems.
C	fjord	Very deep (>200 m) narrow elongate basins, portioned by shallow sills. Weak tidal pumping and river forcing (river inflow small compared to total volume of basin). Circulation (estuarine) driven by outflowing freshwater and balanced by inflow of seawater entrained beneath freshwater. Some 3D wind driven circulation, however the deep and partitioned nature of the basins means that circulation and flushing is poor at depth. Ocean swell and wind wave unimportant.
D	sound	Deep (20 – 70m) narrow elongate basins. Circulation is driven by out flowing freshwater, balanced by inflow of seawater entrained beneath the freshwater. Strong gradient (head to mouth) in hydrodynamic processes with riverine forcing dominating in the headwaters and tidal forcing near entrance.
E	tidal river	Elongate shallow basin. River dominated circulation and mixing and small tidal influence. Good flushing because river outflow is large relative to estuary volume. Salinity less than seawater and water can be fresh during floods. Wave resuspension is unimportant as fetch is small.
F	coastal embay-ment	Shallow elongate, mostly subtidal, basin. Weak tidally forced circulation. Small freshwater influence. Wide entrance to the sea. No sand bodies at entrance. Ocean swell enters the entrance and can rework the bed.
G	tidal lagoon	Shallow basin of various shapes with extensive intertidal areas. Narrow entrance to the sea. Ebb and flood tidal deltas at mouth. Tidally dominated circulation and mixing. Small river influence compared to the tides. Good flushing because much of the water leaves the estuary on the ebb tide. Mixing good because strong tides and shallowness prohibit density stratification. Salinity close to seawater. Wind-generated 2D circulation and mixing and wave resuspension is important in larger systems where fetch is great and wind is strong.
H	drowned valley	Moderate depth elongate / dendritic basin. Deep tidal channels flanked by shallow intertidal areas. Narrow entrance to the sea. Tidally forced circulation. Moderate freshwater circulation by head and density. Wind wave resuspension of seabed important locally in larger systems where fetch is great and wind is strong.

Table 16. Description of categories at the catchment level of the Estuary Environment Classification

FACTORS	MAPPING CHARACTERISTICS	SUB-CATEGORIES	ASSIGNMENT CRITERIA
topography	Catchment rainfall volume in elevation categories	H (high)	> 50% annual rainfall volume falls above 400m
		L (low)	> 50% annual rainfall volume falls below 400m
geology	Proportion of catchment in hard or soft rock types	H (hard)	soft rocks occupy <25% of catchment area
		S (soft)	soft rocks occupy >25% of catchment area
land cover	Proportion of catchment in natural, pastoral, urban and forestry land cover types	N (natural)	sub-category = the spatial dominant land cover category unless P > 25% of catchment area, in which case sub-category = P, or unless U > 15% of catchment area, in which case sub-category = U
		P (pastoral)	
		U (urban)	
		F (forestry)	

Whilst this Estuary Environment Classification classifies estuaries based upon the physical characteristics as a hierarchy, there is no link given between these and the ecological environments that could be expected associated with the different classifications. However, the classification presented does include many physical characteristics of importance to estuarine behaviour. The classification has been tested in a discrete area in New Zealand, though complete testing is yet to be carried out and the authors state that at present this classification should be viewed as a '*hypothesis about the similarities and differences amongst estuaries until fully tested'*.

Furguson (1996) undertook a review of global classification schemes and made refinements to present an approach more applicable to Australian estuaries and allow a biologically relevant physical classification scheme. This is shown in Table 17. Australian estuaries were also classified into five groups by Eyre (1998), according to their hydrological and meteorological characteristics, as given in Table 18.

Digby *et al*. (1999) also defined a physical classification of Australian estuaries: one that allows for the identification of the variability in specific habitat types, namely mangroves and saltmarsh. The classification was based upon statistical methods.

The system, shown in Figure 10, is based upon a hierarchy of classes:

1. climate;
2. tidal range; and
3. intertidal proportion.

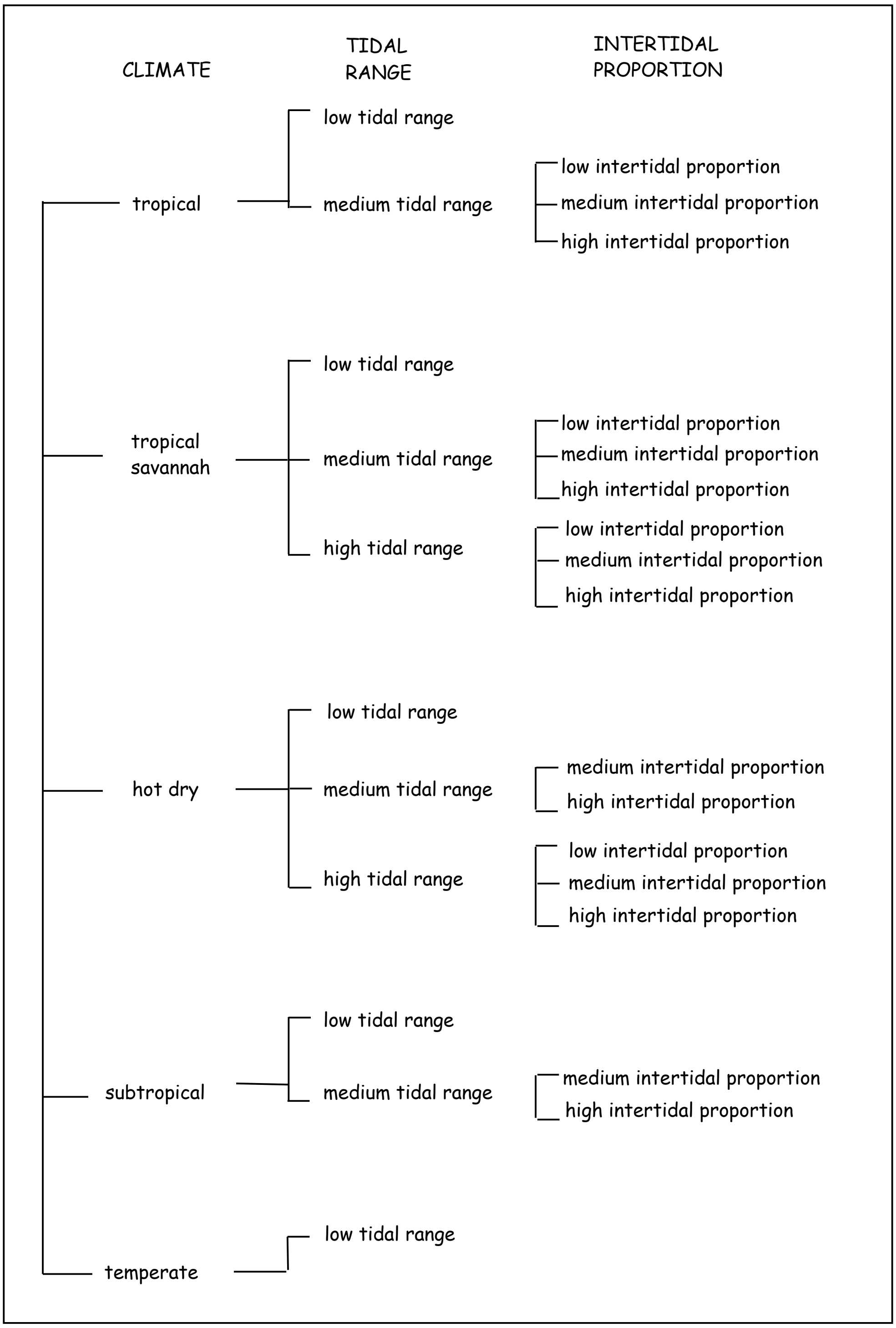
Table 17. Criteria used for the classification of estuaries

CLASSIFICATION TYPE	CRITERIA
Geomorphology	basin morphology / relief catchment geology basin origin sediment dynamics wave climate
Evolutionary stage	stage of infilling channel development
Hydrological processes	freshwater input tide range tidal prism
Climate	annual rainfall runoff evaporation seasonal variation interannual variation
Water quality	suspended sediment dissolved oxygen nutrient status heavy metal pollution bacterial contamination water temperature
Habitat	intertidal communities (mangroves, seagrass etc.) intertidal area substrate types
Land use	degree of disturbance (i.e. pristine vs developed) types of landuse in catchment
Aesthetic	degree of "naturalness" (or disturbance) water quality exotic weed infestations

Table 18. Classification scheme for Australian estuaries

CLASSIFICATION	DESCRIPTION
Mediterranean	those dominated by winter floods and summer drought
Temperate	lack a well defined seasonal variation in flow
Transitional	lack a well defined seasonal variation in flow, but are significantly affected by winter storms
Arid Tropical/Subtropical	evaporation exceeds freshwater input
Wet and Dry Tropical/Subtropical	dominated by summer floods and winter drought

Figure 10. A physical classification of Australian estuaries using first level classifiers of climate and tide, and a second level classifier of intertidal proportion



In order to allow for the sustainable development of the marine aggregate industry in Wales, the Bristol Channel and Severn Estuary has been classified according to the Sedimentary Environments that exist within them (Welsh Assembly Government, 2003). As a consequence of this classification scheme, this estuarine system has been divided into forty-nine Sedimentary Environments. The categories used to define these are given in Table 19.

As a consequence of this classification, each area is further defined. This is achieved using six classes describing the potential for aggregate activities, with respect to sustainable development.

Table 19. Categories used in the determination of the Sedimentary Environments within the Bristol Channel and Severn Estuary

CATEGORY	DESCRIPTION
Geological	Significant geological features that influence the local morphology and sediment regime
Form	local seabed morphology
Sedimentology	Main sediment types
Bedform	Macro-bedform features, in respect to sediment dynamics
Sediment Transport	Sediment behaviour in response to coastal processes
Sediment Volumes	Sediment volumes and resource potential

In addition to the above systems, many authors believe that estuaries world-wide appear to exhibit some consistent relationships between several of the properties that reflect their size and shape (Townend *et al*, 2000). The empirical relationship proposed by O'Brien (1931) is between the spring tidal prism (the volume of water that enters and leaves the estuary during a tide) and the cross-sectional area of the entrance at mean tide level. It is an empirically-derived measure of inlet stability and takes the following form:

$$A = C \_^{n}$$

Where:

A = cross-sectional area of estuary mouth at mean tide level (m^2);
_ = tidal prism (m^3);
C and n = empirical coefficients.

The mean tidal prism can be calculated by subtracting the volume of water in the estuary at mean low water from the volume of water at mean high water.

Application of the relationship demonstrates commonalities for a large number of estuaries, and based upon such empirical findings from a 'group' of estuaries (e.g. perhaps in different geographical regions, or of different estuarine types) it can be used to determine whether the mouth of any particular estuary or its tidal prism are too small or too large compared to the theoretical value.

A study was undertaken as part of the EMPHASYS project to explore the O'Brien relationships for UK estuaries. A full listing of results is presented in ABP Research (2000) and a summary is presented below.

When tidal prism data were plotted against cross-sectional area data for UK estuaries alongside corresponding US, New Zealand and Dutch estuary data, it was apparent that a high degree of scatter and a wide range of scales were observed within the UK data. This reflects a diverse range of estuary systems around the UK coast. A weak sub-division of estuary types was observed, enabling two regional groups to be identified, namely: (i) South-West and South-East Coasts; and (ii) West (including Wales) and East Coasts. The O'Brien relationships for these two groups are:

SW and SE	$A = 0.051\ P^{0.68}$	$r^2 = 0.75$
W and E	$A = 0.003\ P^{0.82}$	$r^2 = 0.78$

Due to the different data sources and data quality used in the assessment, it was recommended that these regression fits be used with great caution.

Further investigation was undertaken to determine whether different O'Brien relationships existed for different estuary types (as classified by Davidson *et al*, 1991). It appeared that a division could be made between different estuaries using the classification in Table 20.

Table 20. Grouping of estuaries based on O'Brien Rule

Group	Type	O'Brien Relationship for UK Estuaries
1	Fjords and fjards	N/A
2	Rias, coastal plain estuaries of the Solent, and selected complex estuaries	$A = 0.0305\ P^{0.747}$
3	All other coastal plain and complex estuaries	$A = 0.0004\ P^{0.911}$
4	Bar-built estuaries	$A = 0.0060\ P^{0.783}$

From the results, it was concluded that Group 2 of the UK data appears to conform to the type of estuary system that has only limited sedimentary influence at the mouth and it is suggested that these estuaries are in an early stage of Holocene development. The complex estuaries that fall into this category were identified to be either deep and wide near the mouth or long narrow channels with little or no inter-tidal. The key attributes of the coastal plain estuaries included in this group is their sheltered location in the Solent. Group 3 is thought to comprise estuaries that have experienced a degree of in-filling with Holocene sediments. Further assessments undertaken during the study revealed no particular influence of isostatic land movement or tidal range on the relationships that existed.

The O'Brien Rule has also been applied to estuaries in the USA, New Zealand and Holland by Townend (2004), with regression relationships of the order of R^2=0.91 to 0.96 (between the cross-sectional area and tidal prism) calculated. It is in the former location that the scatter was concentrated around a single trend line. This rule was applied to UK estuaries where, in comparison with the New Zealand data, the data shows significant scatter. It is suggested that this is due to the variance in estuarine type that exists in both countries, as further supported by the application of Hume and Herdendorf (1993) and Dyer (2002) classifications to UK estuaries. In the paper, the application of the empirical O'Brien Rule to the UK was compared to other estuarine relationships:

- process-based analysis (Kraus, 1998). An equation derived from sediment transport equation has been adapted:

$$A = \left(\frac{\alpha\pi^3 C_k^3 m^2 W_e^{4/3}}{Q_g T^3} \right)^{0.3} P^{0.9}$$

where	$\propto$ and C_k	= empirical coefficients close to unity;
	m	= Mannings coefficient;
	W_e	= width corresponding to the equilibrium area;
	Q_g	= gross alongshore transport; and
	T	= tidal period.

- equilibrium maximum discharge per unit width (Hughes, 2002):

$$A = 0.87 \left\{ \frac{W^{1/9}}{\left[g\left(S_s - 1\right) \right]^{4/9} d^{1/3} T^{8/9}} \right\} P^{8/9}$$

where	S_s	= specific sediment gravity; and
	d	= median grain size diameter.

- surface area and volume relationship (Renger *et al.*, 1974). These are based upon the basin plan areas and the plan area and volume at low water:

$$\frac{S_{lw}}{S_{hw}^{1.5}} = 2.5x10^{-5} \qquad \frac{V_{lw}}{S_{hw}^{2}} = 8x10^{-9}$$

where	S_{lw}	= surface area at low water;
	S_{hw}	= surface area at high water; and
	V_{lw}	= volume at low water.

- asymmetry relationship (Dronkers, 1988):

$$\gamma = \left(\frac{h + a}{h - a} \right)^2 . \frac{S_{lw}}{S_{hw}}$$

where	h	= hydraulic depth; and
	a	= tidal amplitude.

Within EstSim (ABPmer, 2004), the purpose of classifying estuaries was to identify the range of geomorphological elements (such as saltmarshes, flood/ebb channels, etc.) present within each estuarine type (e.g. fjords, rias, tidal inlets, etc.). This provided a starting point for producing behavioural descriptions and systems diagrams of each geomorphic element and taking forwards a systems approach to understanding change in estuaries. Dyer's Futurecoast classification (Defra, 2002) was amended and simplified to provide a working typology with which to progress the study for UK estuaries (Table 21).

Table 21. **Estuary Typology (UK estuaries and associated geomorphological elements)**

Type	Origin	Behavioural type	Spits[1]	Barrier beach	Dune	Delta	Linear banks	Channels[2]	Rock platform	Sand flats	Mud flats	Salt marsh	Cliff	Flood plain	Drainage
1	Glacial valley	Fjord	x	x				X	X	X			X		X
2		Fjard	0/1/2	x				x	x	X	X	X		x	X
3	Drowned river valley	Ria	0/1/2	x				x	X		X	X	X		X
4		Spit enclosed	1/2		X	E/F		X/N		X	X	X	X	X	X
5		Funnel shaped	x		x	E/F	X	X		X	X	X		X	X
6	Marine / fluvial	Embayment			X		X	X		X	X	X		X	
7	Drowned coastal plain	Tidal inlet	1/2	X	X	E/F		X		X	X	X			

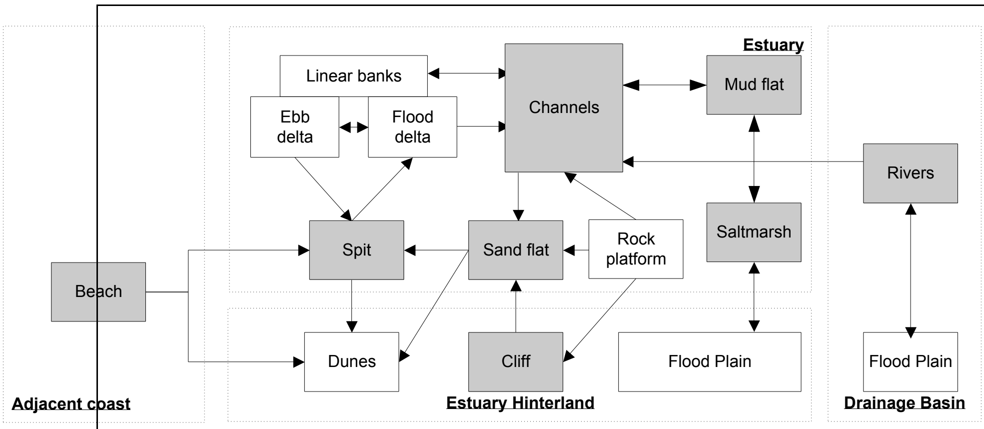
Notes:

[1]Spits: 0/1/2 refers to number of spits; E/F refers to ebb/flood deltas; N refers to no low water channel; X indicates a significant presence

[2]Channels: refers to presence of ebb/flood channels associated with deltas or an estuary subtidal channel.

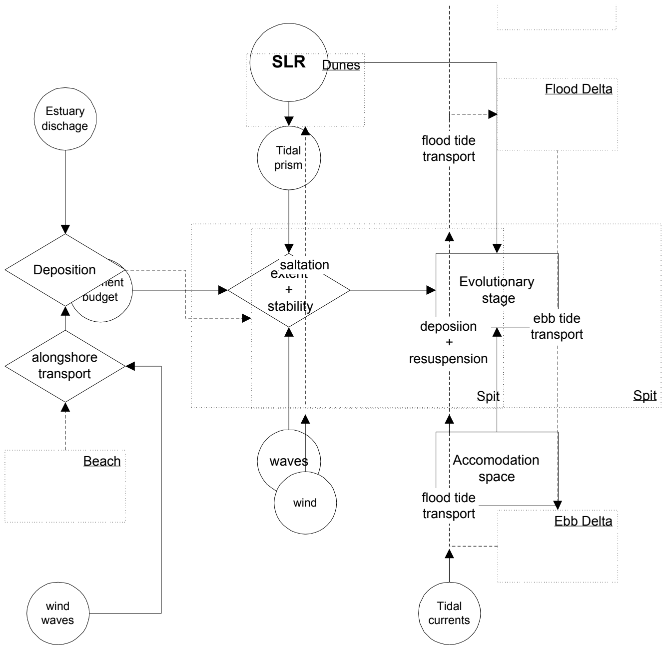
For each of these estuary types a systems diagram was produced to demonstrate the interactions between different geomorphological elements. An example is presented in Figure 11 of a ria, with the boxes highlighted in grey being the elements ‘active’ for this particular type of estuary.

Figure 11. Systems Diagram for a Ria



Rias are drowned valleys located in periglacial areas (that is areas which have been subject to cold climates, but not directly subject to glacial processes), with the original valley being created by fluvial process. Typically, rias are 'v-shaped' in cross-section, with the valley sides being relatively steep and composed of hard rock. In plan form, they exhibit the meandering form that is characteristic of other types of river valleys. Examples of rias with (e.g. Wear) and without (e.g. Tweed, Tyne) spits are common in north-east and south-west England and Wales.

For each geomorphological element a behavioural statement was produced to enable further systems diagrams to be produced. An example for a spit is provided in Figure 12.



SLR
Dunes
Flood Delta
Estuary dischage
Tidal prism
flood tide transport
Deposition
sediment budget
saltation
extent
+
stability
Evolutionary stage
deposiion
+
resuspension
ebb tide transport
alongshore transport
Spit
Spit
Beach
waves
wind
Accomodation space
flood tide transport
Ebb Delta
wind waves
Tidal currents

long term

The difficulties in defining classification schemes that are meaningful can be demonstrated through exemplification of the difficulties in defining even the limits of estuaries. Attempts have been made under the EU Urban Waste-Water Treatment Directive, the EU Habitats and Species Directive, and the EU Water Framework Directive to generically define the limits of an estuary. These efforts have resulted in very ambiguous definitions that allow a wide degree of flexibility in their application.

Elliott and McLusky (2002) published a paper entitled *"The need for definitions in understanding estuaries"*. In a section entitled *"Where does an estuary start and end?"* the authors identified that the limit of tidal rise within an estuary is divisible into three sectors:

- marine or lower estuary, in free connection with the open sea;
- middle estuary, with strong salt and freshwater mixing; and
- upper or fluvial estuary , characterised by freshwater, but subject to strong tidal action.

The authors recognised that the limits between these sectors are variable and subject to constant changes in river discharges and lunar cycles. They additionally made reference to the fact that the seaward limit of an estuary is equally difficult to define, since sub-tidal physical features, such as tidal deltas and linear sandbanks, can extend seaward of the mouth. Consequently, it has been stated that whilst this approach inevitably provokes debate, defining the limit of an estuary is best addressed by an 'expert view' (Elliott and Dewailly, 1995).

In order to provide guidance for those needing to delimit an estuary, whilst still acknowledging the inherent variability of such systems, Elliott and McLusky (2002) produced an 'Expert Judgement Checklist Approach', which contains questions such as:

- *Is there the presence of erosion-deposition cycles in the channels and on the flats?*
- *Is there an asymmetrical flood and ebb tidal flow due to constricting effects and bottom profile of the estuary?*
- *Is there a turbidity maximum zone as found in the upper reaches of most macro-tidal estuaries?*
- *Where does the salinity penetrate on high, medium and low river flows?*
- *Is it possible to differentiate the inter-tidal fauna into marine, transitional and estuarine zones?*

B.3.3 Riverine Classification

Rosgen (1994, 1996) developed a river classification system that was based on:

(i) broad descriptions of major channel types; and
(ii) predominant bed material.

The former category contained consideration of:

- Entrenchment Ratio (E ratio - the vertical containment of a river and the degree to which it is incised in the valley floor) = width of flood plain:surface width of bankfull channel;

- Width/Depth ratio (W/D ratio - a measure of the available energy within a channel) = bankfull surface width:mean depth of bankfull channel;

- Channel sinuosity (S - a measure of the degree of meandering) = channel length:valley length);

- Channel gradient (G - determines channel energy and morphology);

Specific typologies (Aa + to G) were identified as in Table 22.

Table 22 - Rosgen's Classification of Channel Type

Type	General Description	E Ratio	W/D Ratio	S	G	Landform, Soil, Features
Aa+	Very steep, deeply entrenched, debris transport, torrent streams.	<1.4	<12	1.0 to 1.1	>0.1	Very high relief. Erosional, bedrock or depositional features. Vertical steps with deep scour pools; waterfalls.
A	Steep, entrenched, cascading, step/pool morphology. High energy/debris transport associated with depositional soils. Very stable.	<1.4	<12	1.0 to 1.2	0.04 to 0.1	High relief. Erosional or depositional and bedrock forms.
B	Moderately entrenched, moderate gradient, riffle dominated channel with infrequently spaced pools. Very stable plan and profile. Stable banks.	1.4 to 2.2	>12	>1.2	0.02 to 0.039	Moderate relief, narrow, gently sloping valleys. Colluvial deposition.
C	Low gradient, meandering, point-bar, riffle-pool, alluvial channels with broad, well defined flood plains.	>2.2	>12	>1.4	< 0.02	Broad valleys with terraces, alluvial soils
D	Braided channel with longitudinal and transverse bars. Very wide channel with eroding banks.	N/A	>40	N/A	< 0.04	Broad valleys with alluvium, steeper fans. Glacial debris and depositional features. High sediment load.
DA	Multiple channels, narrow and deep with extensive, well vegetated flood plains and associated wetlands. Very gentle relief with highly variable sinuosities and W/D ratios. Very stable banks.	>2.2	Varied	Varied	< 0.005	Broad, low-gradient valleys with fine alluvium and/or lucustrine soils. Very low bedload, high wash load sediment. Well vegetated bars.
E	Low gradient, meandering riffle-pool channel and little deposition. Very stable.	>2.2	<12	>1.5	<0.02	Broad valleys/meadows. Alluvial materials with flood plains. Highly sinuous. Stable, vegetated banks.
F	Entrenched, meandering riffle-pool channel on low gradients.	<1.4	>12	>1.4	<0.02	Entrenched in highly weathered material. Meandering, high bank erosion rates.
G	Entrenched gulley, step-pool morphology on moderate gradients.	<1.4	<12	>1.2	0.02 to 0.039	Gullies. Narrow valleys or deeply incised in alluvial or colluvial materials (i.e. fans or deltas). Unstable, high bank erosion rates.

The predominant bed material was classed as follows:

- Class 1 Bedrock
- Class 2 Boulder
- Class 3 Cobble
- Class 4 Gravel
- Class 5 Sand
- Class 6 Silt/clay

When combined, the resulting classification scheme is relatively comprehensive. Various authors have since used modified versions of Rosgen's classification in their studies. Cooper and Hooke (1998) used it as a means of establishing general guidelines that could be followed by Environment Agency staff in assessing the geomorphological impacts of croys (these are structures placed in river channels with the specific intention of creating scour pools and holding fish for angling purposes). Key impacts ere identified as being:

(i) the creation of hard points within a dynamic system;
(ii) a backwater effect;
(iii) sedimentation upstream;
(iv) bed scour;
(v) downstream sediment deposition of scour material; and
(vi) downstream bank erosion.

Initially, the significance of each of these effects was considered in the context of rivers with high or low sediment loads, gradient (energy) and sediment resistance (and various combinations thereof, e.g. high sediment, high gradient, low resistance). This provided a conceptual framework which was overlain with Rosgen's classification to readily identify:

- those river types where the application of croys would clearly provide a geomorphological/ecological benefit and therefore would be permitted;

- those river types where the application of croys would clearly provide a significant geomorphological/ecological impact and therefore would not be permitted; and

- the considerable 'grey area' in between which was considered something of a paradox. In order for the structures to be effective in achieving their engineered aim, they would necessarily have some adverse geomorphological effect but the scale of that effect required more site-specific assessment.

Brierley (1999), Brierley and Fryirs (2000: 2001) and Fryirs and Brierley (1998; 2000) developed a gemorphologically-derived framework for examining the interactions of biophysical processes in rivers throughout a drainage basin in Australia. Their work was aimed at developing a means by which river management and rehabilitation priorities could be determined in an objective (systematic and rigorous) manner. The approach to considering biophysical processes was based on a geomorphic framework since it was argued that geomorphic processes determine the structure, or physical template, of a river system, impacting directly on habitat availability, viability and aquatic ecosystem functioning.

The framework was loosely based on a modified version of Rosgen's river classification system (1994: 1996), which identifies sediment and hydraulic relationships for each river type, thereby providing a basis to assess ecological interactions. However, a limitation of Rosgen's approach is that it **does not** explain river behaviour or place this within a spatial (e.g. catchment) or temporal (i.e. evolutionary) context. In an attempt to overcome this, Brierley and Fryirs analysed geomorphic behaviour at four inter-lined scales; catchments, landscape units, river styles and geomorphic units. The framework enables 'packages' of genetically associated geomorphic units to be determined for differing river styles. The priorities within the framework are hierarchical, ranging from conservation of remaining near-intact fragments, through working on sections of the catchment with 'high natural recovery potential', to contemplating more difficult tasks. The authors recognised the importance of sediment transfer in targeting effort. For example, stating that it may be pointless to expend effort on fixing a downstream reach if a large sediment slug sits immediately upstream, as the future behaviour of the downstream reach will reflect river responses to the transfer and/or accumulation of those materials.

Key considerations within the framework are:

- considering geomorphic behaviour (including stability and linkages;
- considering system-wide evolution;

hydromorphological aspects

- determination of a physical template of a river of differing positions throughout a catchment;
- provides a basis to determine suitable river structures to support viable habitats.

geomorphic links with river ecology

Eekhout *et al* (1997) recognised the difficulties of classification when attempting to develop a biotic classification scheme for South African rivers. A key challenge was the fact that physical and ecological systems are characterised by indistinct boundaries (i.e. their characteristics vary continuously rather than discretely. Their biotic classification for rivers was ultimate achieved by creating a national database of riverine flora and fauna and the application of cluster analysis (of an hierarchical agglomerative nature using the Bray Curtis similarity index). The spatial units for classification were, somewhat arbitrarily, defined as second-order catchments. The cluster analysis led to the production of a map of biotic regions, enable identification of those regions with similar species composition. It is interesting to note that consideration was given to overlaying these maps with output from independent projects examining regional patterns of flow and water chemistry but this was found to be neither ‘feasible nor desirable’, on the basis that the separate systems provide more information than a composition system would.

The classification that was produced was deemed to group similar systems based on their natural attributes reasonably well and provide sufficient baseline data to determine natural ‘pristine’ conditions (i.e. reference conditions).

Linking more directly to the specific requirements of the Water Framework Directive, Apitz and White (2003) developed a conceptual framework for river-basin-scale sediment management under the auspices of SedNet (European Sediment Research Network, see Brills, 2002). The framework provides a means of considering the sediments within a river basin in terms of their energetic position (from source to sink) and their quality. This enables ‘parcels’ of sediment with high-energy potential and low quality to be identified and managed as a high priority within the context of the WFD since the ecological status of a particular water body is dependent, amongst other things, on sediment quality. Perhaps of most relevance to the present study is a recent report by Entec (2004) on hydrological (rather than hydromorphological) regime methods to support ecological classification of rivers and lakes for the WFD. It provides a hydrological classification method to help identify high status river reaches and outlines possible approaches for lakes. It states that, for a river reach to achieve High Ecological Status, the flow regime must correspond with ‘totally or nearly totally undisturbed conditions’. The work tested the range of possible flow pressure thresholds, as follows:

- zero abstractions, discharges (e.g. sewage treatment works) or impoundments;
- zero abstractions or discharges;
- abstraction and discharge influence <1% of Qn95;
- abstraction and discharge influence <5% of Qn95
- abstraction and discharge influence <10% of Qn95
- abstraction and discharge influence <15% of Qn95
- abstraction and discharge influence <20% of Qn95

Where Qn95 is the natural 95th percentile flow.

Two methods of calculating flow pressure were considered:

(i) total influence (total magnitude of abstractions added to discharge); and
(ii) net influence (net magnitude of abstractions and discharges, with discharges cancelling out abstractions.

It was recommended that 'total influence' should be used in the assessments and that the threshold of total influence less than 1% of Qn95 be used for the definition of hydrological candidate high status river water bodies (i.e. 'nearly totally undisturbed conditions'). However, Entec also recommends that biological metrics be used as the starting point for high status classification and the hydrodmorphologic element (and physico-chemical element) be used to confirm the boundary between high and good status (or high, good and moderate in the case of physico-chemical) – see Figure 13.

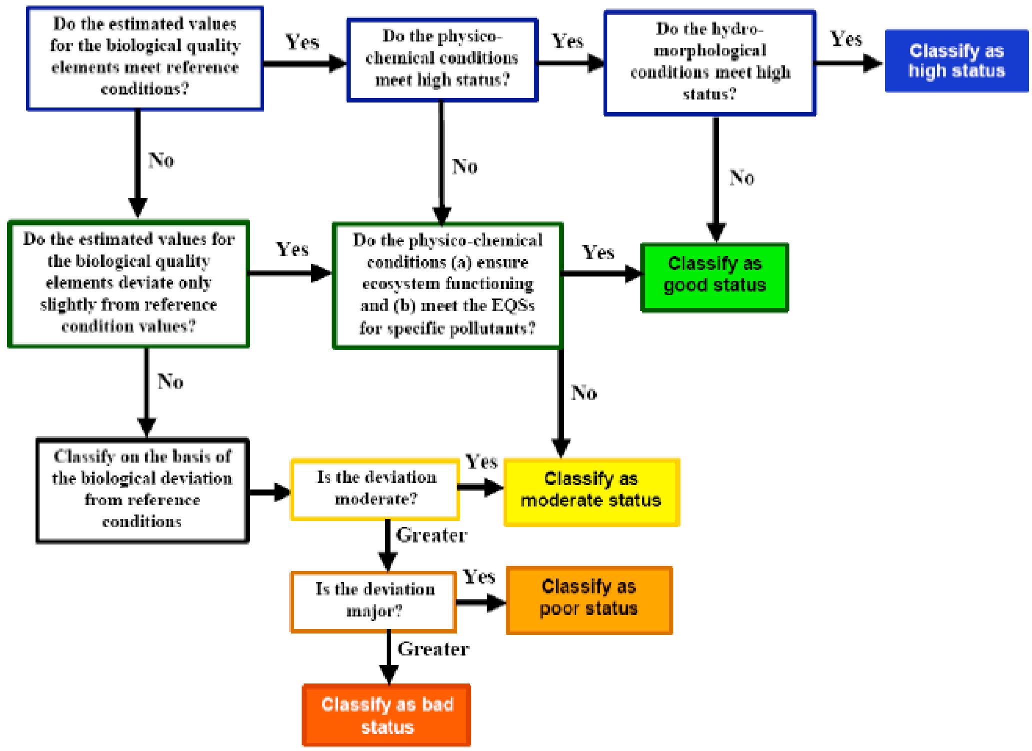


Figure 13. **Indication of the relative roles of quality elements in the classification of ecological status**

Under the approach proposed, no direct assessment of hydrological regime (or morphological pressures) is required to determine the good/moderate ecological status boundary.

Specifically for lakes (the definition of which includes both natural and artificial lakes), a three-step process was proposed:

1. Eliminate potential HMWB and AWB (i.e. reservoirs);
2. Eliminate lakes based on the presence of significant abstraction, discharge or flow regulation pressures according to similar criteria proposed for rivers; and
3. Undertake detailed site-specific hydromorphological investigation and ecological impact assessments to determine suitability for high status designation.

Appendix C

Work Package 2: Methods for Developing Draft Reference Conditions

1. Aims and Objectives of Work Package

The aim of Work Package 2 is to derive a set of draft hydromorphological reference conditions for a representative subset of UK coastal and transitional water body types.

Tables 1.2.3 and 1.2.4 of WFD Annex V set out definitions for high, good and moderate ecological status in Transitional and Coastal Waters respectively. These definitions include statements in relation to the tidal regime and morphological conditions (reproduced as Tables 1 and 2 below). Sections 1.1.3 and 1.1.4 of WFD Annex V also make reference to wave exposure as quality elements that can be applied to the classification of transitional and coastal waters. Discussions with the Project Board have indicated that derivation of reference conditions should be based on these parameters and that, if feasible, references conditions for the tidal regime and morphological conditions should be described separately.

Table 1. Hydromorphological quality elements- Transitional Waters (Annex V, Table 1.2.3)

Element	High status	Good status	Moderate status
Tidal regime	The freshwater flow regime corresponds totally or nearly totally to undisturbed conditions.	Conditions consistent with the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.
Morphological Conditions	Depth variations, substrate conditions, and both the structure and condition of the intertidal zones correspond totally or nearly totally to undisturbed conditions.	Conditions consistent with the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.

Table 2. Hydromorphological quality elements- Coastal Waters (Annex V, Table 1.2.4)

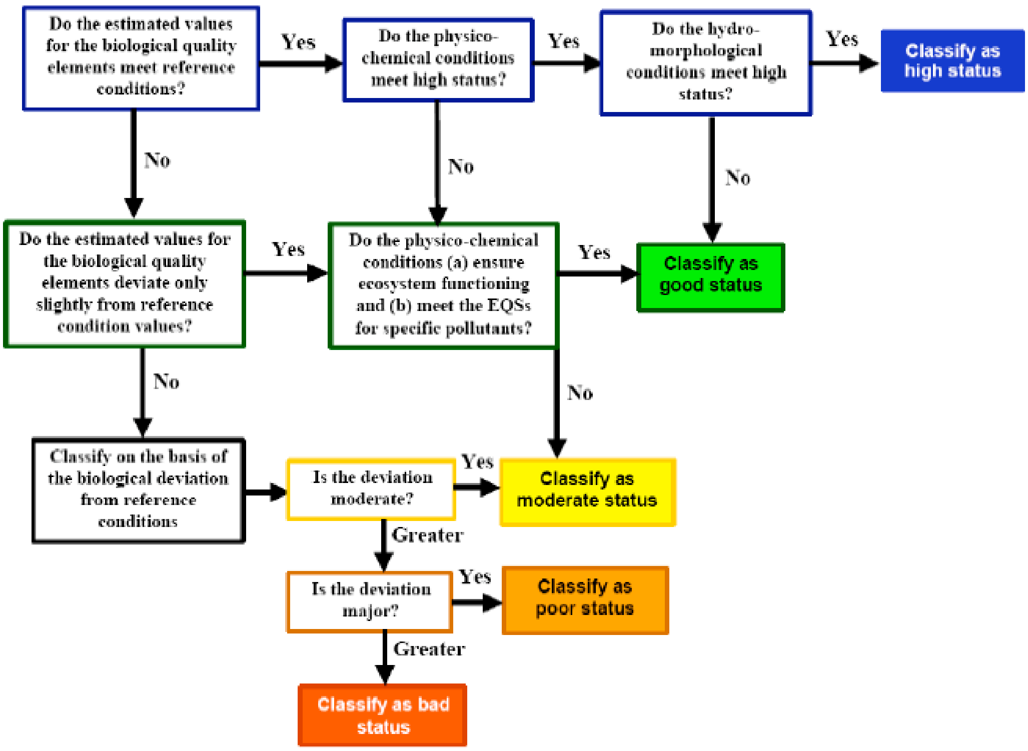
Element	High status	Good status	Moderate status
Tidal regime	The freshwater flow regime and the direction and speed of dominant currents correspond totally or nearly totally to undisturbed conditions.	Conditions consistent with the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.
Morphological Conditions	The depth variation, structure and substrate of the coastal bed, and both the structure and condition of the inter-tidal zones correspond totally or nearly totally to the undisturbed conditions.	Conditions consistent with the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.

ECOSTAT (2003) has produced guidance on the overall approach to be adopted to the classification of ecological status. This guidance provides an explanation of the role of hydromorphological conditions as a supporting element to the classification of ecological status. Paragraph 2.5 of this guidance states:

"The values of the hydromorphological quality elements must be taken into account when assigning water bodies to the high ecological status class and the maximum ecological potential class. For the other status/potential classes, the hydromorphological elements are required to have "conditions consistent with the achievement of the values specified [in Tables 1.2.1 to 1.2.5] for the biological quality elements". Therefore the assignment of water bodies to the good, moderate, poor or bad ecological status/potential classes may be made on the basis of the monitoring results for the biological quality elements and also, in the case of good ecological status/potential, the physico-chemical quality elements. This is because if the biological quality element values relate to good, moderate, poor or bad status/potential are achieved, then by definition the condition of the hydromorphologiocal quality elements must be consistent with that achievement and would not affect the classification of ecological status potential."

A summary of the proposed process of classification is provided below:

Figure 1: Indication of the relative roles of biological, hydromorphological and physico-chemical quality elements in the ecological status classification (from ECOSTAT, 2003)



2. Methods

To achieve the aim of this work package, the project team have been involved in a variety of research-based activities. These are listed below:

- Brain-storming sessions amongst project team members to develop ideas and outline different approaches to identifying reference conditions
- Preliminary testing of concepts and suggestions for alternative approaches

We consider that there is an inherent tautology in paragraph 2.5 of the ECOSTAT guidance on ecological status classification. We accept that it could be possible to determine high status for tidal regime and morphological conditions using the relevant parameters identified in Annex V as suggested. For other status classes, the requirement is to demonstrate "hydromorphological conditions consistent with the achievement of the values specified for the biological quality elements". The text suggests that monitoring of the biological quality elements will provide sufficient basis for assigning water bodies to good/moderate etc classes. However, this can only be the case if the biological quality element classifications already include some quantification of the deviation from reference conditions that can be attributed to hydromorphological impacts. This can only work if (a) the relationship between hydromorphological quality elements and biological quality elements is understood and (b) cut-offs have been determined relating to GES, MES etc. Neither of these constraints have been identified or addressed in the guidance. We therefore do not consider that paragraph 2.5 provides a logical basis on which to proceed.

Indeed, while the Directive presents hydromorphological elements as supporting the biological elements, from a scientific perspective the hydromorphological elements comprise a fundamental component of overall ecological quality. As identified in the basic conceptual model developed under package 1, at broad spatial and temporal scales, hydromorphological factors govern the type and spatial extent of broad habitat types occurring within a water body. Human physical pressures can result in alterations to habitat types and distributions within a water body. Other human pressures e.g. point source or diffuse pollutants will generally affect the quality of the habitats and associated species assemblages that occur within a water body, but will generally not affect the distribution of habitats, except under conditions of gross pollution. Thus, any assessment of overall ecological status will need to include an understanding of the spatial distribution and extent of different ecological resources and some measure of the quality of these resources.

We therefore consider that any system of ecological status classification that is seeking to address hydromorphological factors will need to incorporate information on the nature and extent of occurrence of broad habitat types within water bodies and to derive quantitative relationships that can be used to define class boundaries. To date the biological classification schemes have primarily focused on developing measures for assessing the quality of biological elements at representative points within a water body. Our analysis suggests that these measures need to be supplemented by a broader quantification of the type and extent of habitats within a water body. This has provided the focuses for the lines of research pursued under work package 2.

The limited range of parameters identified as hydromorphological quality elements in Annex V and the differentiation between tidal regime and morphological conditions also raise potentially significant issues for hydromorphological classification. The literature review and conceptual model illustrating the linkages between hydromorphological elements and biological quality elements have identified the complexities of these relationships. In particular, interactions between the driving forces (such as the tidal regime) and morphological conditions (such as substrate) are very important in governing the distribution of habitats and associated biological quality elements. Although yet to be tested, this strongly suggests that the ability of tidal regime or morphological condition parameters to provide a basis for ecologically relevant classification will on their own be limited and that a better fit is likely to be obtained from a classification that integrates all the relevant drivers.

The initial research being undertaken essentially adopts an integrated approach to defining relationships between hydromorphology and ecology. It may be possible in a further stage of development to separately test the strength of relationships with tidal regime and morphological conditions. The present research is based on parameters used in existing physical and ecological data sets, but it is likely that requirements for additional parameters will be identified through the research process.

3. Key Findings

The work undertaken to date has revealed the following three approaches as potentially feasible ways forward. However, these approaches need to be further discussed and developed at the forthcoming project Workshop on 7th and 8th December 2004:

- A predictive approach to identify reference conditions through the coupling of hydromorphological and ecological elements;

- An ecological modelling approach to predict habitat type and infaunal invertebrate distributions on the basis of hydrological and morphological process parameters derived from numerical models; and

- An approach to identify reference conditions through the coupling of observed hydromorphological and ecological elements.

Further detail relating to each possible approach is provided below, with initial outcomes to be presented at the Workshop.

3.1 A predictive approach to identify reference conditions through the coupling of hydromorphological and ecological elements

The approach aims to identify reference conditions through the spatial delineation of ecologically relevant elements on the basis of their close association with the abiotic environment. By quantifying the spatial extent of these ecological elements within water bodies that are subjected to low or no human pressure, it should be possible to use this information to identify criteria for defining reference conditions. The approach is centred on using the UK Marine Habitat Classification (JNCC, 2003), which incorporates the EUNIS classification system.

3.1.1 Using the EUNIS classification

EUNIS has already been adopted in the first draft of UKTAG's guidance on type reference conditions[1] where biological quality elements are described qualitatively. The report provides generalised ecological descriptions for different reference conditions using components of EUNIS. For example, macroalgae reference conditions on the coastal waters of Cornwall, Devon and Somerset are described in terms of the EUNIS biotope classification Littoral Rock (LR).

There are a number of advantages to using the EUNIS classification.

- Biotopes are considered relevant to defining ecologically relevant hydromorphological reference conditions.
- Biotopes are defined at different levels of detail e.g. Level 2: LR (Littoral rock), Level 3: LR.HLR (High energy littoral rock), Level 4: LR.HLR.MusB (Mussel and/or barnacle communities), increasing the likelihood of linking a particular level to a suite if abiotic variables.
- Biotopes are characterised on the basis of their association with the abiotic environment e.g. salinity % (full, variable and reduced), wave % (ranging from exposed to sheltered), which will provide the link to mapping their spatial extent.

Information on EUNIS biotopes are summarised in a matrix, which lists each biotope against nine different abiotic criteria. The characterisation of each biotope based on abiotic features was achieved through a combination of cluster analysis and ordination techniques (namely, TWINSPAN, DECORANA and PRIMER). The analytical process is described in Mills (1994). Consequently, the matrix provides a degree of certainty over the feasibility of applying the biotope classification across a range of different geographical regions covered by the coastal and transitional water bodies of the UK.

[1] UK TAG on the water framework directive: type specific reference condition descriptions for transitional and coastal waters for the UK, 2004 WP8a(03)

Table 3. The framework for the habitat classification and the primary matrix for EUNIS levels 2 and 3.

	SUBSTRATUM	ROCK				SEDIMENT					
		High energy rock [H*R]	**Moderate energy rock** [M*R]	**Low energy rock** [L*R]	**Features on rock** [F*R]	**Coarse sediment** [CS]	**Sand** [Sa]	**Mud** [Mu]	**Mixed sediment** [Mx]	**Macrophyte-dominated sediment** [Mp]	**Biogenic reefs** [BR]
	ZONE	(wave exposed or very tide-swept)	(moderately wave-exposed or tide-swept)	(wave sheltered and weak tidal currents)	(rockpools, caves)	Mobile cobble & pebble, gravel, coarse sand	Clean sands & non-cohesive muddy sands	Cohesive sandy muds & muds	Heterogeneous mixtures of gravel, sand & mud		
LITTORAL	**LITTORAL** [L] (splash zone, strandline & intertidal)	High energy littoral rock [HLR]	Moderate energy littoral rock [MLR]	Low energy littoral rock [LLR]	Features on littoral rock [FLR]	Littoral coarse sediment [LCS]	Littoral sand [LSa]	Littoral mud [LMu]	Littoral mixed sediment [LMx]	Littoral macrophyte-dominated sediment [LMp]	
SUBLITTORAL [S]	**INFRA-LITTORAL** [I] (shallow subtidal)	High energy infralittoral rock [HIR]	Moderate energy infralittoral rock [MIR]	Low energy infralittoral rock [LIR]	Features on infralittoral rock [FIR]	Sublittoral coarse sediment [SCS]	Sublittoral sand [SSa]	Sublittoral mud [SMu]	Sublittoral mixed sediment [SMx]	Sublittoral macrophyte-dominated sediment [SMp]	Sublittoral biogenic reefs [SBR]
	CIRCA-LITTORAL [C] (nearshore deeper and offshore subtidal)	High energy circalittoral rock [HCR]	Moderate energy circalittoral rock [MCR]	Low energy circalittoral rock [LCR]	Features on circalittoral rock [FCR]						

It is proposed that EUNIS biotope level 3 will be the default (Table 3), although more detailed levels may be included if stronger links with the abiotic environment can be made. It is anticipated that levels 2-3 (of which there are 16 different types in total) provides sufficient detail to define reference conditions.

3.1.2 *Using the TYPOLOGY dataset and GIS*

The proposed approach is top-down and therefore suitable for predicting the broad-scale ecological elements such as that described by EUNIS. To map the spatial extent of the EUNIS biotopes, it has been decided that the TYPOLOGY abiotic dataset held by CEFAS would be an appropriate option. There are a number of abiotic variables (e.g. salinity, depth, substrate, exposure, etc.) that closely match the nature and the form of variables used in EUNIS. Since, TYPOLOGY has already developed a GIS capability to map this suite of abiotic variables (to a resolution of 0.1 nm), it should be possible to link these variables to EUNIS biotopes and in turn map their extent based on the strength of this linkage.

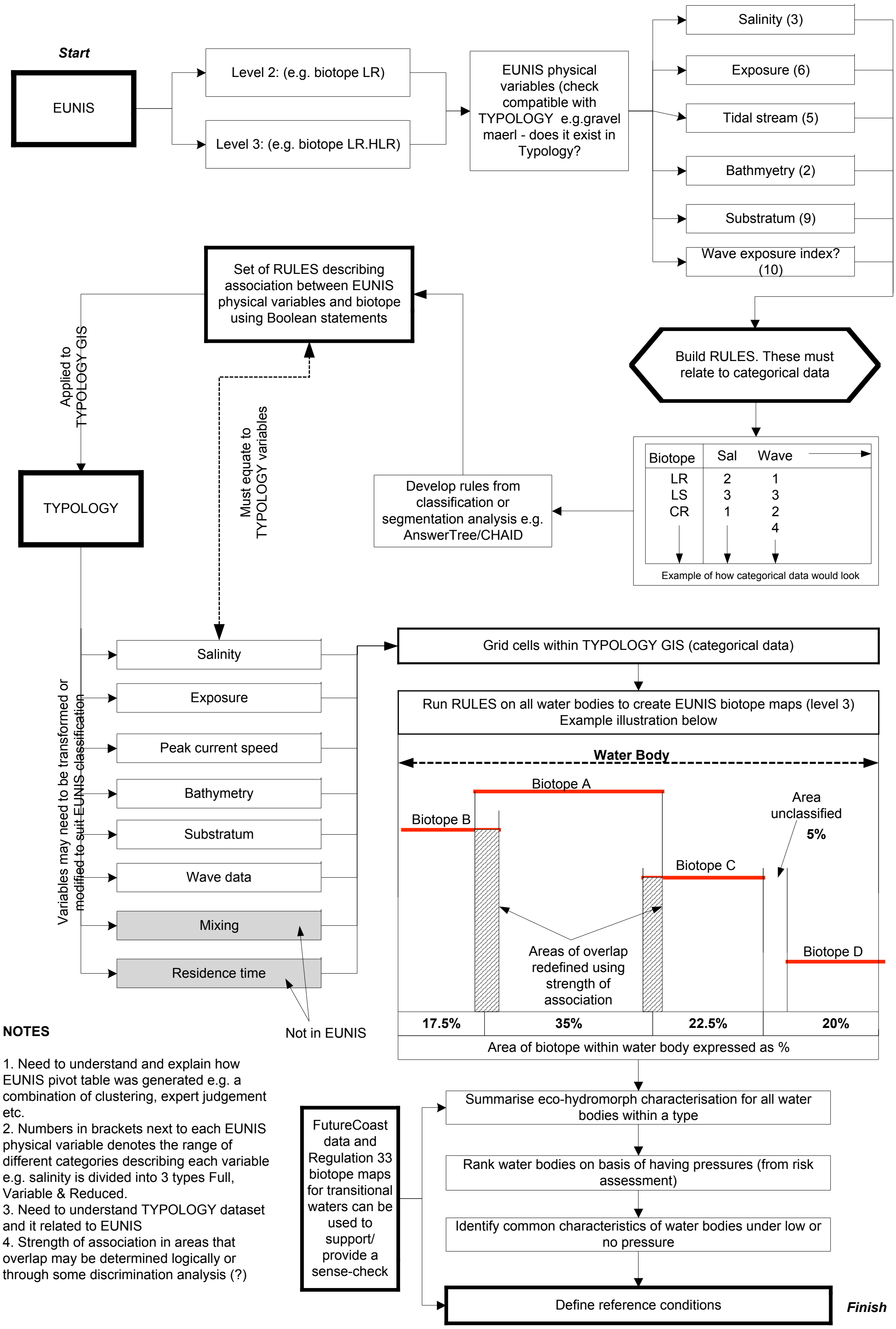
Given the limited timeframe of the project and the investment needed to start a new search for alternative sources of data, the TYPOLOGY dataset is considered by far the most advantageous.

It is envisaged that the abiotic characterisation of EUNIS biotope level 3 will be compatible to those abiotic variables held in the TYPOLOGY GIS. However, there is not a direct match with all the abiotic variables held within the two datasets and some form of manipulation or transformation is required. It is suggested that modifying data into categorical values could overcome this potential limitation e.g. salinity criteria in EUNIS is divided into 4 types (Full: 30-40^{o}/oo, Variable: 18-40 ^{o}/oo, Reduced: 18-30 ^{o}/oo, and Low: <18 ^{o}/oo) where in the TYPOLOGY it is divided into 5 types (Euhaline 30-<40^{o}/oo, Polyhaline 18-<30 ^{o}/oo, Mesohaline 5-<18^{o}/oo, Oligohaline 0.5-<5^{o}/oo and Freshwater <0.5^{o}/oo). These can be re-worked into similar ‘bins’ to EUNIS by combining mesohaline and oligohaline, thus ending up with 4 categories.

3.1.3 *Overview and methodology*

A schematic diagram summarising the approach is presented in Figure 1. The approach will use the EUNIS matrix to develop a set of ‘rules’ that best characterise EUNIS biotopes in ‘abiotic’ terms. This will be done using a classification system developed by AnswerTree software. Here, a set of decision rules that predict or classify the spatial distribution of EUNIS biotopes will be developed. Ultimately, a decision tree will be used to help illustrate these rules and determine more precisely the strength of the association between biotopes and their characteristic abiotic variables. Where rules are less clearly defined, it should still be possible to refine them based on expert judgment (or supported by the literature review).

Figure 1 Schematic diagram of the proposed coupling of hydromorphological and ecological elements



NOTES

1. Need to understand and explain how EUNIS pivot table was generated e.g. a combination of clustering, expert judgement etc.
2. Numbers in brackets next to each EUNIS physical variable denotes the range of different categories describing each variable e.g. salinity is divided into 3 types Full, Variable & Reduced.
3. Need to understand TYPOLOGY dataset and it related to EUNIS
4. Strength of association in areas that overlap may be determined logically or through some discrimination analysis (?)

Since, a range of abiotic variables are captured in the TYPOLOGY database, it should be possible to use the ‘rules’ to predict the distribution of EUNIS biotope using Boolean statements. For each water body, discrete EUNIS biotope maps will be produced and then overlain on top of each other to provide full spatial coverage. Where overlaps between these maps occur, it should also be possible to refine the delineation based on the EUNIS matrix, which provides an indication of ‘confidence’ e.g. 86% of biotope X at EUNIS level 2 is known to occur under abiotic conditions Y, and so on. Alternatively, expert judgment will be used. Validation of outcomes could be derived from other source of data such as conservation datasets and ‘sense-checked’ by the project team and its workshop partners.

The methodology requires some more development of how precisely the rules and predictions will be developed. It should be noted that the project team consider saltmarsh habitats to be less effectively addressed in the present reference condition classifications. There is no specific biotope reference to saltmarsh in the EUNIS matrix and hence will have to be assessed in another format. More work is needed to resolve this aspect. For example, it would be possible to use generalised rules (e.g. Gray et al., 1995) to predict saltmarsh extent if data on MHWN & MHWS tidal elevation were available.

3.2 Ecological Modelling

ABPmer has developed a number of spatial ecological models which predicts habitat type and infaunal invertebrate distributions on the basis of hydrological and morphological process parameters derived from numerical models (ABPmer, 2003a,b; ABPmer, 2004; Frost *et al*, 2004). To date these models have been developed for the Humber Estuary to make predictions about habitats and species over a 50-year period as a contribution to the development of the Humber SMP, but they could also be used to make predictions about antecedent conditions.

The approach is based on the integration of hydrodynamic models with information on the sediment distribution and abundance of ecological resources (saltmarsh, intertidal mudflat/sandflat, intertidal invertebrates) through the development of regression and rule-based models that link physical and ecological parameters.

The following summary will provide an overview of the models developed to date and how they can be adapted to meet the requirements of this project. For a full description of the case studies described below see ABPmer, 2003a,b. The steps required in each of these models is also summarised in Figures 2 & 3.

3.2.1. Hydrodynamic model

A 3D hydrodynamic model developed by ABPmer and WL|Delft Hydraulics (ABPmer and WL|Delft Hydraulics, 2002) was used to simulate the hydrodynamic conditions of the Humber estuary. This allowed the determination of physical parameters (in this case salinity, current speed, friction, elevation and water level) in a series of grid cells (Figure 4).

Since elevation is an important parameter in determining the distribution of habitats and invertebrates within the intertidal zone, the model grid cells were refined to a greater resolution (10m x 10m) using data from the remote sensing system Light Detection and Ranging (LiDAR). By coupling the hydrodynamic model with data from LiDAR, it was possible to predict changes in each of the physical parameters, including water levels, for each individual grid cell. The hydrodynamic model was also used to predict physical conditions on the estuary under a future scenario where the underlying morphology / bathymetry of the estuary is changed. In this scenario, the model outputs were based on a bathymetry for 2050 simulated from a predictive morphological model of the Humber estuary using ESTMORPH (Wang & Jueken, 2003).

3.2.2. Predicting Invertebrate Distributions

The Humber Estuary was first divided into three broad scale assemblages, each characterised by a suite of intertidal species. This was done based on historic data collected by the Environment Agency (EA) which was also used to demonstrate the stability of these patches through time. A detailed sampling programme, targeted within each of the assemblages, was conducted in October 2000 to supplement this information. In each of the three assemblages, sampling stations were located across a range of elevations, with the exact co-ordinates of each station recorded. To obtain the physical characteristics for each of the sample stations, data relating precisely to the co-ordinates collected for each station was extracted from the hydrodynamic model and the LiDAR grid layer using ArcView.

To investigate the strength of the association between the biotic and abiotic parameters the computer learning system AnswerTree™ was used (SPSS, 1998). As an exploratory analysis tool, AnswerTree™ creates classifications displayed in a decision tree by attempting to relate predictive attributes (e.g. likelihood of an invertebrate occurring) to values from continuous variables. A classification and regression tree algorithm, was used to create a number of decision trees. The resulting trees provided a means of representing hierarchical structure in the data (Figure 5). The structure forms the basis for a set of ‘rules’ from which predictions about the distribution of benthic invertebrates can be made.

Rules were developed for six intertidal species, where the relative abundance of each species was considered indicative of each assemblage type identified on the Humber Estuary. The rules for predicting the distribution of each invertebrate species were applied to the entire intertidal sections of the model grid. A spatial map representing relatively high, medium and low abundance levels for each species was then produced. Assemblages were inferred from the overlaying of the distribution maps of the six macrobenthic invertebrates. The rules were validated by comparing the predicted distribution maps with observed data collected by the Environment Agency and ABPmer (unpublished data). Outputs from this process can be viewed in Figures 6 & 7. The rules were also applied to the predicted bathymetry and hydrodynamic model outputs under the 2050 scenario (Figures 6 & 7).

3.2.3. Predicting habitat distributions

The prediction of habitat types in the intertidal zone of the Humber Estuary included mudflats, reedbeds, saltmarsh and transitional grassland. The rules developed for predicting the distribution of each of these habitat types were based on previous and now well established investigations.

Studies conducted by the Institute of Terrestrial Ecology (ITE) now Centre for Ecology and Hydrology (CEH), developed regression equations relating the lower limit of *Spartina anglica* to simple tidal parameters and environmental characteristics (Gray *et al* 1989, 1995; Clarke & Brown, 2002). The lower limit of saltmarsh is taken to be the lower limit of *S. anglica*, as this species can occur further down saltmarsh than any other plant species. The physical parameters investigated included:

- Tidal parameters
  - Relation to MHWN
- Environmental parameters:
  - Area = total surface area of the estuary in km^2
  - Latitude = Latitude (in decimal degrees)
  - Fetch (FetTRAN) = distance (in km) across open water from the point of origin of the transect in the direction of the bearing transect (subject to a maximum of 10km).
  - Estuariness (ESTNESS) = Distance of the transect from the upstream tidal limit expressed as a proportion of the total distance between the upstream tidal limit of the estuary mouth.

The CEH models were developed using data from the south and west coasts of the UK. ABPmer commissioned CEH to use these equations to derive predictions for the lower limit of saltmarsh within the Humber Estuary (Clarke & Brown, 2002). The best fit for the data was obtained from the very simple model (Equation 1) using just MHWN. This equation was therefore used to predict the lower limits of saltmarsh distribution throughout the Humber Estuary.

Lower limit of *S. anglica* = -0.76 + 1.56 MHWN (Equation 1)

Similarly the upper limit of saltmarsh was estimated via an equation developed by Binnie Black & Veatch (2000) in their habitat migration study. The upper limit of saltmarsh has been defined as:

Upper limit of Saltmarsh = MHWS + 0.3m (Equation 2)

The relationships between salinity distribution and the distribution of *Phragmites* stands was also investigated. This, allowed the distinction between the likely areas of saltmarsh and *Phragmites* on the Humber Estuary. The distribution of *Phragmites* is difficult to predict in relation to any one physical factor, it is, however, related to fluctuations in salinity. *Phragmites* typically tolerates salinities between 2-12ppt (Hellings and Gallagher, 1992), and this was used as a guide in the current study where model grid cells with salinities below 12ppt were considered to potentially contain *Phragmites*. The lower limit of *Phragmites* has been estimated as Equation 3 (Binnie Black & Veatch, 2000) The upper limit of reedbeds was taken as the upper limit of intertidal.

Lower limit of *Phragmites* = MHWS - 0.1 (Equation 3)

The remaining intertidal areas, below the estimated lower limit of the saltmarsh and reedbed habitat, were classified as mudflat. These habitat types were mapped in the GIS package ArcView and the approximate area of each was calculated (Figure 8). All outputs have been verified visually by comparing their distribution patterns to those actually recorded in the Humber estuary by Binnie Black & Veatch (2000) and English Nature (2003). As with the invertebrate model the predictive rules have also been run on the bathymetry and hydrodynamic conditions of 2050 (Figure 9) and comparisons made between these two scenarios (Figure 10).

3.2.4. Application to this project

The generality of this approach is currently being tested for different estuarine systems. The models can be used to make predictions for areas undergoing natural and/ or anthropogenic change. While the approach has so far been used to make predictions under future scenarios there is no reason why it cannot be applied to antecedent conditions. For example, the habitat model is currently being run on two scenarios, with and without the existing Humber flood defences to provide a prediction of habitat distribution or extent that may have been present before human intervention occurred. This will provide a worked case study of how the ecological modelling approach can be used to assess human pressures on water bodies.

3.2.5. Limitations of this approach

This approach provides broadscale indicative maps of species and habitat distributions. The overall estimates of extent and distribution patterns for each of the habitat types and invertebrate assemblages were comparable to data collected in the field and previous studies. The rules that have been developed are, however, generic and do not take into account localised or site specific issues. The outputs are also dependent on the accuracy of the hydrodynamic model and LiDAR data which have their own inherent constraints. This approach is very data intensive as it requires extensive data for the hydrodynamic and morphological type models as well as sufficient biological information. When looking at current conditions the habitat model is, however, less dependent on having a full hydrodynamic model providing adequate tide gauge information is available for an area.

3.3 Defining reference conditions using observed data

A third possible approach relies on existing habitat maps that are contained within Regulation 33 Advice packages or other spatial plans. It is a requirement of Regulation 33(2) of the Conservation (Natural Habitats &c.) Regulations 1994 that the appropriate nature conservation body provides documentation to advise relevant authorities as to the conservation objectives for European Marine Sites along with any operations which may cause deterioration of natural habitats or the habitats of species, or disturbance of species for which sites might have been designated.

A Regulation 33 Advice document has therefore been, or is being, produced for all European Marine sites around the UK. Within many Regulation 33 Advice packages, maps are provided showing the distribution of all the features of interest (Figure 11). It is therefore possible to estimate the relative proportion of each habitat feature within each of the European Marine Sites. The habitat maps, where available digitally, can be directly overlaid onto a corresponding map of the relevant UK water body. From these maps it would be possible to derive relative habitat areas for those water bodies for which maps exist. One obvious limitation of this approach is that not all water bodies will have overlapping habitat maps. In addition the boundaries of these designated sites may be different from some water body boundaries. The habitat maps contained within the Regulation 33 packages are also incomplete in their coverage and contain areas which are unclassified in terms of their habitat type. A possible solution to overcome this problem would be to express the relative habitat areas as a proportion of the classified area. Water bodies within a type could then be ranked in relation to extent of human pressures based on the risk assessment (Environment Agency, 2004). Reference conditions could be defined on the basis of common characteristics of water bodies subjected to no or low human pressure.

Appendix D

Work Package 3: Workshop

1. Aims and Objectives of Work Package

The aim of Work Package 3 was to organise and run a workshop involving the Project Board, key members of the Project Team, and individuals with expertise in the fields of transitional and coastal waters. Its objectives were to review the work that has been undertaken to date on Work Packages 1 and 2 of the study, and consider issues surrounding the development of hydromorphological reference conditions and hydromorphological classification schemes in order to identify potential ways forward with subsequent work packages.

2. Methods

To achieve the aims and objectives stated above, a suitable workshop location (HR Wallingford), date (7th-8th December 2004) and structured workshop agenda was agreed between the Project Board and Project Team (see Annex A). A range of recognised experts in the fields of hydromorphology and ecology were identified and invited to attend. The workshop was managed and run by various members of the Project Board and Project Team.

3. Workshop Summary

The following individuals attended the Workshop:

Project Board:

- Andrew Richman - Environment Agency
- Roger Proudfoot - Environment Agency
- Dave Jowett – Environment Agency
- Gina Martin – SNIFFER (7th December only)
- Jane Rawson – Environment Agency
- Larissa Naylor – Environment Agency
- Chris Vivian – CEFAS
- James Mckie - FRS Marine Lab
- Mark Charlesworth – Environment and Heritage Service
- Alison Miles – Environment Agency
- Andrew Mackenny-Jeffs – Environment Agency
- Jean Erbacher – UKTAG/SNIFFER (7th December only)

Note: Apologies were received from Anton Edwards of SEPA.

Project Team:

- Steve Hull – ABPmer
- Nick Cooper – ABPmer
- Steve Freeman – ABPmer (7th December only)
- Ian Townend – ABPmer (7th December only)
- Richard Whitehouse – HR Wallingford
- Chris Hutchings – HR Wallingford (8th December only)
- Alan Brampton – HR Wallingford
- Jez Spearman – HR Wallingford (7th December only)
- Mike Panzeri – HR Wallingford (8th December only)
- Mike Elliott – Institute of Estuarine and Coastal Studies
- Jim Allen - Institute of Estuarine and Coastal Studies
- Michelle Devlin - CEFAS

External Experts:

- Helen Dangerfield - Royal Haskoning
- Keith Dyer - University of Plymouth
- John Widdows – Plymouth Marine Laboratory
- David Connor – Joint Nature Conservancy Council (7th December only)
- Suzanne Ware – CEFAS
- Donald McLusky - University of Stirling (7th December only)

- Phil Elliott – Environment and Heritage Service
- Deirdre Quinn – Environment and Heritage Service
- Roger Morris – English Nature (7th December only)
- Peter Balson – British Geological Survey (7th December only)

Note: Apologies were received from John Pethick (independent consultant) and Piers Larcombe (CEFAS).

Prior to the workshop, Working Papers 1 and 2 were circulated to all attendees. The workshop agenda was then arranged around the work that had been undertaken to date in Work Packages 1 and 2, and work remaining on the study in subsequent Work Packages. The Workshop involved a series of presentations, opportunities for discussion and a breakout session specifically to consider possible methods for defining hydromorphological reference conditions. A summary of the proceedings is presented in the following sections.

3.1 Introduction and Context

Delegates were welcomed to the Workshop by Andrew Richman (AR), the Environment Agency's Project Manager for the study. AR explained that the purpose of the overall project was to develop hydromorphological reference conditions and draft classification scheme for transitional and coastal waters, as required under article V of the Water Framework Directive, as part of the statutory reporting by the UK TAG Marine Task Team for the Water Framework Directive.

It was explained that the Project is being jointly funded by the Environment Agency and SNIFFER and is being managed via a Project Board, many of whom were in attendance at the Workshop. The Environment Agency awarded a contract for the study in September 2004 to a consortium led by ABP Marine Environmental Research Ltd (ABPmer) and involving HR Wallingford, CEFAS and Institute for Estuarine and Coastal Studies (IECS).

AR highlighted the following as being key components of the study:

- Conduct a comprehensive literature review;
- Develop a conceptual framework (in parallel with the literature review and include expert consultation);
- Define type specific reference conditions for all UK TraC water types;
- Develop a classification scheme(s) to quantitatively define high status for each water body and assess the level of deviation allowable to achieve good status and good to moderate status consistent with the achievement of the values defined for the biological quality elements defined in article V of the Directive;
- Conduct initial pilot testing of the classification scheme on a sample set of water bodies agreed with the Project Board.

AR also confirmed that the Project Board recognised a number of complexities associated with the study, as listed below:

- TRaC are complex ecosystems; they are not clearly understood at present;
- TRaC are influenced by short and long-term antecedent conditions, both natural and anthropogenically influenced;
- TRaC need to be understood and conceptualised further for this project, using a hierarchical, scale based framework. TRaC water bodies are highly variable and no one water body will behave in the same way as another;
- There is no simple relationship between hydrology, geomorphology and ecology. These relationships are dependent on the spatial and temporal scales considered and are at present poorly understood.

Dave Jowett (DJ) provided a comprehensive presentation on typology, reference conditions and classification systems of transitional and coastal waters. This included a background to the Water Framework Directive and how it is being implemented in the UK, through a variety of Steering Groups, Technical Advisory Groups (TAG) and Task Teams covering specific topics. Further background information can be found from the following sources:

- Environment Agency Website, www.environment-agency.gov.uk
- UKTAG Website www.wfduk.org
- SEPA Website www.sepa.org.uk
- Europe EU Commission Website http://europa.eu.int/index_en.htm and search for WFD

UK typology of coastal waters has been based on a number of mandatory factors, such as latitude and longitude, tidal range and salinity, and optional factors such as exposure, to yield the following coastal water body types:

CW1 Exposed, Macro-tidal;
CW2 Exposed, Meso-tidal;
CW3 Exposed, Micro-tidal;
CW4 Moderately exposed, Macro-tidal;
CW5 Moderately exposed, Meso-tidal;
CW6 Moderately exposed, Micro-tidal;
CW7 Sheltered, Macro-tidal;
CW8 Sheltered, Meso-tidal;
CW9 Sheltered, Micro-tidal;
CW10 Coastal Lagoons;
CW11 Shallow Sea Lochs;
CW12 Deep Sea Lochs.

For transitional waters, further optional factors have been considered, such as dominant substrate[1] and extent of inter-tidal area to yield the following transitional water body types:

TW1 Partly mixed or stratified, meso or polyhaline, macrotidal, intertidal or shallow subtidal, predominately sand and mud;
TW2 Partly mixed or stratified, meso or polyhaline, mesotidal, intertidal or shallow subtidal, predominately sand and mud;
TW3 Fully mixed, polyhaline, macrotidal, sand or mud substratum, extensive intertidal areas;
TW4 Fully mixed, polyhaline, mesotidal, sand or mud substratum, extensive intertidal areas;
TW5 Transitional Sea Lochs;
TW6 Transitional Lagoons.

DJ confirmed that typology is essentially the foundation upon which reference conditions and classification can be built, and that the key challenge will be in defining these reference conditions and classification systems, with expert knowledge expected to play an essential role in achieving this.

It was also stated that reference conditions must encompass a range of time variation (e.g. daily, tidal, yearly, inter-annual, decadal) and that administratively, every 6 years, the characterization of water bodies must be reviewed, commencing in 2013.

With this background context established, Nick Cooper (NC) went on to explain the purpose of the Workshop. It was noted that the project brief recognized the complexity of the challenge in defining reference conditions and classification, and for this reason a 'team approach' was required, involving the experience and expertise of not only Project Board and Project Team members, but also experts from the wider scientific community, many of whom had been contacted during the course of Work Package 1 and several of whom were in attendance at the Workshop.

It was stated that the purpose of the Workshop was to gather opinion on:

[1] See note in 4.3 about use of the term substrate

- Links between hydromorphology and ecology;
- What is a 'hydromorphological reference condition' and how much deviation is tolerable?;
- Methods proposed for taking study forward; and,
- How the hydromorphological impact of various activities can be assessed to ensure ecological status is maintained/improved.

3.2 Hydromorphological Concepts and Classification

This session was opened by a presentation from Nick Cooper (NC) on hydromorphological concepts and classification. Essentially it summarised Sections 4.1, 4.3 and Appendices B1 and B3 of Working Paper 1, which was circulated in advance of the Workshop.

The presentation covered an assessment of:

(i) present knowledge of dynamic hydrological and geomorphological processes (hydromorphology);
(ii) an understanding of their interactions over different spatial and time scales; and
(iii) the identification and review of other classification schemes.

In summary, it was considered that different hydromorphological elements of the physical system are relatively well understood in their own right (e.g. forces applied by waves or tides, sediment transport, the influence of geology on evolution, and the geomorphic behaviour of different landform units), but their interactions over various spatial and temporal scales are complex. The way in which such interactions have been incorporated in recent or ongoing studies was examined, and it was found that even the 'simplified' approaches used in some studies are complex in nature. It is generally considered that small-scale change can relatively reliably be examined through use of process-based numerical models, and larger-scale change can be examined, perhaps more qualitatively, through 'systems-based' approaches that consider the behavioural tendencies, interactions, controls, and feedback mechanisms between different elements of a system.

A number of different existing classification schemes for coasts, estuaries and rivers were also presented, but it was considered that most were essentially typologies that did not necessarily reveal vastly useful information about hydromorphological status (as required in this study). A handout was circulated (extracted from Working Paper 1) listing the key hydromorphological parameters that may typically be used in a hydromorphological study.

Alan Brampton (AB) then provided some additional thoughts (and a handout) on how various hydromorphological parameters can usefully become reference conditions and used in classification in the context of the Water Framework Directive (i.e. emphasis was placed on those most relevant to habitats/ecology of coastal and transitional water bodies). AB considered that suitable classification schemes may be founded on some (but not necessarily all) of the parameters that he listed, and suggested focusing on those parameters that can be measured or modelled practicably and at reasonable cost.

AB suggested that criteria to consider when defining reference conditions should be their accuracy, representativeness (considering spatial and time variations), and thresholds (whether precise or fuzzy).

Discussion:

Brief consideration was given to whether some of the classification schemes reviewed incorporated similar hydromorphological parameters to the typology discussed by Dave Jowett, since if it was felt that ifthe typology was lacking in any way, it might not provide a sufficiently robust framework for the subsequent development of reference conditions and classification.

Many scientists in attendance felt that clarification needed to be provided of the nomenclature used in the presentation, since 'typology' and 'classification' are often assumed synonymous. It was instead suggested that the terms 'typology'/'classification' and 'hydromorphological status' should be used to reflect their true meaning in the context of the presentation and hence avoid potential confusion.

It was considered that 'groundwater flow' and the importance of 'biological feedback' should be added to the list of parameters to consider in hydromorphological studies.

3.3 Links Between Hydromorphology and Ecology

This session was opened by a presentation from Larissa Naylor (LN) on saltmarsh classification. She emphasised the importance of understanding the links both between ecology and morphology and between ecology and hydrology. Also of importance was the role of suspended sediments and salinity on physio-chemical and hydromorphological regimes. Key questions posed were 'what is the level of acceptable change in saltmarsh in terms of spatial extent?' and 'can we just consider substrate as a simple means of investigating links between hydromorphology and ecology?'. LN proposed that to monitor the hydromorphological status of saltmarsh, the following aspects could be considered:

- Extent of saltmarsh;
- Change in location of marsh edge;
- Level of marsh surface;
- Internal dissection.

Steve Freeman (SF) then presented findings from the work undertaken as part of Work Package 1 on the links between hydromorphology and ecology. This essentially was a summary of Section 3.2 and Appendix B, which was circulated before the Workshop. The presentation focused on benthic invertebrates, macroalgae, angiosperms, fish in transitional waters and phytoplankton. It was recognised that the following were important to consider:

- Substrate;
- Zonation/Exposure;
- Wave Action;
- Hydrographic Regime: tides, currents;
- Topography, Geology & Aspect;
- Erosion/Deposition;
- Salinity.

<u>Discussion</u>:

Reference was made to further bodies of work on the links between hydromorphology and fish that should be considered when taking the study forward.

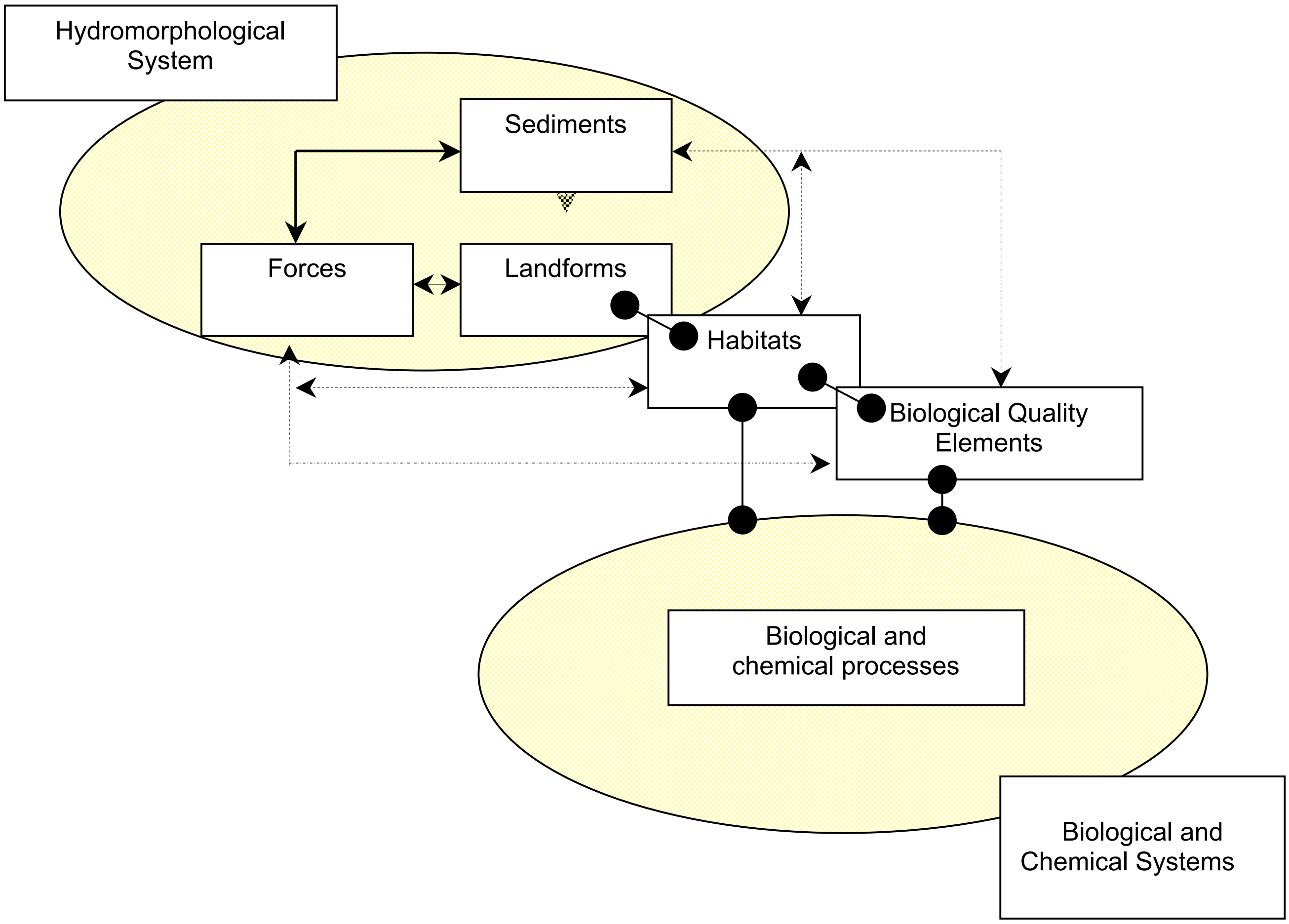
[1]A further matter of nomenclature was discussed: hydromorphologists tend to consider 'substrate' to mean the solid rock basement on which sea bed sediments are deposited, whereas ecologists tend to refer to 'substratum' as the sea or estuary bed. It was considered that clarity needed to be expressed when discussing these terms.

3.4 Conceptual Framework

Steve Hull (SH) presented a conceptual framework within which it was proposed to take the study forward (Figure 1). This summarised the work undertaken during Work Package 1, which was reported in Section 5 of Working Paper1. This framework is essentially predicated on the following key concepts:

- A combination of hydromorphological factors drive habitats;
- Habitats provide the key link between hydromorphology and some biological quality elements; and
- No single approach can encompass everything, but using habitats as an integrated assessment of hydromorphological quality may provide a way forward.

Figure 1: Conceptual Framework



Discussion:

Many delegates supported the approach of using habitats as the integrator of hydromorphological pressures and the link between hydromorphology and ecology, particularly as there was some degree of commonality between this approach and that of the biological task team. However, it was considered important not to forget the role of biological feedback to the geomorphology.

Some discussion surrounded consideration of how issues associated with climate change would be factored into the methods. It was felt that such pressures would be built into the system's response and the 6-year review cycle would facilitate its consideration.

Considerable discussion surrounded how to incorporate natural variability, including long-term cycles such as channel switching, within different systems and morphologically-driven step change. Whilst it may not be possible to clearly differentiate through monitoring between natural change and that induced by a changing hydromorphological pressure, any such change is likely to be first manifest through habitat quality (as the integrator of such pressures). Habitats are also generally much more stable over time than hydromorphological parameters and therefore provide a better indication of long-term change.

There was also comment that what is being observed at the habitat scale needs to be put into the context of what is occurring at a larger (i.e. water body) scale.

In terms of monitoring and reporting on status, if the habitat-based approach is to be used, it may not be necessary to monitor anything other than habitat, but if other hydromorphological parameters are considered important determinants of habitat quality in their own right (i.e. not manifest through changes in habitat, but impacting directly on biological quality elements: an example being salinity), then they too may need monitoring.

3.5 Methods

In the work undertaken as part of Work Package 2, the Project Team identified three possible ways of taking the study forward, namely: (i) through coupling of hydromorphological and ecological data from EUNIS and TYPOLOGY datasets and applying a series of rule bases; (ii) through ecological modelling; and (iii) classification based on observed data. These three methods were described in Working Paper 2, which was circulated prior to the Workshop.

Jim Allen (JA) presented the first method based on integrating data from JNCC's EUNIS Habitat Classification and the WFD Typology for UK and Ireland. The approach used the physical data held within the typology to predict level 3 EUNIS habitat types based on known relationships between the physical parameters and habitat types.

Preliminary findings from the research suggested that the approach has strong potential to derive ecologically relevant (habitat-based) hydromorphological reference conditions and also to be able to discriminate between water bodies subject to different degrees of hydromorphological pressure. The limitations of the approach were identified as:

- Resolution of coastal water bodies is relatively coarse
- Sediment data for inshore areas is very approximate
- The EUNIS classification scheme only extends to MHW and therefore does not include saltmarsh habitats (although it would be possible to incorporate information on such habitats at reasonable cost based on OS saltmarsh data).

The ecological modelling approach was presented by Steve Freeman. This involved the use of both a benthic model (able to predict distributions of inter-tidal invertebrates) and a habitat model (able to predict distribution of inter-tidal habitats), based on the environmental parameters listed below:

- Elevation (m);
- Salinity (ppt);
- Current speed (m/s);
- Bed shear stress (N/m^2);
- Average water level (m).

The limitations of the approach were identified as listed below:

- Data intensive;
- Requires hydrodynamic model;
- Generic rules;
- Outputs dependent on accuracy of model and elevation data.

Steve Hull (SH) presented the final method, based on observed data (largely dependent on Regulation 33 information (Regulation 33(2) of the Conservation (Natural Habitats &c.) Regulations 1994). Essentially the approach involves overlaying habitat and water body maps to derive habitat areas for each water body. Water bodies within a type are then ranked in relation to human pressures and reference conditions derived based on the common characteristics of water bodies observed to be subject to no or low pressure. The limitations of this approach are listed below:

- Overlap of habitat maps and water body types in some areas is poor;
- Lack of availability of a nationally (UK) consistent digital habitat data set;
- Areas within a water body remain unclassified;

- Large areas of saltmarsh are outside of present water body boundaries (i.e. above MHW).

Following the presentations, a breakout session was held, during which delegates debated: (i) the listing of hydromorphological parameters that were considered as being potential indicators of hydromorphological status; and (ii) the strengths and weaknesses of the three proposed methods, together with any alternative methods (or alternative combinations of the three proposed methods) for taking the study forward. Delegates were spilt into two groups A and B (see Annex B), one led by Dave Jowett and the other by Steve Hull. Richard Whitehouse and Nick Cooper recorded the discussions and reported key findings to the Workshop when delegates reconvened.

Key Findings of Group A

(a) Hydromorphological Parameters

Discussion points included the following:

- We still needed to agree what are the key elements for description of the environment to meet the needs of WFD. The methods need to help us to understand what is there now, and will need to help us to work out the % change from the reference condition. The methods may use observational data or predictive modelling, or a combination of approaches;
- It was noted that some of the key physical parameters that had been listed earlier in the workshop, namely Geological, Topography and Hydrodynamics, were a set of the normative definitions in WFD. It was agreed that wave exposure needed to be included in the characterisation;
- We need to get the physical hydromorphological characterisation right to help the biologists. The biological elements work had started earlier than the current project and hence there needed to be a close level of interaction with the Biological Task Team;
- In morphological terms sediment transport is a process, and not just a physico-chemical element to be measured. It may be the key process relating to morphological change because that change takes place as a result of sediment transfer. In terms of system characterisation, taking the example of the turbidity maximum in an estuary, water and sediment are indivisible due to the often high concentrations of sediment present;
- What is the role of salinity and turbidity in WFD requirements? – they are not mentioned. Salinity is a linking element between the physical and chemical areas;
- Why is the freshwater flow regime mentioned in WFD Annex V tables for estuaries? It may be because this is a key parameter that is present or absent, and when present is an important parameter that can be quantified. One approach to gauging change in pressures on ecological status might be to check whether the freshwater input to a system has changed. In natural circumstances the tidal regime is generally quite stable. The fluvial input to transitional and coastal waters is gauged at many sites and other approaches, such as the Low Flows 2000 decision support tool from CEH designed to estimate river flows, can help for ungauged sites;
- The original water body typology work applied at the whole estuary level and it is recognised that we are now moving towards the habitat level for classification; there is an intermediary level of definition, for example, the top, middle and lower reaches of the estuary which needs to be considered. For example, an estuary of one type might have a wide range of characteristic sediment turbidity producing spatially varying light penetration, sediment supply to estuary fringe, food source for benthos;
- Consideration of timescale is a key factor. With sea level rise during the Holocene period (c. 10,000 years before present) there was an associated "pulse" of sediment made available for morphological development. In terms of the WFD it is presently unclear as to whether we should determine future change from baseline with respect to the current position rather than from "pristine" conditions. Sediment

is important from the point of view of the availabilty for vertical movement of land surface in response to the pressure of Sea Level Rise. It was noted that some saltmarshes had disappeared from some estuaries in the Holocene;

- The pressures and impacts study for rivers (paper circulated) has already performed a risk assessment on the anthropogenic impacts. It was noted that the USA legislation allows for some level of anthropogenic impact in setting baseline conditions;
- The implication is that the reference conditions necessarily need to be broad. The baseline condition should take account of natural variation. In terms of defining the reference conditions, e.g. for a protected coast, would the reference condition be the behaviour of that coastal unit in it's unprotected state?
- Whatever method was adopted now would probably evolve and hence it was not ruled out that a different approach might be taken in the future. The important thing was to get the correct framework in place now.

(b) Methods

The strengths and weaknesses of the three approaches to hydromorphological classification were evaluated as follows:

Strengths	**Weaknesses**
EUNIS database approach • Physical basis to prediction of habitats • Whole water body • Provides a baseline	EUNIS database approach • Data quality – complete and correct? • Saltmarsh – proportion missing • Complementary datasets not included • Uncertainty as to whether it is the correct database to use for the baseline • Interpretation of results to meet WFD reporting requirements
Note for Refcon: best example of estuary in condition of type needs to fit description of type	
Process rules-based approach • Hindcasting and forecasting capability • Tested on Humber, Mersey, Soton Water • Could develop approach based on extension to existing process based models of water bodies	Process rules-based approach • Uncertainty as to whether rules lead to same classification as EUNIS • Missing the sub-tidal and coastal area at present • Data requirement is high in order to increase certainty in results • Cannot afford to develop models for whole of E, S, W and NI • Interpretation of results to meet WFD reporting requirements
Note: Check predictions tie in with EUNIS approach	
Observed data approach • Simple data based approach	Observed data approach • Need to determine available data and identify missing data (data gaps) • Interpretation of results to meet WFD reporting requirements
Note: estuary may only have 10% of maximum extent of possible saltmarsh and yet still be a healthy system	

It was concluded that a hybrid approach combining data and (process) modelling was probably a useful way forward.

Key Findings of Group B

(a) Hydromorphological Parameters

- It was generally considered that focusing on the requirements of the WFD with respect to the hydrological and morphological parameters contained within the Annex V tables was constraining, but there was recognition that these parameters must be used in execution of the study;

- The slight difference in parameters between coastal and transitional waters was noted;

- The hydromorphological parameters listed on the handouts were considered useful, but need to be related back to the Annex V definitions;

- However, some problems with the Annex V tables were recognised, namely the inclusion of freshwater flow in coastal waters and the absence of any explicit reference to wave activity from the tables;

- It was suggested that rather than focusing too much on the Annex V definitions, we perhaps should consider what parameters can be measured for observed changes over a 6-year reporting cycle. Also, the Annex V definitions should be interpreted as broadly as possible.

(b) Methods

- Rather than a single means of identify reference condition(s), a number of tools may be needed to consider the effect of all potential hydromorphological pressures;

- Perhaps our starting point should be to identify any schemes or activities that could change hydromorphological processes sufficiently to alter the status of a water body. If we assume definitions of micro-, meso- and macro-tidal there really are very few activities/schemes that would trigger a switch between these categories (i.e. only likely to be the construction of a barrage);

- The simplest method would be to consider seabedcondition only: this would address many (but importantly not all) of the biological quality elements. However, this approach would neglect the importance of other hydromorphological parameters (e.g. hydrological regime), which are important in determining the quality of other biological elements;

- The EUNIS/typology methodology found some favour, but there were some concerns raised about the data supporting it. Some delegates felt that it did not sufficiently consider seabed condition or other hydromorphological parameters (such as sediment movement through the system). It was noted that in the typology study, substrate was considered very broadly and perhaps this proposed approach is stretching the use of these data beyond its capability;

- Generally, it was felt that some basics of hydrodynamics and geomorphology were required within the methods (rather than just mapping of static datasets);

- Whilst it may not be possible to extend the hydromorphological approach too far, we can at least establish a baseline now that can be referred back to in the future. This could contain broad information relating to parameters such as salinity, seabed material, tidal currents, tidal range, wave disturbance, rainfall, etc, of existing water body types;

- The use of 'habitat' as the integrator between hydromorphology and ecology may work, but needed further consideration of the scale at which hydromorphological change needs to be considered.

Discussion:

- Should we be focusing on system-scale change or change at a single point?

- In the context of the WFD, transitional waters are not confined to estuaries, since there are many transitional waters across Europe that have no tidal flow;

- The relevance of freshwater flow to estuary systems was stressed during the discussion. A related question has arisen subsequent to the Workshop, namely 'is freshwater flow into the estuary a parameter in the ecological model? If so, have any scenarios been run changing only the freshwater flow rate to test the sensitivity of habitat change to freshwater flow?' Although freshwater flow can be an input to the numerical model, the suggested approach has not been tested in this manner. However, it should be noted that the Low Flows 2000 project might have useful information on the freshwater flow impacts on ecological status.

Summary:

Overall, delegates considered that two possible ways forward were worthy of further consideration, namely:

- EUNIS/typology approach, with improved datasets for certain existing parameters and incorporation of other parameters of relevance. This approach would be founded on the concept of using 'habitat' as the integrator of hydromorphological pressures and processes, in which case it may be necessary only to monitor habitat; or

- A more simplified approach that aims to establish the hydromorphological parameters presently observed to create a baseline reference against which future changes could be compared. This may, for example, include definition of whether a particular water body type is micro-, meso- or macro-tidal. This approach could be linked directly with the Annex V tables and these hydromorphological parameters could be measured.

This concluded the first day of the Workshop.

3.6 Way Forward

The second day of the Workshop commenced with the summary that many delegates considered that a more simplified approach to deriving hydromorphological reference conditions could/should be adopted. Steve Hull (SH) and Keith Dyer (KD) then proceeded to demonstrate some initial thoughts on how this might be achieved.

SH presented a matrix upon which it would be possible to derive hydrological reference conditions for different coastal water body types (Table 1).

Table 1 Hydrological Reference Conditions for Coastal Waters (see definitions in Section 4.1)

			Tidal Range		
			Micro-tidal	Meso-tidal	Macro-tidal
			<1m	1m-5.0m	>5.0m
Exposure	Significant wave height, H_s	Low	CW9	CW8	CW7
		Medium	CW6	CW5	CW4
		High	CW3	CW2	CW1
			all salinity > 30		

Note: There is a need to further consider how CW 10-12 may be incorporated.

This approach could also be modified and extended to transitional waters through use of the following hydrological parameters:

- Tidal Range (micro/meso/macro);
- Salinity (meso/polyhaline);
- Freshwater flow discharge (Qn_{95}/Qn_5).

KD presented how this approach could also be applied to morphological parameters for both coastal and transitional waters (Tables 2 and 3, respectively).

Table 2 Morphological Reference Conditions for Coastal Waters

Substrate	Depth			
	>10m	2-10m	LWMT-2m	HAT-LWMT
Rock	CR	CR	IR	LR
Gravel/Sand	SCS	SCS	SCS	LCS
Muddy Sand	SSa	SSa	SSa	LSa
Muddy Gravel	SMx	SMx	SMx	LMx

Definitions of reference types for Tables 2 and 3: CR (Circalittoral Rock), IR (Infralittoral Rock), LR (Littoral Rock), SCS (Sublittoral Coarse Sediment), LCS (Littoral Coarse Sediment), SSa (Sublittoral Sand), LSa (Littoral Sand) , SMx (Sublittoral Mixed Sediment), LMx (Littoral Mixed Sediment), SMu (Sublittoral Mud) LMu (Littoral Mud)

Table 3 Morphological Reference Conditions for Transitional Waters

Substrate	Depth			
	>10m	2-10m	HWMT-2m	HAT-HWMT
Rock	CR	IR	IR	LR
Gravel	SMx	SMx	LMx	LMx
Mud	SMu	SMu	LMu	LMu
Sand	SSa	SSa	LSa	LSa

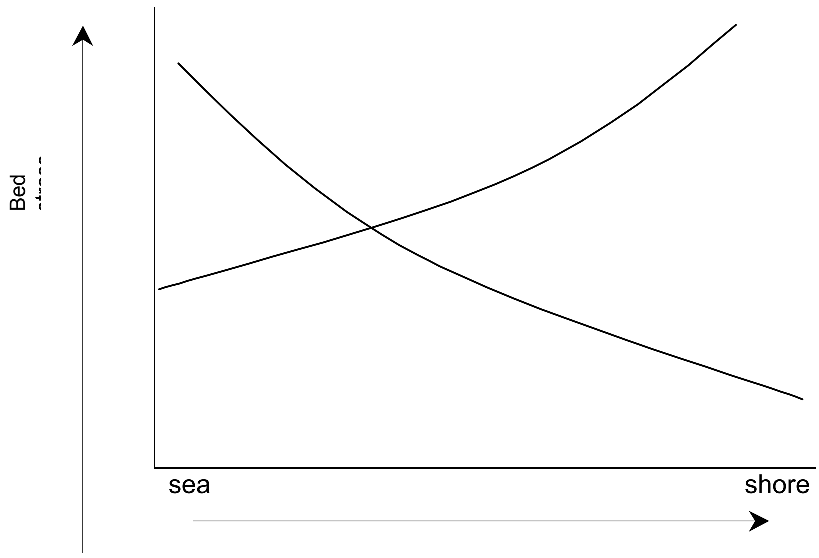
The physical controls on the substrate were also considered in the context of Table 4.

Table 4 Physical Controls on Substrate

Substrate	**Depth**			
	>10m	**2-10m**	**HWMT-2m**	**HAT-HWMT**
Rock	High stress	High stress	High stress / waves	Waves
Gravel	High stress	High stress	High stress / waves	Waves
Mud	Low stress	Low stress	Low stress	Low stress
Sand	Moderate stress	Moderate stress	Moderate stress	Moderate stress

This table reflects how the bed shear stress induced by waves increases with progression to the shore and that induced by tidal action decreases with progression to the shore in the manner presented in Figure 1.

Figure 1 Schematic representation of changing bed stress with progression from the ocean to the shore – wave stress increases and tidal current stress decreases



Discussion:

- The proposed approaches found much favour amongst delegates, despite the fact that any such reference conditions may be relatively insensitive to change. It will, however, provide a reference condition for the different coastal and transitional water body types;

- The approach would primarily deal with the quality of hydromorphological elements, rather than quantity;

- It may be wise to separate out subaerial zones, upper inter-tidal and lower inter-tidal to fully be able to consider processes such as exposure and dessication

- Thought could also be given to incorporation of 'sediment stress' (i.e. surplus or deficit of sediment), degree of modification, and sensitivity of different morphological elements, e.g. along the lines of the Futurecoast study;

- It may be possible to consider this approach further along the lines discussed during Work Package 4 (the next stage of the study) and then further develop it during subsequent stages of the study, possibly combining it with EUNIS data to deal with the next levels of complexity, i.e. spatial dimensions and ecological relevance;

- It was noted that the study to develop biological reference conditions is adopting a similar approach, keeping matters simple at first and then further developing if/as necessary;

- The simplified approach was considered as the best way forward with the immediate tasks on the study, enabling a broad, generalised baseline understanding of where we are now to be set down as a framework (albeit without a spatial context) within the tight timescales for delivery of Work Package 4 (draft due on 28 January 2005, to be finalised by the end of February 2005).

3.7 Data and Monitoring Issues

Having defined a suitable way forward with the immediate study tasks, the focus of the Workshop then turned to two other Work Packages that will be commenced later in the study, namely WP5 'Development of a decision-making framework for managing alterations to the morphology of TRaC waters' (reported in section 4.8) and WP7 'Identification and collation of supporting datasets' (reported in this section).

Andrew Richman presented a range of techniques that are available to monitor various hydromorphological parameters in coastal and transitional waters. These included:

- Lidar;
- Swathe bathymetry;
- SAR;
- Digital aerial photographs;
- Aerial video.

Many of these techniques were considered to be suitable means of measuring/monitoring certain hydromorphological parameters.

Alan Brampton considered data collection of relevant hydromorphological parameters in terms of broad interpretations of the Annex V tables. The parameters discussed are listed below:

"Tidal regime", interpreted as hydrodynamics:
- Range, extreme levels, % time at each level;
- Tidal currents (speed, energy, direction, residual);
- Freshwater flow discharges (Qn90%, Qn70%, min 4 hour flow);
- Flushing/water exchange rates;
- Salinity/mixing or stratification;
- Waves (Hs 50%, 5% seasonal, annual, average).

"Substrate", Sub-tidal:
- Bathymetry: % area above 10m, 5m, 2m + slopes, features e.g. reefs, pits;
- Seabed sediment cover (% bedrock, mud, sand etc);
- Seabed (landforms) (sand waves, ripples etc);
- Bedrock/ substrate type (petrology, roughness etc.);
- Trend for erosion/ deposition (or invariant/ relict);
- Area regularly disturbed by natural/ human processes.

"Substrate", Inter-tidal:
- Bathymetry: % area below MHW, % area above MHW to extreme HW, slopes and features e.g. reefs;
- Bed sediment cover (% bedrock, mud, sand etc);
- Bedforms (sand waves, ripples etc);
- Bedrock/ substrate type (petrology, roughness etc.);
- Trend for erosion/ deposition (or in tidal prism);

- Area regularly disturbed by natural/ human processes.

Measurement of the above parameters should be considered in the context of what is practical, relevant and achievable, and should be viewed in the context of both anthropogenic and natural changes (e.g. 18.6 year cycle in tidal levels).

In many cases, AB felt that numerical simulation of conditions, calibrated against measurements at a few discrete locations might be a practical method of examining changes over wide areas of the seabed and over various time periods. For many of the parameters mentioned, data gathering and modelling is already taking place, or could be extended inexpensively.

Discussion:

- Whilst the techniques presented for monitoring hydromorphological parameters was of keen interest, some delegates pointed out that some areas of the UK do not have ready access to such facilities or adequate resources to fund such monitoring initiatives;
- The role of supplementary parameters obtained during biological sampling, such as sediment characteristics yielding particle size distributions, should be considered.

3.8 Decision-making Framework

Roger Proudfoot took the opportunity to inform Workshop delegates of the planned approaches to Work Package 5 of the study. Essentially the aim of the package is to develop a decision-making framework for managing alterations to the morphology of TRaC waters. It may be considered as a means of formalising existing approaches and identifying anything that has the potential to 'fall through the net' of present approaches.
The role of the Marine Consents and Environment Unit was introduced and their figure on the Geographical Extent of Principal Marine Works Controls: England & Wales was used during the discussion:
http://www.mceu.gov.uk/MCEU_LOCAL/fepa/consents-extent.htm

Discussion:

- It was suggested that the Broad Scale Environmental Impact Modelling study may usefully link up with this project;

- Clarification was provided that this task is not simply taking and expanding the approaches previously developed in the Heavily Modified Water Bodies study, but instead is a different process (i.e. a means of formalising assessment of the morphological effect of new developments). It will apply some of the lessons and knowledge gained from the HMWB study, but will have to consider the whole of the UK;

3.9 Workshop Close

Andrew Richman thanked all of the delegates for their valuable contributions over the course of the Workshop. He invited comments on Working Papers 1 and 2 (previously circulated in advance of the Workshop) and outlined the following timetables for the next steps with the study:

- Circulation of **Workshop Summary** by **17th December 2004**
(ACTION = Project Team);

- Provision of **comments** on the Workshop Summary report and Working Papers 1 and 2 by **14th January 2005**
(ACTION = Project Board, Workshop Delegates);

- Preparation of **draft report** for Work Package 4 by **end January 2005** (ACTION = Project Team);

- **Project Board Meeting** on **10th February 2005** (ACTION = Project Board);

- Finalisation of report for **Work Package 4** by end **February 2005** (ACTION = Project Team).

The Workshop was then closed.

ANNEX A WORKSHOP AGENDA

Tuesday 7th December 2004

09:00	Registration/coffee	
09:00 – 10:15	Introduction and Context	
	▪ Purpose and scope of Project	A Richman
	▪ Water Framework Directive – role and purpose	D Jowett
	▪ What are 'Classification Schemes'?	D Jowett
	▪ What are 'Types and Reference Conditions'?	D Jowett
	▪ Purpose and structure of Workshop	N Cooper
10:15 – 10:45	Review: Hydromorphological concepts and classification	N Cooper & A Brampton
10:45 – 11:15	Tea / Coffee	
11:15 – 11:45	Review: Links between hydromorphology and ecology	L Naylor & S Freeman
11:45 – 12:00	Method: Conceptual Framework	S Hull
12:00 – 12:30	Discussion of Review and Conceptual Framework	All
12:30 – 13:30	Lunch	
13:30 – 14:30	Methods: Possible workable methodology	J Allen, S Freeman & S Hull
14:30 – 15:30	Breakout Session (2 groups)	Led by S Hull and D Jowett
	▪ Strengths and weaknesses of approaches	
	▪ Alternative suggested approaches	
15:30– 16:00	Tea / Coffee	
16:00 – 16:30	Summary of Breakout Sessions	R Whitehouse and N Cooper
16:30 – 16:45	Discussion	All
16:45 – 17:00	Summary and Close	A Richman

Wednesday 8th December 2004

09:00 – 09:45	Summary of way forward/Discussion	S Hull
09:45 – 10:15	Monitoring Techniques	A Richman
10:15 – 10:45	Tea / Coffee	
10:45 – 11:15	Data/Monitoring Issues	A Brampton
11:15 – 12:00	Decision-making framework for managing alterations to morphology of TRaC waters	R Proudfoot
12:00	Close	A Richman

ANNEX B BREAKOUT SESSION GROUPS

GROUP A	GROUP B
Lead: Dave Jowett	Lead: Steve Hull
Rapporteur: Richard Whitehouse	Rapporteur: Nick Cooper
Jane Rawson Jean Erbacher Alison Miles Chris Vivian Mark Charlesworth Steve Freeman Mike Elliott Jez Spearman Ian Townend John Widdows Phil Elliott Helen Dangerfield Roger Morris Dave Connor	Andrew Richman Roger Proudfoot Larissa Naylor Andrew Mackenny-Jeffs Jean Erbacher James Mckie Jim Allen Michelle Devlin Alan Brampton Keith Dyer Donald McLusky Deirdre Quinn Suzanne Ware Peter Balson

List of Abbreviations

ABPmer	ABP Marine Environmental Research Ltd.
BGS	British Geological Survey
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CW	Coastal Water
EA	Environment Agency
EUNIS	European Nature Information System
HRW	HR Wallingford
IECS	Institute of Estuarine and Coastal Studies
SNIFFER	Scottish and Northern Ireland Forum for Environmental Research
TRaC	Transitional and Coastal (Water Bodies)
TW	Transitional Water
UKTAG	United Kingdom Technical Advice Group
WFD	Water Framework Directive

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