ESTUARY BEHAVIOURAL SYSTEMS

This document presents an overview of the systems-based approach and its application to estuaries (EstSim Consortium, 2007), including a review of the principles behind the systems approach and methodology applied within EstSim. It considers issues associated with the application of the systems-based approach, such as the use of systems diagrams and levels of systems abstraction. A discussion is then provided of the application of systems principles in estuarine environments, and a discussion of the development of behavioural, or qualitative, models. The document then concludes with systems diagrams for UK estuary types, as presented under Estuary Setting.

The Systems Approach

The systems-based approach involves separating out sub-systems and their interactions in order to understand the system organisation and define its behaviour. It thus combines both the physical elements and the dynamics of the interactions between them in order to explain how the different components make up the system interact and respond to change (Cowell & Thom, 1994; Capobianco *et al*. 1999).

The systems approach has been applied and reviewed by various workers (Chorley & Kennedy, 1971; White *et al*., 1984; Cowell & Thom, 1994; Capobianco *et al*., 1999; Townend, 2003) and some of the key issues identified from these studies are summarised here.

Systems Diagrams

Systems diagrams provide a means of capturing the key attributes of a system by identifying the system elements and their interactions. A systems diagram is a flowchart representation and its ability to capture the behaviour of the systems will depend upon the fundamental knowledge of coastal processes and the ways in which these are expressed. Different examples of system diagrams that demonstrate a number of key features are presented in Figures 1-4.

It is important to note that in the examples provided in Figures 1-4, the systems diagrams are attempting only to identify the presence of, and interactions between, the key elements within natural systems. The systems diagrams do not include any anthropogenic influences on these systems.

The objective of defining systems diagrams is to represent the interactions between system components. This should ideally capture the behavioural attributes of the system and inform abstraction and aggregation to different system levels.

The physical components of an estuary system can be simply identified within a systems diagram by different symbols/nomenclatures (Figure 5) after adapting the convention used by Wilson (1982).

In order to better express system interactions, this convention can be extended where the relationships between different system elements are known. For instance, the example given in Figure 2 shows how an interaction or coupling flow can be defined in terms of the nature of the element's response. In this case the response can be for a positive or negative tendency/effect.

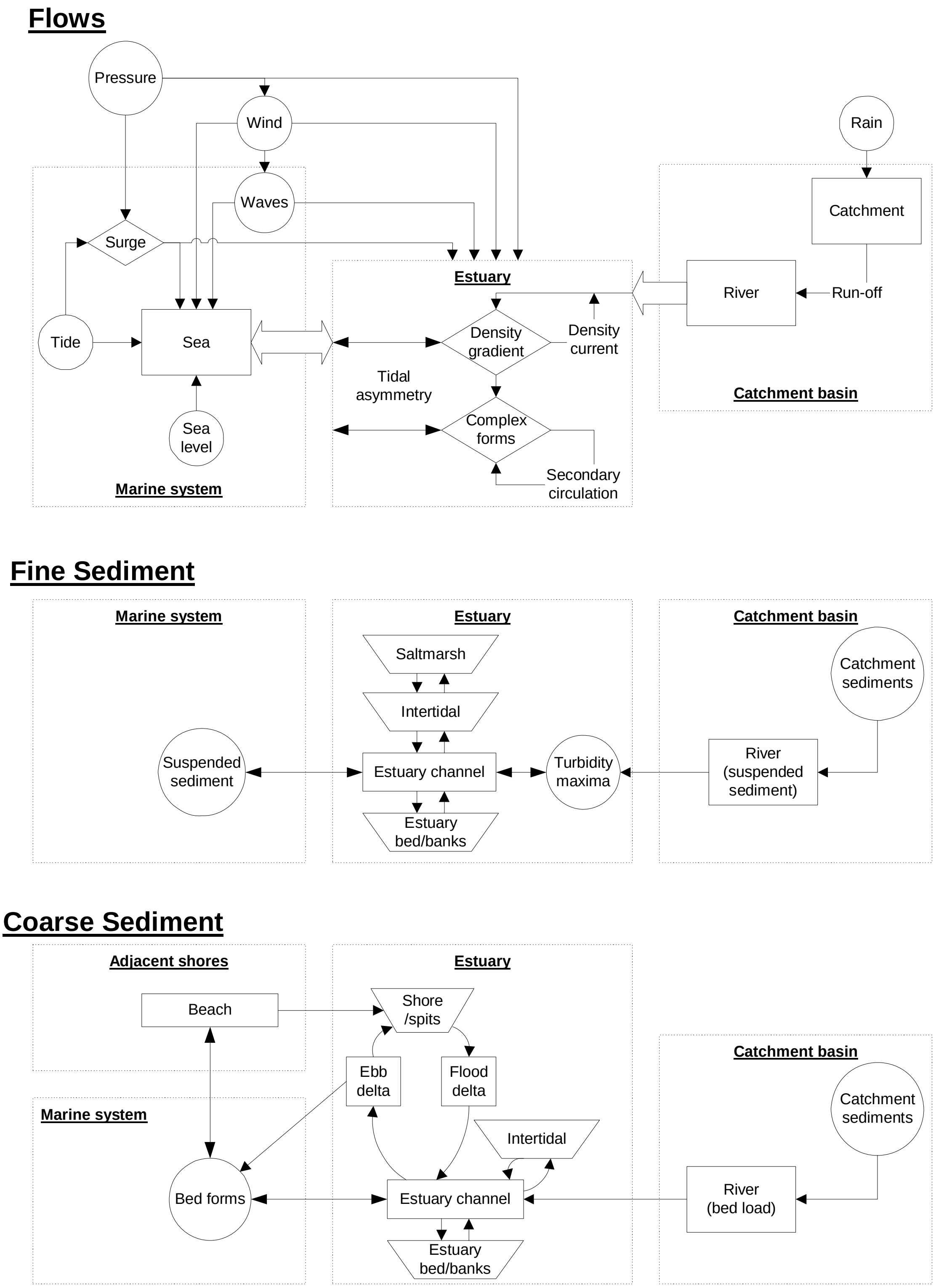


Figure 1. **Estuary represented as flows, fine and coarse sediment interactions (Townend, 2003)**

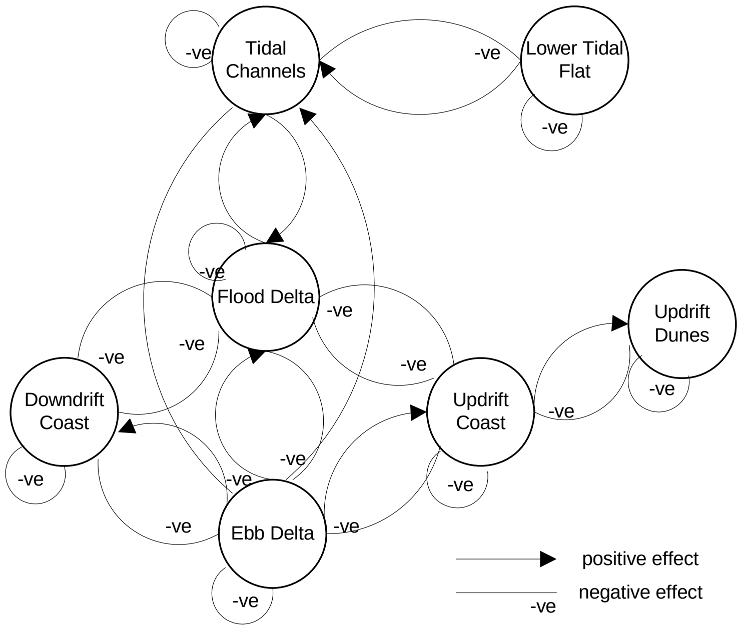


Figure 2. **Signed graph representation for the impacts of sea-level rise on an inlet or lagoon entrance (Capobianco *et al*., 1999)**

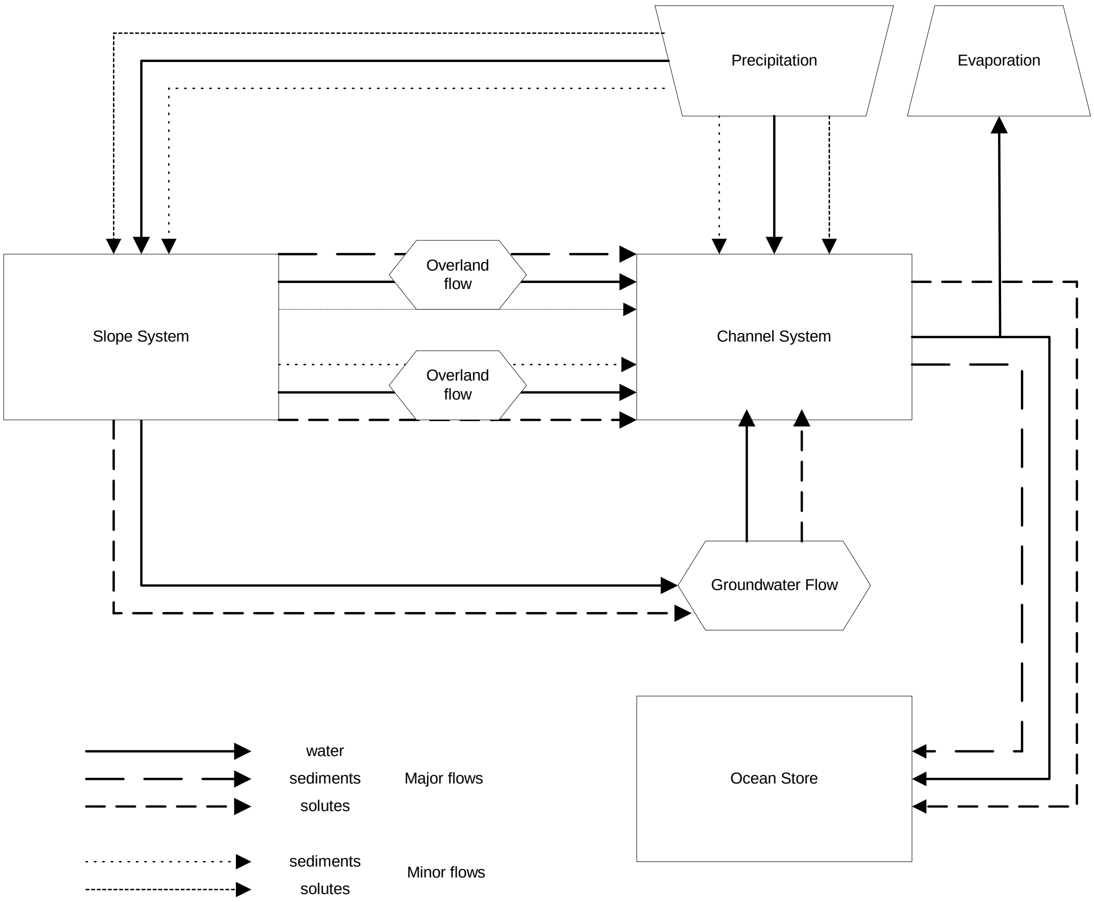
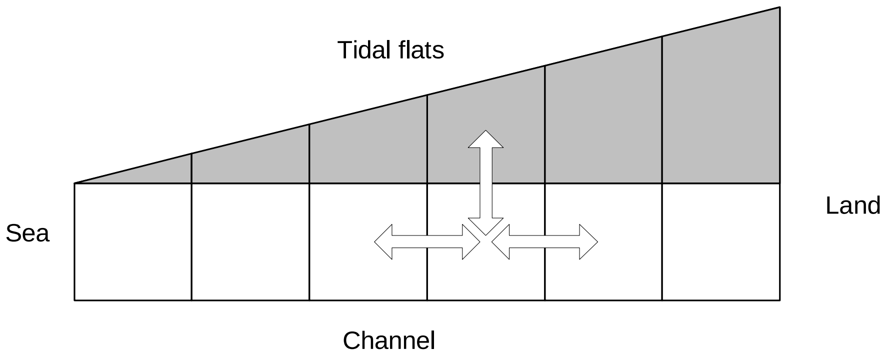
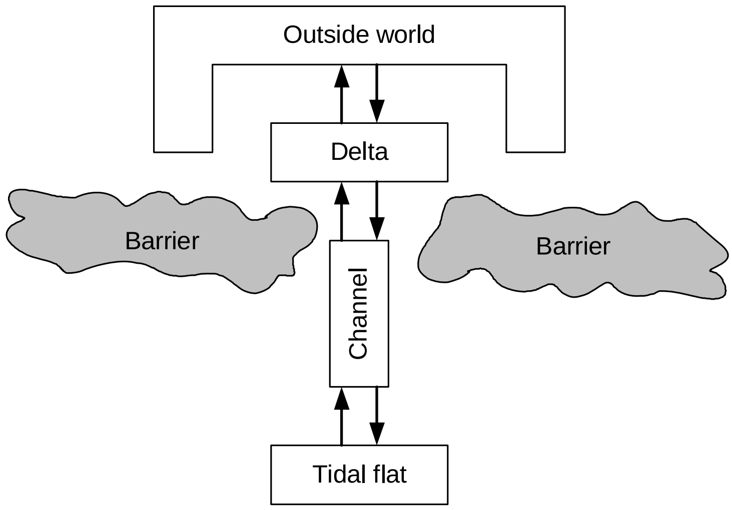


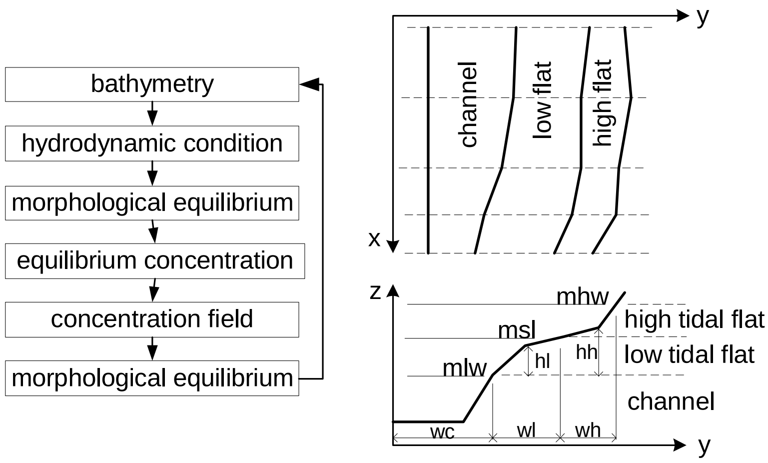
Figure 3. **Diagram showing the pathways through the catchment basin system (White *et al*., 1984)**



a) Tidal basin schematisation used by van Dongeren and de Vriend (1994)



b) Schematisation of elements and exchanges within the ASMITA model

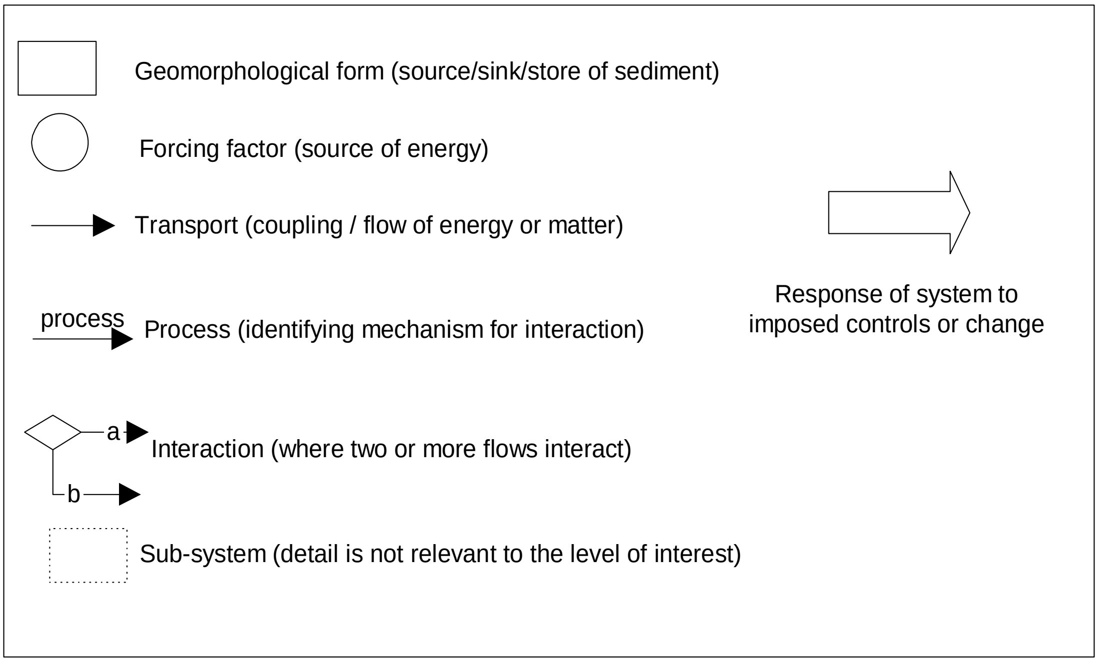


c) Procedure and schematisation used in ESTMORF (Wang et al, 1998)

Figure 4. Schematisations used in selected tidal inlet models

A systems diagram can be used to show the relative dominance of interactions and flows (Figure 3), where minor and major flows are differentiated by the boldness of the connector. This system can also differentiate between the transport of different substances on the same system level by using a range of line types or colours.

Use of the above convention is not meant to constrain systems representation. Alternative techniques should be applied where these can convey the desired system behaviour or response.



Note: The nature of the geomorphological form in terms of its role as a source/store and/or sink will implicitly be given by the presence/absence of a connecting flow and the direction of transport.

Figure 5. System diagram symbol convention

Abstraction and Systems Levels

The complexity of the coastal system, range of physical processes present and relevant spatial and temporal scales will determine how the system is represented.

If every known system element and interaction were presented on one system diagram, the complexity would inhibit an understanding of the whole system. Hence, abstraction is an important procedure for separating the system into layers. Figure 1 demonstrates abstraction of different processes involving different mediums (water and coarse/fine sediments) into three separate layers operating over the same timescale. Abstraction must also be considered over the hierarchy of spatial and temporal scales (Figure 6).

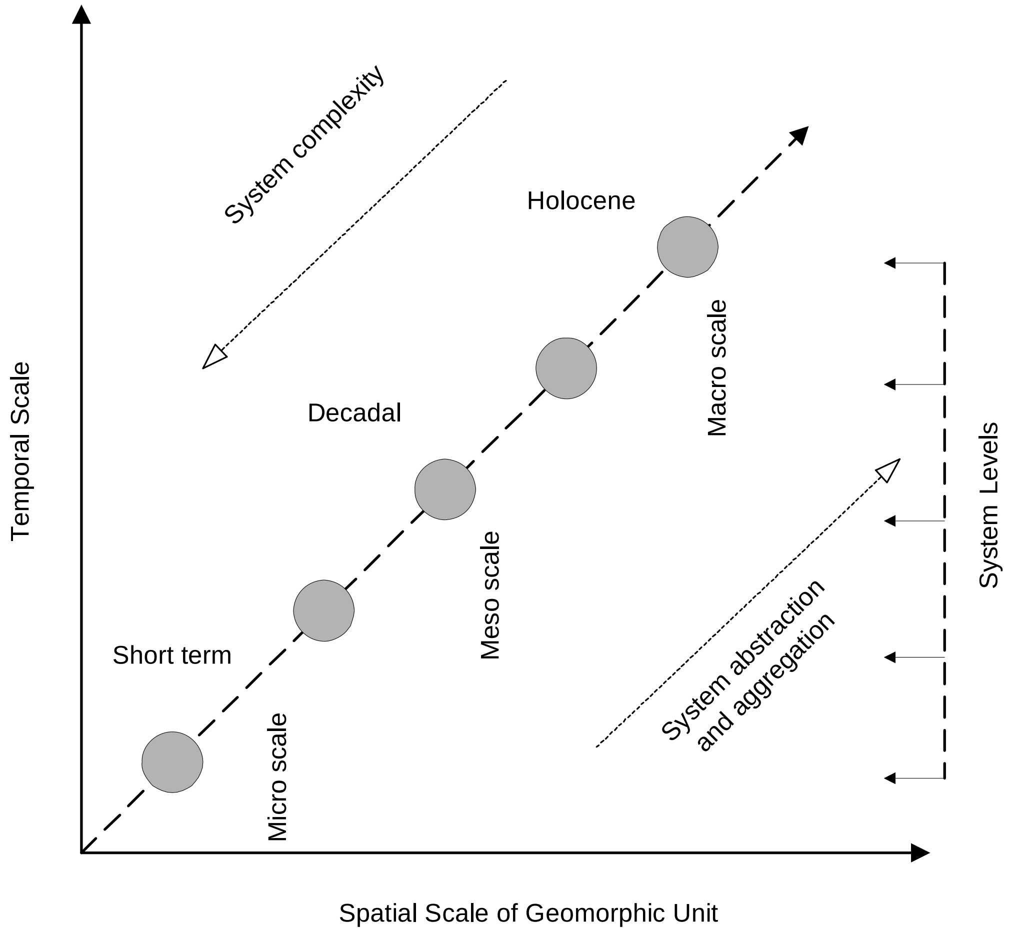


Figure 6. General relationship between temporal and spatial scales of geomorphic evolution showing different levels of system abstraction

For coastal geomorphology various levels of abstraction have been cited and categorised (Townend, 2003; Cowell *et al*., 2003).

One possible categorisation of spatial scales is as follows:

- Macro-scale: regional land mass behaviour;
- Meso-scale: geomorphological unit behaviour;
- Micro-scale: geomorphological features;
- Nano scale: particle behaviour;
- Atto scale: sub-atomic/quantum behaviour.

Each level of abstraction could be defined as a behaviour model, which can be chosen on the basis of the type of question we are seeking to answer.

At any one level of abstraction, elements and interactions that add detail and complexity, but make only a minor contribution to system response, can be omitted. This is an explicit process when abstracting from a high level of detail to subsequent lower levels but is also an important property of qualitative/behavioural modelling (aggregation) where the behavioural description of system interactions does not need to be based on the underlying physical processes. Essentially, it follows that the detailed system/processes that dominate the level of interest will be taking place at the next level down. Therefore each level is doing some form of averaging to relate the detailed structure at one level to the more general behaviour at the next level (Schumm & Lichty, 1965).

An example of a top-level abstraction of an estuary system, shown as a simple tidal inlet, is given by the ASMITA model (Figure 4b). This is outlined in more detail in the Uniform sediment flux tools document. Here, sub-systems could be added to provide the detail of subsequent lower levels. However, abstraction should be treated with care to ensure that relatively small exchanges at any one level are not ignored at a higher level purely on the basis of their scale, since the accumulation of these small exchanges may actually produce morphologically significant effects (Cowell *et al*., 2003).

In determining the rationale for system abstraction for each level, there does not seem to be an obvious choice. Each level may comprise elements that interact over the same temporal or spatial scales or may be more complex as noted above. Cowell *et al*. (2003) suggest the 'cascade' of levels is partitioned on the basis that each level forms an internally sediment-sharing system.

One of the driving aims behind this research is to inform decision-making concerning coastal management issues over the medium-term (decadal period) where uncertainties in current modelling approaches limit the accuracy of solutions.

Behavioural / Qualitative Modelling

The discussion so far has focused on the role of the systems approach and systems diagrams to map out interactions within an estuarine system. This approach can map the system components (elements and interactions) at a specified level of interest. However, attempting to model this detailed system is limited by current understanding of the detailed processes and is one of the reasons why a behavioural systems approach is being investigated as an alternative to detailed process modelling.

The limitations of the systems diagram approach are, however, fully recognised (Townend, 2003). It is noted that that whilst systems diagrams make clear the nature of flows of energy and matter, and the interactions and feedbacks between elements, they say little about the relationship between components and the character of any response.

This is where behavioural or qualitative modelling (Capobianco *et al*., 1999) can be thought of as extending the basic systems approach. The concept of behavioural modelling is to develop an understanding of the behaviour of the system by capturing the nature of relationships between system components and mapping it onto a simple model, which exhibits the same behaviour, but which does not need to have any relationship to the underlying physical processes. Whereas systems diagrams highlight the presence of interactions, the behavioural approach places emphasis on developing the interaction as a relationship (response). The difference between the two approaches is evident in Figure 7, which both identifies interactions and provides a behavioural response. In the context of an estuarine system the identification of a behavioural system is an attempt to integrate geomorphological units that are spatially contiguous into a unified entity that reflects how it is likely to change.

A behavioural system representation of the coast is therefore essentially a top-down view as it seeks to capture an overall coastal response. However, it can be seen that arriving at such a system view could be developed in a number of ways such as from either a bottom-up 'reductionist' starting point with a gradual increase in abstraction and aggregation, or directly from the top after understanding a form of coastal response that can be captured by a behavioural relationship.

The potential of qualitative modelling as a means of providing indicative rather than strictly quantitative insights into the behaviour of systems specified in this manner, has been highlighted by Capobianco *et al.* (1999), who identified seven stages associated with the development of a qualitative model of system behaviour (Figure 7). These include the identification of qualitative variables and the causal linkages between them, which typically involve the construction of system diagrams of some form. Modelling of system behaviour then requires the definition of a mathematical quantity space to represent interaction between these qualitative state variables. Figure 2 shows a qualitative model for a generic tidal inlet system subject to a rise in sea level, wherein the quantity space is defined in terms of a signed graph, with positive or negative effects connecting the main system variables. Transfer rules and knowledge formalisation are then needed to convert either quantitative understanding (which might take the form of empirical scaling relationships or physically-based process laws) or linguistic understanding (e.g. a statement describing the behaviour of a sub-component) of system linkages into a set of cause-effect relationships.

1. *Identification of qualitative variables* and the likely relationships between them.
2. *Conceptual representation* and definition of causal inference network.
3. *Definition of a quantity space* - a finite set of symbols to define values of state variables.
4. *Establish transfer rules* that can be used to develop qualitative relationships between variables.
5. *Knowledge formalisation*, in which transfer rules are used to define cause-effect relationships.
6. *Qualitative translation of measurements*, where variables are assigned values from the quantity space.
7. *Application of qualitative calculus* to analyse characteristics of the model.

(Adapted from Capobianco *et al.*, 1999)

Figure 7. Construction of a qualitative model

Systems Diagrams for UK Estuaries

This supporting document provides a brief textural description and generic system diagram (Figure 8) of each of the estuarine types identified in Estuary Setting. The geomorphological units present within each different estuary type are highlighted on each system diagram (with infilled boxes) and the arrows indicate one or two way linkages.

A mapping of the estuary system in terms of key geomorphological elements within the coastal and river basin setting is shown in Figure 8 and a more detailed representation of the generic estuary elements shown in Figure 9. Using this generic figure (Figure 9) as a basis, system diagrams have been prepared for each estuary type.

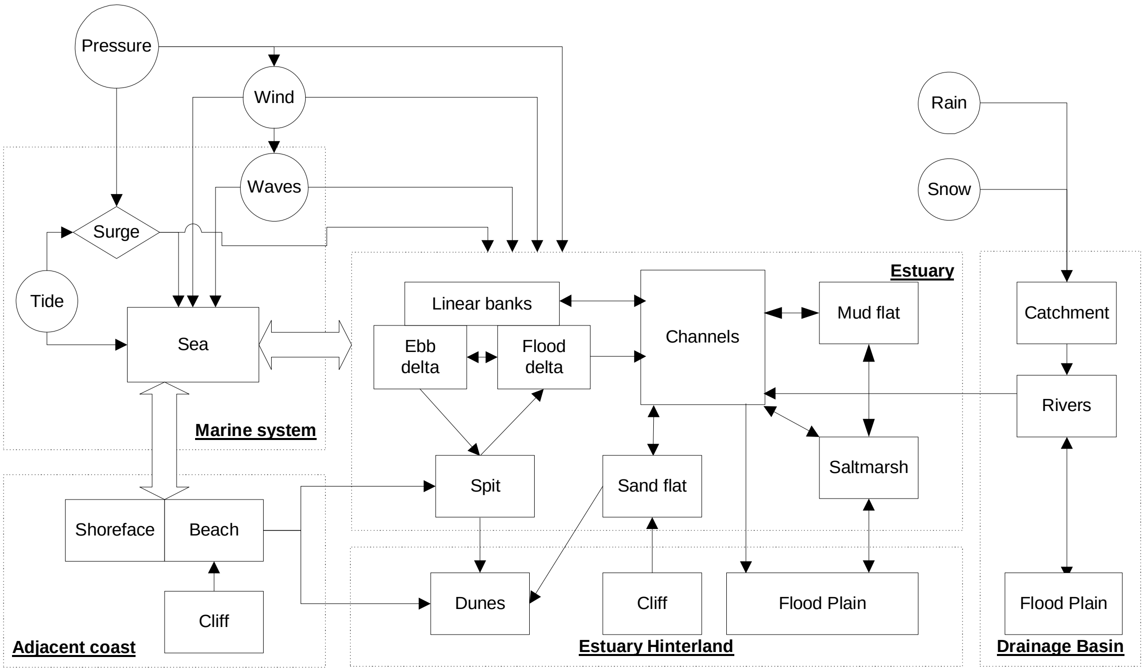


Figure 8. Systems map of the estuary within a coastal and catchment setting

Notes:
- (i) Holocene bed is not shown, but will be present as a consequence of long-term accretion and consolidation.
- (ii) Channels can include both ebb/flood channels and/or a subtidal channel.
- (iii) Sand flats include mixed sediment beds.
- (iv) Linear banks and the ebb/flood delta are alternatives (usually reflecting the tidal range).
- (v) Flood plains are differentiated between those in the upstream drainage basin and those adjacent to the estuary, although they may represent a continuum.

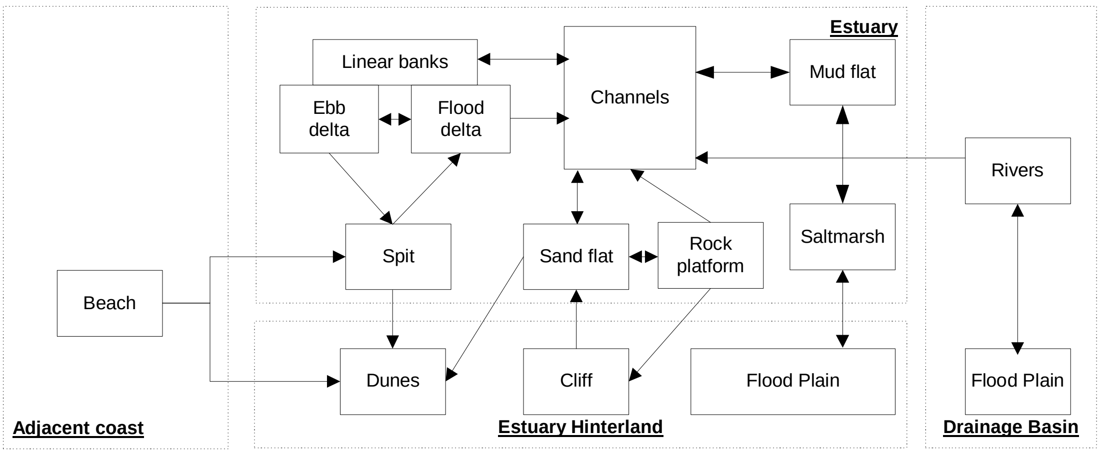


Figure 9. Generic estuary geomorphological units

1 *Estuarine Behavioural Type 1: Fjord*

Fjords are generally long, deep and narrow features that are bounded by relatively erosion-resistant, steeply rising slopes. They are formed by the submergence of glacially over deepened valleys (known as troughs) due to a rising relative sea level after the melting of the Pleistocene ice sheets. Fjords extend to great depths along most of their length, even close to their head, but tend to shallower depths close to their mouths to form a sill in solid rock. They generally have only small but highly seasonally variable river flow, often with tributary streams entering the system as waterfalls from hanging valleys. Only a small number of fjords exist in the UK, confined mainly to Highland regions in Scotland. One of the best UK examples of a fjord is Loch Etive in Western Scotland.

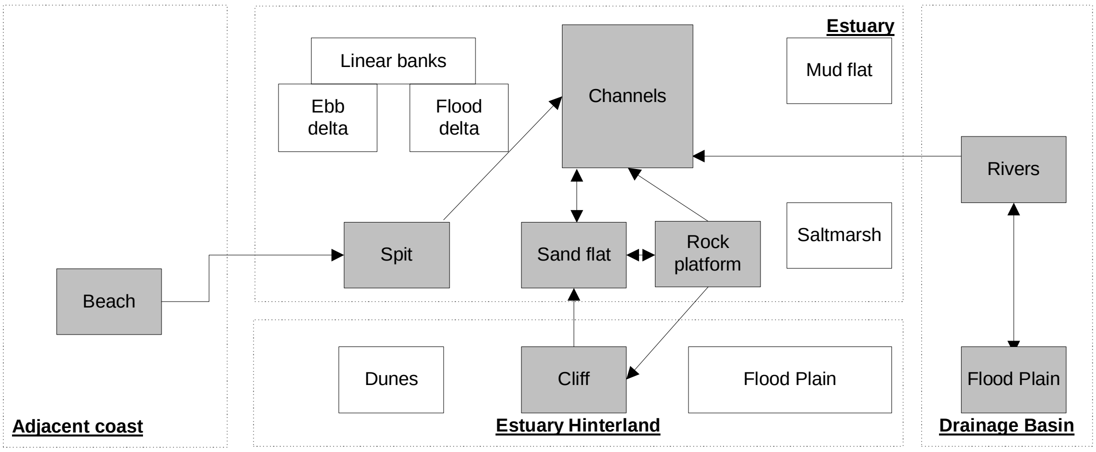


Figure 10. Generic fjord

2 *Estuarine Behavioural Type 2: Fjard*

Fjards are indented, drowned features fringing rocky, glaciated lowlands. Whilst they do not posses the deep glaciated troughs of a fjord, they generally reach greater depths than a ria. They generally have only small but highly seasonally variable river flow and have greater potential than fjords for the creation of spits at their mouths. Pwllheli Harbour in Wales is an example of a very small fjard with spits.

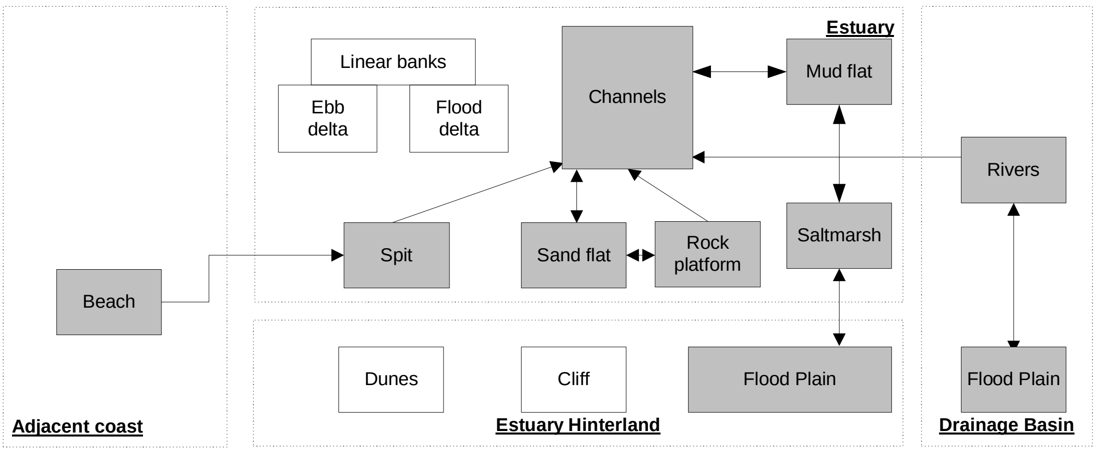
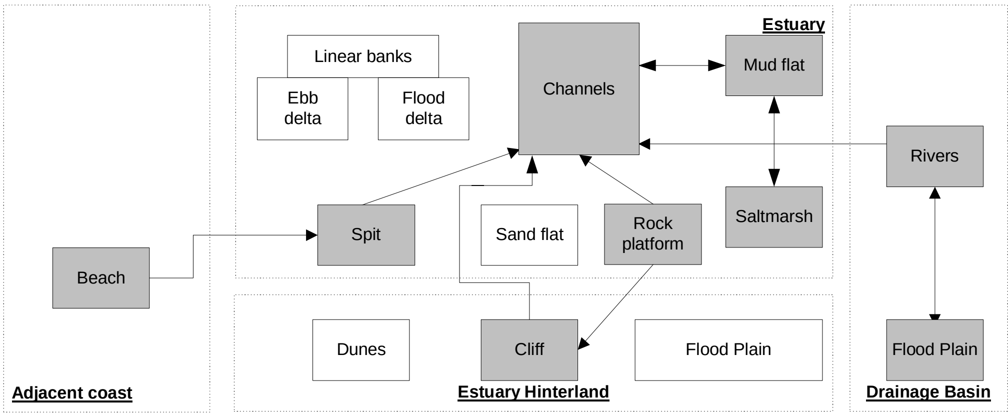


Figure 11. Generic fjard

3 *Estuarine Behavioural Type 3: 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 northeast and southwest England and Wales.



Note: Not all rias have spits.

Figure 12. Generic ria

4 *Estuarine Behavioural Type 4: Spit-enclosed Drowned River Valley*

River valleys composed of soft rocks generally possess a more subdued relief than is experienced in harder rock areas, but have been subject to the same marine inundation processes caused by post-glacial (Holocene) sea-level rise. Many such areas possess drowned river valleys that have single or double spits at their mouths that tend to limit the mouth width and the physical processes occurring there. Many spit-enclosed estuaries, whilst experiencing high tidal velocities through their mouths, observe limited wave penetration due to the shelter provided by the spit(s) and at low water, salinity levels can be very low due to river flow. Often, spit-enclosed estuaries have flood and ebb tidal deltas and many examples of spit-enclosed drowned river valleys exist throughout eastern, southern and southwestern England (e.g. the Teign), with the largest being the Humber, which has a single spit.

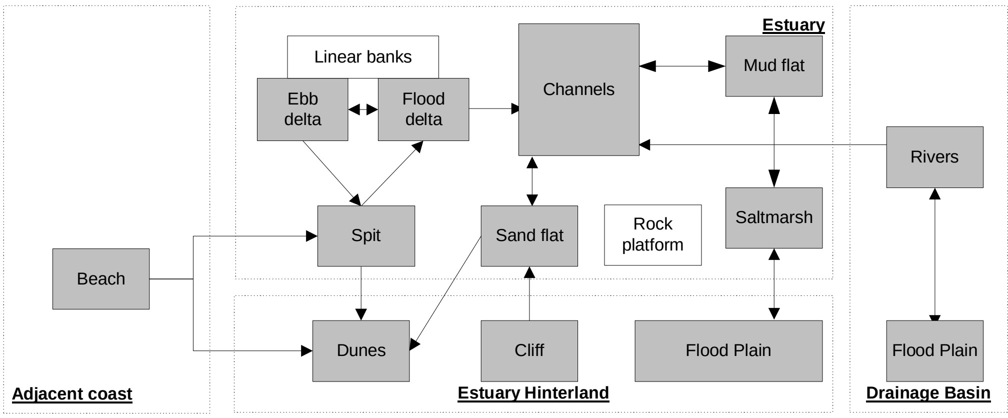


Figure 13. Generic spit-enclosed drowned river valley

5 *Estuarine Behavioural Type 5: Funnel-shaped estuary*

Funnel-shaped estuaries are considered likely to be close to the classical definition of equilibrium form. They do not possess spits, indicating a strong tidal motion and relatively weak littoral drift of sediment from the adjacent coasts. Often such estuaries will possess elongated linear sand banks within the area of the estuary mouth, aligned parallel to the current flow direction. The area of the estuary mouth can, in some cases, cover a large region. The rivers Thames and Ribble are examples of funnel-shaped estuaries.

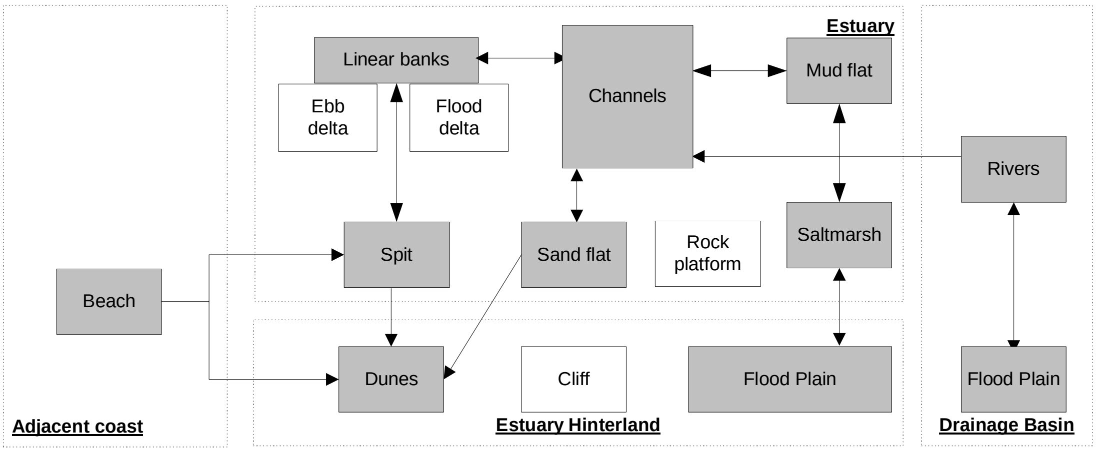


Figure 14. Generic funnel-shaped drowned river valley

6 *Estuarine Behavioural Type 6: Embayment*

Embayments are formed where several rivers converge and their joint valleys create a wide mouth area open to large wave and weather effects. They are characterised by large intertidal areas and high salinity throughout the embayment at High Water. The Wash is a classic example of an embayment.

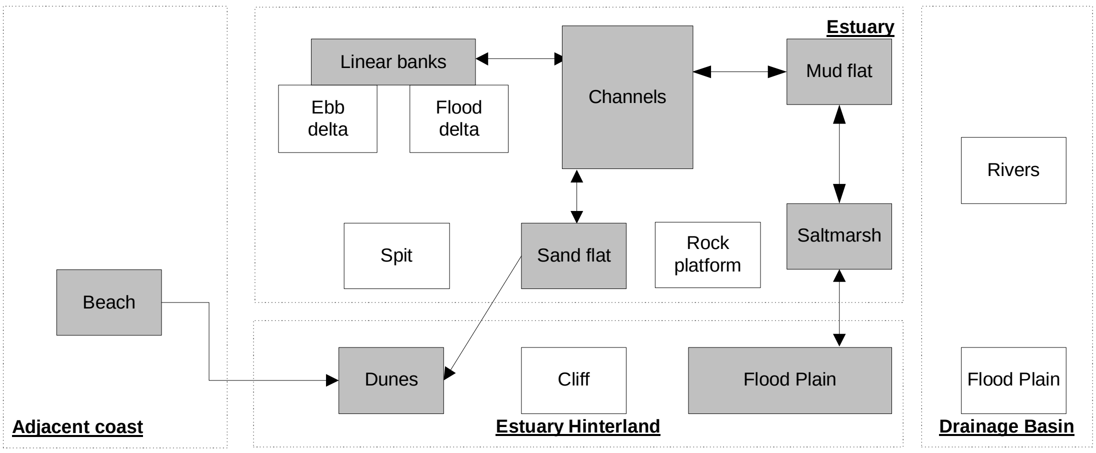


Figure 15. Generic embayment

7 *Estuarine Behavioural Type 7: Tidal Inlet*

Tidal inlets are produced where the relative sea-level rise has occurred over an extremely low relief coastal plain. These are characterised by narrow channels through fronting barrier beaches, and are backed by extensive tidal lagoons. In more tidally dominated areas, the inlet channel will typically be perpendicular to the coast, whilst in more wave-dominated areas the channel may be more obliquely aligned. Several examples of tidal inlets exist in close proximity along the south coast of England, namely Portsmouth, Langstone, Chichester and Pagham Harbours.

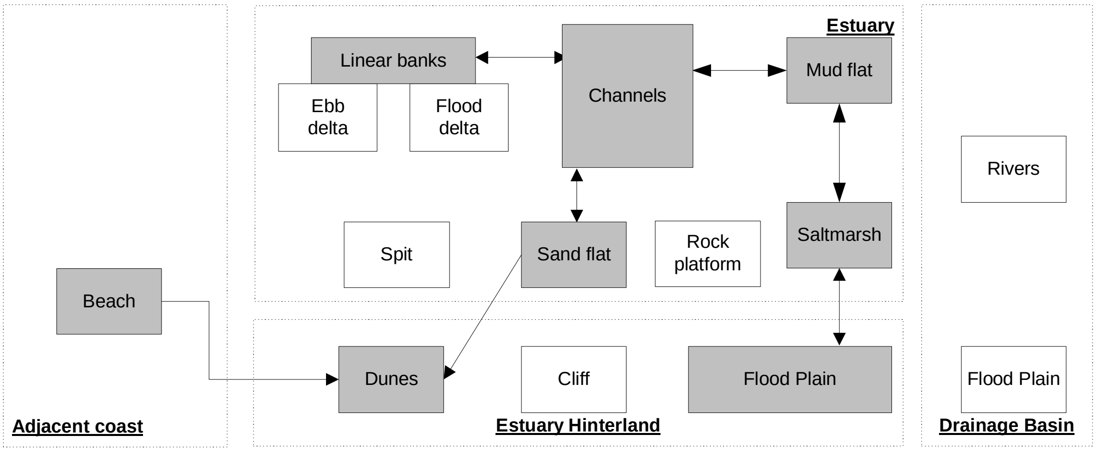


Figure 16. Generic tidal inlet

References

Capobianco, M., de Vriend, H., Nicholls, R. and Stive, M.J.F., 1999, Coastal area impact and vulnerability assessment: the point of view of a morphodynamic modeller, Journal of Coastal Research, 15(3), 701-716.

Chorley RJ, Kennedy BA, 1971, Physical geography: a systems approach, Prentice Hall, Englewood Cliffs.

Cowell, P.J. & Thom, B.G., 1994, Morphodynamics of coastal evolution. In: R.W.G. Carter & C.D. Woodroffe (eds.) *Coastal evolution: late Quaternary shoreline morphodynamics*. Cambridge, Cambridge University Press, pp 33-86.

Cowell, P.J., Stive, M.J.F., Niedoroda, A.W., de Vriend, H.J., Swift, D.J.P., Kaminsky, G.M. & Capobianco, M., 2003, The Coastal-Tract (Part 1): A Conceptual Approach to Aggregated Modelling of Low-Order Coastal Change. *Journal of Coastal Research,* 19(4), 812-827.

EstSim Consortium, 2007, Development and Demonstration of Systems-Based Estuary Simulators. R&D Technical Report FD2117/TR, Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme, 247pp.

Schumm, S.A. & Lichty, R.W., 1965, Space, time and causality in geomorphology. *American Journal of Science* 263, 110-119.

Townend, I.H., 2003, Coast and estuary behaviour systems, In: Davis, R.A. (ed.). *Coastal Sediments '03*: Crossing Disciplinary Boundaries - Proceedings of the Fifth International

Symposium on Coastal Engineering and Science of Coastal Sediment Processes, East Meets West Productions (EMW) Inc., Corpus Christi, USA, pp. 1-14.

van Dongeren, A.R. and de Vriend, H.J., 1994, A model of morphological behaviour of tidal basins. Coastal Engineering, 22, 287-310.

Wang, Z. B., Karssen, B., Fokkink, R. J. and Langerak, A., 1998, A dynamic-empirical model for estuarine morphology, in J. Dronkers and M.B.A.M. Scheffers (eds.), *Physics of estuarine and coastal seas.* Balkema, Rotterdam, pp. 279-286..

White, I.D, Mottershead, D.N., & Harrison, S.J., 1984, *Environmental Systems: An introductory Text*. Chapman & Hall. 616pp.

Wilson, A.G., 1982, *Geography and the environment: systems analytical methods.* John Wiley & Sons, Chichester.