ESTUARY GEOMORPHIC ELEMENTS

Textural descriptions for each of the eleven geomorphic elements, based on the structure presented in Coast and Estuary Behaviour Systems. Each geomorphic element is represented by a systems diagram, which covers the short to medium-term and medium to long-term.

1. Behavioural Description for Cliffs

1.1 Definition of Geomorphological Element

Cliffs are defined as vertical or steeply sloped faces, forming a distinct break in slope between the land and the shore. Sea cliffs can be found along the open coast, sometimes close to an estuary mouth, and glacially formed cliffs can form the boundaries of some types of estuary valley. Coastal slopes (or bluff) are similar, but of a generally lower gradient. Both types of feature can be active (i.e. exposed to marine action) or relict (i.e. formed during previous stages of (higher) relative sea level history and now left stranded).

It is important to note that sea cliffs and slopes are not only affected by marine action (e.g., waves, tides and currents acting at their toe), but also by sub-aerial (weathering) and sub-surface (groundwater) processes which act upon the slope above the limit of wave action. Indirectly, sea spray may affect the sub-aerial processes; indicating the complexities associated with gaining an understanding of the processes to which a sea cliff or coastal slope may be exposed.

1.2 Function

In terms of their primary function within an estuary, cliffs act as a boundary to the overall system. Within certain types of estuary valleys, the cliff or coastal slope may limit the extent of marine inundation (and by implication, may impede transgressive 'rollover' of the estuarine intertidal during a rise in sea level).

In addition to this, cliffs can also supply sediment to an estuary system, although this is very much dependant on the nature of the cliff and the degree of exposure. This function dictates that cliffs are, by their very nature, an erosional landform.

1.3 Formation and Evolution

Cliff or slope recession is initiated when the stresses acting on the feature exceed the shear strength of the material. This situation may arise due to a combination of a number of factors. In basic terms, these comprise external factors which may exist or occur which increase the shear stresses applied or internal factors which may exist or arise which result in a decrease in the shear strength of the material.

Evolution is also highly dependent on the rate of supply of material to the cliff or slope toe from the face relative to the rate of removal of this debris by wave or tidally-induced currents at the cliff base. The variations in resultant form of cliffs can be illustrated by considering two extreme scenarios. Firstly, in a system where the rate of supply of debris is considerably greater than the rate of its removal from the cliff base, debris material will accumulate over a period of time. This results in the creation of a talus slope with a profile angle consistent with the angle of repose of the debris material. This form is produced most frequently in sea cliff systems that experience a rotational mass movement and the overall sea cliff slope angle decreases as a result.

In the opposite extreme case, where the rate of material input from sea cliff erosion is considerably less than the rate of removal of debris from the cliff toe, the sea cliff slope will retreat whilst generally maintaining a constant slope profile angle. The actual slope angle and rate of retreat will depend upon the lithology of the material of which the cliff is comprised. An example of the typical recession rates in rock materials of different lithology is presented in Table 1.

Table 1. Typical recession rates of cliffs composed of different materials (After Sunamura, 1983)

Cliff Composition	Typical Recession Rate (m per year)
Granite	< 0.001
Limestone	0.001 to 0.01
Shales	0.01
Chalk	0.1 to 1
Tertiary sedimentary (sandstone, mudstone)	0.1 to 1
Quaternary sedimentary	1 to 10
Recent volcanic	10 to 100

The strength of the rock plays an important role in the pattern and rates of cliff or slope erosion throughout the UK. For example, in broad terms, the sea cliffs formed of relatively hard rock comprise a steep face and are presently retreating very slowly where marine erosion and cliff recession are of limited frequency and often small-scale. Such cliffs may be fronted by a boulder apron, narrow beach, rock platform or plunge directly into deep water. In contrast, intense marine erosion and cliff recession rates occur on the unprotected cliffs or coastal slopes formed of soft sedimentary rocks and glacial (drift) deposits along the south and east coasts of England.

1.4 General Form

It has been suggested (MAFF, 1996) that for a particular geological setting and set of environmental conditions there will be a characteristic set of recession processes (cliff behaviour) giving rise to characteristic cliff forms, as defined below and illustrated in Figure 1 below:

1.4.1 Simple cliff face systems

These systems are generally characterised by a steep cliff face, narrow foreshore zone and rapid removal of toe debris. Erosion typically occurs as rockfalls, topples or slides from which material is deposited directly on the foreshore.

1.4.2 Simple landslide systems

These systems are first time failures in previously un-sheared ground, or repeated failures in recently sheared ground. Toe erosion of cliff debris leads to oversteepening of the cliff face and a deep-seated rotational slide develops.

1.4.3 Composite systems

These systems typically comprise inter-bedded hard and soft rocks. This can generally be as either soft rock caps resting on hard rock or as hard rock caps resting on softer rock. The latter case presents greater sensitivity to recession.

1.4.4 Complex systems

These systems comprise a series of sub-systems, such as scarp and bench features, within the cliff. Each sub-system has its own input, storage and output of material, whereby the output from one sub-system forms a cascading input to the next. There can be some considerable time lag before material reaches the cliff toe.

1.4.5 Relic systems

These systems comprise sequences of pre-existing landslides, which are presently subject to relatively little recession, but could be susceptible to re-activation due to debris removal, foreshore lowering or increasing pore water pressure.

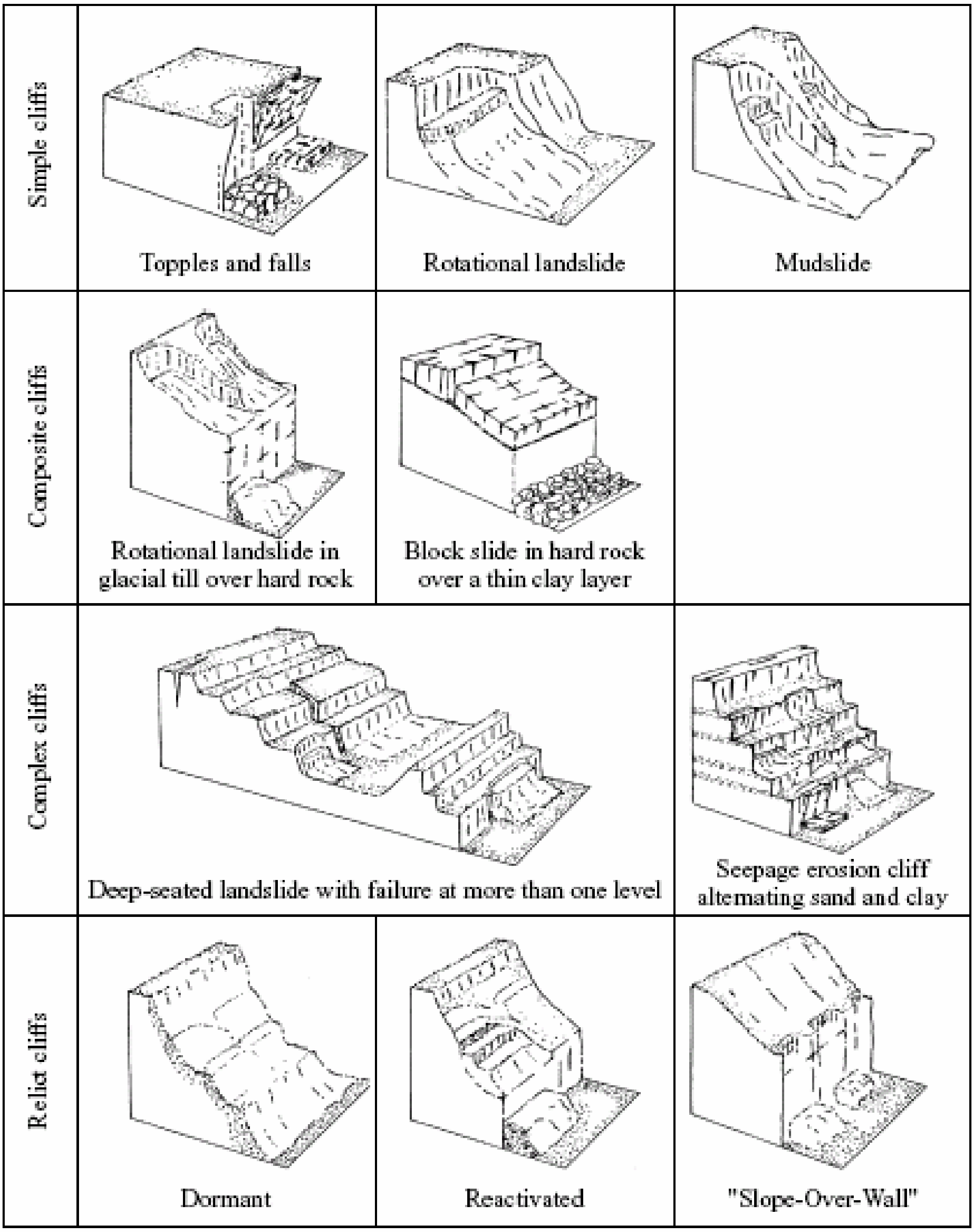

Figure 1. **Characteristic cliff behaviour unit types (MAFF, 1996)**

1.4.6 Sub-features - Caves, arches and stacks

Differential erosion between relatively resistant and relatively erodable cliff materials can result in the creation of caves, arches, stacks and other related sub-features. Such features often are the result of accelerated erosion along structural weaknesses, particularly bedding, joint and fault planes, and in the fractured and crushed rock produced by faulting. These features form in rocks, which, despite containing weaknesses, have sufficient inherent strength to stand as near vertical faces, or as the roofs of caves (Trenhaile, 1997).

1.5 General Behaviour

In general terms, sea cliff behaviour displays a number of important components. Firstly, unstable conditions will be created within the cliff, possibly due to any one, or any combination, of the following: foreshore lowering and undercutting of the slope base by marine action, possibly leading to over-steepening of parts of the cliff face; sub-aerial weathering; increase in groundwater pressure). Following “triggering events” such as storms and/or intensive rainfall, material becomes detached from the cliff and is transported, via a number of potential mechanisms, to the foreshore near the cliff base. This debris is deposited and accumulates, providing a degree of protection to the cliff base against direct wave action until, ultimately it is removed by marine processes and re-distributed elsewhere within the coastal system.

Unlike many other coastal landforms (e.g. beaches, tidal flats), sea cliffs cannot experience regression (a seaward advance of the landform whilst maintaining a constant profile through the deposition of sediments) in response to changing environmental conditions.

Sea cliff recession will depend upon a number of factors, which may:

- Promote mass movement of cliff material; and
- Control the rate of removal of debris from the cliff base.

1.6 Forcing Factors

The principal forcing factors are marine erosion, weathering and groundwater conditions.

The amount of marine erosion is dependent upon the balance between the shear strength of the material in the cliff or slope and its exposure to waves and tidal currents, which generate shear stresses. The magnitude of these stresses is dependent on the exposure of the site, which is governed by the offshore conditions, its water depth and nearshore topography, and the degree of protection offered by the fronting inter-tidal area (e.g. inter-tidal beach or flat, shore platform).

Weathering can take two main forms, namely corrosion (the chemical alteration (or decomposition) of the rock by salt water) and corrosion (the mechanical weathering (or disintegration) of the rock by abrasion). Mechanical weathering may more rapidly break down large pieces of rock, which then become subjected to increased rates of chemical weathering. Mechanical weathering may be caused by a number of factors (e.g. mechanical loading/unloading; thermal loading/unloading (e.g. cycles of freeze and thaw); wetting and drying cycles; pressure effects from salt crystal growth; and root wedging. Chemical weathering too may be caused by a number of factors (e.g. solution; oxidation; reduction; hydration; hydrolysis; leaching; cation-exchange), which serve to alter rock crystals, sediment grains or the cements, which bind grains together (Blyth & de Freitas, 1984). In combination, these may:

- Create fissures and enlarge joints, thereby reducing the strength of the cliff-forming materials;
- Create pathways for the ingress of water into soft rocks, thereby aiding in the process of decomposition;
- Cause small movements which tend to reduce shear strength;
- Provide sufficient stresses to trigger failure.

Changes in groundwater conditions within certain types of cliff or slope can be a major triggering factor of landsliding. The voids (or pores) between particles of sediment are filled with fluid (water or air). The pressure of the fluid within the pores can increase due to periods of long and intense rainfall, snowmelt, groundwater seepage, undrained loading, blockage of subsurface water flow, poor surface water disposal and leakages from pipes. This can lead to the promotion of instability within the cliff, although a time lag between the perceived cause and the actual event is common.

In addition, biological factors may also reduce the strength of rocks. Examples include: boring and grazing of coastal rocks by marine organisms, and the growth of plant roots into joints and bedding planes. Biological weathering is rarely a triggering factor in cliff recession, but assists in preparing a cliff for failure by slightly reducing its material strength. It should be noted, however, that biological factors may also enhance stability of soft cliffs, through the binding of material within plant roots. Indeed, stabilisation programmes involving cliff vegetation through the use of engineered swards have been used in southern England (Tyhurst, 1996).

1.7 Evolutionary Constraints

At the most fundamental level, cliff or slope recession is constrained by:

- The strength of the material in the cliff or slope;
- The stresses applied to the cliff or slope; and
- The rate of removal of debris from, or foreshore lowering at, the cliff or slope toe.

1.8 Behavioural Timescales

1.8.1 Short-term (responses within a year)

When considered over the short-term, cliff behaviour appears episodic, complex and uncertain. Behaviour is often characterised over this timescale by no change along many cliff sections with relatively localised failures in one or two particular locations in response to lowering foreshore levels and/or increasing pore water pressure.

1.8.2 Medium-term (responses over decadal to century scale changes)

Over the medium term, more uniform patterns of recession emerge, as the entire cliff appears to move landwards.

1.8.3 Long-term (Responses over decadal to Holocene timescales)

Over the longer-term (e.g. centuries), cliff behaviour may be controlled by larger-scale plan form evolution such as the creation of embayments within headlands.

1.9 Interactions with Other Geomorphological Elements

1.9.1 General interactions (Elements within estuary system)

A proportion of the material released from cliff or slope erosion may be relatively coarse, non-cohesive sand or gravel of a sufficient size and composition to contribute to the debris stock of sediment at the cliff or slope toe. Ultimate re-distribution of this debris may result in material contribution to beach building or feeding of offshore bars, barrier beaches or spits elsewhere in the coastal system. Also, a proportion of the material released from cliff erosion may be fine, cohesive silts and clays of a size and composition which results in their immediate suspension in the water column and transport offshore or along the coast to feed estuaries and their tidal flats and saltmarshes.

It is also important to recognise that cliffs and slopes are also afforded a degree of natural protection against marine action by the fronting inter-tidal zone (beach, tidal flat, rock platform and, occasionally, saltmarsh). These features dissipate, refract and reflect incoming energy (generated by waves and tides) and reduce the amount of energy that reaches the toe of the cliff or slope. A classic study by Savigear (1953) attributed a spatial transition from marine to subaerial cliff profiles within Carmarthen Bay to a progressive reduction in wave energy resulting from the extension of the Laugharne Spit and the growth of saltmarsh. Alternatively, the presence of coarse sediment within the breaker zone may reinforce wave erosion as a positive feedback mechanism.

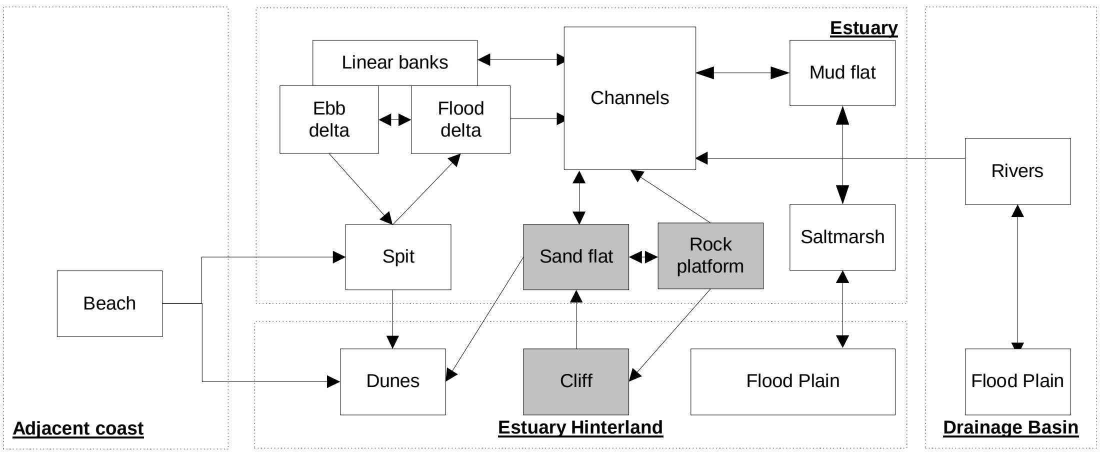

Figure 2. Interaction with other elements - Cliff

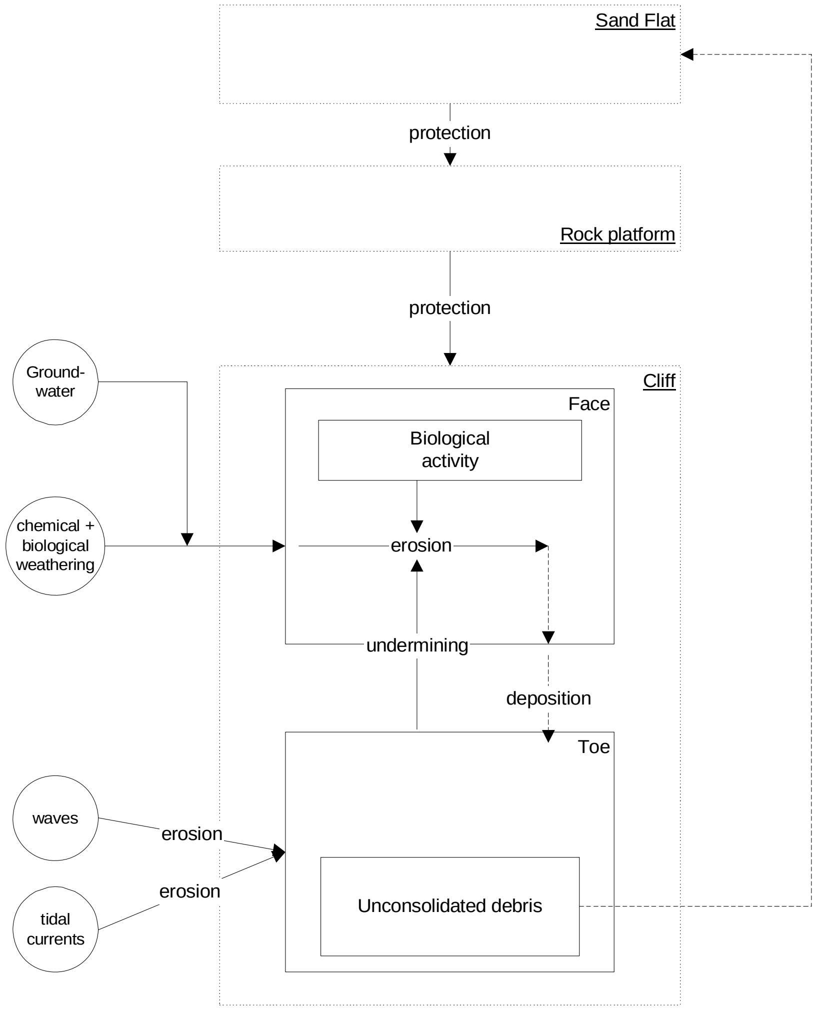

Figure 3. Short to medium term system diagram - Cliff

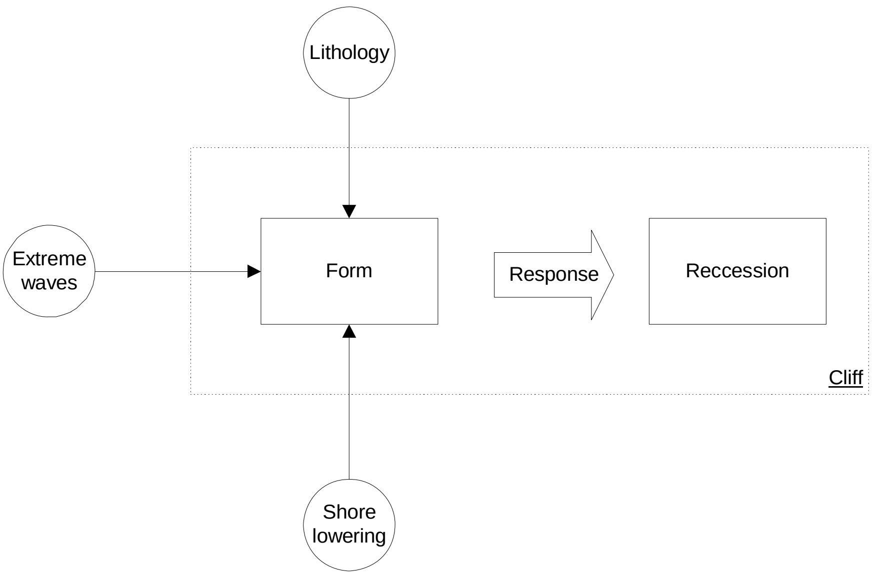

Figure 4. Medium to long-term system diagram - Cliff

2. Behavioural Description for Barrier Beaches

2.1 Definition of Geomorphological Element

Barrier beaches are narrow and elongated accumulations of sand and/or shingle fronting low-lying hinterland. Barrier features can become breached during severe storm events, leading to the creation of a tidal inlet if the breach is not sealed by either natural processes or by management intervention. A recent UK example is the breaching of the Porlock gravel barrier in Somerset in October 1996, which has led to the creation of a new tidal inlet.

2.2 Function

The function of barrier beaches is to provide a 'barrier' against tidal flooding to the hinterland. This is achieved by means of tidal and wave energy dissipation and physical blocking of rising tidal levels.

2.3 Formation and Evolution

Typically barrier beaches can be formed either by the breaching of a spit or by the emergence and subsequent enhancement and landward transgression of an initial bar, built by constructive wave action. In the latter case, the barrier formation started as relative sea levels rose during the Holocene and swept up sediments lying on the present-day seabed, transporting them landwards where they accumulated sufficient sediment volumes to form bars that then further developed into barriers. As relative sea levels continued to rise, so the barriers transgressed landwards until their interception with rising topography, such as sea cliffs, to form inter-tidal beaches. In areas where the topography is low-lying, the barriers remain in a transgressive mode in response to continued relative sea level rise. Due to the relative exhaustion of seabed sediment stocks, most barriers are contemporarily fed with sediments by littoral processes.

Where barriers have become permanently breached, so a tidal inlet will form, with an associated inlet channel and ebb and flood tide deltas present. In these cases, the low-lying hinterland will revert to areas of sand flat, mud flat or salt marsh.

2.4 General Form

Barriers can be comprised of sand and/or gravel and posses three components: a seaward face; a crest; and a landward face. In addition, dunes may be perched on the barrier crest. Gravel barriers will generally exhibit a steeper seaward profile gradient than their sand counterparts, whilst the crest and landward face of either sediment class may be vegetated.

Sub components may include wash over fans and wash over flats, both of which are accumulations of sediment on the landward face of the barrier created by water flows pushing material over the crest.

2.5 General Behaviour

Under the presence of a sufficient supply of sediments, barrier behaviour will mostly be transgressive, with landward migration in response to rising relative sea levels. This will occur through repeated processes of crest build up followed by episodic washover, with the over-flowing water pushing sediments from the crest to the landward face (Carter, 1988).

Where sediment supply becomes critically low, for example due to the provision of coastal defence works along adjacent updrift coastal frontages or exhaustion of seabed sediment stocks, the form of the barrier is likely to change from a drift-alignment to a more segmented, swash alignment.

Breaching may result from crest cutback due to erosion of the seaward face and crest, the lowering of crest levels during periods of overwashing, or a combination of both processes. Single or multiple breaches may develop. In the absence of sufficient longshore sediment supply, the breach can remain intact and a new tidal inlet can form (Orford *et al.*, 1996). If longshore sediment supply is large (when compared against the flushing power of the new inlet), then the breach is likely to be ephemeral and naturally become sealed.

Overstepping occurs when the barrier is unable to maintain its entire form in response to increases in relative sea level rise. In such cases, the barrier will usually become overwashed initially, with a base of material remaining on the seabed and the remainder of the material being dispersed by wave and tidal processes.

2.6 Forcing Factors

Barriers are subject to wave-driven longshore and cross-shore sediment transport processes, and, to a lesser extent, tidal processes. Where barriers are intact features protecting a low-lying hinterland, they can also be subject to hydraulic forces caused by seaward flow through the barrier of an excess water head caused by overtopping events or after periods of high intensity rainfall. In addition, the reverse process can also occur whereby seawater may cross a barrier from the seaward to the landward side, through seepage (Carter, 1988). This process is dependant on the nature of the deposits, with a significant role on gravel barriers due to their higher permeability and an insignificant role on sand barriers. The process of seepage can, in certain situations, reduce barrier stability and hence increase the potential for barrier breaching. Where breaches occur and a new inlet is formed, barriers become subject to marine processes on both their seaward and landward sides.

2.7 Evolutionary Constraints

The key constraints to barrier evolution are sediment supply and wave exposure, backshore characteristics and the rate of relative sea level rise. Sediment supply is the key factor which dictates the health of the barrier and hence its susceptibility to breaching during periods of extreme wave activity. Where sediment supply is sufficient, it is likely that the barrier will be less susceptible to permanent breaching and tidal inlet creation and the barrier will remain more dynamically responsive to short-term and long-term pressures. However, where contemporary sediment supply is constrained, the barrier may be both more susceptible to breaching (due to reduced volumes of sediment within the barrier structure and a change in its planform morphology from drift- to swash-alignment) and less likely to naturally seal any breach that does occur.

The transgressive response of barriers to rising relative sea levels will become constrained by rising topography as the barrier moves back to intercept such landforms. The topography of the hinterland is also important in the context of shallow depressions or channels, into which barrier sediments can transgress, effectively reducing the crest height of the barrier. The geological nature of the hinterland is also important as this too may influence the ability of the barrier to transgress. Additionally, the rate of relative sea level rise may determine whether the barrier is able to transgress or whether instead it will become outpaced by relative sea level rise and ultimately will be overstepped and break down.

2.8 Behavioural Timescales

2.8.1 Short-term (responses within a year)

Over the short term, barriers will exhibit dynamic responses to individual ‘frequent’ storm events and seasonal wave climates, with processes of cross-shore and longshore sediment movement occurring and changes in profile gradient and crest height observed.

2.8.2 Medium-term (responses over decadal to century scale changes)

Where wave activity is such that overwashing occurs, barrier sediment can be moved from the seaward face, to and then over the crest, to become deposited on the landward face, causing washover fans and flats to encroach on the hinterland. Overwashing can result in two potential responses: (1) beach roll-back and crest lowering or (2) crest roll-back and reforming at higher elevation (Bradbury, 2000). Over this medium term barrier behaviour will therefore be dominated by changes in vertical and horizontal position. The ability of a barrier to respond to changing forcing and migrate accordingly will depend on rate of relative sea level change, sediment supply and the degree of wave exposure. In the case of a transgressive barrier response, the barrier could migrate across the hinterland, at a rate controlled by rate of relative sea level rise, exposure to storm conditions, sediment composition and supply and hinterland topography and lithology.

2.8.3 Long-term (responses over century to Holocene timescales)

Over the longer timescale, barrier behaviour could cover a significant range of occurrences, from landward migration in response to modest relative sea level rise, through breakdown processes (e.g. segmentation, washover, overstepping or breaching and new inlet formation) under conditions of reducing sediment supply and/or increasing wave exposure.

2.9 Interactions with Other Geomorphological Elements

2.9.1 General interactions (Elements external to the estuary system)

Barriers are fed with sediment from adjacent beaches by processes of littoral drift and from any available offshore sources. The latter process can occur as slow, progressive feed during periods of constructive wave action, or as a large pulse of sediment during storm conditions, which mobilise material from storage in offshore banks or deltas. However, such periods of storm activity can also cause barrier crest cut-back and temporary movement of sediment from the barrier to the lower foreshore. Periods of storm action can also result in offshore transport of sediments from a barrier.

2.9.2 General interactions (Elements within the estuary system)

When a barrier becomes breached, it will enable tidal waters to flood the hinterland and a new tidal inlet, with associated channels and ebb and flood deltas, to form.

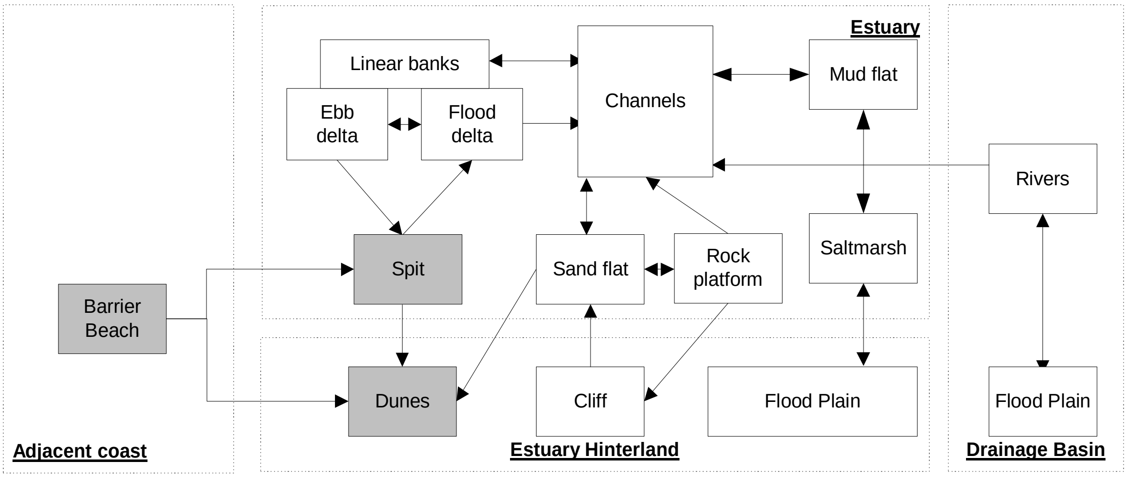

Figure 5. **Interaction with other elements - Barrier beach**

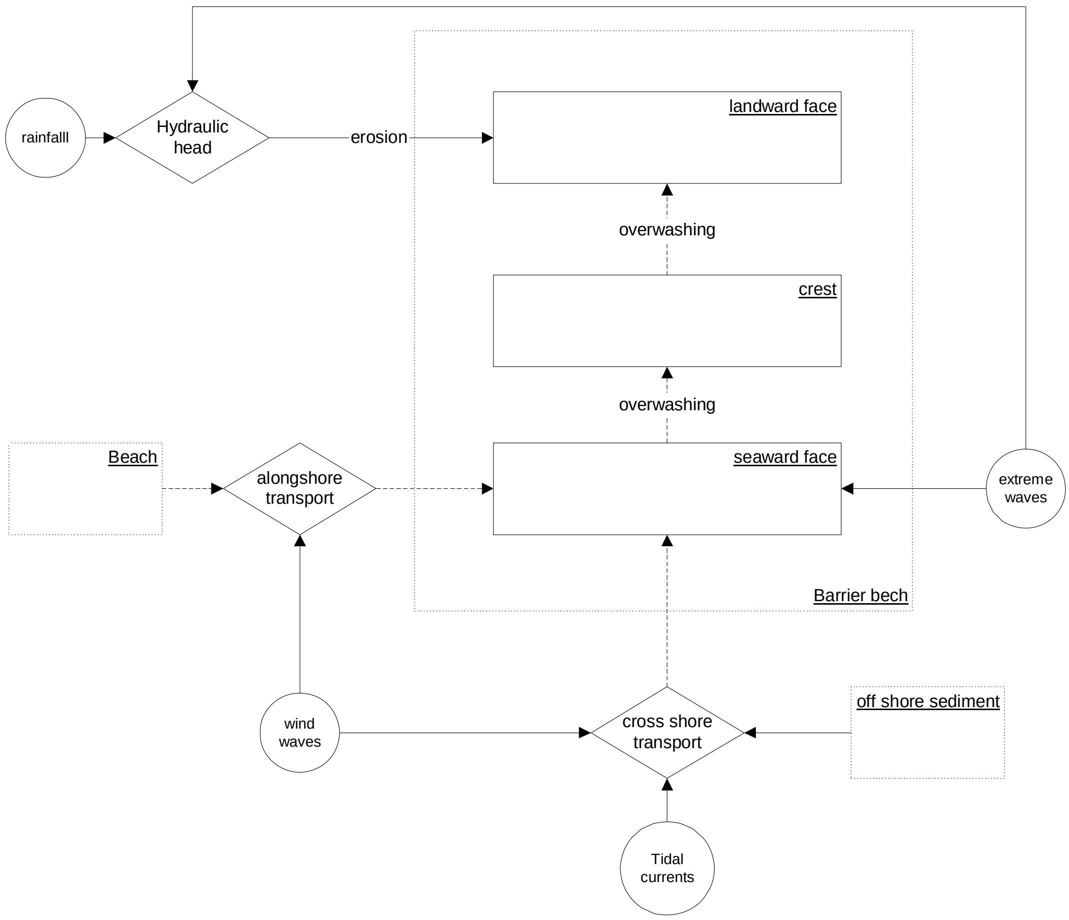

Figure 6. Short to medium term system diagram - Barrier beach

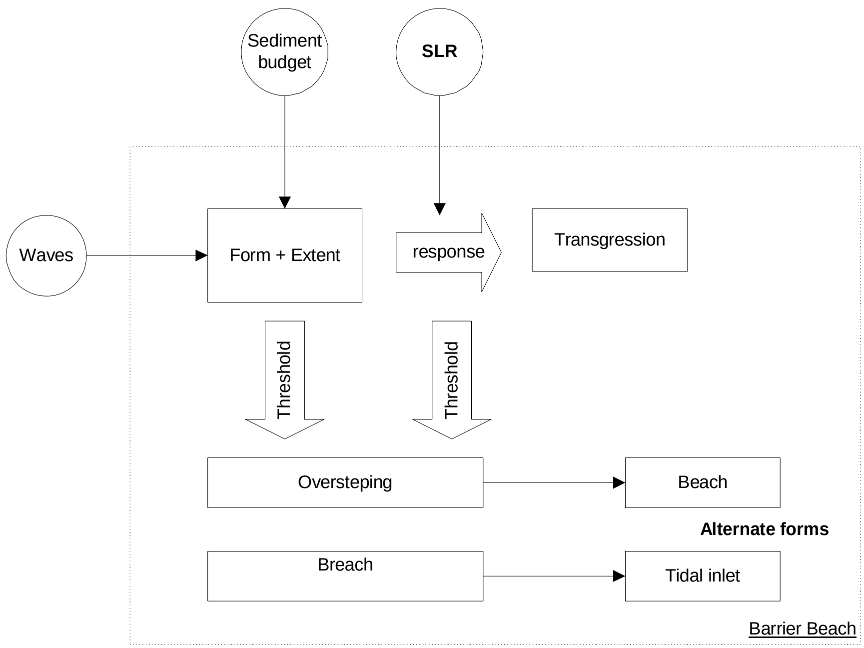

Figure 7. Medium to long-term system diagram - Barrier B=beach

3. Behavioural Description for Spits

3.1 Definition of Geomorphological Element

Spits are narrow and elongated accumulations of sand and/or gravel that project out from the coastline across part of the mouth of an estuary and, as such, are influenced by marine processes on both their seaward and landward sides. They are formed as a product of the interaction between longshore drift, moving non-cohesive sediment along the coastlines adjacent to the estuary mouth, and the tidal processes operating through the mouth. In areas where local coastal drift reversals, or 'counter drift', exists updrift of the estuary, spits can form at both sides of an estuary mouth, growing towards each other. These are referred to as double spits and classic examples can be found along many of the harbours in The Solent. Many spits are characterised by a curved termination at the distal end, caused by the wave action acting at this location.

3.2 Function

Spits can be seen to serve several functions within in the context of an estuary system. Spits represent a sedimentary interaction between the adjacent open coast and an estuary and as such their existence provides a constraint on the estuary mouth, acting as a barrier to tidal inundation, constraining the estuary channel and mouth and providing shelter to the generally intertidal areas in their lea.

3.3 Formation and Evolution

For spits to develop, there is a requirement for the along-shore coastal transportation of sand or gravel and the presence of an abrupt change in the main coastline configuration, such as caused by the presence of an estuary. As the shore-parallel littoral processes become influenced by the ingress and egress of water from the estuary, so the longshore transport rate is reduced and much sand or gravel becomes deposited at the estuary mouth. As this deposition continues, the spit will grow in length, prograding across the estuary mouth. This will continue until some critical balance is achieved between the longshore supply and deposition of sediment and the passage of tidal waters through the estuary mouth. In estuaries with relatively low volumes of tidal discharge and/or extremely high volumes of longshore drift, continued spit growth can divert the mouth of an estuary significant distances along the coast (e.g. River Adur in West Sussex) or, ultimately, lead to mouth sealing (e.g. Combe Haven, East Sussex). However, in many cases of extensive spit growth, episodes of breaching are often characteristic, thereby creating a new mouth position, followed by further periods of elongation. For example, in the hundred years leading up to the mid 1930s, Mudeford spit at the mouth of Christchurch Harbour experienced five cycles of significant progradation and breaching (Kidson, 1963). Much debate exists in the literature concerning whether double spits at estuary mouths are the result of breaching processes (e.g. Robinson, 1955) or counter-drift (Kidson, 1963). Whilst breaching of a spit can provide a 'plug' of material that can be transported to the opposite side of the estuary mouth, from where an opposing spit can develop, counter-drift usually remains responsible for re-sorting this material and in most cases where double spits exist, it is most likely that some form of counter-drift is responsible for spit formation and development.

3.4 General Form

Spits can be comprised of sand and/or gravel and possess three components: a seaward face; a crest; and a landward face. In common with barrier beaches, dunes may be perched on the crest of a spit. Gravel-dominated spits will generally exhibit a steeper seaward profile gradient than their sand-dominated counterparts, whilst the crest and landward face of either sediment clast may be vegetated. Sand dominated spits tend to be flatter features. Typically, spits front low-lying sand or mudflats and saltmarshes, which are protected by the spit against wave activity.

3.5 General Behaviour

As spits are formed at locations where wave-driven littoral drift and tidal processes combine, they are usually relatively dynamic features that can be subject to changes in profile gradient, crest height, planform position and even their presence.

Considering the longshore behaviour, a spit is dependent on the balance of interactions between the littoral sediment supply and subsequent deposition, and the tidal processes operating through the estuary mouth. This can either curtail spit development to a limited length (where the tidal processes are more significant than littoral processes) or can lead to spit elongation across the estuary mouth, diversion of the mouth and even eventual mouth blockage (where the littoral processes are more significant than tidal processes). In areas where spit elongation is observed, it is often possible to identify a series of recurves within the feature, each of which marks the former end of the spit.

In a cross-shore sense, a spit generally behaves in a similar fashion to a barrier, in that tidal and wave activity tends to push material up-profile during 'normal conditions'. During slightly more extreme conditions, material may be moved so far up the profile that it becomes deposited on the spit crest, but during extreme conditions, the crest material is pushed back down the landward face, thereby causing a landward migration of the plan form position.

Episodes of temporary or permanent spit breaching can also occur, caused by either wave activity lowering the crest so that flooding occurs through the breach, or by tidal processes operating from the landward side of the spit causing destabilisation.

Over longer timescales, spits can exhibit major changes in form. Their response to rising relative sea levels will depend on the rate of relative sea level rise and the stability and inertia of the spit itself. Under modest rates of relative sea level rise, a spit is likely to experience landward transgression, whereas during periods of rapid relative sea level rise, the feature may be unable to transgress at a sufficient pace and instead break down to form a lower chenier on a sand or mud flat.

3.6 Forcing Factors

Spits generally are more common in areas of micro-meso tidal range, such as parts of eastern and southern England and west Wales (Pethick, 1984). They exist due to a combination of both wave-driven along-shore transport processes and tidal processes through the estuary mouth.

3.7 Evolutionary Constraints

Sediment supply to the spit is often important to its continued presence. This is because spits are initially formed as 'drift-aligned' features (i.e. the shoreline is oriented obliquely to the dominant wave crests so that some alongshore transport of sediment is observed along the shore). Although spits are often considered to be sinks of sediment, some material is continually removed from the spit and transported offshore, into the estuary or further along the coast, bypassing the estuary mouth within ebb tidal shoals where present. In the absence of continued supply, the spit will tend to become progressively denuded of sediment and its appearance will become progressively more segmented and 'swash aligned', caused by internal re-working of available sediments.

A constraint on the degree of spit growth, in the case of continued sediment supply, is the flushing capacity of the estuary. This flushing capacity is a balance between the rate of sediment supply along the spit, predominately controlled by wave action, and the action of tidal flows and fluvial discharge through the mouth. The action of waves driving transport along the spit will act to elongate the spit whereas the flows through the mouth will act to maintain a cross-sectional area and hence prevent spit growth in certain situations. For example, in estuaries with a very large tidal prism, it is improbable that a spit could grow sufficiently to seal or significantly divert the mouth. However, in estuaries with a small tidal prism, spit growth can commonly divert the estuary mouth, unless training works or artificial sediment recycling/bypassing activities are in place to limit this.

3.8 Behavioural Timescales

3.8.1 Short-term (responses within a year)

Over the short-term, spits will exhibit dynamic responses to individual 'frequent' storm events and seasonal wave climates, with processes of cross-shore and longshore sediment movement occurring and changes in profile gradient and crest height observed.

3.8.2 Medium-term (responses over decadal to century scale changes)

Over the medium term spit behaviour will vary according to a number of factors, for example sediment supply. Spit behaviour may involve erosion or accretion, resulting in vertical or horizontal changes in the form of the feature, and changes in the position of the feature. For example, under a scenario of relative sea level rise, a spit may migrate landward through the process of sediment being moved from the seaward to the landward side.

In addition, spits are known in a number of cases to exhibit cyclical behaviour over these medium term timescales. This can involve a period of spit growth and elongation followed by a breach. If the breach is maintained, the sediments in the isolated section may become dispersed and the spit may begin a further stage of elongation and growth.

3.8.3 Long-term (responses over century to Holocene timescales)

Over the longer term, spit behaviour could cover a range of occurrences, from significant progradation, through landward migration in response to modest relative sea level rise, to breaching or breakdown of the feature during more extreme (i.e. less frequent) storm events or rapid rates of relative sea level rise.

3.9 Interactions with Other Geomorphological Elements

3.9.1 General interactions (Elements external to the estuary system)

Spits have important interactions with the adjacent shore beaches. It is from these areas that sediment is supplied to the spit.

3.9.2 Deltas

In some particular types of estuary, namely spit-enclosed drowned river valleys and tidal inlets, both spits and flood and ebb tidal deltas can be present. In these cases, important sediment transport pathways exist that incorporate both the spit and the deltas. A proportion of the sediments will become stored within the spit or delta features, whilst other sediments will pass through the complex pathways, episodically moving off the spit to the flood tide delta, then to the ebb tide delta and then back to temporary storage in the spit or ultimately progressing to the downdrift side of the estuary mouth and thereby bypassing the estuary.

3.9.3 Sandflats, mudflats and saltmarsh

Some material exchange can also occur between the spit and the adjacent sand flats within the estuary. Spits provide a degree of protection to backing sand flats, mud flats and salt marshes from direct wave attack. As the position, or presence, of the spit changes (e.g. due to landward migration, temporary or permanent breaching, breakdown of the feature), so the exposure to wave penetration of parts of the outer estuary changes. This could, for example, have the effect of causing or accelerating erosion of inter-tidal areas, or reducing the rate of accretion.

3.9.4 Channel

Spit behaviour will have a direct impact on an estuary or inlet mouth. The spit will exert an influence on channel dimensions at the mouth and channel dimensions will respond to any cyclic behaviour involving spit elongation and breaching. In the event of a spit breach that is maintained through tidal and wave action, the siltation is likely to be experienced in the estuary or inlet mouth (Pontee *et al.*, 2002).

3.9.5 Dunes

Spits can become vegetated on their crests and landward slopes and in the case of particularly large sand spits, dunes can develop due to aeolian transport of sand and subsequent colonisation by vegetation.

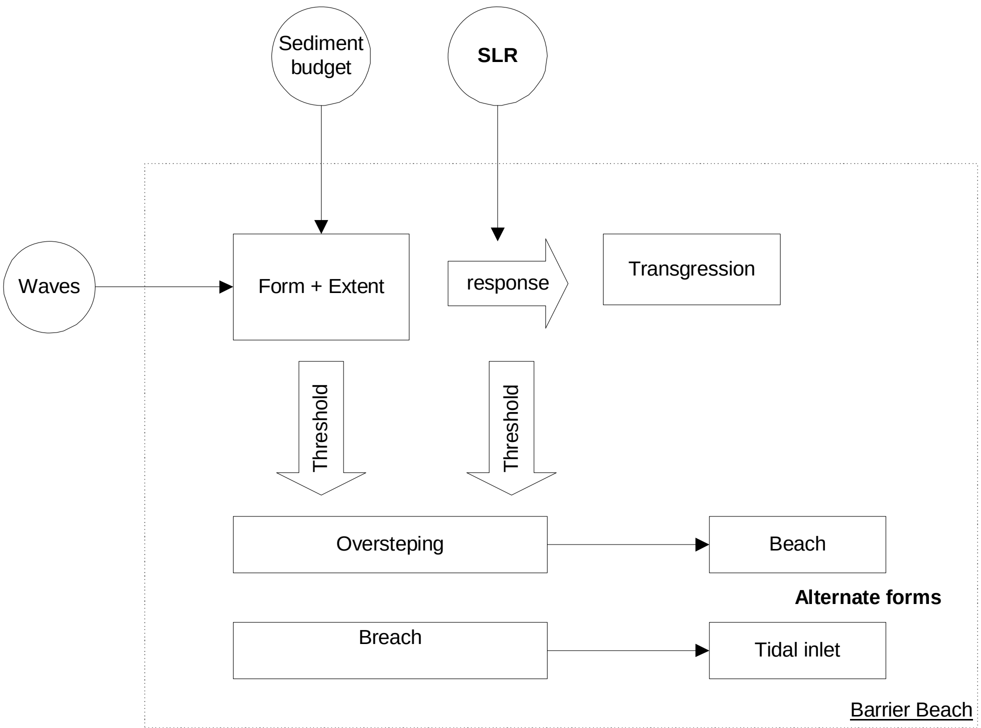

Figure 8. Interaction with other elements – Spits

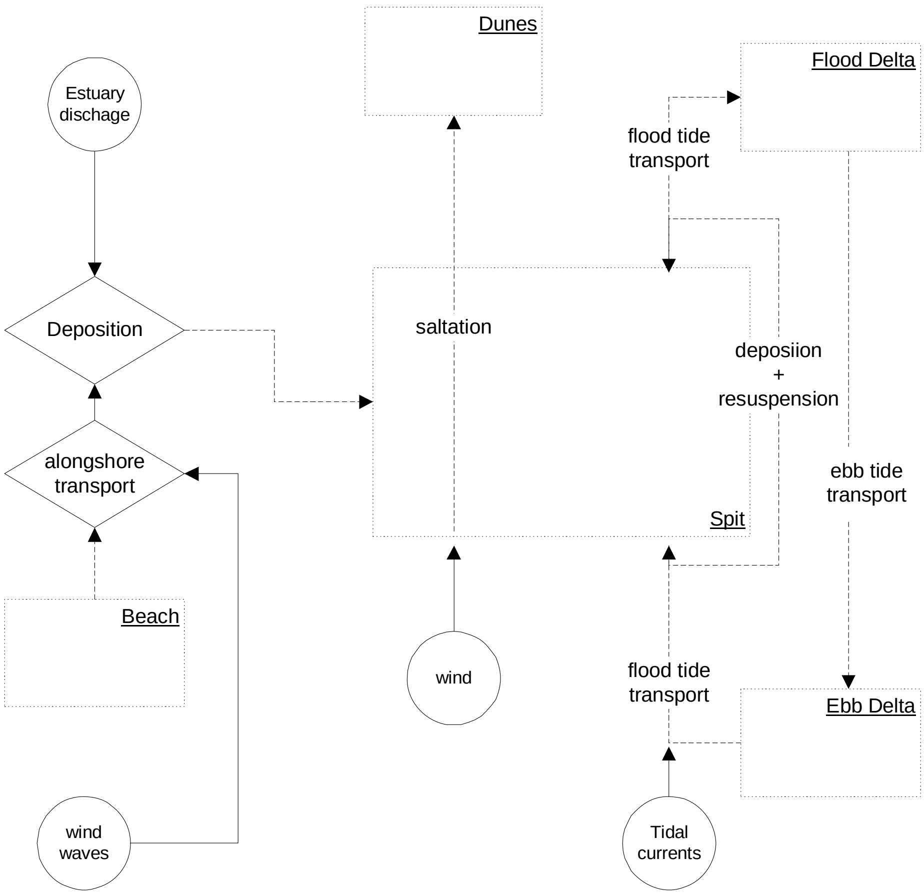

Figure 9. **Short to medium term system diagram - Spits**

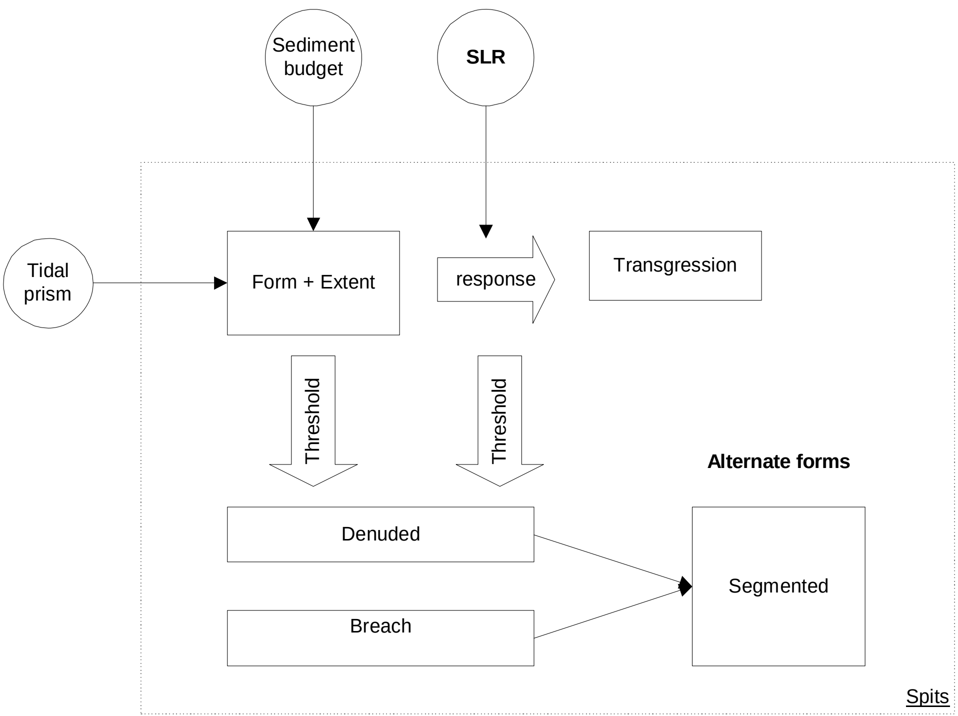

Figure 10. **Medium to long-term system diagram - Spits**

4. Behavioural Description for Dunes

4.1 Definition of Geomorphological Element

Coastal dunes are accumulations of sand that has been blown by the wind from the foreshore to the backshore. Such features are characterised by the presence of vegetative cover.

4.2 Function

The function of a dune system is both to provide protection to the adjacent landward hinterland and to provide a store of sediments available to the fronting foreshore. In terms of the wider coastal or estuarine system, the function is therefore fulfilled primarily during extreme events. Under such conditions, dunes provide an energy dissipation role, acting as a buffer to extreme waves and protecting the adjacent hinterland. In addition, during these extreme events, dunes provide a supply of sediment to replenish the fronting foreshore, allowing the foreshore to adapt its form.

4.3 Formation and Evolution

The wind-blown (aeolian) processes that result in dune formation are initiated when the wind stresses acting on sand particles of the foreshore exceed the shear strength of the material (which is related to sediment grain size). This process is known as saltation and particles move in this manner until their progress becomes interrupted by some obstruction, such as debris at the mark of the highest tide. Here, accumulation starts and as the mound of sand increases to form embryonic dunes, so vegetation can start to colonise. As embryonic dunes continue to accumulate sediment, they rise in height, increase in width and connect with neighbouring embryonic dunes to form more continuous ridges (often up to 2m in height) parallel to the shoreline. These ridges, due to their increased elevation, become vegetated by major dune species (e.g. marram grass). These species increase the surface roughness of the foredune and assist in the trapping of sediment, resulting in rapid deposition within the vegetated zone. This leads to rapid increases in dune height, which, in the UK, can be up to approximately 10m.

As the foredune height increases towards a self-limiting level, it will become subjected to an increasingly stronger wind velocity regime at its crest, which, eventually, will result in saltation processes moving sand landwards. On the lee side of the dune crest, the velocity regime decreases substantially, resulting in deposition and the initiation of the development of a new dune ridge. Due to the process of erosion from the crest and lee-side deposition, the entire dune ridge appears to “rollover” and move landwards (Pethick, 1984; Carter, 1988). Assuming an accretional environment prevails, as the ‘roll-over’ process occurs, new dunes are created seaward of the migrating ridges. This results in the creation of a series of fully developed ridges, separated by troughs or valleys.

4.4 General Form

A coastal dune field will often comprise a series of sand ridges running parallel to the shoreline, with each ridge being separated from another by marked troughs or valleys (Pethick, 1984). Other fields may have a more complex form, comprising ridges running perpendicular, or at oblique angles, to the shoreline. Typical ridge heights in the UK range from 1 or 2m to 20 or 30m and their morphology generally comprises relatively steep windward slopes and gentler lee slopes (Pethick, 1984). Each dune ridge represents a different stage in a dune field’s development (Goldsmith, 1978). The crest of each ridge may be flat or undulating, but occasional areas of unvegetated low depressions (known as blow-outs) may occur.

As dune ridges migrate landwards through a succession, they eventually become lower in height and less parallel to the shoreline. This is due both to the progressive reduction in saltation that occurs with progressive movement landward through the dune field, and to the reduction or disappearance of marram grass within older dunes. As a result, the ridges become fragmented, increasingly susceptible to blow-outs and, ultimately, the creation of u-shaped parabolic dunes. Parabolic dunes typically have vegetated arms orientated roughly parallel to the predominant wind direction and unvegetated centres which are subjected to downwind movement.

4.5 General Behaviour

Dune behaviour is generally linked to its stage of succession, with pioneer stages (embryonic dunes and foredunes) being typified by sand deposition to enable dune formation and growth. Intermediate stages involve the migration of dune ridges and formation of new ridges to establish dune fields, whilst the mature stages are characterised by the lowering of dune ridges, loss of vegetation cover and, due to increasing susceptibility to blow-outs, the formation of parabolic dunes. Generally, dune fields are perceived to be sediment stores, but episodically dunes can supply sediment to the fronting inter-tidal beach when wave activity is extreme.

4.6 Forcing Factors

Unlike all other coastal landforms, dunes are formed by wind-induced sediment movement rather than water-induced movement (Pethick, 1984). This involves, during periods with strong onshore wind velocities, aeolian processes transporting sand-sized sediment landward. Hence wind speed and direction is an important forcing condition in dune formation and evolution.

During periods of relatively high wave action, some of the sediment stored within the dune system can be eroded and moved seaward to feed the beach profile. This is often perceived to be a major concern to coastal management since the volumes of material involved can be relatively large, but this is a temporary state and following periods of calmer wave action, sand will once again usually move from the beach to be stored within the dunes (Carter, 1988). In addition, sediment stored within a dune system can be lost inshore.

4.7 Evolutionary Constraints

The evolution of dunes could be constrained by either a reduction in sediment supply or the lack of accommodation space to enable dune succession.

4.8 Behavioural Timescales

4.8.1 Short-term (responses within a year)

In the short-term, dune behaviour can be extremely dynamic, with significant sediment accumulation or significant local sediment loss, due to blow-outs or erosion of the seaward margins, both possible outcomes.

4.8.2 Medium-term (responses over decadal to century scale changes)

Dune behaviour over medium timescales will consist of changes in the position and nature of a dune system. Depending on the degree of landward space and the sediment supply, a dune system may 'roll-over' landward in response to an increase in relative sea level. Conversely, under a scenario of falling relative sea level a dune system may prograde seaward, under a scenario of sufficient sediment supply.

4.8.3 Long-term (responses over century to Holocene timescales)

Over longer-time periods entire dune fields can develop, containing a series of ridges created during different stages of its evolution. Over similar timescales, entire dune fields may also be lost due to erosion or inundation or alternatively a dune system may stabilize or become a relict feature. The change in relative sea level is the critical controlling factor in the behaviour of dune systems over this timescale. In addition, the supply of sediment will determine the nature of the features response the prevailing relative changes in relative sea level.

4.9 Interactions with Other Geomorphological Elements

4.9.1 General interactions (Elements within estuary system)

The key interaction is between the dune and the fronting inter-tidal foreshore. Sand is supplied to the dune from the foreshore by aeolian processes, but can also be temporarily supplied from the dune to the fronting foreshore during extreme events.

Dunes can also develop on the crest of major spit or barrier features; with Spurn Head being a classic example. In such situations, it is possible that a marsh system may develop in the lee of the dunes, to which the dune system provides protection.

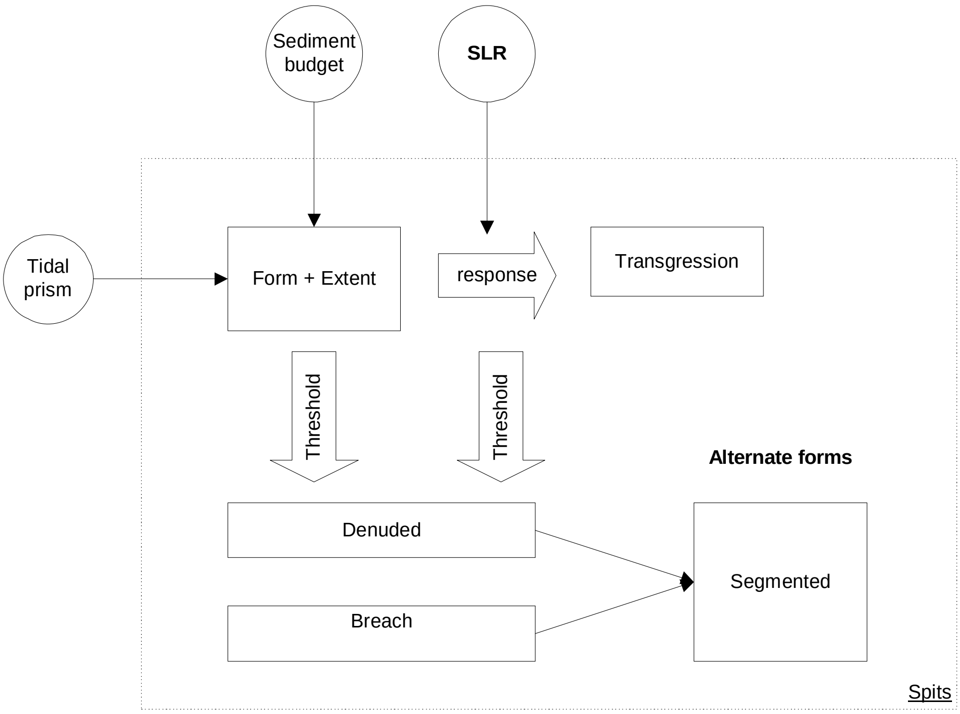

Figure 11. Interaction with other elements – Dunes

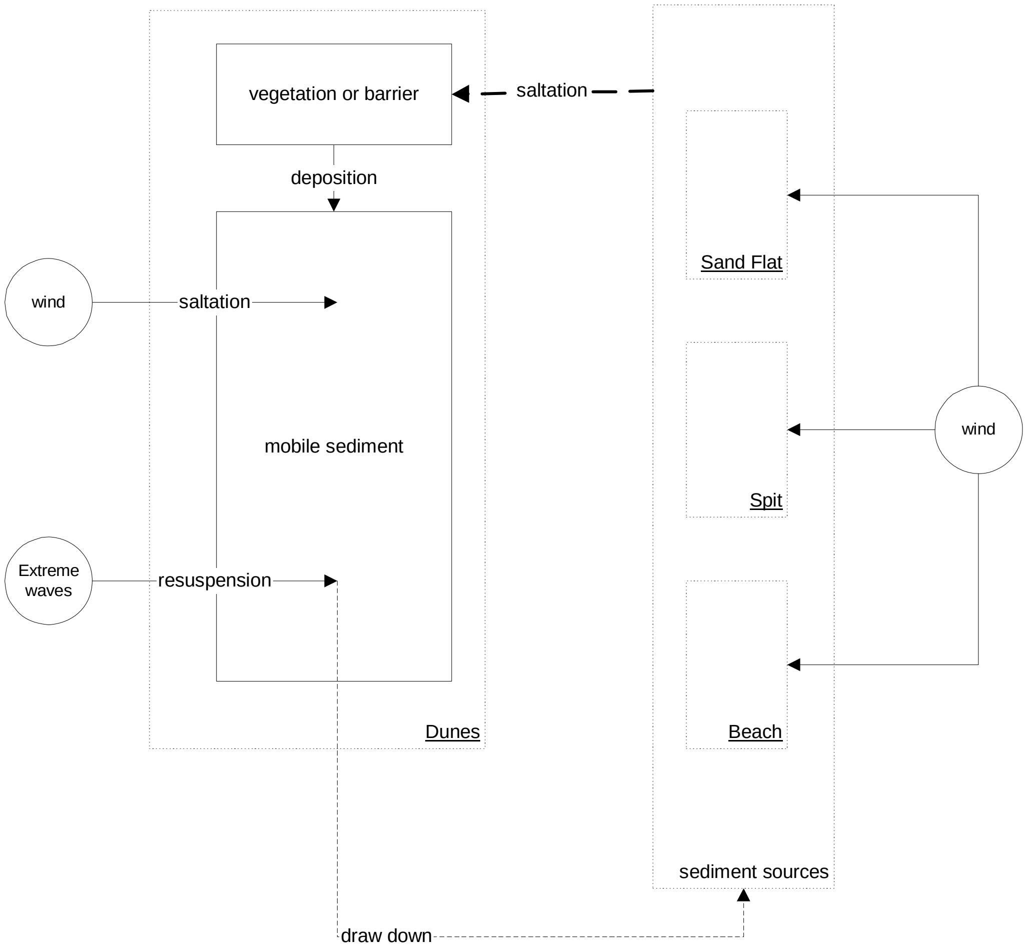

Figure 12. Short to medium term system diagram - Dunes

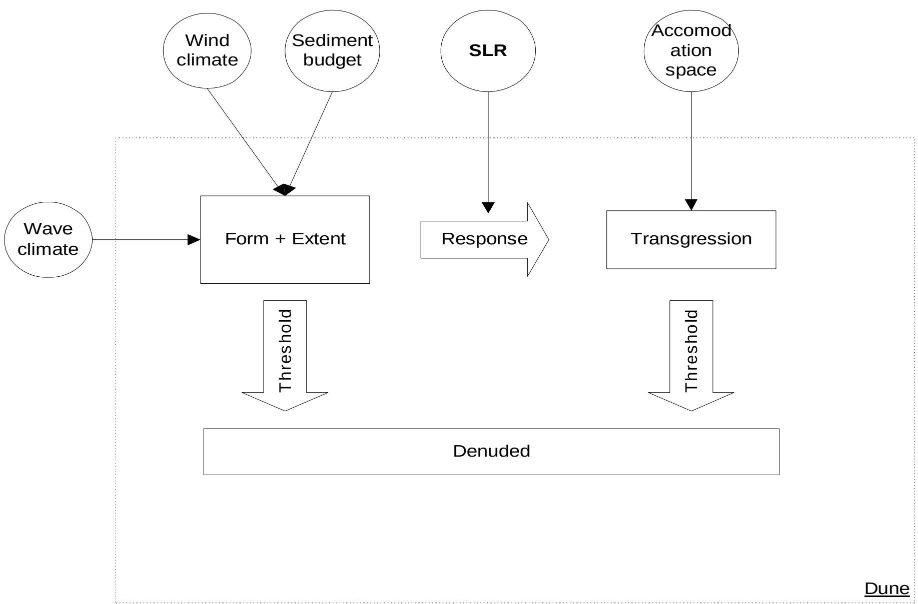

Figure 13. Medium to long-term system diagram - Dunes

5. Behavioural Description for Deltas

5.1 Definition of Geomorphological Element

Deltas can be defined as accumulations of river- or marine-borne sediment found in the vicinity of the estuary mouth. Their existence is dependant upon a sufficient supply of material and favourable wave and tidal conditions. Deltas can exist as flood or ebb features. For the purpose of this study the occurrence of linear sand banks within an estuary mouth is considered as a modified delta with littoral supplied sediment to the mouth of an estuary incorporated into elongated sand accumulations aligned with the current flow.

5.2 Function

Within the estuarine system, deltas act to dissipate wave energy at the estuary mouth thus providing protection. In addition, they also act as a sediment sink. Under certain conditions the delta will also act as a sediment source i.e. when the wave characteristics provide sufficient energy to suspend bed material. A delta represents a sedimentary interaction between the estuary and the coastline to either side of the estuary mouth.

5.3 Formation and Evolution

If more sediment is supplied to an estuary mouth or tidal inlet than can be redistributed by the dominant processes, then a delta will be formed. Conversely if the waves and currents can remove more sediment than is being delivered to the estuary mouth, then the delta retreats or the sediment load is incorporated directly into the beach or within an estuary and delta is not formed.

There are therefore two generalised situations in which delta formation will occur:

- If the fluvial sediment supply exceeds the flushing capacity of processes at the estuary mouth;
- When wave driven longshore transport supplying sediments to an estuary mouth from an adjacent coastline is interrupted by the interaction of wave and tidal processes at the mouth.

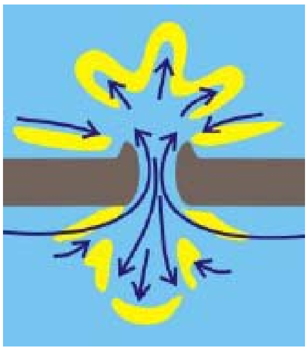

Figure 14. Schematic Illustration of Delta Formation Processes at a Tidal Inlet/ Estuary Mouth

5.4 General Form

Deltas can be classified according to the relative importance of fluvial, tide and wave processes in their formation. The relative importance of these processes will play a role in dictating the form of the Delta. Van Rijn (1998) classified three distinct types of deltas, as follows:

- River-dominated deltas form where rivers supply a sufficiently large sediment load to overwhelm the rate of marine-induced re-working and removal. They are often comprised of numerous branching river distributary channels and the presence of lobes. These deltas tend to be long narrow features;
- Wave-dominated deltas form where river- or coastal-borne sediment is sorted and transported from the estuary mouth in both longshore directions by waves. Such sediment is often transported to features such as beaches, barriers and spits. Typically such deltas are wide features with multiple outlets; and
- Tidally dominated deltas form in meso-tidal estuaries where the tidal conditions are sufficient to transport sediment to the estuary mouth. Such deltas tend to comprise ebb delta located seaward of the estuary mouth or tidal inlet and flood delta located inside the estuary mouth or tidal inlet.

A modified delta may form in macro tidal estuaries as linear sand banks with sand accumulations aligned parallel to the flow.

5.5 General Behaviour

Delta behaviour is complex and results from a combination of the relative dominance of the driving processes (fluvial, wave and tidal processes) and the supply of sediment. Whilst tidal processes play the predominant role in the formation of the tidal delta, wave-generated processes are also important, tending to supply the coarser material to the flood tidal delta. Often finer materials are progressively removed from the flood tidal delta resulting in an eventual differential between the adjacent updrift and downdrift beaches. However, fine sediments may also be transported from the flood delta to the ebb delta and subsequently feed the downdrift coastline.

5.6 Forcing Factors

At the mouth of an estuary three processes will contribute to delta formation and the distribution of sediments (Defra, 2002):

- Inertia-dominated material: The inertia created by high velocity outflow results in the material spreading and diffusing as a turbulent jet. The expansion of this jet reduces its velocity resulting in a reduction of its sediment carrying capacity. The sediments are deposited in a radial pattern, with the coarsest material deposited near to the point where the jet expansion begins and the finer material further afield. With the continual discharge of sediment, the delta will accrete vertically and eventually have a frictional effect on the material;
- Friction-dominated material: The continual deposition of sediment from the turbulent jet will eventually cause the restriction of the jet. This in turn will result in the formation of bars and channels;
- Buoyancy-dominated material: The mix of fresh and saline water often results in stratification, which in turn initially results in the material being isolated from bottom friction effects. Consequently, the sediment will be distributed over a wide area until the upward entrainment of seawater across the density interface results in its deceleration and settlement.

Within tidally dominated estuaries, tidal interaction has three important effects:

- At estuary mouths, mixing obliterates the effect of vertical density stratification thus eliminating the effects of buoyancy;
- Tide-dominated sediment transport is bi-directional; and
- The zone of fluvial-marine interactions extends across a wider area.

5.7 Evolutionary Constraints

The evolution of a delta may be constrained by a number of factors, such as:

- Sediment supply (including the source and nature of sediments and the rate of supply);
- River, wave and tidal processes, and their interaction at an estuary mouth;
- Coastal alignment and nearshore bathymetry (including the configuration of the adjacent coastline, the position and nature of the estuary mouth, the behaviour of adjacent spits etc).

5.8 Behavioural Timescales

5.8.1 Short-term (responses within a year)

In the short-term, delta behaviour will be dominated by changes in size and form and migration of the feature. This behaviour will be in response to variations in forcing processes of river flows, waves and tides resulting in variations in exposure and sediment supply.

5.8.2 Medium-term (responses over decadal to century scale changes)

Over the medium term, even if the tidal inlet as a whole is in dynamic equilibrium with the forcing factors, appreciable local changes in morphology can be observed. These may lead to the spatial relocation of the complete inlet system, or just components within it. Examples of such local changes are the shoal-channel cycles, which for the Wadden Sea inlets have cycle periods of many decades (de Swart, 2002).

5.8.3 Long-term (responses over century to Holocene timescales)

Over longer-time periods, delta behaviour will be linked to the behaviour of the estuary mouth in response to changes in relative sea level and variations in sediment supply.

While the gross morphological changes of outer deltas may be determined by global processes forcing these changes such as relative sea level rise or a gradual decrease of the basin area, it is expected that the local, (quasi-) rhythmic changes of outer deltas are determined by processes intrinsic to the outer delta. This so-called free behaviour is hypothesised to be driven by subtle, second-order effects embedded in the first-order signal of intra-tidal and intra-event fluxes of water and sediment interacting with the bottom evolution (de Swart, 2002).

5.6 Interactions with Other Geomorphological Elements

The interactions of deltas with other geomorphological elements have been investigated to varying degrees. Typically the ebb tidal delta has been the focus of much of this work, especially along US coast and within the Wadden Sea (van der Vegt *et al*., 2004). In most recent years this work has taken the focus of modelling the interactions, behaviour and evolution of such features over varying timescales. An example is that of the ASMITA model which has recently been developed from a one element to a three element numerical scheme (Stive, 2003).

Deltas are ultimately dependent upon the presence of a river or estuary and the supply of sediment from:

- Rivers (via channel system); and/or
- Longshore transport from shoreline sources (spits); and/or
- Onshore transport from the eroding seabed.

5.6.1 General interactions (Elements external to the estuary system)

Essentially, deltas play an important role in the exchange of material between the coastal zone and estuary (or backwater basin) (*cf.* van Leeuwen *et al*., 2003). There is therefore an important sedimentary interaction between a delta and adjacent coastlines.

These features often provide considerable natural protection to the coastline adjacent to estuary mouths (Dyer & Huntley, 1999). Reductions in the delta volume, sediment supply or reclamation within the estuary, will lead to reduced natural protection to adjacent shorelines and, hence, increase their susceptibility to erosion.

The response of a tidal delta (in terms of volumetric reduction) to such anthropogenic changes can be very significant, but is not instantaneous. Instead, due to the inherent time lags within the coastal system, it can take decades or centuries of slow progressive ebb-delta modification to fully respond to such interventions.

Deltas/linear banks act as large sediment stores. Whilst this material tends to remain within the bank temporarily, it may, due to changes in forcing factors, be released to re-enter the sediment transport pathway. This could be either in the longshore, onshore or offshore directions. It is likely that this behaviour will be over a short- to medium-term period, rather than the long-term, whilst the bank responds to changing conditions to re-attain equilibrium.

Perhaps the more significant interaction that the banks have with other elements within the local system is with the immediate shoreline. Here banks refract incoming waves influencing wave energy at the shoreline. In turn this will control shoreline evolution and, subsequently, backshore features in response to wave processes.

5.6.2 Spits/barrier beaches

The above 'general interactions' discussion focuses on the link between deltas and the adjacent coastline. This interaction equally applies to spits and barrier beaches. A strong linkage exists between spit/barrier beach behaviour and delta behaviour, with cycles of spit/barrier growth and breaching affecting the location and nature of the estuary mouth or tidal inlet and hence the behaviour of any delta associated with the mouth.

Deltas and spits/barriers therefore often provide the sediment linkage between an estuary and adjacent coastlines.

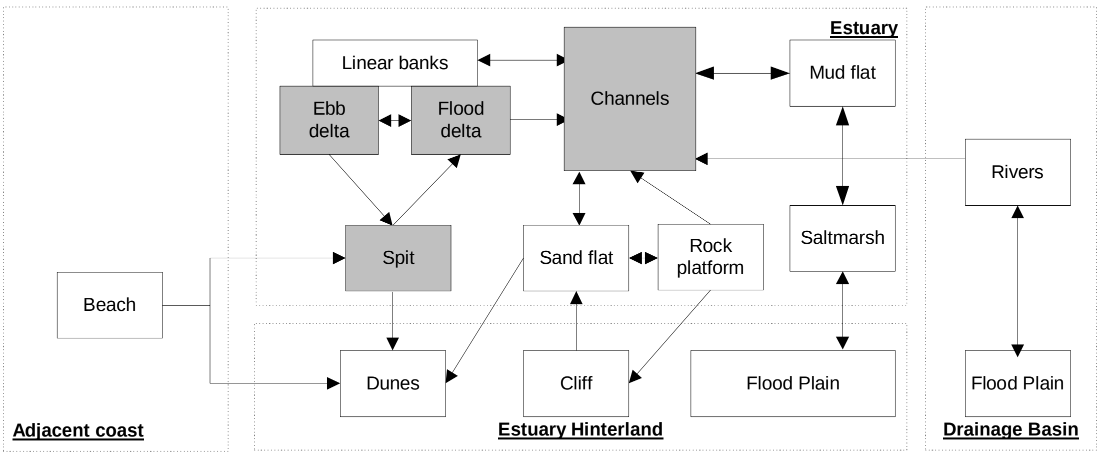

Figure 15. Interaction with other elements – Delta

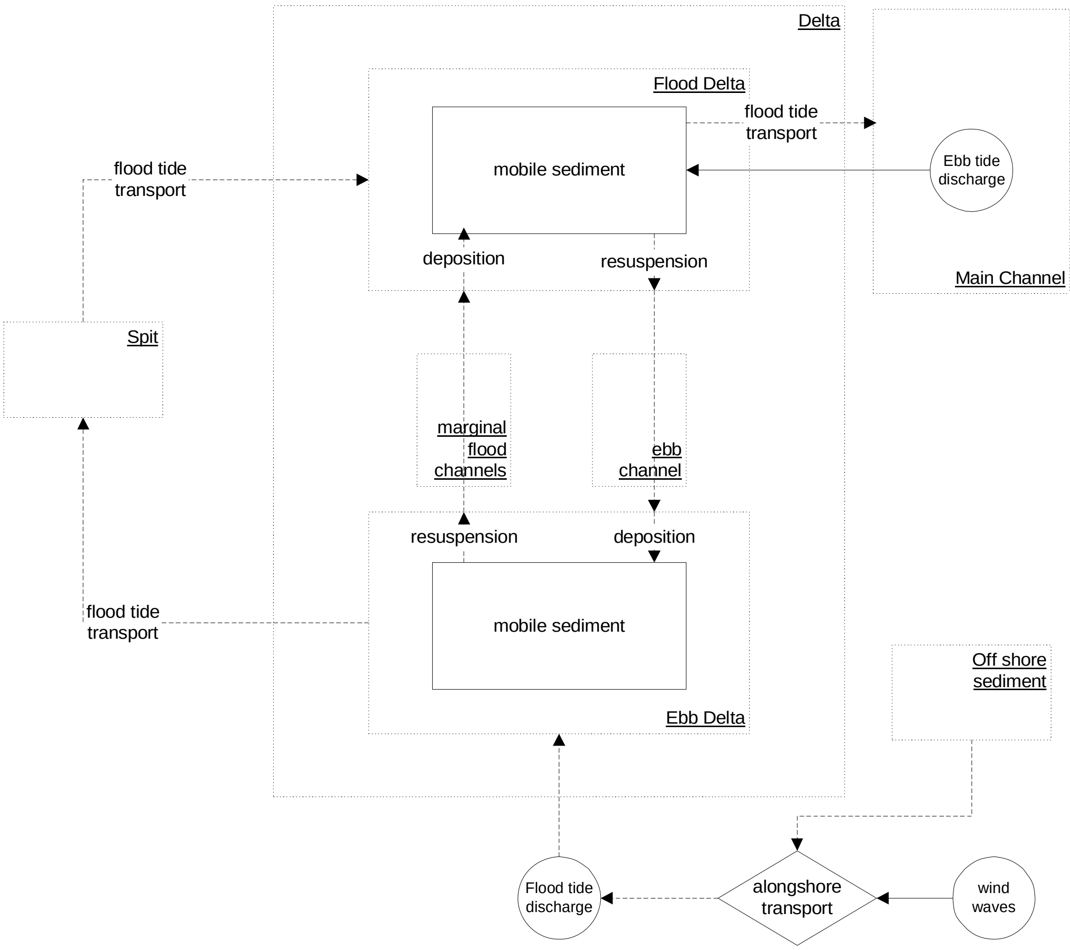

Figure 16. Short to medium term system diagram - Delta

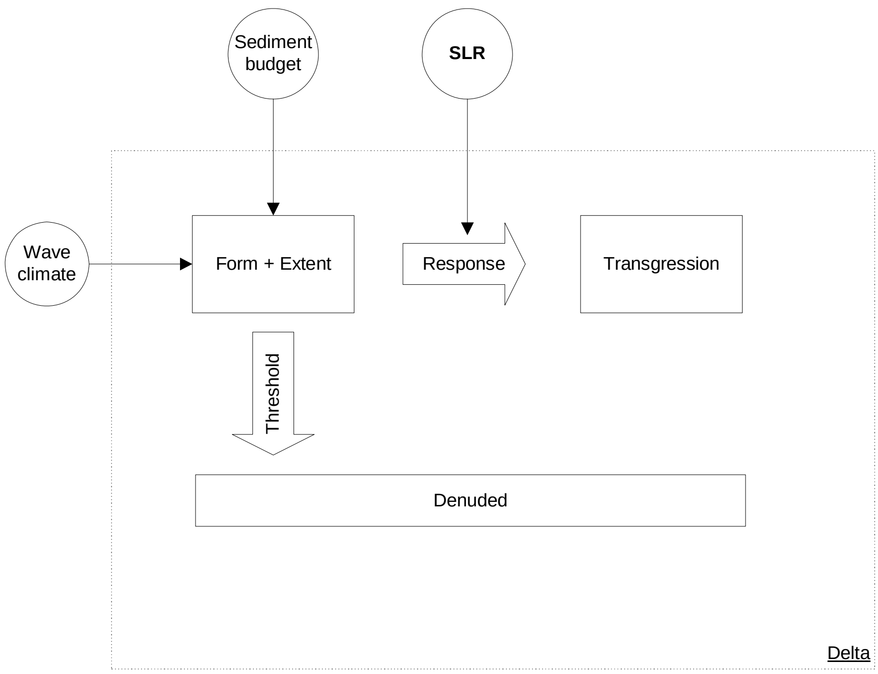

Figure 17. Medium to long-term system diagram – Delta

6. Behavioural Description for Rock Platforms

6.1 Definition of Geomorphological Element

Rock platforms are defined as relatively flat erosional rock bench bedforms extending across, and sometimes seaward of, the inter-tidal zone (Carter, 1988). It is important to note that they are affected not only by marine processes (such as mechanical wave erosion or abrasion by mobile non-cohesive sediments) but also by sub-aerial, chemical and biological processes that can serve to weaken the rock structure.

6.2 Function

The function of a rock platform is to reduce wave and tidal energy before it reaches the upper inter-tidal zone. Additionally, as rock platforms erode (lower), so they: (i) control the rate of recession of backing cliffs; and (ii) release sediment, some of which can contribute to the littoral sediment budget (coarser material) and/or some of which can be transported in suspension offshore or into estuaries (finer material).

6.3 Formation and Evolution

Rock platforms are often backed by sea cliffs and the lithology and geotechnical properties of the two are often closely related. Similarly to cliff evolution always being recessional (albeit at varying rates dependent on the rock geology), so shore platforms will not experience regression (seaward or vertical advance of the landform) since they represent a finite feature that can only become progressively more denuded. Consequently any erosion (lowering) that they experience is irreversible.

Shore platform lowering is initiated when the stresses acting on the feature exceed the shear strength of the material. This situation may arise due to a combination of a number of factors. In basic terms, these comprise external factors that may exist or occur which increase the shear stresses applied or internal factors that may exist or arise which result in a decrease in the shear strength of the material.

An example of the typical foreshore lowering rates of rock platforms comprised of rocks of different lithology is presented in Table 2.

Table 2. Typical lowering rates of platforms composed of different materials (Sunamura, 1983)

Cliff Composition	Typical Recession Rate (mm per year)
Granite	< 0.1
Limestone	0.1 to 1
Shales	1 to 10
Firm sandstone, mudstone	1 to 100

In depositional environments, beach sediments may sit on top of a shore platform and protect it (to some degree) against erosion, although such deposits are very mobile and, consequently, usually would only remain in-situ temporarily. Indeed, as they move across the platform, they can contribute to lowering processes through abrasion. In erosional environments, shore platforms would usually be bare of superficial sediment cover and subjected to slow rate, progressive lowering due to erosional forces.

Pethick (1984) identified that the presence or absence of a (semi-) protective sediment covering on the platform was not a simple relationship, but involved a feedback mechanism whereby a lowering of the shore platform would raise the effective depth of water. Hence, the platform would be subjected to reduced bed shear stress due to waves, with resulting values possibly being lower than the critical shear stress for erosion, at which point superficial sediments may once again begin to cover the shore platform.

6.4 General Form

Bird (1968) identified three generic types of shore platform:

- Horizontal surface lying at high tide level;
- Horizontal surface lying at low tide level; and
- Sloping surface between high and low tide levels.

Despite the above classifications, Trenhaile (1978) identified that the mean elevation of shore platforms from around the world clustered around the mid tide level.

Shore platforms around the UK generally are gently sloping or quasi-horizontal in profile and variable in width, up to a maximum limit of 1km (Pethick, 1984).

6.5 General Behaviour

In general terms, shore platform evolution displays a number of important components. Certain processes will lead to the detachment of clasts of material from the platform, which will then be transported by nearshore currents, often in a landward direction. These materials will then be deposited, often on the foreshore, where they constitute valuable sediment input to the beach material stock. Ultimately, these processes lead to a noticeable lowering of the elevation of the platform over time.

As previously stated, shore platform behaviour can only involve erosion, leading to lowering. The rate of lowering will depend upon a number of factors, which may: promote the erosion of clasts of material from the platform; and control the rate and direction of transport of the released material.

In broad terms, these factors can be influenced by the hardness, structure (e.g. faulting) and solubility of the rock, biological processes and the exposure of the platform to wave attack.

6.6 Forcing Factors

The primary external cause of shore platform lowering is wave action, which may have the following impacts:

- Quarrying of rock by mechanical hammering, shock or air compression;
- Generating the oscillatory movement of abrasive particles across the shore platform, resulting in its denudation;
- Determining the subsequent transport of released material (i.e. moving sediments that potentially could provide a (semi-) protective covering away from the platform, re-exposing it to direct wave attack).

In addition to this, internal factors may result in a decrease in the shear strength of the material of which a shore platform is comprised, making the rock surfaces more susceptible to erosion by wave action. Mechanical, sub-aerial, chemical or biological weathering could cause such effects. For example, the alternating wetting and drying of the platform due to tidal movements results in water-layer weathering. This may involve physical rock breakdown caused by salt crystallisation or swelling of rock grains.

The fate (rate and direction of transport) of sediment released from platform lowering is dependent upon its composition, the direction and magnitude of the forces to which it is subjected.

6.7 Evolutionary Constraints

Unlike many coastal landforms, shore platforms will only experience lowering over time since they constitute a finite feature, which is progressively subjected to erosion, leading to lowering.

At the most fundamental level, shore platform behaviour is dependent on:

- The strength of the material in the platform;
- The stresses applied to the platform; and
- The direction of transport of released material.

6.8 Behavioural Timescales

6.8.1 Short-term (responses within a year)

In the short-term, platforms will be subjected to erosion at locations where the rock has been weakened during periods of higher than usual wave and/or tidal energy exposure. This will release clasts of sediment from the platform that will subsequently be transported by the forcing conditions.

6.8.2 Medium-term (responses over decadal to century scale changes)

In the medium-term, behaviour is manifested though a general lowering of the entire platform.

6.8.3 Long-term (responses over century to Holocene timescales)

Over longer timescales, platform behaviour will be dominated by changes in relative sea level, affecting the elevation of a platform relative to water levels and hence exposure to erosive processes.

6.9 Interactions with Other Geomorphological Elements

6.9.1 Cliffs

Hutchinson (1986) suggested that the rate of platform lowering controls sea cliff recession in the following way:

Rate of sea cliff recession = Rate of platform lowering/shore platform gradient

The implications of this relationship are that, irrespective of platform gradient, a lowering platform has direct implications for the degree of cliff recession. Both of these aspects in turn have implications on the volume (and type) of material that is released through erosion and becomes available to contribute to the littoral sediment budget (coarse sediments) and provide input to estuaries (fine sediment).

The rate of platform lowering can be reduced when a (usually temporary) veneer of sediment covers the platform (although this can actually also lead to increased erosion due to abrasion when the veneer is very thin and mobile).

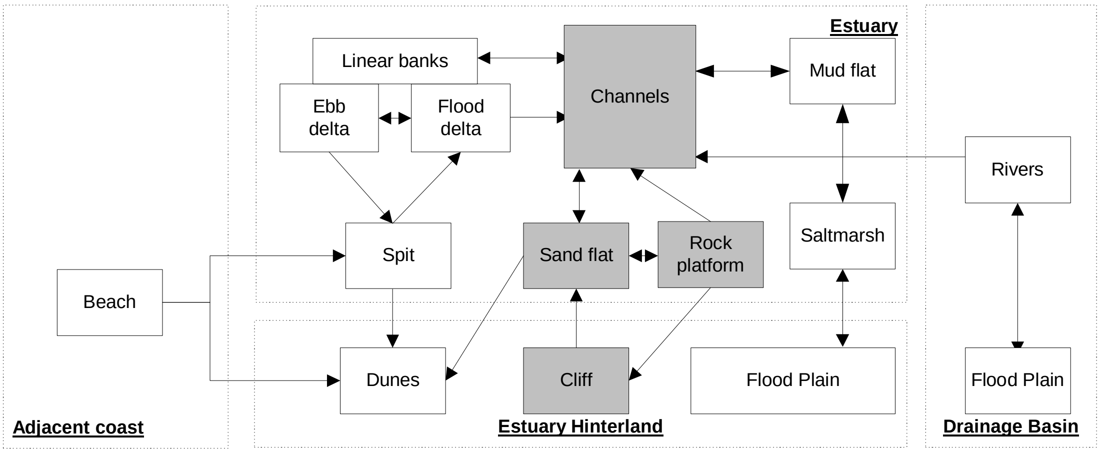

Figure 18. Interaction with other elements - Rock platform

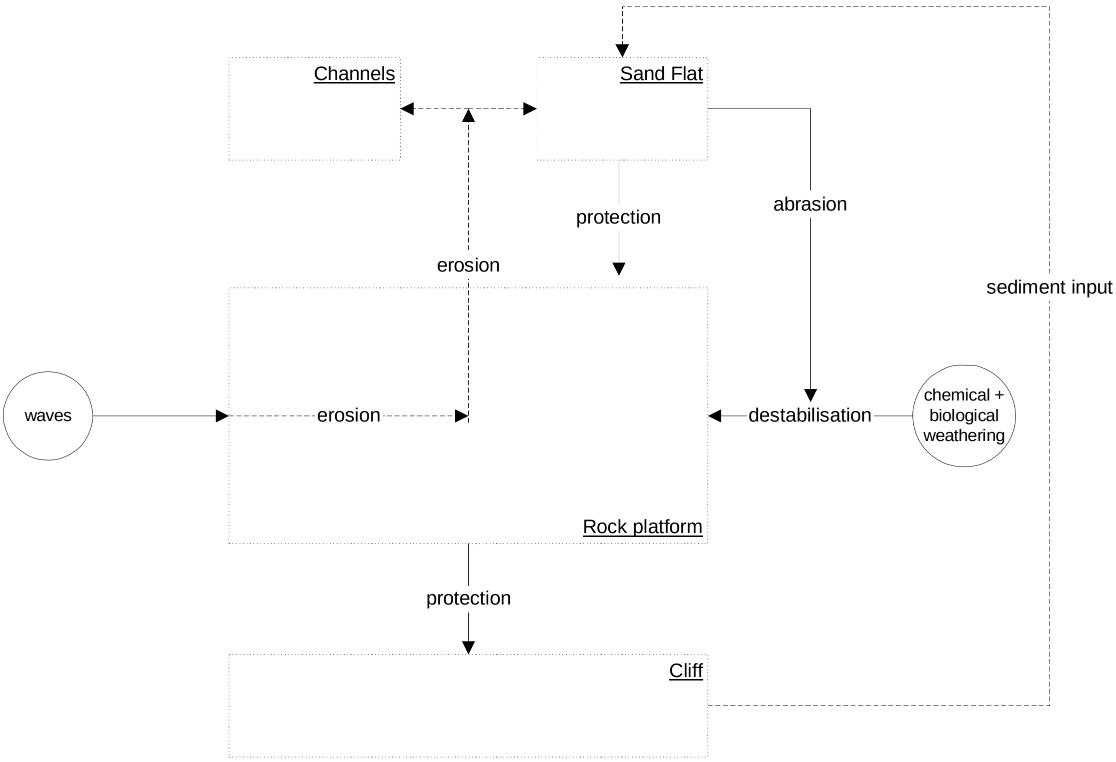

Figure 19. Short to medium term system diagram - Rock platform

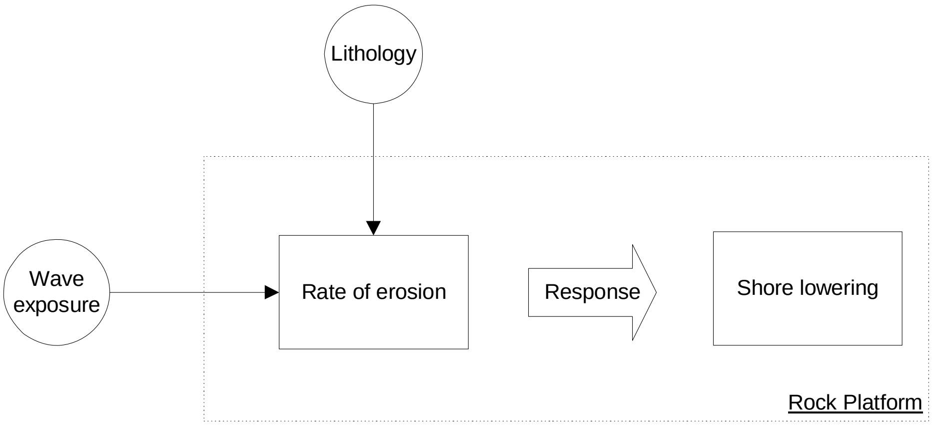

Figure 20. Medium to long-term system diagram - Rock platform

7. Behavioural Description for Channels

7.1 Definition of Geomorphological Element

Channels can be defined as sub-tidal morphological elements within the estuary bed, which are deeper than the surrounding deltas, banks or tidal flat features. The existence of these features is dependant upon favourable sediment and tidal conditions and can be present as a flood, ebb or main feature.

7.2 Function

The main function of channel is the discharge of fluvial flows through the estuary to the marine environment. Channels also allow for the tidal exchange of saline waters. As such the channel therefore allows the transmission of energy and sediment throughout the estuary and in doing so provides the link between many of the geomorphic elements within the system.

7.3 Formation and Evolution

The nature of the main channel will be dependant upon antecedent conditions and the degree of Holocene infilling with wave climate and tidal processes providing contemporary physical controls. The evolution of a main estuary channel is intrinsically coupled with evolution of the whole estuary form. A morphological concept that attempts to describe this evolution is based on the application of regime theory.

Regime theory describes an approach to channel theory that assumes some form of equilibrium relationship between certain morphological parameters, such as width, or depth and hydraulic parameters such as hydraulic slope, discharge, or flow velocity. A summary of the range of relationships available has been drawn together by Spearman and these are briefly summarised in (Spearman, 1995) and ABPmer Estuaries Morphological Guide (ABPmer, 2004). In its simplest form the relationship dictates that cross sectional area of a channel will adjust to changes in flows and *Vice versa* in order to attain equilibrium.

An alternative model of estuary and channel evolution is associated with tidal asymmetry (Pethick, 1994). In this model, tidal propagation within a wide deep channel results in a flood dominance and potential net import of sediment and accumulation on intertidal areas. As this change progresses, the morphological form evolves towards a central 'slot' channel with reduction in flood dominance and ebb dominance prevailing resulting in a potential export of sediment. Thus a morphological equilibrium is attained between the two channel types (see Figure 21, below).

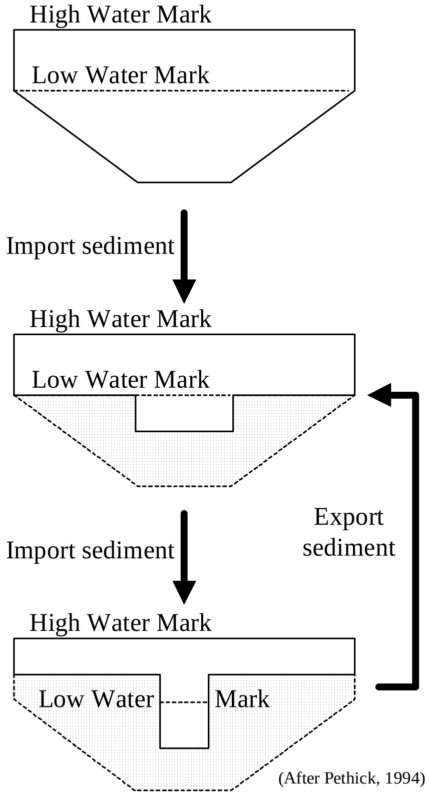

Figure 21. Stages of estuary development (Pethick, 1994)

7.4 General Form

The general form of channels is highly variable and site specific. The principle forms of channel can be identified according to their function. Feeder channels exist linking the catchment basin to the main channel and the main channel provides the principle conduit for energy and sediment exchanges in the estuary. In certain cases, flood and ebb flow separation can occur, with peak velocities occurring in different channel at different stages of the tide. In large estuaries, the Coriolis force (due to the earth's rotation) can be an important factor in flow separation and the development of flood and ebb channels. In plan form, channels can vary form predominately straight, to meandering and braided. This form is related to channel length, gradient and energy distribution.

7.5 General Behaviour

Channels have a range of behavioural responses to different forcing (van Rijn, 1998):

- **Meandering**. This behavioural response involves changes in the channel curvature due to erosion and accretion patterns along the channel edge. Depths will be greater and of a steeper gradient on the outside of the curve and shallower and of a gentler gradient on the inside. Meandering is an important characteristic found in the inner, or landward, sections of a number of estuaries. Meander formation in estuarine channels is complex, relative to fluvial channels, due to the presence of bi-directional flows and the mixing of saline and freshwater. Meander wavelengths in estuaries are related to tidal discharge and freshwater flows, with estuarine wavelengths greater than river wavelengths.

Meandering in estuaries can be associated with mid channel shoals, either with switching occurring involving the migration of the channel from one to the other side of the shoal or flow separation either side of the shoal;

- **Lateral shift/channel switching**. A consequence of sediment erosion along the channel edges. This occurs in the direction of the net cross-channel sediment flux. Sediment eroded from the bars and shoals is transported into the channel and result in a reduction of the cross-sectional channel area. As a result of the systems need to return to equilibrium, currents will act to erode the channel sides resulting in a net shift of the channel. Channel instability of this nature is a process related to meandering and can be an important process in certain estuaries. This process can result in progressive lateral shifting of the channel, as defined by the movement of the thalweg, or sudden channel switching. The precise causes of catastrophic channel switching are likely to be estuary specific. However, at a generic level a number of triggers can be identified, such as high freshwater flows (above a critical threshold level and coincident with a certain tidal state) and antecedent conditions. Channel switching has been noted as an important process in a number of UK estuaries, notably including the Humber (Pontee *et al.*, 2004);

- **Widening and narrowing**. Changes in the channel form due to variations in the tidal volume passing through the channel;

- **Rotation**. A larger scale lateral shift can occur at the channel mouth. This can be a consequence of changing wave action or other forcing which acts to cause deposition on the updrift side and eroded on the downdrift side of the estuary. This change will be accompanied by channels on the ebb delta;

- **Length change**. This is a consequence of the currents cutting into a bar or shoal. This process results in an increase in channel length. Length changes may also occur due to channel infilling. This may result in a channel becoming incised or alternatively may cause an increase in channel sinuosity thereby increasing the channel length.

7.6 Forcing Factors

Physical processes within a channel are essentially dependant upon the gross properties of the estuary within which the channel is a component, including:

- Tidal Range;
- Wave climate;
- River discharge;
- Channel scale (width and depth and cross sectional area); and
- Sediment availability and composition.

The interaction of these influences with the morphological form determine the specific internal characteristics and behaviour, including:

- Energy dissipation and speed of tidal propagation;
- Tidal asymmetry and ability for net import and export of sediment; and
- Degree of mixing (longitudinally and laterally) between saline and freshwater (and effect on sediment transport through residual currents, position of turbidity maximum and flocculation).

7.7 General Behaviour

The behaviour of a channel will in part be a function of its location within the estuarine system. Upstream channels associated with the transitionary zone between fluvial and fully estuarine conditions will have a form dependant to a greater degree from fluvial discharges, where as the form of a main channel of an estuary co-adjusts with physical processes.

7.8 Behavioural Timescales

7.8.1 Short-term (responses within a year)

Over the short term channel behaviour will be influenced by episodic events, such as fluvial flood events. These events can act as triggers to channel switching.

7.8.2 Medium-term (responses over decadal to century scale changes)

Over the medium term, channels will also undergo a morphological adjustment to sea level rise. This response occurs over a long temporal period, but is ultimately dependant upon the rate of sediment supply and relative sea level change. Two examples have been taken from van Rijn (1998):

(1) Relatively rapid sea level rise:

- Sediment supply is insufficient therefore the channels are unable to respond;
- The tidal channel volume will increase, in turn leading to an increased tidal prism;
- Whilst the channels will undergo some siltation, this will be more than balanced by increased channel dimension in order to accommodate for the increased tidal prism; and
- Channels within the outer delta will increase.

(2) Relatively slow sea level rise:

- Sediment supply is sufficient to allow the channels to respond;
- Tidal channel volume, and thus tidal prism, remain constant; and
- Equilibrium is maintained, as the sediment supply and demand balance remains constant. However, if supply were to outmatch demand, deposition will occur. This may ultimately lead to a decrease in the tidal prism and estuary closure.

7.8.3 Long-term (responses over century to Holocene timescales)

Over the longer term, the development of the channel will be linked to the evolution of the overall estuary form. The channel is likely to widen or narrow and lengthen or shorten as the estuary translates in position in response to relative changes in relative sea level.

7.9 Interactions with Other Geomorphological Elements

7.9.1 General interactions (elements within the estuarine system)

Whilst the responses of the channels have been described above in the context of sea level rise, the changes that occur will be intrinsically linked to other features within the estuarine system. Indeed any changes to the form and behaviour of channels will be observed in corresponding changes to, primarily, the intertidal area (saltmarsh and mudflat), deltas and banks and spits.

This process occurs as the migration of channels allows the release of sediment surrounding geomorphic elements e.g. sand and mudflats, saltmarshes, dunes, spits, etc. This sediment is then available to be reworked by the prevailing processes and deposited elsewhere to contribute to these existing geomorphic elements or form new versions of the pre-existing elements.

In addition to this direct impact on features from channel migration, the movement of the channel may also impact on adjacent features through changes to the degree of exposure to wave and tidal action.

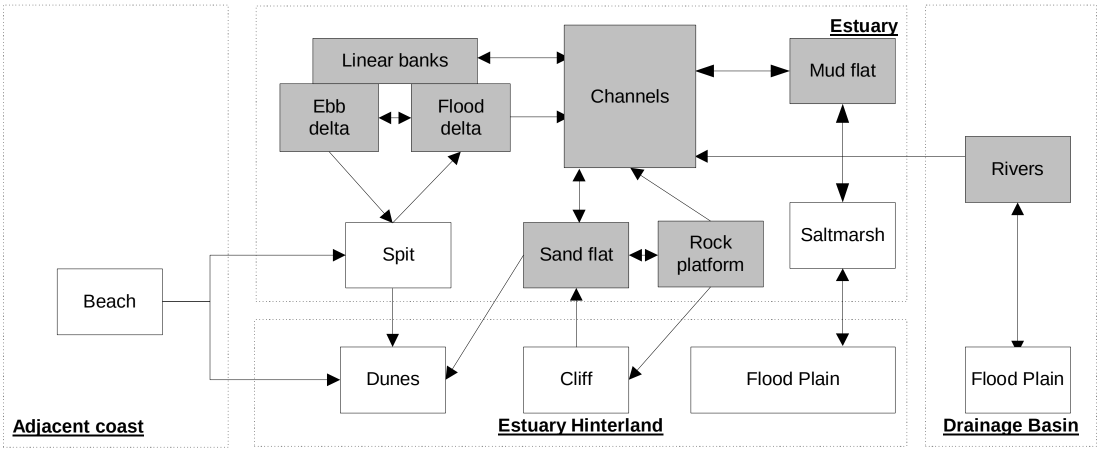

Figure 22. Interaction with other elements – Channels

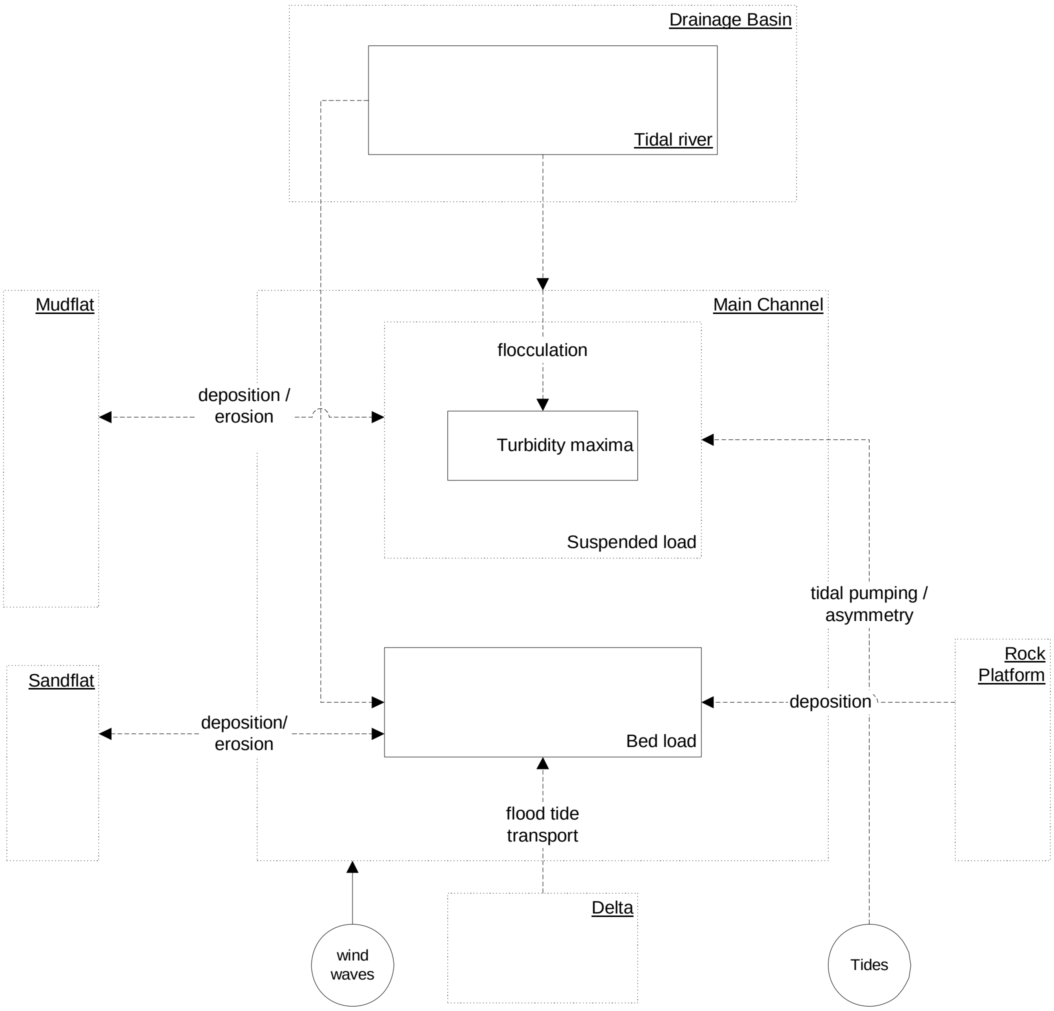

Figure 23. Short to medium term system diagram - Channels

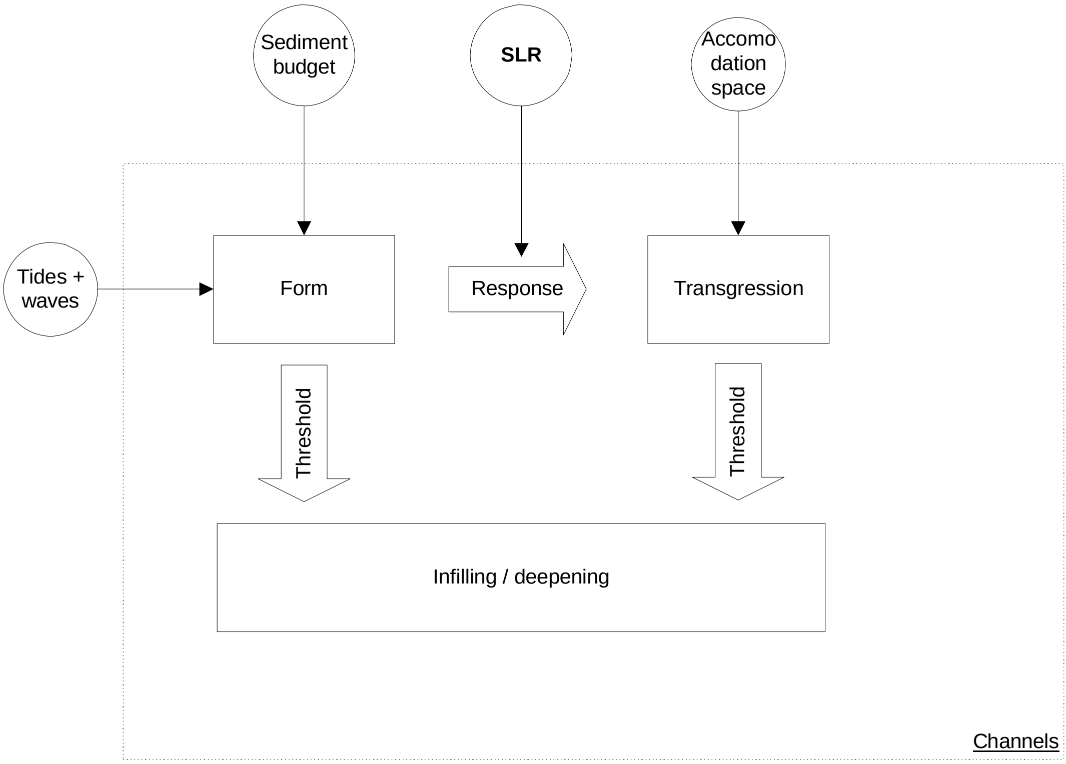

Figure 25. Medium to long-term systems diagrams - Channels

8. Behavioural Description for Mud Flats

8.1 Definition of Geomorphological Element

Intertidal mudflats can be defined as accumulations of cohesive sediments found along the margins of estuaries where there is a sufficient supply of fine grained sediment and prevailing conditions that permit their deposition in intertidal areas. Mudflats occur in estuaries from around the mean low water mark to around the mean high water mark. Therefore mudflats are often bounded to their seaward side by the subtidal channel of an estuary and to the landward side they translate into areas of saltmarsh. In areas where saltmarsh is absent on the landward side of the mudflat the flat may be bounded by some form of sea defence or the rising topography of the hinterland.

8.2 Function

Within an overall estuarine system, a mudflat performs a number of functions. In terms of energy, the main function is the dissipation of wave and tidal energy. In terms of sediments, the mudflat can act as a source or a sink for fine grained sediments depending on variations in the factors controlling mudflat development.

8.3 Formation and Evolution

It has been suggested that there are two end conditions, or profiles states, in terms of mudflat cross-shore profile shape (Kirby, 1992) (See Figure H1). These two profile states can be related to the general behaviour of the profile and the prevailing forcing processes.

- Convex Profile: This profile shape involves the steepest (i.e. highest gradient) section being located close to the low water mark (i.e. the lower mudflat). The minimum slope will be towards the upper end of the profile (i.e. the upper mudflat). This profile is associated with depositional processes, whereby there is a net increase in sediment on the mudflat over time (Dyer, 1998);
- Concave Profile: This profile involves the maximum slope occurring at the upper mudflat with the minimum slope close to low water. This profile shape is associated with erosion and a net deficit in terms of sediment input. This type of profile is often characterised by a small cliff at the saltmarsh - mudflat boundary. This feature is present due to the fact that a steep slope occurs at the top of the profile concentrating wave attack at high water over a narrow area of mudflat (Dyer, 1998).

Characterising a mudflat according to profile shape provides a good initial basis with which to understand the behavioural trends of this geomorphological element. As profile shape can be related to behavioural trends such as erosion or deposition, these trends can in turn be related to the processes that are dominant in causing, or controlling, the trends. The convex, depositional profile is generally associated with mudflats dominated by tidal flows whereas a concave, erosionary profile is generally associated with mudflats dominated by wave action.

Relating profile shape to behaviour is, however, a general rule and cannot be universally applied. The contradiction of this general rule is likely to reflect the influence of another factor on behaviour or the occurrence of a constraint to morphological development that prevents the natural behavioural tendency. One influence on profile shape that has been suggested is shore plan shape, with lobate shorelines demonstrating slightly more concave profiles and embayed shorelines a less concave profile.

In reality mudflats are likely to be between these two end states of concave and convex and it is possible that elements of both will be present within the same profile. As such, the profile at any point in time will reflect the dominance of the various driving forces and constraints at that time.

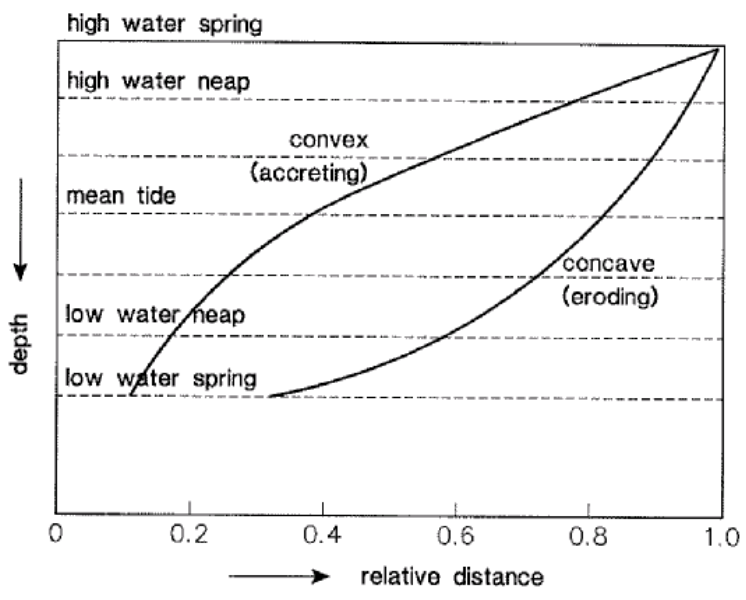

Figure 26. Characteristic concave and convex mudflat profiles (van Rijn, 1998)

8.4 General Form

Mudflats can be subdivided by their cross-sectional profile. This profile can be conveniently divided into three sections, as follows (Dyer, 1998):

- The lower mudflat: from mean low water springs to mean low water neaps;
- The middle mudflat: from mean low water neaps to mean high water neaps; and
- The upper mudflat: from mean high water neaps to lower margins of saltmarsh or mean high water springs.

On this profile a distinctive break in gradient often exists within the middle mudflat, distinguishing the lower from the upper mudflat.

A number of morphological features are often present on the mudflat profile. Channels cutting through the mudflat have a variety of forms and vary in depth and nature according to their location on the mudflat profile and the width of the flat. The occurrence of cliff features within the mudflat are generally an indication of erosional processes (Dyer, 1998), although it should be noted that these features can also be formed in accretional environments. Most commonly these features either occur at the upper limit of the mudflat (i.e. at the boundary with saltmarsh) or around mid-tide level, where the break in slope between the upper and lower mudflat occurs.

8.5 General Behaviour

The behaviour of the mudflat will be dictated to a large extent by the balance between erosion and deposition processes.

8.5.1 Deposition

Cohesive sediments are fine grained and as such will be transported as suspended load as opposed to bedload. Deposition of suspended sediments will occur when the settling velocity of the sediments is greater than the shear velocity of the flow. In accordance with this the rate of deposition will therefore, be controlled by the velocity of flows, suspended sediment concentrations and the grain size of material in suspension.

The grain size of a suspended sediment particle will determine its settling velocity. This will, in the case of cohesive sediment, be relatively low and based on this velocity alone a particle would not have sufficient time, even during slack water periods, in which to settle through the water column and deposit on the mudflat. However, the process of flocculation makes the deposition of the fine grained, cohesive sediments on a mudflat possible.

8.5.2 Erosion

Erosion of mudflats mainly consists of the re-suspension of cohesive sediments. The rate of erosion is controlled by the balance between wave and current induced shear stress and mud shear strength and the duration of exposure of sediments to wave attack and flows.

The shear stress imposed, by waves on the mudflat is determined by the wave height and the water depth (as a function of tidal range as discussed above).

The shear strength of the mudflat (i.e. the erodibility) will be determined by a number of factors. The most influential of these is de-watering of the deposited sediments. This occurs during exposure to the atmosphere due to the fall of the tide. The decrease of surface moisture content that occurs during the de-watering process results in cohesion. This cohesion has the effect of raising the threshold for sediment erosion. Biological processes can also impart additional strength on the sediments (e.g. algae acting to bind sediment together).

8.5.3 Wave current interactions

The above sections have discussed the relative important of waves in exerting a control on the erosion of mudflat sediment and tidal current in the deposition of sediment on the mudflat. These roles can be explored further to provide an insight into how their interaction exerts a control on mudflat behaviour and hence form. Waves are rapidly attenuated across a mudflat and refracted to be approximately shore normal. Wave action acts to stir up the bed and re-suspend sediments. The subsequent transport of these sediments is however, then controlled by tidal flows.

8.5.4 Biota

It is also important to recognise the role of biota in exerting an influence on the processes of erosion and deposition on an intertidal mudflat. This is the subject of ongoing research attempting to further understanding and quantify the influence of biota. Within the EstProc (EstProc, 2004) project investigations have focused on quantifying the impact of biota on estuary hydrodynamics and sediment dynamics.

In broad terms the influence of biota can be grouped into stabilising processes or destabilising processes. These processes will obviously exert an influence on erodibility, either contributing to accretion or erosion across a mudflat.

8.6 Forcing Factors

The processes of transport erosion and deposition of suspended sediments are driven by the forcing from waves and tidal currents.

Wave processes across mudflats will largely dictate erosion, or re-suspension, of sediments across the mudflat profile. Sediment cohesion following deposition and exposure of material will raise the erosion threshold such that re-suspension by tidal currents on following tides is less likely. As a result of this, waves control mudflat erosion and ultimately provide a check on mudflat morphology.

The duration of wave attack is a crucial factor determining the degree of erosion. The period over which any particular location on a mudflat profile is exposed to wave attack is a function of tidal range. Typically, tidal range therefore exerts a fundamental influence, or constraint, on the extent of intertidal mudflat in an estuary. Intuitively, considering this principle, the greater the tidal range, the shorter the duration of wave attack at high water and therefore the greater the extent of fine-grained mudflats. Mudflats are likely to be much more extensive in macro- relative to meso-tidal estuaries.

Due to the relatively low settling velocities of cohesive sediment, settling through the water column and deposition on the mudflat surface is unlikely to occur under wave action. Tidal flows across mudflats largely dictate deposition of sediments on the mudflat. As tidal level rises, velocities increase until around the mid-tide level, when half the flats are covered and velocities are at their maximum. As the tide reaches the upper mudflats at high water, velocities fall approaching slack water (Pethick, 1984). Deposition rates would therefore be expected to be greatest on the upper mudflat. This depositional process associated with varying tidal velocities results in a grading of sediment composition, with sediments on a mudflat fining landwards (Pethick, 1984). In general, deposited sediments can vary from sandy silts below mid-tide to silty clays in the high tide zone.

The role of waves and currents in forcing, and hence controlling form, can also be considered with reference to tidal flat hypsometry (i.e. the distribution of surface area with respect to elevation). Hypsometric trends on tidal flats can be related to the relative dominance of waves or tidal currents. Under wave domination, a concave hypsometry results while a higher relative importance of tides leads to convex hypsometry and long-term accretion. Plan shape has also been shown to exert a significant influence on tidal flat hypsometry, with this influence of equal importance to the dominance of either waves or tides.

8.7 Evolutionary Constraints

A number of constraints to mudflat development can be identified:

- Suspended Sediment Supply: The process of mudflat formation and subsequent evolution is dependant on a supply of cohesive sediment. This supply is required to allow the mudflat to adjust to the applied driving forces. The development of a mudflat under a scenario of adequate suspended sediment supply and a deficit in supply would be significantly different;
- Migration Space: The dynamic nature of mudflats mean they require space in which to migrate in response to changing conditions. A lack of migration space will constrain the position of the mudflat profile and result in different behavioural trends. There are many forms of constraint that fall under the overarching migration space heading. These can be either natural (such as a geological hard point or rapidly rising hinterland topography) or man-made (such as sea defences);
- Tidal Range***:*** Tidal range can be considered a constraint to evolution in the sense that it will control the extent, and to some degree the composition, of mudflats that can develop in an estuary.

8.8 Behavioural Timescales

8.8.1 Short-term (responses within a year)

Over tidal cycles, a process of sediment re-cycling occurs on mudflats. This process involves the transport of material between the upper and lower mudflat on successive tides. This recycling and movement of sediment within the mudflat profile is the mechanism through which the profile is able to respond the variations in forcing over these short time scales.

8.8.2 Medium-term (responses over decadal to century scale changes)

Mudflat behaviour over this timescale is driven by the occurrence of low frequency, high magnitude wave events and intervening calmer periods. A mudflat may exhibit accretional or erosional behaviour depending on the prevailing forcing. This behaviour will be reflected in the mudflat profile. In addition to these changes in form, changes may also occur in the vertical and horizontal position of mudflats over this timescale.

Additionally, over this timescale, mudflat behaviour may be influenced by migration of any adjacent channels, affecting the degree of mudflat exposure. Biotic factors can also play a role in influencing mudflat behaviour. For example, the presence of eelgrass can afford a mudflat surface a degree of protection from prevailing surface. Any change in the presence or extent of eelgrass may therefore affect behaviour.

8.8.3 Long-term (responses over century to Holocene timescales)

Mudflat behaviour over this longer timescale is driven by relative sea level rise. The behavioural response to this forcing is variable and dependant on a number of factors. As a result a number of different scenarios can be considered each with different potential behavioural responses.

Under a scenario of adequate supply of suspended sediment and sufficient migration space for the mudflat to migrate into (i.e. no geological or man made constraints) the response of the mudflat would be to accrete vertically and migrate landward to maintain the same position in the tidal frame.

Under a scenario of restricted suspended sediment supply, the mudflat is unlikely to be able to accrete to keep pace with relative sea level rise. This accretion is required if the mudflat is to maintain its position within the tidal frame. The lack of sediment to achieve this may result in the eventual drowning of the mudflat profile.

Under a scenario of restricted migration space, e.g. through rising topography or a fixed line of sea defence, the mudflat would attempt to migrate landwards. However, with a static landward margin the mudflat would become progressively squeezed between the migrating mudflat edge and the static landward boundary. This is the process of coastal squeeze.

8.9 Interactions with Other Geomorphological Elements

8.9.1 Saltmarsh

Mudflats and saltmarsh are interdependent geomorphological elements. Given the dependence of the two units it is vital to consider the two in conjunction with each other and to do this each of the links must be clearly defined, as follows:

Mudflat development essentially creates a low energy environment at an elevation relative to the tidal frame that is conducive to saltmarsh development. As mudflats develop, under adequate sediment supply, their ability to dissipate wave energy will increase and as a result the upper mudflat will progressively become a low energy environment. This environment encourages sediment deposition and as a result elevations increase. Hence the mudflat is progressively able to provide a surface at the correct elevation for saltmarsh colonisation.

Under relatively benign forcing conditions, there is likely to be a transfer of sediment from the mudflat surface to the saltmarsh to be deposited on the saltmarsh surface. Exchanges from saltmarsh to mudflat mainly occur during high magnitude low frequency events. Under these conditions, the saltmarsh acts as a temporary sediment supply to the mudflat. This supply is caused by the increased wave energy eroding the saltmarsh and transporting the material onto the neighbouring mudflat. In geomorphological terms, this supply of material allows the mudflat to adjust its profile to the applied forcing through widening and flattening.

In addition, under these storm conditions the saltmarsh provides migration space into which the mudflat can migrate to allow the morphological response of profile widening.

8.9.2 Channel

The channel is the mechanism through which the main forcing factors (tidal flows and waves) are applied to the mudflat surface. The location and nature of the channel will determine the degree of exposure of the mudflat to these processes.

A channel acts as a conduit for sediment transport to the mudflat. Variations in the supply from this source would significantly affect the behaviour of the mudflat. In addition the deposition of sediments within the subtidal channel may affect the availability of sediment for deposition on the mudflat.

8.9.3 Protective features

For prevailing conditions to allow the formation and maintenance of mudflats, a degree of protection is required. In the middle and upper sections of an estuary, the form of the estuary itself is likely to provide this. However, in the outer sections of an estuary this protection may be afforded by another geomorphological element, such as a spit, a sandflat or an ebb tidal delta.

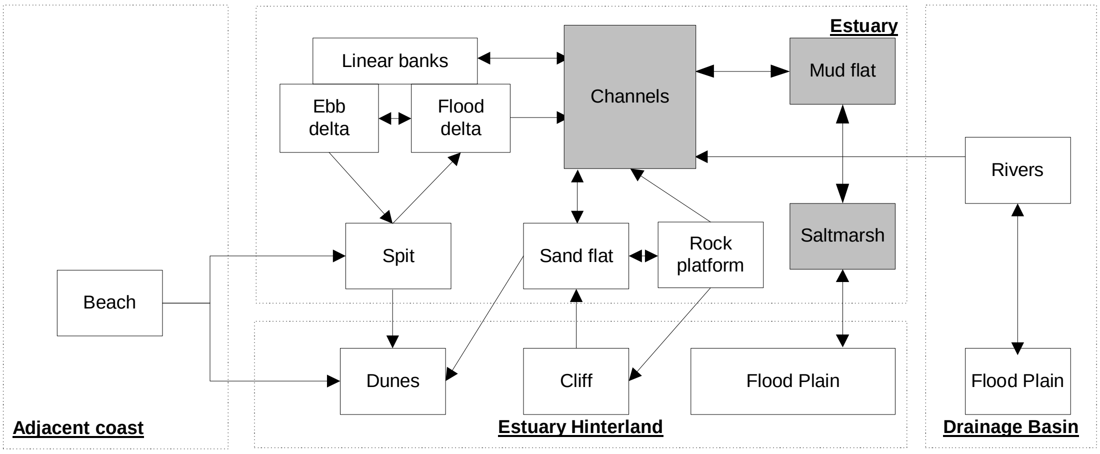

Figure 27. Interaction with other elements - Mudflats

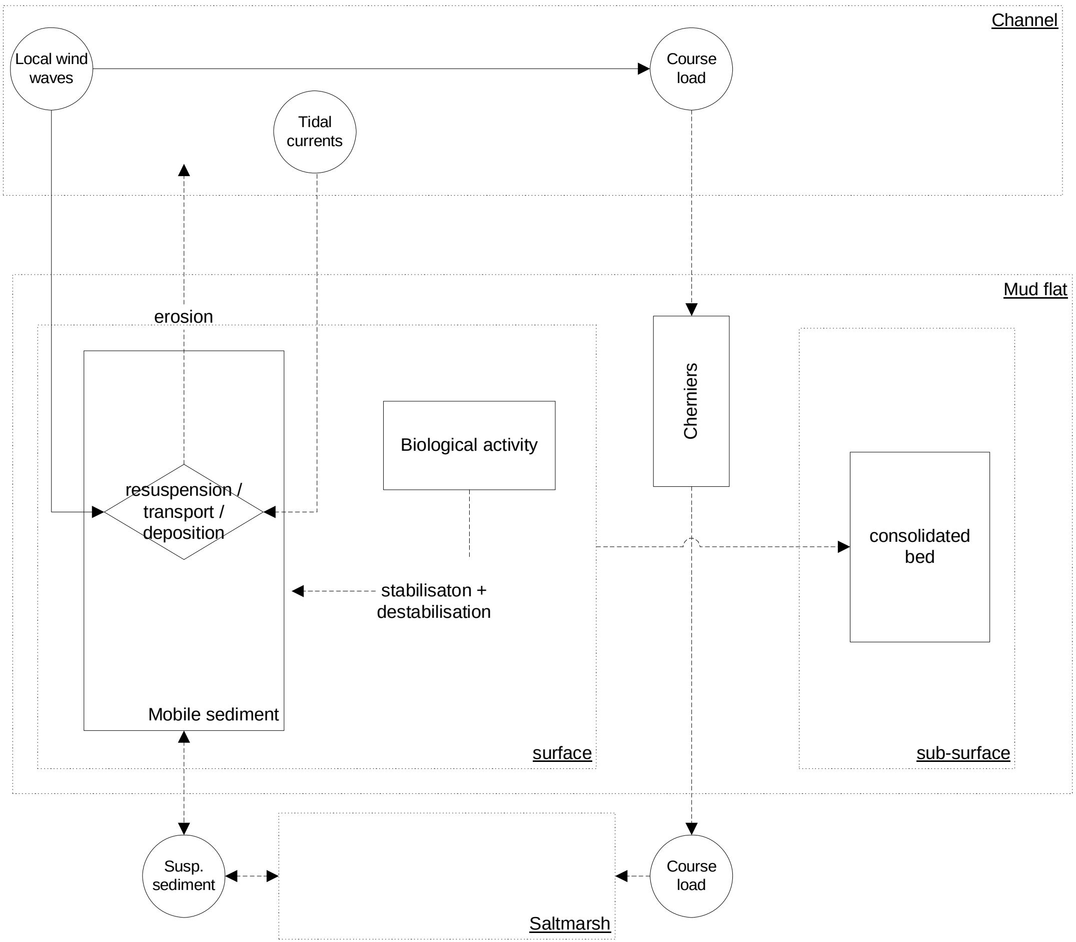

Figure 28. Short to medium term system diagram – Mudflats

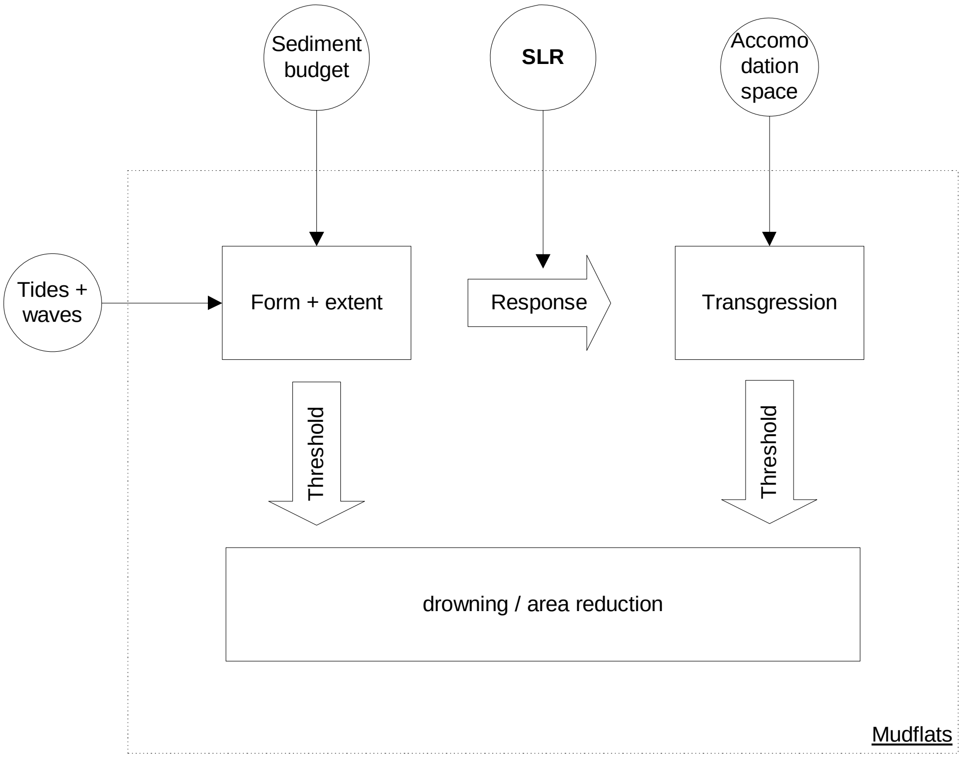

Figure 29. Medium to long-term system Diagram - Mudflat

9. Behavioural Description for Sandflats

9.1 Definition of Geomorphological Element

Distinction has been made here, for the purpose of defining morphological behaviour, between mudflats and sandflats. It is recognised that these landforms are part of an intertidal continuum and in many cases will occupy a similar position within an estuary in terms of the tidal frame. However, as noted, the primary concern here is behaviour and the two forms will exhibit subtle behavioural differences. These differences are the product of the differing nature of cohesive and non-cohesive sediments. The resultant changes to behaviour are explored in the following sections. It is recommended that this statement be read in conjunction with the mudflats statement.

Intertidal sandflats are defined here as accumulations of non-cohesive sand sized sediments deposited in the intertidal areas of an estuary.

9.2 General Function

The function of a sandflat is the dissipation of wave and tidal energy. This is in common with that of a mudflat. However, differences in the interaction of form and processes, and hence energy dissipation, between the sandflats and mudflats is fundamental to behavioural differences. Sandflats also act as a store of sediment within the estuarine system.

9.3 General Behaviour

The behaviour of a sandflat will be linked to the balance between the processes of erosion and deposition. However, the will be a subtle difference in the balance between the two processes on a sandflat relative to a mudflat. This is a critical distinguishing behavioural difference between a cohesive and non-cohesive intertidal area and is dictated by the different responses of the two sediment types to forcing conditions. The key behavioural difference is due to the difference in the critical erosion threshold between the two forms. Mudflat sediments will be more resistant to erosion (Pethick, 1984) with a higher erosion threshold than non-cohesive sandflat sediments. This difference will affect sediment transport on a sandflat and will alter the nature of the behavioural responses of this element over different timescales. Lee & Mehta (1997) note that mud profiles are generally flatter than their sand counterparts.

9.4 Forcing Factors

Both tides and waves will play important roles on sandflats. In addition to the direct influence of both these processes, tides will also play a role in behaviour by controlling the location of wave processes across the profile and hence the duration of wave attack. A combination of the tidal range and the sand flat profile will control the width over which wave process will be translated.

9.5 Behavioural Timescales

9.5.1 Short-term (responses within a year)

Over the short term, a sandflat is able to alter its profile to adapt to variations in forcing, for example seasonal variations in wave climate.

9.5.2 Medium-term (responses over decadal to century scale changes)

Over this medium timescale, a sandflat is likely to adopt a profile form in response to trends in forcing (for example changes in storminess). In addition to these changes in form, changes may also occur in the position (both vertical and horizontal position) of sandflats within the estuary system over these timescales.

Additionally, over this timescale, sandflat behaviour may be influenced by migration of any adjacent channels, affecting the degree of sandflat exposure.

9.5.3 Long-term (responses over century to Holocene timescales)

Sandflat behaviour over this longer timescale is driven primarily by relative sea level variations, with the nature of the response controlled by a number of factors. As a result a number of different scenarios can be considered each with different potential behavioural responses. Sandflat behaviour over this timescale is similar to that described for mudflats:

Assuming an adequate supply of sediment and sufficient migration space for the sandflat to migrate into (i.e. no geological or man made constraints), the response of a sandflat under rising relative sea levels would be to accrete vertically and migrate landward to maintain the same position in the tidal frame.

Under a scenario of restricted sediment supply, the sandflat is unlikely to be able to accrete to keep pace with relative sea level rise. This may result in the eventual drowning of the profile. Under a scenario of restricted migration space, e.g. through steeply rising topography or a fixed line of sea defence, the sandflat would attempt to migrate landward but would become progressively squeezed between its migrating seaward edge and the static landward boundary. This is the process of coastal squeeze.

9.6 Interactions with Other Behavioural Elements

9.6.1 Beach/dune

Sand flats may in certain situation be backed by beach and dune systems to the landward side. Where present, the behaviour of these elements will be closely linked. The formation of a dune system to landward of a beach and sandflat will be controlled by a number of factors. The period of drying will dictate if the required aeolian transport of sands will occur. This will in turn be controlled by the period tidal range and cross-shore profile of sandflat. In addition the sediment composition will exert an influence as will the orientation of the flat with respect to prevailing winds.

9.6.2 Channel

The channel is the mechanism through which the main forcing factors (tidal flows and waves) are applied to the sandflat surface. The location and nature of the channel will determine the degree of exposure of the sandflat to these processes.

The channel will provide the main conduit for sediment transport supplying the sandflat with sediment (sediment may have originally been derived from offshore via longshore drift movement on a spit and through an ebb/flood delta). During erosional events, sediment may also be lost to the channel for redistribution within the system.

Lateral migration of a channel may erode a sand flat, thereby releasing sediments into the estuary system.

9.6.3 Cliff

In a situation where a sandflat is directly backed by a cliff, cliff erosion can provide a direct feed of material during high energy conditions. A sandflat will also provide energy dissipation to a backing cliff feature providing protection.

9.6.4 Rock platform

In the case where a rock platform is present, overlying sandflat sediment may aid erosion of the rock platform through abrasion but can also provide protection from direct wave attack.

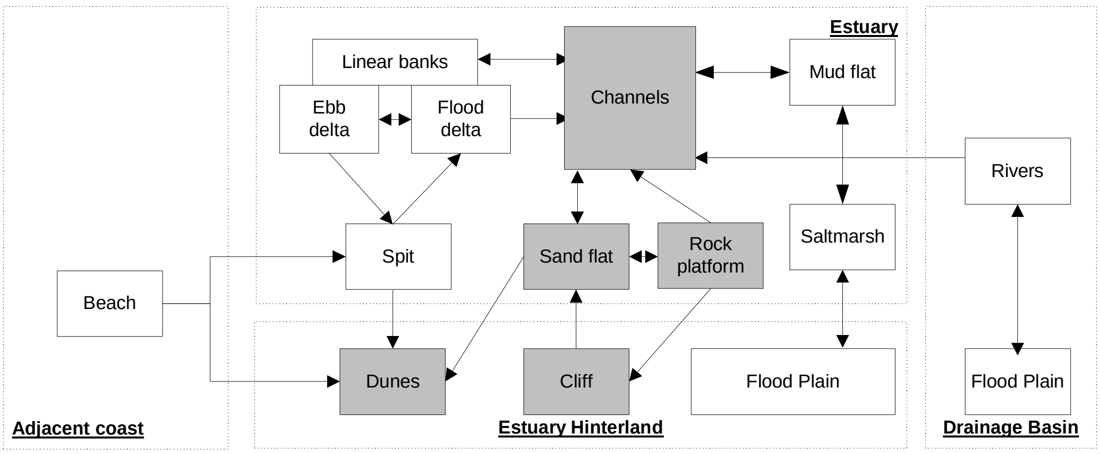

Figure 30. Interaction with other elements – Sandflats

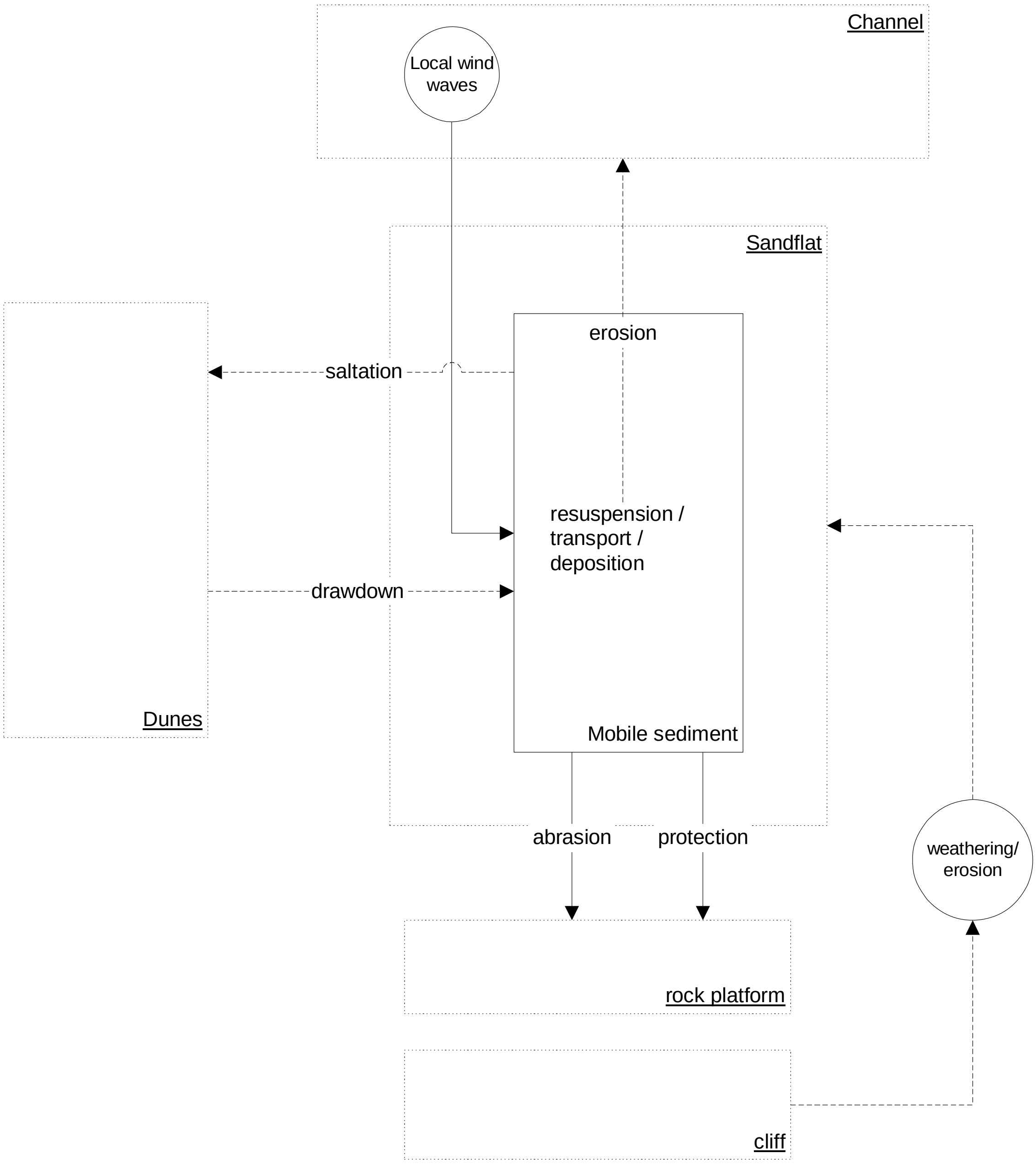

Figure 31. Short to medium term system diagram - Sandflats

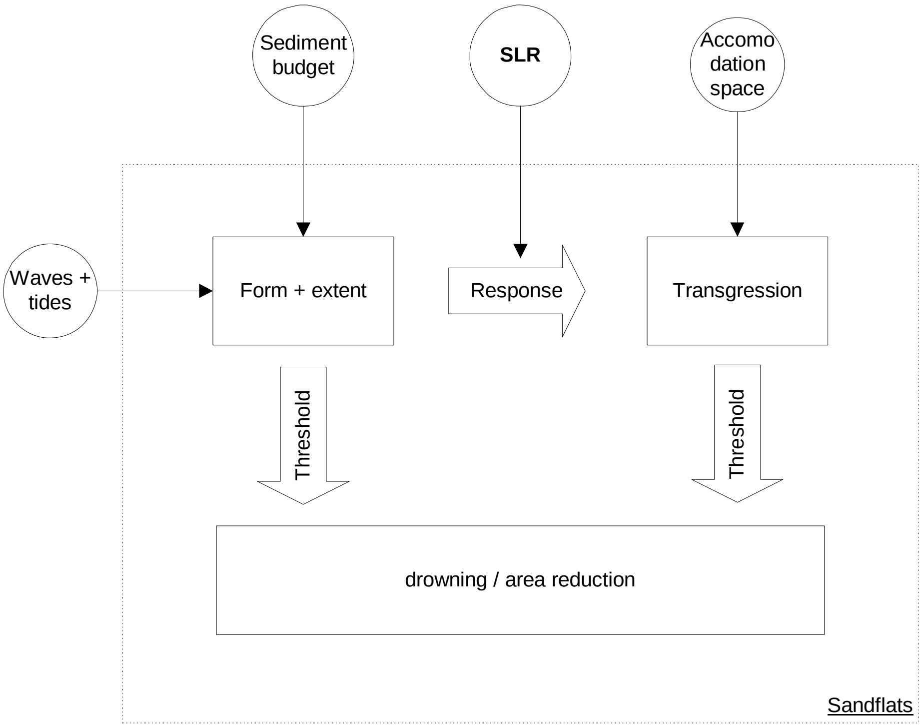

Figure 32. Medium to long-term system diagram - Sandflats

10. Behavioural Description for Saltmarsh

10.1 Definition of Geomorphological Element

Saltmarshes can be defined as accumulations of cohesive sediments vegetated by salt tolerant plant species found along the intertidal margins of estuaries. Saltmarshes generally occupy the upper inter tidal zone at higher elevations of mudflats, in areas inundated less frequently by the tide in the UK. Typically saltmarshes occur between mean high water neaps to high water spring tides. Above this elevation, the marsh is likely to give way to either terrestrial fresh water plant species or some form of defence or sea wall or the rising topography of the hinterland. At its lower margins saltmarsh is likely to be bounded by mudflat. In areas without mudflat, saltmarsh may adjoin the main sub tidal channel of an estuary or lie in the lee of a feature that acts to dissipate tidal and wave energy. The presence of vegetation on the saltmarsh surface results in significantly different processes, morphology and behaviour relative to neighbouring mudflats.

10.2 Function

Within the overall estuary system areas of saltmarsh act to dissipate wave and tidal energy and hence afford protection to the adjacent hinterland, in addition a saltmarsh represents a significant sink for sediments within the estuary.

10.3 Formation and Evolution

For saltmarsh to develop there is a requirement first for a sandflat or mudflat to form and evolve. For this to occur the prevailing conditions must be conducive to the transport and deposition of cohesive sediments. This requires a relatively sheltered low wave energy environment with adequate supply of suspended sediments. Eventually, as elevations rise at the upper mudflat, this process will lead to a decrease in the duration of tidal inundation on the upper intertidal (Pethick, 1984). A critical point will be reached where the duration of exposure of the mudflat permits colonisation by halophytic (salt tolerant) vegetation.

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).

Initial colonisation is likely to occur on mudflat areas of higher elevation than the surrounding intertidal. These higher elevation areas could be the result of a number of factors, such as:

- Organic activity; and
- Relatively higher areas between pre existing mudflat channels.

The establishment of this initial vegetation then encourages further sediment deposition and further colonisation, forming patches of vegetation (Pethick, 1984). In addition, marshes may grow up around existing creeks within intertidal flats. Patches of developing vegetation will, over time, become joined to form a continuous area of vegetation. As this development takes place, important changes also occur to the flow regime across the newly formed marsh. Flow becomes more confined to channels or creeks. As accretion of the marsh surface occurs the number and duration of tidal inundations is further reduced. This allows different plant species to colonise these higher levels of the marsh.

Over the long term the rate of deposition decreases as the reduced tidal inundations limit the sediment supply. A marsh matures asymptotically, towards an elevation at which further deposition is sufficient to offset the effects of relative sea level rise and compaction.

10.4 General Form

When considering the form and behaviour of areas of saltmarsh it is convenient to consider the different geomorphological features that are present within this element. Four principal component features occur on areas of saltmarsh. These are:

- Saltmarsh surface;
- Creeks;
- Salt pans; and
- Cliffs.

Each of these features will be controlled by different processes and hence will perform a different function or role within an overall area of saltmarsh. However, it is the combination and interaction of each of these features that will determine the behaviour of the saltmarsh system as a whole. The processes associated with each of these features are discussed below.

10.4.1 Saltmarsh surface

A large proportion of saltmarsh area is marsh surface. The saltmarsh surface plays a role in the dissipation of wave and tidal energy. Studies regarding the role of the marsh surface in wave attenuation have shown that wave height reduction over saltmarsh is approximately four times higher that over sand flats. In addition, the marsh surface acts as a significant sink for sediments.

Marsh surface behaviour will vary both vertically and horizontally in the long term. Vertical variations will occur as the marsh matures in a feedback relationship between elevation, tidal inundation and sedimentation. Short term vertical variations may also occur, driven by variations in, for example, suspended sediment concentration and biological activity.

The cross-sectional shape of a saltmarsh is likely to vary over time. The variations are a reflection of spatial variations in sediment deposition across the marsh surface. A convex profile will be produced when sedimentation rates are greatest towards the centre of the marsh, falling off to landward and seaward, whereas a concave profile will be the result of deposition towards the upper or lower sections of the marsh. A number of factors will control the shape of the saltmarsh profile, not least the maturity of the marsh, i.e. the stage of development of the marsh will dictate where on the marsh surface the zone of maximum accretion occurs.

The typical mature cross sectional profile of a saltmarsh can be characterised as convex - concave (See Figure 33) (Pethick, 1984). At the seaward margin the saltmarsh exhibits a convex profile, with a flat main central section and a concave landward slope. This profile is a reflection of the number of tidal inundations and therefore the likely deposition rates i.e. a convex lower slope indicative of deposition processes at the lower marsh where inundation numbers and durations will be highest and the concave upper marsh landward slope located in an area of limited inundation and hence limited deposition (Pethick, 1984).

In horizontal terms, the marsh surface may extend or migrate landward or seaward. The seaward limit of the saltmarsh surface can be marked by the presence of a cliff feature up to 1m in height. These cliffs can be formed and develop in both an erosional and accretional environments.

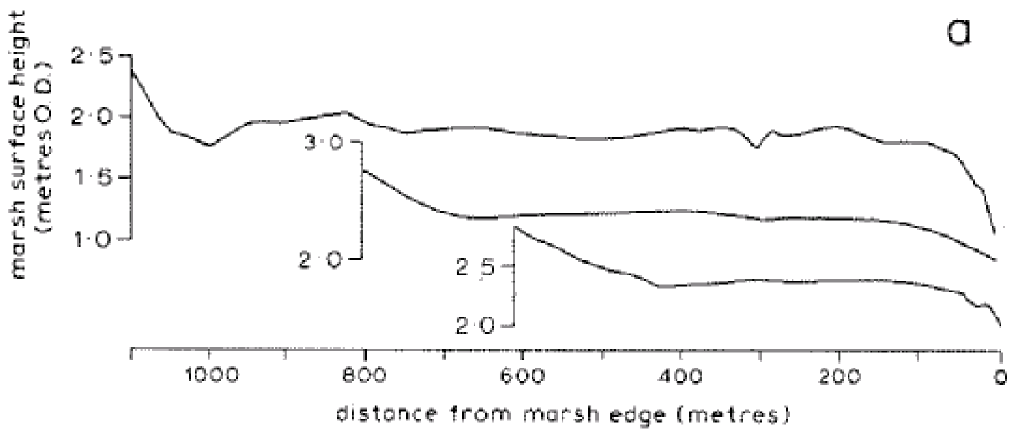

Figure 33. Profile across saltmarshes in the Tamar Estuary (Pethick, 1984)

10.4.2 Marsh creeks

The creek systems found within saltmarshes are a vital component of the overall system. In plan view, creek systems appear similar to fluvial drainage systems. However more detailed consideration shows distinct differences between the two. Flows within saltmarsh creeks are two way and in addition saltmarsh creeks experience bank full conditions on a regular (tidal) basis. Investigation of the surface area of marshes and the relation to creek density suggests that the main function of the creeks is not drainage of the ebb tide from the marsh. Rather the details of the creek systems appear to be dependent on the tidal prism entering the marsh on the flood tide. This suggests, therefore, that the function of saltmarsh creeks is to dissipate tidal and wave energy in a similar way to a main estuary channel. In addition, marsh creeks can also act to drain freshwater flows.

Creeks act to funnel the oncoming flood tide and distribute the tidal water into the marsh (Carter, 1988). The creeks transfer water through progressively smaller channels thereby dissipating the tidal energy through increased friction. As water levels in the creeks rise and the banks are overtopped water is allowed to spill onto the marsh surface (Carter, 1988). The increased frictional resistance on the surface then causes deposition of sediments in suspension. From this perspective the creeks perform an irrigation function transporting water and, hence suspended sediments, to the marsh surface.

In addition to transporting suspended sediments associated with tidal flux, flow in the creeks also acts to recycle sediments within the marsh system (Carter, 1988). This occurs as creek banks are undercut causing bank slumping. The sediment produced by this process may be transported seaward or alternatively (i) re-deposited in creeks or (ii) deposited on the saltmarsh surface. Within the creeks, deposition is most likely to occur in the vicinity of creek meanders. On the saltmarsh surface, areas of greatest deposition occur adjacent to the creeks as material is deposited immediately after spilling onto the marsh during bank full stages of the tide. This results in the formation of levees (Carter, 1988). Levee deposition of this sort will in term effect the nature of the local colonising species.

10.4.3 Salt pans

A further common saltmarsh feature is saltpans. These consist of shallow pools filled with water on the marsh surface. Although these features are an element of the overall saltmarsh form they are essentially relict features, as defined above, and are therefore not included as a component within the systems diagram.

10.4.4 Cliffs

A cliff feature regularly occupies the transition zone between mudflat and saltmarsh zones and indicates the boundary between mobile mudflat sediments and the more stable saltmarsh sub-surface, which is influenced by the vegetation root structure. It is believed that these features can occur in both erosional and accretional environments (Gao & Collins, 1997) and under wave action (local wind waves or ship wash) these zones can be come highly dynamic.

10.5 General Behaviour

Much of the behaviour of a saltmarsh is dependant on the balance between the processes controlling erosion and deposition.

10.5.1 Deposition

As an area of mudflat becomes colonised by saltmarsh species, the nature of the deposition processes are dramatically altered. Saltmarsh vegetation presents an increased frictional roughness to the intertidal surface. This results in two specific impacts on the flow regime above the saltmarsh surface. Firstly, a zone of zero velocity occurs close to the bed. Secondly to compensate for this dramatic decrease in the lower layers of flow, the upper layers of the flow increase in velocity. The net result of this is actually a lower sedimentation rate on a saltmarsh relative to a mudflat. However, reduced near bed velocities protect the recently deposited sediment from re-suspension and as a result saltmarsh tends to accrete far more rapidly than mudflat.

In addition to this basic process, the presence of vegetation on the saltmarsh surface exerts several other important influences on deposition, for example:

- Plant stems set up flow eddies trapping sediments and resulting in areas of high deposition;
- Increases in flocculation locally can be caused by plant species that provide salt from their stems increase salinity levels. This increased flocculation could, in theory, lead to increased deposition; and
- Saltmarsh plants may be underlain by algal mats producing a sticky surface that traps sediments more effectively.

Deposition of sediments on a saltmarsh can occur on differing parts of the marsh, including:

- Saltmarsh Surface Accretion: The main mechanism of marsh growth and expansion is deposition on the marsh surface. This can cause the vertical and/or horizontal development of the marsh; and
- Creek Deposition: Sediment may also be deposited within tidal creeks either from the re-working of pre-existing saltmarsh sediment or the introduction of new sediments.

10.5.2 Erosion

Due to the frictional influence of saltmarsh vegetation on flows, erosion of a saltmarsh through the re-suspension of fine-grained sediments is less frequent than erosion on neighbouring areas of mudflat. Erosion of saltmarsh sediments will occur when the shear stress imposed by physical processes exceeds the shear strength of the saltmarsh surface.

As with deposition, saltmarsh erosion can occur in relation to any of the geomorphological features identified, as follows:

- Erosion of the marsh edge (cliff);
- Enlargement of the pans or creeks. This process can occur via either bank collapse or headward erosion/retreat and may result in the occurrence of areas of bare un-vegetated mudflat within the marsh; and
- Marsh surface erosion. The deterioration of marsh vegetation can lead to generalised scour and surface lowering.

The process of erosion and deposition and hence the behaviour of a saltmarsh should also be viewed in the context of biological interactions.

10.5.3 Biota

It is also important to recognise the role of biota in exerting an influence on the processes of erosion and deposition on an intertidal mudflat. This is the subject of ongoing research attempting to further our understanding and quantify the influence of biota (EstProc, 2004). In broad terms the influence of biota is exerted through a number of processes that can be grouped into stabilising processes or destabilising processes. These processes will obviously exert an influence on erodibility, either contributing to accretion or erosion across a mudflat.

10.6 Forcing Factors

The processes of erosion and deposition discussed above are driven, in the case of saltmarsh, by the two principal driving forces of waves and tidal currents.

Wave processes in marsh areas will dictate the erosion or re-suspension of sediments. However, due to the high position of areas of saltmarsh within the tidal frame, both the frequency and the duration over which the saltmarsh surface will be exposed to wave attack is limited relative to seaward areas of mudflat and can lead to changes in saltmarsh area.

Tidal processes across saltmarshes largely dictate deposition processes. Tidal processes transport suspended sediment onto the saltmarsh. Tidal flows are distributed through the marsh area via the marsh creeks and, at higher stages of the tide, over the marsh surface itself.

As noted, the tidal stage will also regulate wave attack and in this sense exerts an indirect influence on marsh erosion.

10.7 Evolutionary Constraints

A number of constraints to saltmarsh development can be identified:

10.7.1 Suspended sediment supply

Sediment supply to the saltmarsh surface is critical to the depositional processes that are central to the formation, evolution and maintenance of saltmarshes. The rate of deposition is dictated by suspended sediment concentrations in the tidal water over the marsh surface. Variations in sediment supply will significantly affect the way in which the saltmarsh behaves in response to the applied driving forces.

10.7.2 Migration space

A saltmarsh is a dynamic landform. In order for this landform to respond to changing forcing, there is often a requirement for migration space. This is essentially space into which the saltmarsh is able to migrate. The behaviour of the saltmarsh may be significantly different if there is a constraint imposed on the migration space. This constraint could be in the form of a natural factor (such as a geological hard point or rapidly rising hinterland topography) or man made (such as sea defences).

10.8 Behavioural Timescales

10.8.1 Short-term (responses within a year)

Over the tidal durations, water and sediment exchanges occur that are critical to sustain the vegetation on the saltmarsh surface. The saltmarsh surface is subject to periodic tidal inundation, the frequency and duration of which is dictated by the elevation relative to tidal levels, supplying suspended sediment. Flows and suspended sediments are affected by the frictional influence of the vegetated surface providing the potential for sediment deposition. This periodic cycling of sediment onto the saltmarsh surface over a tidal frequency provides the means for saltmarsh morphological response.

10.8.2 Medium-term (responses over decadal to century scale changes)

Over this medium timescale, the behaviour of a saltmarsh will be dictated by the saltmarsh response to low frequency high magnitude wave events and intervening tidally dominated calmer periods. During storm events, erosion of the saltmarsh is likely to occur and marsh edge erosion will act as a sediment supply to the adjacent mudflat, thus allowing the two elements to respond to the applied forces. During these periods it is also possible that the boundary between the saltmarsh and mudflat (potentially marked by a cliff feature) will migrate landward. These erosional processes are replaced with depositional processes during the tidally dominated intervening periods. In these calmer periods sediment is transported onto the marsh area via the fronting mudflat and deposited. This allows marsh recovery to occur (both vertically through deposition on the marsh surface and horizontally through recovery seaward of the marsh edge).

It is also possible for biotic factors to influence saltmarsh behaviour over these timescales. The influence of Spartina *(Spartina anglica*) in UK estuaries is an example of this. The grass spread, partially naturally and partially due to deliberate introduction, in the late 1800s and early 1900s and resulted in initially rapid sediment accretion (Toft *et al.*, 1995). The subsequent regression of Spartina then led to saltmarsh erosion.

10.8.3 Long-term (responses over century to Holocene timescales)

Saltmarsh behaviour over this longer timescale is driven by primarily by relative sea level change. Relative sea level rise will mean an increase in water depth and hence a change to the frequency and duration of tidal inundation on a particular area of marsh surface. This change will affect marsh accretion rates and marsh development. The actual behavioural response to this change in forcing is highly dependant on the nature of a number of factors, leading to a number of different scenarios:

A scenario can be considered whereby there is an adequate supply of suspended sediment and sufficient landward migration space for the saltmarsh to migrate into (i.e. no geological or man made constraints). Under rising relative sea levels the marsh surface will rise vertically and translate landward (or potentially advance). Under this response the marsh accretes to keep pace with relative sea level rise and maintain its relative position within the tidal frame.

Under a restricted sediment supply scenario, the marsh surface is unlikely to be able to accrete vertically to maintain its position in the tidal frame to compensate for the rise in water level. As a result water depths over the marsh will progressively increase and the marsh may eventually drown.

Under a restricted migration space scenario, an area of saltmarsh would attempt to migrate landwards. However, with a static landward margin, e.g. through rising topography or a fixed line of sea defence, the marsh would become progressively squeezed between the migrating saltmarsh edge and the static landward boundary. This is the process of coastal squeeze.

These idealised behavioural responses over the long term assume a monotonic increase in relative sea level that would lead to a progressive change in forcing with a corresponding response. However, in reality, fluctuations in the rate of change of relative sea level and the direction of change will occur with corresponding potential for recession as well as progradation.

10.9 Interactions with Other Geomorphological Elements

10.9.1 General interactions (Elements within the estuary system)

The exchanges between saltmarsh and mudflats are explored in Appendix H. In addition, the saltmarsh interacts with an estuarine floodplain through the action of flooding and drainage during extreme water levels and rainfall events respectively.

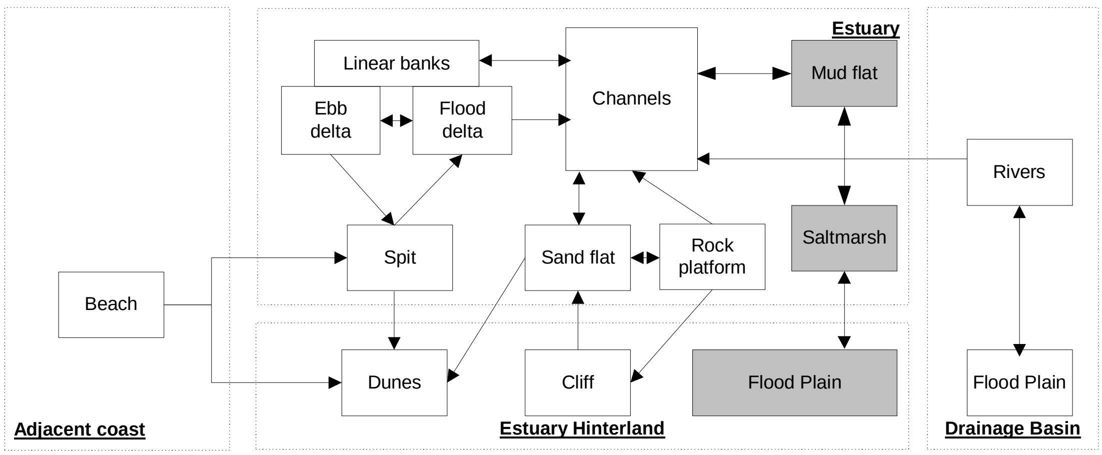

Figure 34. System diagram (saltmarsh) - Interactions with other elements

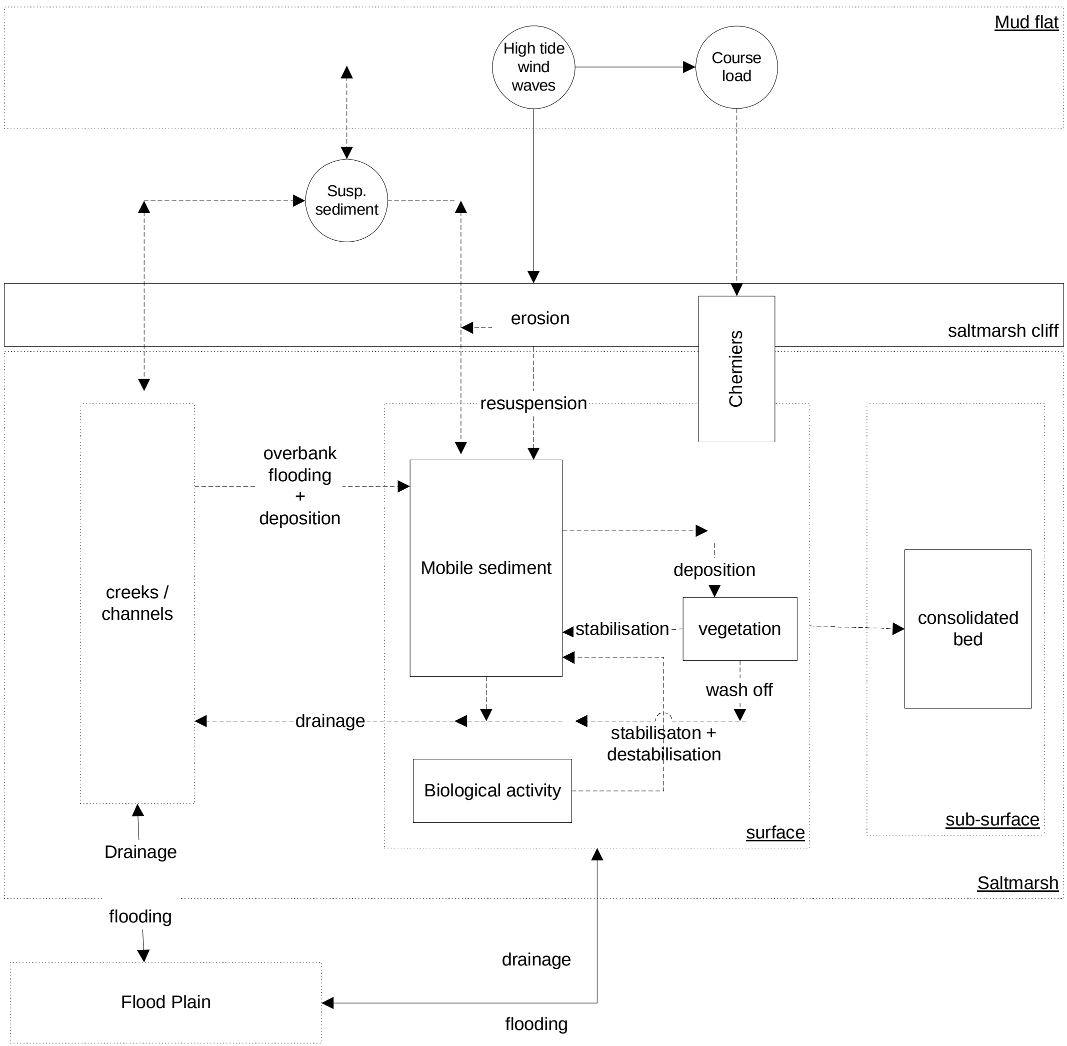

Figure 35. System diagram (saltmarsh) - Short to medium term

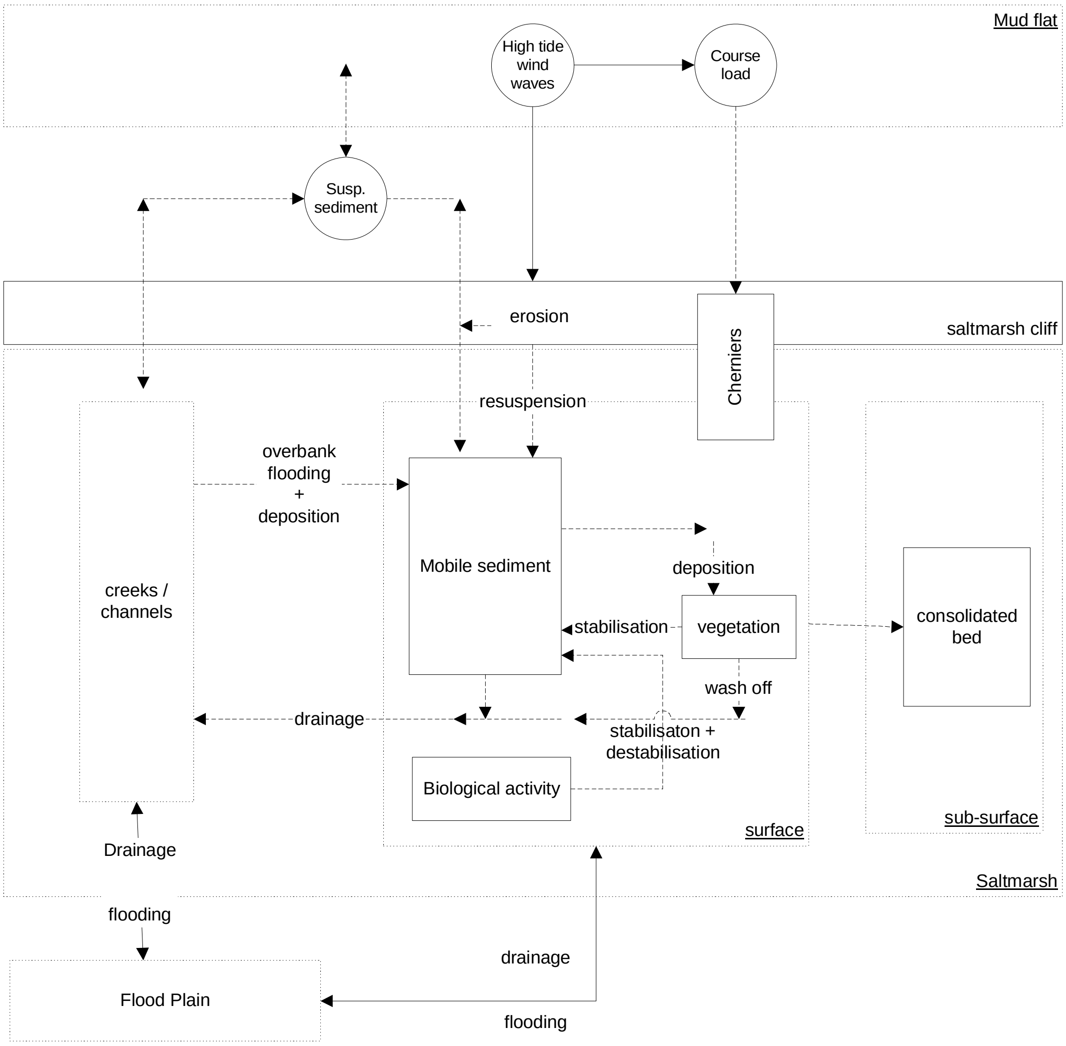

Figure 36. System diagram (saltmarsh) - Long-term

11. Behavioural Description for Drainage Basin

11.1 Definition of Geomorphological Element

A drainage basin is the topographic region from which a river receives its water due to drainage. It can be considered as the area covered by a single fluvial (non-tidal) system with division between other drainage basins defined by watersheds that act as topographical barriers.

11.2 Function

The primary role of a drainage basin is to enable the storage and subsequent transportation of water and sediment derived from the local climate and the basin watershed via the river network, to the estuary and sea.

In the context of the estuarine system, the drainage basin therefore regulates the inputs of water and sediment to the system and interacts with the estuarine form and processes. In general terms, UK estuaries are less influenced by fluvial activities than their counterparts in more mountainous regions of the world.

11.3 Formation and Evolution

The formation of a river basin is a function of its inherited topographic location. Evolution of its form and characteristics will then result from modification to the key forcing factors that input energy to the system. The climatic conditions have the most important direct influence on the drainage basin characteristics with changes to precipitation regimes and vegetation cover altering other system elements and drainage characteristics. This is discussed in more detail below.

11.4 General Form

The inherited relief and geological composition dictates the initial form with ongoing physical processes altering this form through erosion and accretion.

The drainage basin is a morphological feature that is composed of a range of connecting and overlapping elements:

- Topographic surface/catchment;
- River network (rivers, streams and channels);
- Tidal river; and
- Flood Plain;

11.4.1 Topographic surface/catchment

The characteristics of the topographic surface influences many of the internal attributes. Important characteristics and their role include:

- Size of the catchment (volume of water transported);
- Length, shape and relief (rate of water transport - discharge);
- Underlying lithology and soils composition (structure of channel network, channel density and form, groundwater storage and sediment availability); and
- Vegetation (slope stability).

The topographic surface is the route for energy input to the system in the form of precipitation (rainfall and snow) and also losses from the system in the form of evaporation.

Important processes on the topography include, weathering of solid bedrock to supply sediments downslope, rain-splash, sheet, rill and gully erosion, infiltration to provide groundwater flow and surface run-off, which can erode and transport unconsolidated soils and sediments.

11.4.2 River network

The network of rivers, streams and channels is the primary route for the transport of water and sediment downstream out of the river basin and into the estuary.

The form of the river network can be varied in terms of their length, density, shape (straight, meander or braided), slope, composition and cross-section. The network density is regarded as a fundamental characteristic of a drainage basin since it provides a measure of availability of channel flow (and hence total discharge) which is more efficient than surface or groundwater flow. The form of a river network can therefore be considered as one, which maximises discharge within the context of the topographic and geological constraints and under equilibrium conditions channel form tends to be morphologically stable (in regime).

The form of individual channels is a direct response to the flow received from upstream. This differs from the estuarine morphology where discharge through any one section is coupled to the form of the channel.

An important property of the water transported within the drainage basin is the low concentration of solutes. This property of freshwater prevents flocculation of fine sediments until exchange with saline water (in order of 2ppt) within the estuarine environment.

Key processes within the channel network primarily include those of sediment transport (erosion and deposition).

11.4.3 Tidal river

The lower reach of a river network that accepts tidal and fluvial flow is an important feature as it represents the transition between fluvial and estuarine processes. Its form will reflect the gradual transition between the fluvial environment where form is dependant on discharge and the estuary where form and discharge mutually co-adjust.

11.4.4 Flood plain

The flood plain is the area of relatively flat land adjacent to the river network. It functions as a temporary sediment store as sediment moves downstream and can also accommodate floodwater storage during periods of extreme discharge.

Two processes are responsible for the formation of flood plains:

- Lateral accretion; and
- Overbank deposition.

Within a meander channel, deposition naturally occurs on the convex bend to create point bars during periods of low flow. During high flow erosion occurs on the concave side of the bend. This deposition and erosion cycle accommodates the lateral movement of a channel through the floodplain primarily during below bank flow conditions.

During overbank conditions, where water volume exceeds channel capacity the flood plain is inundated and deposition of suspended sediment occurs across the flood plain or locally to form levees.

It has been noted that the frequency of overbank stage is relatively uniform (typically 1:1-1:2 year event) for a range of rivers in differing regions (Leopold *et al*., 1964). Coupled with the knowledge that channels do not become progressively deeper as floodplain deposition occurs, implies that under equilibrium conditions the channel form adjusts to accommodate the typical basin discharge and that the floodplain can adjust to accommodate more extreme discharges.

Definition of an estuarine floodplain as a separate morphological form is perhaps unwarranted since as a river channel merges into the coastal setting it can be regarded as part of a continuum. However, there is a transition between dominance of tidal over fluvial processes in a downstream direction and the scale of the river channel increases, as does its stability, and these factors will alter the relationship between the channel and the floodplain.

Where the watershed input to the fluvial system is responsible for overbank conditions in the drainage basin, it is tidal waters that are responsible for flooding of the estuarine floodplain (although this can be in-combination with high river discharges).

11.4.5 Vegetation

Vegetation plays an important role in the drainage basin. Vegetation cover determines the exposure of soil cover, the stability of sub-surface soils (through root structure) and the magnitude of modification of precipitation processes at surface. It therefore can modify the net input to the system (interception and transpiration), affect storage and influence rate at which water and sediments are transmitted through the system.

11.5 General Behaviour

The importance of the behaviour of a drainage basin and its component systems lies in its function of transporting water and sediment into the estuary.

An understanding of the lithology of the basin, soil composition and land use informs on the type and quantity of sediment load input to the estuary. Knowledge of the discharge characteristics tells us something about the total volume discharged into the estuary and its distribution through time.

Both sediment and water volume can have an important influence on estuarine dynamics where such inputs are in sufficient proportion to estuarine flows or occur at sensitive periods in time. For instance, fluvial sediment can be an important component of the estuarine sediment budget and extreme water discharges can influence upstream estuary morphology.

The likely influence of the drainage basin on estuarine processes and morphology can be inferred from the ratio between river discharge and tidal prism, although the same analysis for extreme events can indicate the potential for influence on estuary morphology.

11.6 Forcing Factors

The major forcing factor on the system is the climate that controls precipitation and temperature regimes, and together with the inherited geology, these determine the sediment yield, river network structure and vegetation cover.

11.7 Behavioural Timescales

11.7.1 Short-term (responses within a year)

The nature of river discharge for one gauging station, for instance at the tidal limit is expressed by a flood/storm hydrograph. This shows several important characteristics, including, peak flow, peak flow, total run-off and the rate of discharge rise and fall. When the rainfall is plotted on the same graph, the lag time to peak flow can be determined.

Flood hydrographs will clearly vary according to season for any particular drainage basin as a function of precipitation, temperature, lithology, soil composition and vegetation cover. Over the short-term variations in precipitation will be the dominant process that determines channel discharge and inputs to the estuary.

11.7.2 Medium-term (responses over decadal to century scale changes)

Much of the work within a drainage basin is accomplished by intermediate frequency, moderate magnitude events (extremes) of perhaps only a few times per year. With a long enough time series of discharge measurements annual extreme events can be identified and their relationship to estuary tidal prism understood.

Annual extremes or those over a longer period (shown by a flood frequency curve) may be particularly influential for estuary morphology under equilibrium drainage basin characteristics. Inputs of sediment may have functional importance for the estuarine sediment budget and discharges may alter inner estuary morphology.

Over the decadal period anthropogenic changes in the drainage basin may be important in influencing the interaction with the estuary. Changes to land use such as through agriculture may alter the availability of sediments. Whilst urbanisation and other associated interventions including, bank stabilisation and protection and canalisation is likely to significantly alter the drainage characteristics. Urbanisation reduces surface permeability thereby reducing the lag time of the flood hydrograph and increasing the flood peak and frequency of overbank discharge.

11.7.3 Long-term (responses over century to Holocene timescales)

Over longer timescales, erosion of the drainage basin surface will act to lower its relief and climatic factors will be important for evolving the drainage basin characteristics. Changes in precipitation and temperature regimes coupled with subsequent changes to vegetation cover may evolve the channel network to a new quasi-equilibrium state and result in altered discharge and sediment volume input.

Over this time frame the influence of sea level rise will become important. Changes to relative sea level will influence the tidal regime and hence will play an important role in modifying estuary morphology. Where an estuary has sufficient (unprotected) flood plain then sea level rise can be accommodated by migration of the estuary form both laterally and towards the rive basin at the head of the estuary.

11.8 Interactions with Other Geomorphological Elements

11.8.1 Estuary floodplain

In the context of a rising and falling tide it is the intertidal surface that can be considered as the estuary floodplain with flooding on a twice daily frequency (for semi-diurnal tides). In the estuary, overbank condition can be considered as occurring when the tidal elevation exceeds the subtidal channel and water movement occurs laterally across the intertidal.

In an estuary where there is sufficient unconfined accommodation space, then more extreme tidal ranges will overbank the typical high water boundary and flood adjacent land in a manner more analogous to fluvial flooding. However, whilst the fluvial floodplain behaves more as a temporary sediment store for downstream transport, the estuarine floodplain does not over the short timescale appear to have this role, although can accommodate lateral channel movement.

Over long timescales the estuary floodplain can accommodate sea level rise by allowing space on the hinterland for the estuary form to migrate laterally.

11.8.1 Estuary channel

The focus of the earlier discussion has been on the interaction between the drainage basin and the estuary. This interaction by way of the tidal river element provides a source of fluvial discharge and sediment (bedload and suspended) into the estuarine setting.

The importance of the suspended load imported into the estuary for other geomorphic elements (mudflats, saltmarsh and estuary channels) will be dependant on the scale of the drainage basin. The scale of the contribution to the estuarine sediment budget from sediment load derived from the drainage basin, will be determined by, amongst other factors, the geology of the basin.

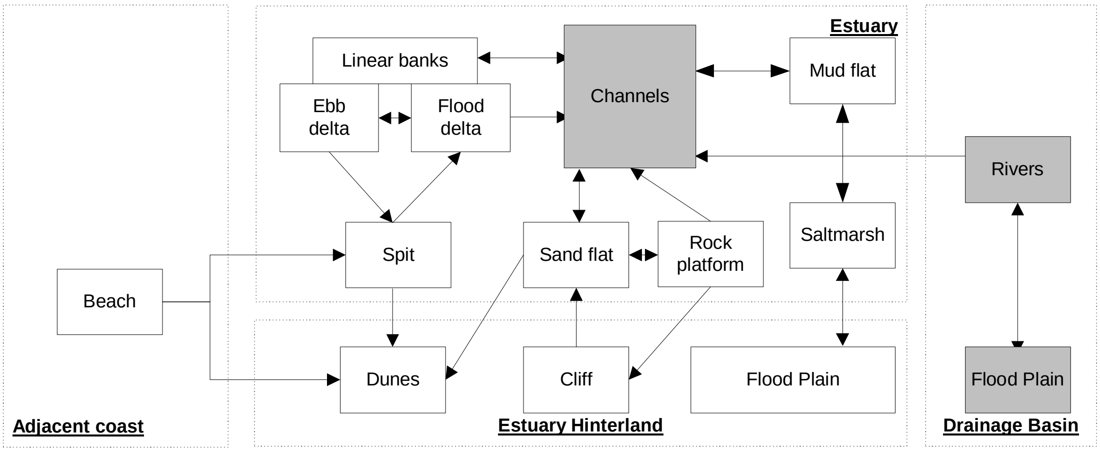

Figure 37. Interaction with other elements - Drainage basin

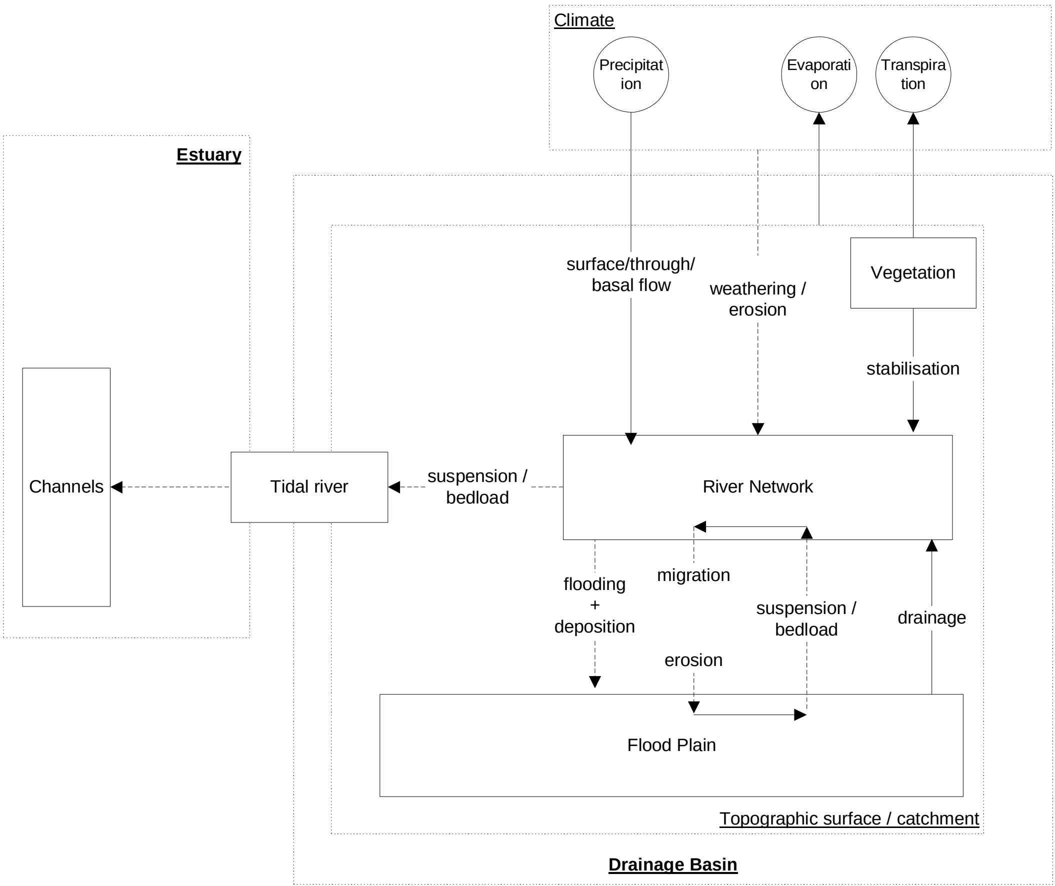

Figure 38. Short to medium term system diagram - Drainage basin

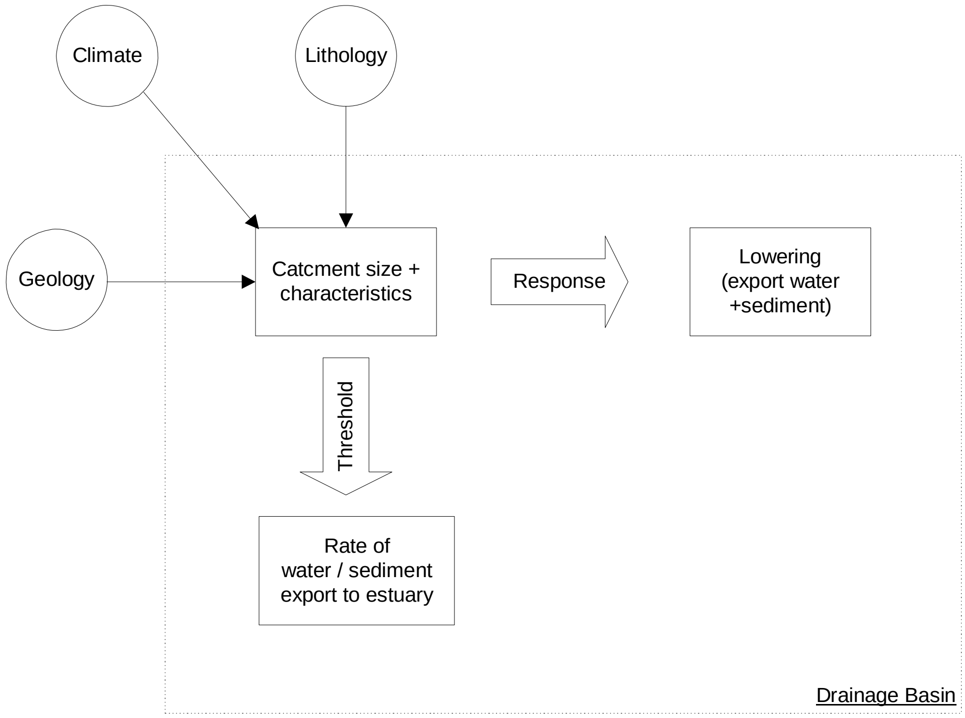

Figure 39. Medium to long-term system diagram - Drainage basin

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