ESTUARY SETTING

There are many types of estuary determined by their geological setting and dominance of particular processes. This chapter:

- Outlines estuary classification and setting according to topographical and geomorphological classification (Figure 3.1);
- Reviews the ways in which estuaries have been classified in the past;
- Describes estuarine processes, which contribute to the changing geomorphology of an estuary, and assist in the definition of estuary classification;
- Discusses estuarine geomorphological characteristics;
- Summarises estuarine characteristic parameters including estuary length, tidal prism, cross sectional areas and sedimentology;
- Discusses the form and function of an estuary according to controls and constraints of estuary characteristics and process.

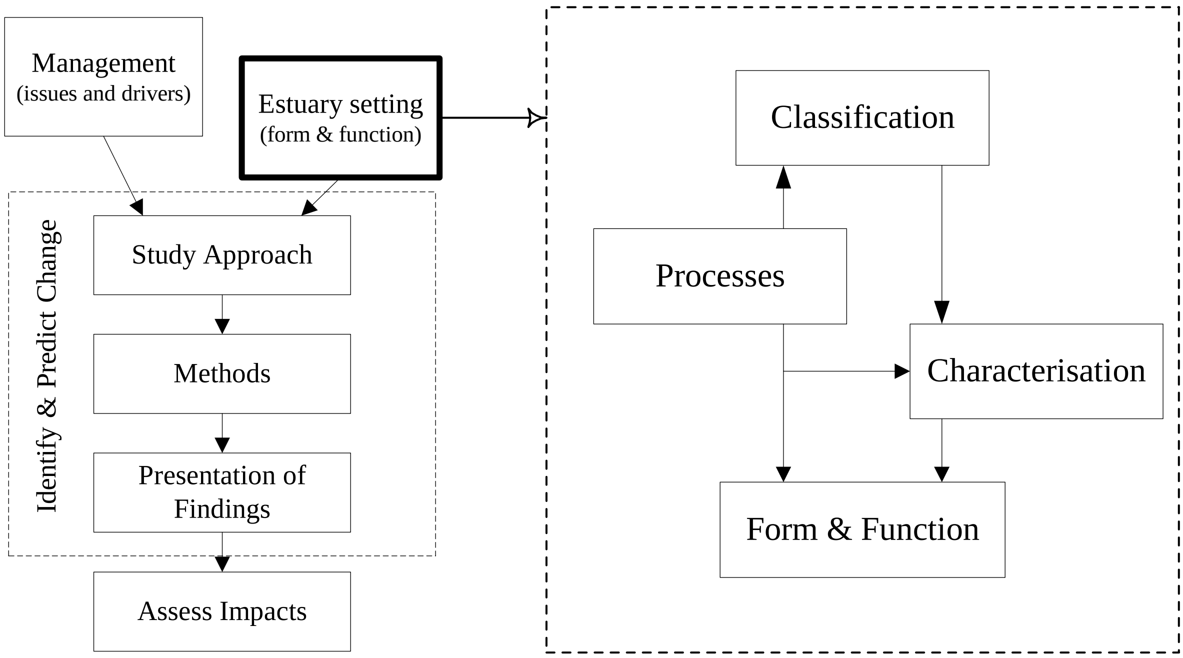

Figure 3.1 Flow diagram of estuarine setting

Introduction

There are many things that contribute to the form and functioning of an estuary, for example, the size and length of the river catchment, the amount of river flow, the tidal range and geological setting of the estuary (often referred to as the antecedent conditions i.e. what went before). The recent geological record aids the understanding of the behaviour of estuaries. In particular, the period known as the Holocene (approximately the last 10,000 years, going back to the last ice age) is important because this determines the recent history of infilling by sediments. This has occurred as sediments are washed down the rivers, or carried in from the sea by the tide, and dropped in the more tranquil conditions of the estuary. The pre-Holocene geology is usually much harder and defines the basin in which the estuary sits. It may also provide local hard points, such as the "narrows" to be found at the mouth of the River Mersey in England.

Examining the amount of infilling that has taken place over the Holocene allows different types of estuary to be identified. Firstly, there are the deep fjords and fjards found in Scotland, Norway and New Zealand, where any infilling is insignificant and the shape and size of the estuary is entirely dependent on the shape carved out by earlier ice ages. Then there are a group of estuaries known as rias, which are also rock forms, usually carved by rivers or ice melt waters, and now partially infilled. Examples are to be found on the south coasts of Ireland and England and again in New Zealand. There are also three groups that are almost entirely formed within Holocene sediments. All are a result of marine transgression, the first being drowned river valleys, which are referred to as spit enclosed or funnel-shaped estuaries. The second are the embayments, which are river or marine in origin (i.e. not glacial) and where one or more rivers meet at the mouth; and the third are drowned coastal plains where tidal inlets have formed. All three are to be found on the numerous sedimentary coasts around the world.

This progression provides some clues as to how an estuary develops. Clearly there is a progressive infilling taking place that depends on the size of the initial basin and the amount of sediment available (Figure 3.2); either from erosion in the catchment, or supplied from the marine environment. Beyond a certain point, however, a sort of balance is reached and the estuary begins to release sediment, rather than retain it. This is all to do with a bias in the tide. When there is not much sediment present the greater depth at high water means that the tidal wave travels faster at high water than at low water. This helps to bring sediment in from the sea (Dronkers, 1986). However once the mudflats build up so that, even at high tide, water depths are quite shallow, this has the effect of slowing the tidal wave at high water. Clearly, this distortion will have the opposite effect and tend to export sediment from the estuary. As changes take place in the tides, the level of the sea, the flows draining from the rivers and the supply of sediment, so the balance will continuously adjust (Pethick, 1994).

The same progression allows the different types of estuary to be classified and with an appreciation of the dominant processes, a more detailed characterisation of a particular estuary can be undertaken, as explained in the following sections.

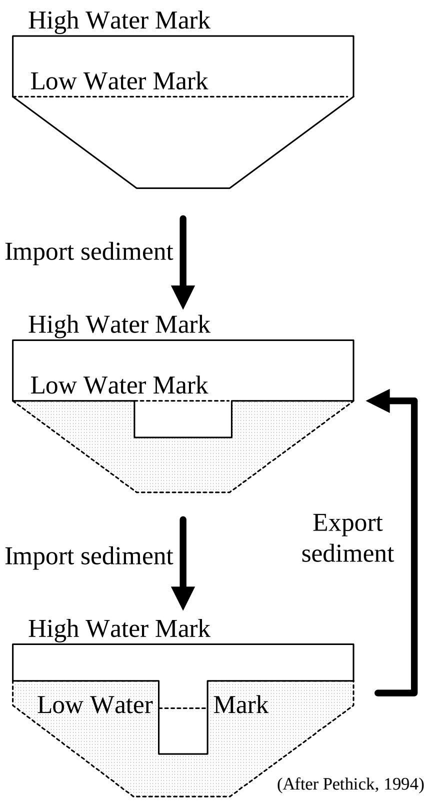

Figure 3.2 Estuary infilling and sediment balance

Estuary Classification

There are many ways in which estuaries have been defined, but by their very nature as places of transition between land and sea, no simple definition readily fits all types of estuarine system. Perhaps the most widely used is that proposed by Pritchard: *"An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage"* (Pritchard, 1967). Pritchard went on to propose a classification from a geomorphological standpoint with four subdivisions: (1) drowned river valleys, (2) fjord type estuaries, (3) bar-built estuaries and (4) estuaries produced by tectonic processes.

A very similar classification was used for the Estuaries Review undertaken in the UK (Davidson *et al.*, 1991). On the basis of geomorphology and topography, estuaries were divided into nine categories: (i) fjord, (ii) fjard, (iii) ria, (iv) coastal plain, (v) bar built, (vi) complex, (vii) barrier beach, (viii) linear shore and (ix) embayment.

Hume and Herdendorf (1988) undertook a review of these and several other classification schemes before developing a scheme to cover the range of estuary types to be found in New Zealand. In this scheme, estuaries are grouped into five classes, according to the primary process that shaped the underlying basin, prior to the influence of Holocene sediment deposits Table 3.1. Within each of these five classes, there is further subdivision based on the geomorphology and oceanographic characteristics of the estuary; tides and catchment hydrology being the two most important.

Table 3.1 Estuary classification proposed by Hume & Herdendorf (1988)

Type	Primary Mode of Origin	Estuary Type	
1	Fluvial erosion	Funnel shaped	
2		Headland enclosed	
3		Barrier enclosed	Double spit
4			Single spit
5			Tombola
6			Island
7			Beach
8		River mouth	Straight bank
9			Spit-lagoon
10			Spit-lagoon
11			Deltaic
12	Marine/fluvial	Coastal embayment	
13	Tectonism	Fault defined embayment	
14	Volcanism	Diastrophic[1] embayment	
15		Volcanic embayment	
16	Glaciation	Glacial embayment	

There is some evidence that these various types can be grouped to reflect the degree to which the antecedent conditions have been altered as a result of Holocene sedimentary processes (Townend *et al.*, 2000). The resultant groupings are as follows (Table 3.2):

Table 3.2 Influence of Holocene sedimentary processes on estuary types

Group	Description	Types
A	Limited or no sedimentary influence	12, 14, 16
B	Relatively "young" systems in terms of Holocene evolution	1, 13, 15
B/C	Fall between Groups B and C possibly because of headland control	2
C	Fully developed Holocene environments	3-11

A more recent classification of UK estuaries (Defra, 2002) has developed the first three geomorphological types identified by Pritchard (1967) by including behavioural type to suggest the following seven subdivisions (note: this excludes tectonic/volcanic origins which are found elsewhere in the world) (Table 3.3):

1 Movement of the earth's crust to produce surface irregularities.

Table 3.3 Defra (2002) Estuary classification

Type	Origin	Behavioural Type
1	Glacial valley	Fjord
2		Fjard
3	Drowned river valley	Ria
4		Spit enclosed
5		Funnel shaped
6	Marine/fluvial	Embayment
7	Drowned coastal plain	Tidal inlet

This classification has been further developed by the EstSim Project (FD 2117, EstSim Consortium, 2007) to identify specific geomorphological elements of UK estuaries in the form of an estuary typology (Table 3.4). This estuary typology has been applied to UK estuary data and developed into a rule base, presented in Table 3.5. The resulting classification for UK estuaries can be found on the EstSim website. Each of the estuary types has been mapped in terms of their key morphological components, termed their geomorphic elements (described below), in Systems Diagrams for UK Estuaries.

Table 3.4 Estuary Typology (modified from Futurecoast; Defra, 2002)

Type	Origin	Behavioural Type	Spits[1]	Barrier Beach	Dune	Delta	Linear Banks[2]	Channels[3]	Rock Platform	Sand Flats	Mud Flats	Salt marsh	Cliff	Flood Plain[4]	Drainage Basin
1	Glacial valley	Fjord	X					X	X	X			X		X
2		Fjard	0/1/2					X	X	X	X	X		X	X
3	Drowned river valley	Ria	0/1/2					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
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		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] Linear Banks: considered as alternative form of delta.
[3] Channels: refers to presence of ebb/flood channels associated with deltas or an estuary subtidal channel.
[4] Flood Plain: refers to presence of accommodation space on estuary hinterland.

Table 3.5 EstSim rules to Identify Estuary Type Using the UK Estuaries Database

Type	Behavioural Type	Rule
1	Fjord	Glacial origin, exposed rock platform set within steep-sided relief and with no significant mud or sand flats
2	Fjard	Glacial origin, low lying relief, with significant area of sand or mud flats
3	Ria	Drowned river valley in origin, with exposed rock platform and no linear banks
4	Spit-enclosed	Drowned river valley in origin, with one or more spits and not an embayment
5	Funnel-shaped	Drowned river valley in origin, with linear banks or no ebb/flood delta and not an embayment
6	Embayment	River or marine in origin (i.e. not glacial), with multiple tidal rivers meeting at or near mouth and a bay width/length ratio[1] of 1 or greater, and no exposed rock platform
7	Tidal inlet	Drowned coastal plain in origin, with barrier beaches or spits

Note:
[1] Where bay extends from sea opening to the confluence of the rivers

Such classifications provide a broad description of the type of estuary and are particularly relevant when considering the likely functioning of an estuary using regime concepts (see section on Study Methods). However, estuaries also contain a number of other distinct features, which distinguish them from marine and terrestrial habitats. For instance, they generally contain wetlands that form at the margins of the land and the sea, and are unique in that they link marine (subtidal and intertidal), freshwater and terrestrial ecosystems. On the seaward side are banks, shoals, sand flats, mud flats and saltmarsh habitats, which link to fringing habitats such as sand-dunes, shingle ridges and coastal marshes, in turn linking to progressively less saline terrestrial habitats, such as freshwater marshes and coastal grassland, in a landward direction.

Characteristic features of estuaries include:

(i) Extensive intertidal areas including saltmarshes, mudflats and sand flats;
(ii) Semi-diurnal or diurnal tidal regime;
(iii) Wave shelter;
(iv) Water layering and mixing;
(v) Temperature and salinity gradients;
(vi) Sediment suspension and transport;
(vii) High productivity;
(viii) High levels and rapid exchange of nutrients;
(ix) The presence of plants and animals particularly adapted to these conditions; and
(x) The presence of migrant and seasonally fluctuating populations of animals (particularly birds).

Within EstSim (EstSim Consortium, 2007) the physical features of estuaries have been classified into the following units:

- Cliffs;
- Barrier beaches;
- Spits;
- Dunes;
- Deltas;
- Rock platforms;
- Mudflats;
- Sandflats;
- Saltmarsh; and
- Drainage basin.

A generic description of each of the above elements can be found in Estuary Geomorphic Elements under the following headings:

- **Definition of Geomorphic Element (GE):**
  Providing an overall definition of the GE in question through for example, a description of the key aspects of the form, formation, processes or location within an estuary system;

- **Function:**
  Defining the role of the GE within the physical system in terms of exchanges of energy and mass;

- **Formation and Evolution:**
  Providing details of the processes that lead to the formation of the particular GE and how the GE develops and evolves over time;

- **General Form:**
  Describing the characteristic shape (or component shapes) of the GE, where appropriate highlighting the prevailing conditions under which a particular form will be adopted;

- **General Behaviour:**
  The general behaviour of the GE is described in terms of how the GE may respond to the varying forcing to which it can be exposed;

- **Forcing Factors:**
  This section describes the key processes (for example, wave attack) responsible for shaping the GE, with details provided where appropriate of role of the forcing processes;

- **Evolutionary Constraints:**
  This section details the factors that may alter or constrain the development of the GE leading to a differing evolution due to that constraint;

- **Behavioural Timescales:**
  As discussed above, landforms will respond to forcing over a range of time and space scales, and will exhibit characteristic responses of differing scales. For each GE, the behaviour of the element is discussed over different timescales; and

- **Interactions with Other Geomorphic Elements:**
  Each GE will be linked to other GEs present within a particular estuary system. This section identifies the interactions in terms of flows of energy and/or matter between GEs. Interactions are identified and discussed either in terms of general interactions (for both elements within the estuary system and external to the estuary system) or interaction with specific geomorphic elements.

Estuary Processes

The prevailing processes in the estuary clearly determine many of these characteristic features. It is therefore important to have a sound appreciation of what processes one might expect to find and how to go about determining the relative importance of the different processes. Fortunately this is an area that has been the subject of considerable research and as a result there is a lot of background information available. A good starting point is a number of standard texts on the subject of which there are many. For example, from a physical perspective the books by Ippen (1966), McDowell & O'Connor (1977), and Dyer (1997) provide a useful introduction and from a more geomorphological perspective, books by Pethick (1984), Carter (1988), and Carter and Woodroffe (1994) have chapters on estuaries.

The estuary is an area of transition from the tidal conditions seaward to the freshwater flows from landward. Not only does this involve a change from the reversing tidal flow to the uni-directional river flows upstream, but there is also a transition from saline to freshwater conditions. As saline and freshwater bodies meet, mixing takes place, to a greater or lesser degree, and can give rise to a marked interface between the two bodies and the occurrence of internal waves on the interface between the two. Such salinity gradients can also set up density flows, which can be directed both along and across the estuary depending on the size of the estuary. These water movements are further complicated by the presence of surface waves. As well as waves formed within the estuary, waves can also be generated externally (i.e. offshore) and propagate into the estuary.

The complexity of water movements is reflected in the sediment transport pathways within the system. Sediments can be supplied from marine or freshwater sources. In some estuaries, sediment is brought down rivers when they are in flood, and in from the sea during periodic storms. There can be a high degree of sediment reworking within an estuary, and erosional and depositional shores can exist in close proximity. Although many intertidal mudflats and sand flats appear relatively stable at least in the medium term, such areas can be quite dynamic, with deposition and erosion taking place at comparable rates and leading to a form of dynamic equilibrium. Sediments can be cycled on a variety of timescales, for example, changes in the configuration of channels and bed forms can occur over periods as short as days, whilst also responding to longer-term effects such as changing sea levels. The feedback between accretion, water movements and sediment transport is expressed schematically in Figure 3.3.

Estuaries are often characterised by the deposition of fine sediment. This means that the movement of fine material (sand and mud) is a crucial component of estuarine sediment pathways and this will often be superimposed on the movement of coarser sand fractions. Hence, the variety of environments and sediment sources, coupled with the linkage between erosion and accretion in different areas in the same estuary, highlight the need to consider the estuary system as a whole.

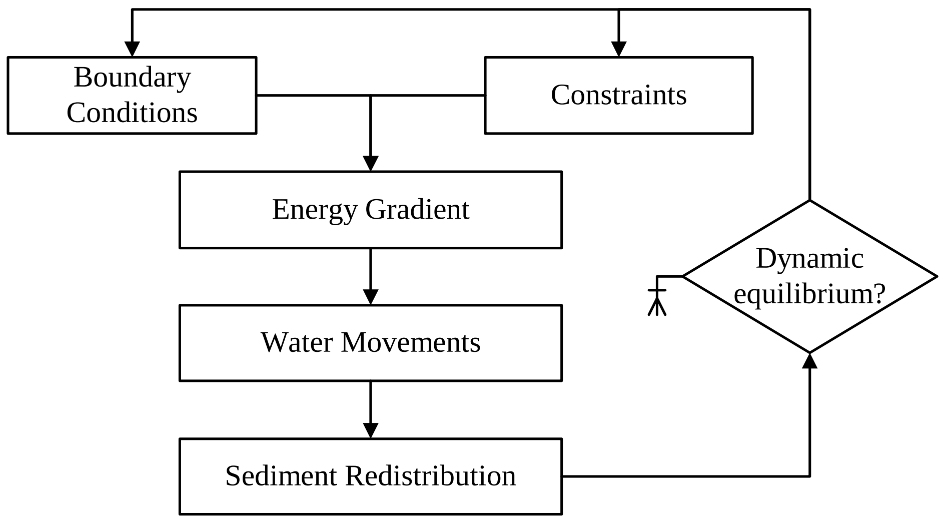

Figure 3.3 Simplified representation of morphological model

Estuary Characterisation

There are a number of measures that do not require detailed modelling but collectively convey a great deal about the type of estuary. These can be as simple as an examination of the length and depth compared to the tidal range, the plan form in terms of variation of width along the estuary or the dimensions of any meanders. The following tables set out some of the properties which, collectively, can be used to characterise an estuary (Dun & Townend, 1998). The first table defines a range of measured, or observed, properties, Table 3.6. These are often supplemented with a number of interpreted or derived properties that express particular attributes of the system, particularly in relation to equilibrium or steady state concepts as summarised in Table 3.7.

Table 3.6 Summary of measured estuary properties

Property	Definition or Reference
Lengths	Usually overall and to key change points (e.g. from mouth to tidal limit).
Plan Areas	Helps to include area of catchment and floodplain as well as estuary area at various elevations. Features such as saltmarsh and intertidal may also be analysed individually.
Cross-sectional areas	Typically at the mouth and tidal limit.
Volumes	Usually in terms of volume below a given level (e.g. MHW, MLW) and the volume of the tidal exchange (prism). Useful to also examine variation with chainage.
Widths and Depths	Indicative values at mouth, tidal limit and as an average over estuary length.
Tidal levels and range	Spring and neap values at locations along the estuary.
Freshwater flows	Magnitude of annual mean daily flow rate and peak values.
Geology	Usually mapped from available borehole records and provides essential information on potential constraints to long-term change.
Geomorphology	Mapped from maps, charts, aerial photographs, remote sensing images and field survey data to show all major forms - includes features such as saltmarsh, mudflat, cheniers, spits and nesses, bed forms, artificial channels and reclamations, ridges, cliffs, dunes, etc.
Sedimentology	Surficial sediments need to be characterised to assess sediment sources, sinks and transport regimes (McLaren & Bowles, 1985).

Table 3.7 Summary of derived estuary properties

Property	Definition or Reference
Form descriptions	Parameters for variation of width, depth and cross-sectional area to power and exponential law descriptions, see (Prandle & Rahman, 1980; Prandle, 1985).
Estuary number	Indicates degree of stratification (Ippen, 1966).
Tidal wavelength (λ)	Simplistically this can be obtained using linear wave theory and either the depth at the mouth or the average depth. Ippen (1966) gives a method of computing the wave number and hence the wavelength for a standing wave, including friction. This gives a very rough indication of possible tidal resonance ($\lambda/4$) but methods using the shape functions are more reliable (Prandle, 1985)..
Tidal constituent ratio's	The diurnal/semi-diurnal ratio indicates the dominant duration of the tidal cycle (McDowell & O'Connor, 1977). An examination of the M_4 to M_2 ratios (magnitude and phase) also gives a useful measure of the importance of non-linear effects within the estuary, (Friedrichs & Aubrey, 1988).
Tidal asymmetry	Examination of the duration and magnitude of flood and ebb velocities, together with timing of slack waters provides a useful indication of potential movement of coarse and fine sediments and the type of tidal basin (Dronkers, 1986; Dronkers, 1998).
Hydraulic geometry relationships	Measures of form against discharge or tidal prism properties (usually derived from a model and/or measurements) - tidal prism v cross-sectional area (O'Brien, 1931; Gao & Collins, 1994), plan area v volume (Renger & Partenscky, 1974) and hydraulic geometry or regime relationships (Langbein, 1963; Spearman *et al*., 1998).

An example of the sort of information that can be extracted is given in Table 3.8. This presents the data for the Humber Estuary in the UK and both measured and derived information are presented in the same table to provide an overview. Where more detailed information on water levels, currents, salinity gradients and suspended sediment loads are available it is possible to elaborate on many of these descriptions. As a simple example, where water levels over a tidal cycle are available at intervals along the estuary, by overlaying them it may be possible to get an immediate impression of how the tidal wave alters as it propagates upstream. If high and low waters occur at about the same time and there is little distortion taking place this is characteristic of a standing wave. Where high waters are delayed in an upstream direction, the characteristic is closer to a progressive wave. Marked amplification and asymmetry further indicate that there are significant shallow water effects. If information on tidal currents is also available this can be used to examine various measures of tidal asymmetry in more detail (see section on asymmetry in Study Methods).

Table 3.8 Key characteristics for the Humber Estuary

Property	Values for the Humber
Lengths	To Trent Falls, 62km; to tidal limit on R Trent, 147km
Plan Areas	Catchment area = 23,690 km^2; Flood plain area = 1,100 km^2 Plan area @ HW = 2.8 x 10^8 m^2; @ LW = 1.8 x 10^8 m^2 (*) Intertidal area = 1 x 10^8 m^2 (*); Saltmarsh area = 6.3 x 10^6 m^2 (*) (* between Spurn and Trent Falls)
Cross-sectional areas	CSA @ mouth = 85538 m^2 to mtl
Volumes	Total volume @ HW = 2.5 x 10^9 m^3 and @ LW = 1.1 x 10^9 m^3 Tidal prism, springs = 1.5 x 10^9 m^3 and neaps = 0.8 x 10^9 m^3.
Widths and Depths	Width @ mouth = 6620 m; hydraulic depth @ mouth = 13.2 m Width @ tidal limit = 52 m; hydraulic depth @ tidal limit = 2.9 m Average width = 4265 m; average hydraulic depth = 6.5 m
Form descriptions	Area=84·exp(6.7·x/l); r^2 = 0.99; Width=198·exp(3.7·x/l); r^2 = 0.89; Depth=0.55·exp(3·x/l); r^2 = 0.91 (Length, l=145 km)
Tidal levels and range	MHWS = 3.0; MHWN = 1.6; MLWN = -1.2; MLWS = -2.8 (all levels metres Ordnance Datum Newlyn at Bull Sand Fort)
Freshwater flows	Average flow = 240 m^3/s; High flow = 1600 m^3/s
Estuary number	Average fresh water flow, springs = 3.43; neaps = 0.75 High fresh water flow, springs = 0.52; neaps = 0.11 (cf E > 0.09 indicates progressively well mixed conditions, (Ippen, 1966)
Tidal wavelength	Using linear theory (i) with depth at mouth, λ = 500 km; (ii) with average depth, λ = 350 km
Tidal constituent ratio's	F=0.06 i.e. tide is semi-diurnal (o[0.1] semi-diurnal, o[10] diurnal) M_4/M_2 amplitude = 0.003; $2M_2$-M_4 phase = 223 at mouth M_4/M_2 amplitude = 0.25; $2M_2$-M_4 phase = 52 at Burton Stather on R. Trent. (i.e. significant sea surface distortion and ebb dominance at the mouth changing to flood dominance upstream)

Property	Values for the Humber	
Tidal asymmetry	Dronkers gamma -1 = -0.05; 0.13; 1.51 Net excursion* = -1.35; -10.35; -0.9 km Net slack duration+ = 0.18; 0.22; 0 hrs Values are for Spurn, Hull and Trent Falls. Positive values indicate flood dominance.	Indicates dominance for: - tidal equilibrium - coarse sediment - fine sediment Thresholds used: * >0.9m/s; + <0.2m/s
Hydraulic geometry relationships	CSA/tidal prism = 5.7 x 10^{-5} m^{-1} (springs) and 1 x 10^{-4} m^{-1} (neaps) LW volume/HW plan area^2 = 1.32 x 10^{-8} m^{-1} LW plan area/HW plan area$^{1.5}$ = 3.8 x 10^{-5} m^{-1} Discharge exponents: Mean velocity, m = 0.1 (r^2=0.39) Width, b = 0.48 (r^2=0.85) Mean depth, f = 0.41 (r^2=0.91) Energy slope, z = -0.2 (r^2=0.89)	
Geology	See Jones (1988); BGS (1982), and Humber Holocene chronology (ABPmer, 2003)	
Geomorphology	See McQuillin *et al.* (1969)	
Sedimentology	See McQuillin *et al.* (1969)	

Form and Function

Whilst classification, as discussed above, says something of the origin of an estuary, and the characterisation sets out some important properties, neither fully explains the observed form. For this we need to consider what is the purpose, or function, of an estuary and how does this influence the ensuing form? Fairbridge (1980) defines an estuary as "*an inlet of the sea reaching into a river valley as far as the upper limit of tidal rise*". In general, there is no forcing that creates an inlet from seaward. Rather, antecedent conditions give rise to low-lying land within a valley that as sea level rises can be flooded from seaward. Such valleys can be formed by a number of different processes as indicated in Table 3.1. Alternatively, river flows cut a channel to the sea, which as the channel grows in size, or the river deposits sediments to form a tidal delta, progressively allows greater penetration from the sea.

For inlets and estuaries around the world, the tide and river flows can each vary from being dominant to non-existent. Hence there is a spectrum that encompasses the full range of possible interactions. The function of the estuary is to accommodate this interaction and in doing so its form must reflect this role. Of course superimposed on this are other functions, more typical of any water-land interface, where, for instance, the action of waves and current give rise to characteristic forms for the beaches or banks.

The inflow from rivers and the movement of tides give rise to sediment transport in and out of the estuary. Thus the estuary functions as an open system with exchanges of energy, water and sediment with the surrounding systems (catchment and open sea). However in transporting water and sediment there are inevitable losses of energy due to dissipative processes, such as friction and heat loss. As such, this type of open system continuously expends energy and the ceaseless flow of energy gives rise to a dynamic 'steady state', taking the place of equilibrium (or steady state) (Thompson, 1961). The various forms of equilibria are illustrated in Figure 3.4. This dynamic steady state is itself transient simply because the inputs from external environments change and the constraints on the system also change as the estuary develops (e.g. the solid geology may vary).

The time taken to respond to a given perturbation will also vary for individual features and this will tend to introduce lags into the system. Consequently, it is more probable that the system will be in transition, moving towards a steady state, rather than in a steady-state condition.

In other words, it is a juxtaposition of:

(i) the behaviour of the component parts, each seeking their own target state, but subject to changes in linked components; and
(ii) the mix of space and time scales.

Thus, when discussing system states (of whatever form: equilibrium, steady, dynamic, quasi, etc), there is a need to be very clear about which parts of the system are involved and over what timescale the state is determined.

From this, it can be concluded that the function of the estuary is to accommodate an energy exchange by redistributing water and sediment. At any instant, the prevailing conditions may generate a "target" steady state and the estuary will seek to adjust to achieve this. As the estuary is observed, it may, therefore, be fluctuating about its steady state, or transiting towards the steady state and fluctuating as it does so. Superimposed on this behaviour, will be the changes in input conditions and constraints, which together may:

(i) alter the rate of transition towards a given state,
(ii) cause a switch to different but similar (in form) target state, or
(iii) cause a switch to a different state altogether.

In the context of the entire estuary, the system is searching for an optimum state. To move to a different state would require a major perturbation of the surrounding landform, such as an earthquake, volcanic eruption or glaciation. So it can happen but is very rare. For most purposes and timescales of interest, the estuary form, as a whole, can be considered to be stable. The system will simply continue to adjust its form in response to changes in energy inputs and constraints. These changes are generally internal to the estuary system and as a consequence it is the internal features that exhibit the range of responses outlined as the system searches for an optimum steady state. Thus a progressive increase in river flows might cause channels to enlarge (a transition), whereas a major flood event might cause channel switching (a switch in position), or a switch from meandering to braided channels (a switch in form). The first two are essentially changes in the given state. In contrast, the switch in form is an example of moving to a different state, for the channel feature, but not the estuary as a whole.

This provides a basis for thinking about the overall condition of the system and how specific features within it may behave. However the interaction of processes and form remains something of a conundrum. Although the size and shape of an estuarine channel is a response to tidal processes, it is nevertheless apparent that tidal discharge is itself dependent on the morphology of the estuarine channel since this determines the overall tidal prism. Entering this loop requires some of the constraints in the system to be identified.

One of the principal constraints that defines the size and shape of an estuary must be the antecedent form of the catchment basin, as already discussed. This determines the tidal length of the estuary, a characteristic dimension, which is dependent on the macro-scale slope of the coastal plain, fluvial discharge, and the tidal range in the nearshore zone. The tidal range and morphology within the estuary is then a response to these independent factors.

In some specific cases, further constraints to the closed cause-effect system are present. These constraints may be geological features such as sills, moraines or changes in geological strata, which limit control how the estuary can adjust. Equally, anthropogenic limits to width or depth, such as urban areas or harbour facilities, can constrain how an estuary responds to changing conditions.

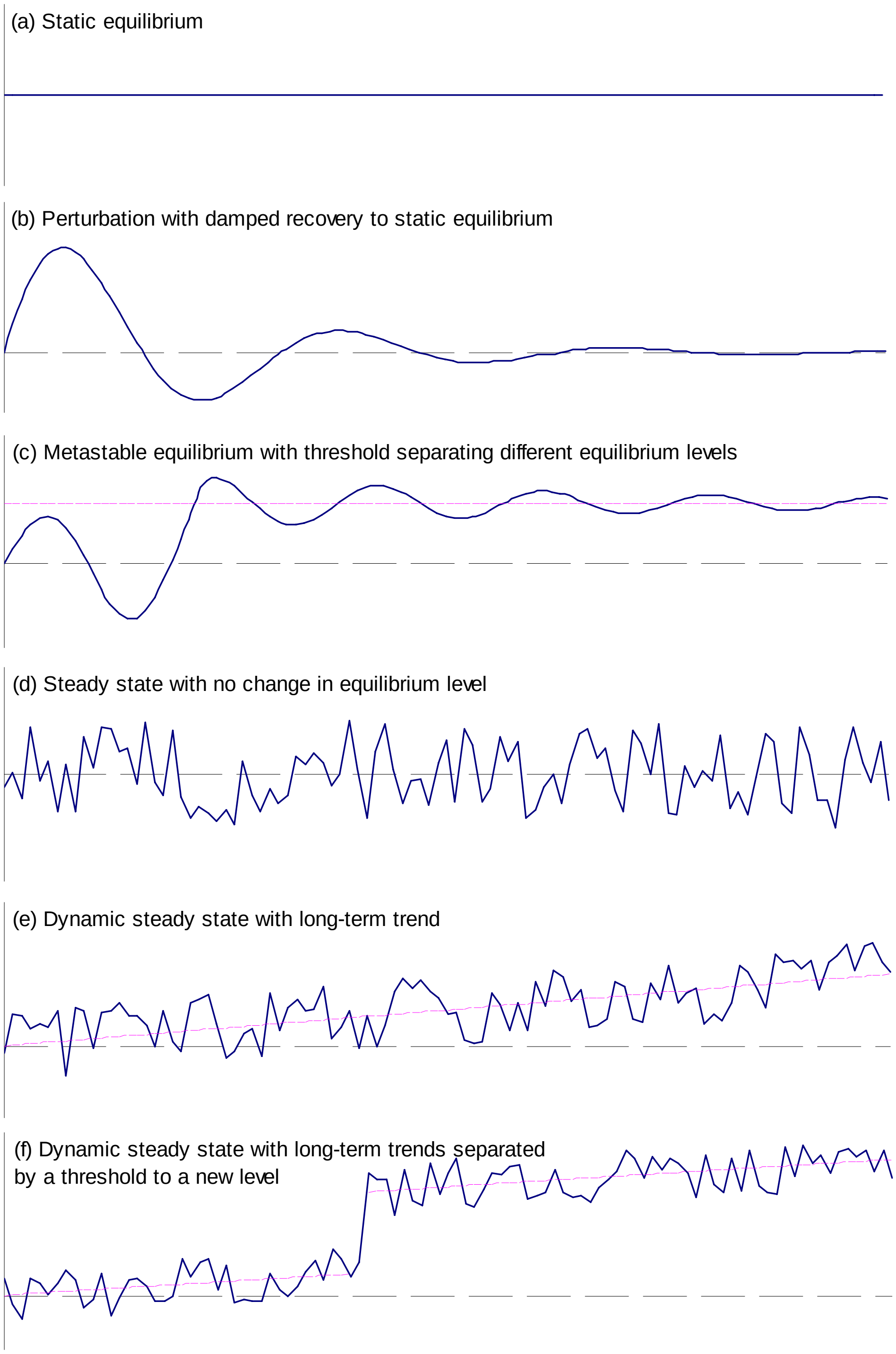

Figure 3.4 Forms of equilibrium (Chorley & Kennedy, 1971)

In each case, the identification of such constraints can be seen as a method of reducing the number of degrees of freedom and providing a point of entry into the cause-effect feedback loop. It is for this reason that developments within an estuary need to be considered in terms of both their local and estuary wide impacts (Pontee & Townend, 1999). Consequently, when examining development proposals or new activities, it is essential that the local and estuary wide implications be taken into account.

Given the extensive developments that have taken place in and around estuaries, there are now moves to restore the natural system or to "design" a natural estuary. An estuary forms a mix of habitats depending on the prevailing constraints. If the constraints are changed, then the estuary will adjust to establish a new dynamic equilibrium, consistent with the existing and new constraints. In order to "design" a natural estuary, the first stage would involve setting out societal preferences for particular types of habitat, as a basis for determining what constraints should be adjusted. This then runs the risk of establishing an even more artificial situation simply to meet societal preferences. A more preferable approach is, therefore, to take advantage of any opportunity that will increase the room in which the estuary can move, to respond to such things as sea level rise, by removing unnecessary constraints.

References

BGS, 1982, Eastern England from the Tees to the Wash, HMSO, London.

Carter RWG, 1988, Coastal Environments, Academic Press, London.

Carter RWG, Woodroffe CD (Eds), 1994, Coastal Evolution: Late Quaternary shoreline morphodynamics, Cambridge University Press, Cambridge, UK.

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

Davidson NC, Laffoley Dd, Doody JP, Way LS, Gordon J, Key R, Drake CM, Pienkowski MW, Mitchell R, Duff KL, 1991, Nature conservation and estuaries in Great Britain, Nature Conservancy Council, Peterborough, UK.

Defra, 2002, Futurecoast, Halcrow, Defra CD-Rom, 3 Vols.

Dronkers J, 1986, Tidal asymmetry and estuarine morphology, Netherlands Journal of Sea Research, 20(2/3), 117-131.

Dronkers J, 1998, Morphodynamics of the Dutch Delta, In: Dronkers J, Scheffers MBAM (Eds.), Physics of Estuaries and Coastal Seas, Balkema, Rotterdam, pp. 297-304.

Dun R, Townend IH, 1998, Contemporary estuary morphology and long-term change, In: Littoral '98, Suport Serveis, SA, Barcelona, pp. 281-293.

Dyer KR, 1997, Estuaries: A Physical Introduction, John Wiley and Sons Ltd, Chichester, 2nd Edn. 195pp.

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.

Fairbridge RW, 1980, The estuary: its definition and geodynamic cycle, In: Olausson E, Cato I (Eds.), Chemistry and biogeochemistry of estuaries, John Wiley, Chichester.

Friedrichs CT, Aubrey DG, 1988, Non-linear tidal distortion in shallow well-mixed estuaries: a synthesis, Estuarine Coastal and Shelf Science, 27(5), 521-546.

Gao S, Collins MB, 1994, Tidal inlet equilibrium in relation to cross-sectional area and sediment transport patterns, Estuarine Coastal and Shelf Science, 38(2), 157-172.

Hume TM, Herdendorf CE, 1988, A geomorphic classification of estuaries and its application to coastal resource management, Journal of Ocean and Shoreline Management, 11, 249-274.

Ippen AT, 1966, Estuary and Coastline Hydrodynamics, McGraw-Hill, New York.

Jones NV, 1988, A Dynamic Estuary: Man, Nature and the Humber, Hull University Press.

Langbein WB, 1963, The hydraulic geometry of a shallow estuary, Bulletin of Int Assoc Sci Hydrology, 8, 84-94.

McDowell DM, O'Connor BA, 1977, Hydraulic Behaviour of Estuaries, The Macmillan Press.

McLaren P, Bowles D, 1985, The effects of sediment transport on grain-size distributions, Journal of Sediment Petrology, 55(4), 457-470.

McQuillin R, Arnold SE, Tully MC, Hull JH, 1969, Cruise Report, Humber Investigations, 1968, Institute of Geological Sciences, Keyworth, Report No: 69/3, 1-22.

O'Brien MP, 1931, Estuary tidal prism related to entrance areas, Civil Engineering, 1(8), 738-739.

Pethick JS, 1984, An introduction to coastal geomorphology, Edwin Arnold, London.

Pethick JS, 1994, Estuaries and wetlands: function and form. In: Wetland Management, Thomas Telford, London, pp. 75-87.

Pontee NI, Townend IH, 1999, The development of a framework for estuary Shoreline Management Plans, In: Coastal Management: Integrating Science, Engineering and Management, Thomas Telford, pp. 117-126.

Prandle D, 1985, Classification of tidal response in estuaries from channel geometry, Geophys.J.R.astr.Soc., 80, 209-221.

Prandle D, Rahman M, 1980, Tidal response in estuaries, Journal of Physical Oceanography, 10(10), 1552-1573.

Pritchard DW, 1967, What is an estuary: physical viewpoint, In: Lauff GH (Ed.), Estuaries, American Association for the Advancement of Science, Washington DC, pp. 3-5.

Renger E, Partenscky HW, 1974, Stability criteria for tidal basins, In: 14th International Coastal Engineering Conference, American Society of Civil Engineers, pp. 1605-1618.

Spearman JR, Dearnaley MP, Dennis JM, 1998, A simulation of estuary response to training wall construction using a regime approach, Coastal Engineering, 33(2-3), 71-90.

Thompson DW, 1961, On growth and form, Cambridge University Press, Cambridge.

Townend IH, Wright AP, Price DM, 2000, An investigation of the gross properties of UK estuaries, Report TR 111, EMPHASYS Consortium, Modelling Estuary Morphology and Process, Final Report, HR Wallingford, Wallingford, Report No: Paper 12, 73-81.