Appendix A1

Saltmarsh Processes and Morphology

A1. Saltmarsh Processes and Morphology

A1.1 Estuary and bay morphology

The estuary channel plan shape reflects a balance between two opposing forces. The first is a tendency for tidal amplitude to increase as the channel narrows upstream, causing energy concentration. The second is a tendency for the narrowing of the channel to cause increased friction and a reduction in tidal amplitude. The shape adopted by most estuaries in order to satisfy these two opposing tidal forces is a trumpet shape, in which not only does the channel become narrower inland but the rate at which the width is reduced also increases inland.

There appears to be a relationship between the rate at which this narrowing takes place and the tidal amplitude. Estuaries experiencing a relatively large tidal range (>4m) generally have long, thin channels with a low rate of narrowing. Estuaries with smaller tidal ranges (2-4m) could be described as short and squat, i.e. their rate of narrowing is extremely rapid. This rule of thumb for channel morphology is in line with the concept of frictional drag, whereby larger tides are not reduced as effectively by the friction of the channel, and thus estuaries with larger tides are generally longer than those with smaller tides.

A1.1.2 Estuary tidal prism and cross-sectional area

An estuary's tidal prism (or tidal volume) can be defined as the volume of water that enters the estuary on each tidal cycle (the volume difference between high water and low water). This is usually calculated both for spring and neap tides. Tidal prism can also be calculated at any point along the length of the estuary, where the tidal prism is the volume of tidal water upstream of that point.

There is a simple relationship between tidal prism and channel cross-section. At the mouth of an estuary the tidal prism (and hence tidal discharge) is large, whilst in the upstream reaches of the estuary the tidal prism, and tidal discharge, are much smaller. From observation, the mouth of the estuary has a corresponding large cross-sectional area and, in the upstream reaches, the channel is relatively small. The larger the tidal prism, and therefore the tidal discharge through a channel cross-section, the larger the cross-section and vice versa (see Figure A1.1).

For any cross-section within an estuary, an increase in the tidal prism will lead to an increase in tidal discharge, resulting in increased velocities within that cross-section. These increased velocities may initiate erosion and, therefore, the cross-section will increase in area in response to the original increase in tidal prism. This process of adjustment will continue until a new equilibrium is reached between the tidal prism and the cross-sectional area.

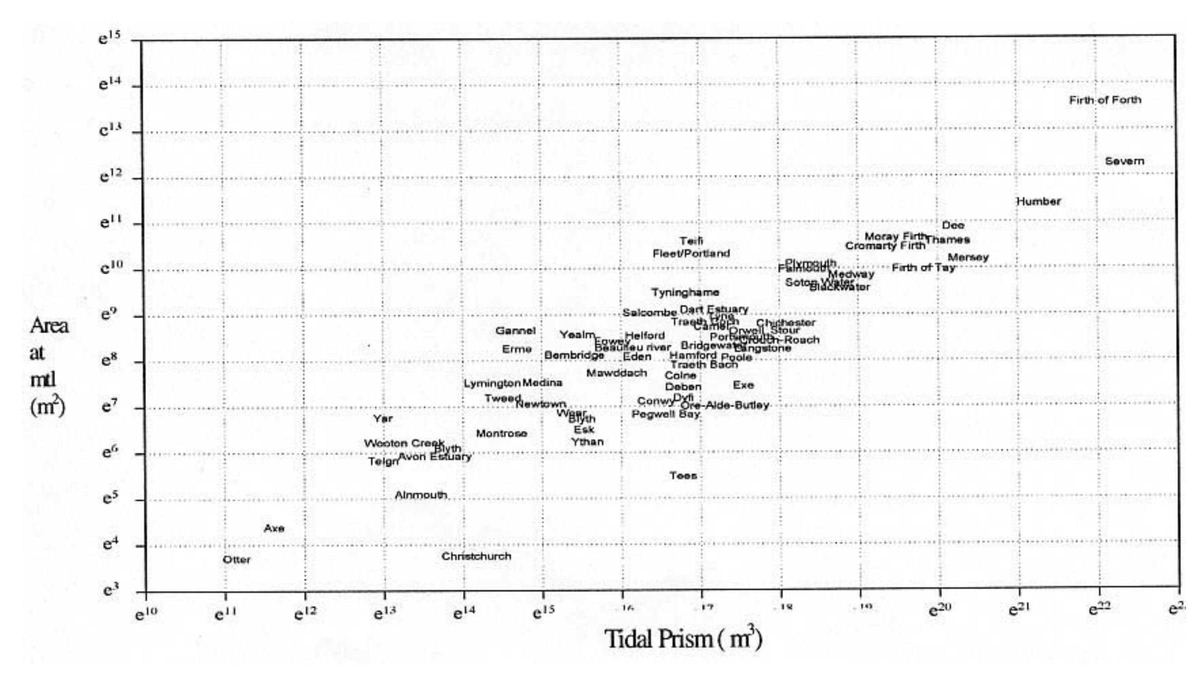

Figure A1.1 Plot of tidal prism against cross sectional area (mean tide level) for United Kingdom estuaries (after Townend *et al*., 2000)

Quantification of this relationship allows it to be used for predictive purposes to assist in management. For example, there are a number of factors that can impact upon estuary tidal prism or cross-section:

- managed realignment will result in increased cross-sections within an estuary;
- sea-level rise will increase the tidal volume entering the estuary; and
- land claim may reduce cross-sectional area at certain locations.

Although the effects of the dynamic balance in the ratio between mouth cross-sectional area and tidal prism are comparatively easy to see (Figure A1.1), the interaction between the shape and size of an estuary is not only reflected in the width of its mouth but in all sections throughout its length. Thus, each cross section along the axis of an estuary can be regarded as the mouth for the stretch of the channel upstream. Changes in estuary dimensions at any point along its length, such as those set up by land claim or managed realignment, will result in changes in the tidal prism and, thus, in modification of the entire channel morphology.

A1.1.3 Bay form

In simple terms, a bay or embayment may be defined as a landward indentation in the coastline. Some bays are relatively shallow in plan form (i.e. have a large length to width ratio) and may have a gently accurate form, while others are relatively deep (have a low length to width ratio) and may even be virtually enclosed, forming natural 'harbours' with narrow entrances, such as Poole Harbour, Chichester Harbour and Pagham Harbour on the south coast. Examples of shallow, arcuate embayments in the UK are Colwyn Bay and Lyme Bay, while The Wash and Morecambe Bay provide examples of large, relatively deep embayments. Rias, sea lochs and fjords provide a special case where coastal submergence or sea level rise have flooded a highly indented rock coastline in which deep, linear depressions have been created by tectonic processes or glacial action. These features are distinguished from estuaries in having little or no freshwater flow from rivers. Examples in the UK are found mainly in the southwest peninsula, southwest Wales and Scotland.

Some bays have estuaries within or adjacent to them; for example, the Wyre, Lune and Kent estuaries within Morecambe Bay. Saltmarshes may occur both on the relatively open shore of the bay (for example, at Silverdale within Morecambe Bay) and within the more sheltered estuaries.

Both 'open' and 'closed' embayments may contain islands which provide areas of local shelter within which intertidal sediment can accumulate and marshes become established. Examples include Brownsea Island in Poole Harbour and Walney Island at the northern entrance to Morecambe Bay.

A1.2 Mudflat and saltmarsh morphology

Higher intertidal mudflats and saltmarshes are generically linked and have complex, interrelated physical and biological controls. Three broad categories of shoreline morphology are encountered involving mudflats and the backing saltmarsh (Figure A1.2). First, a smoothly sloping surface on which there is a gradual upward and landward appearance of vegetation. Shorelines of this kind are generally accreting, advancing seaward as well as growing vertically. Second, a cliffed saltmarsh edge is usually indicative of erosion, although the rate may not be rapid. Cliffed marsh edges commonly occur within estuaries where wave fetch and height are limited, and where both wave and current scour operate for long periods at low states of the tide. Third, a gently to moderately sloping ramp, carved transversely into finger-like spurs and narrow, wave scoured furrows. This shoreline may represent a transitional stage between slope and cliff, and is typically found on marsh fronts which experience slow or episodic erosion under relatively high (exposed shore) wave energy conditions.

The seaward extent of the saltmarsh is dependent on the location of the most sensitive feature of the saltmarsh system, the outer edge, which represents a geomorphological balance between mudflat and saltmarsh processes. Two basic forms may be recognised: outer exposed saltmarshes and inner sheltered saltmarshes.

A1.2.2 Exposed marshes

In intertidal locations where sea waves are able to propagate and impose open ended wave distributions on the morphology, the expectation is for increasing wave height to be associated with increased return periods, and the mudflat/saltmarsh edge is repeatedly, although infrequently, eroded. Since saltmarshes do exist in these locations (Figure 2.1a-c) it follows that, over the long term, such erosion must be balanced by deposition. Thus, a 1 in 10-year storm may cause erosion of the outer 1m of a saltmarsh but, on average, deposition will make good this loss of saltmarsh in the intervening period before a similar event. This process suggests that there must be a lower critical threshold to saltmarsh edge erosion, determined partly by the width and wave dissipation properties of the fronting mudflat.

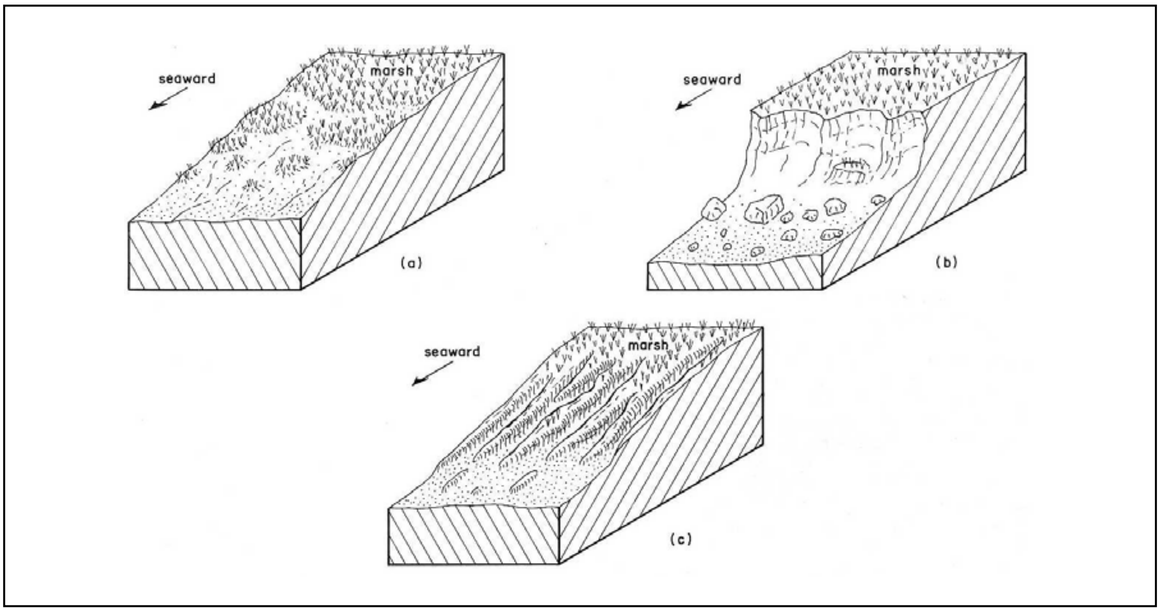

Figure A1.2 High tide morphologies along a muddy shoreline: (a) smooth transition from mudflat to saltmarsh, (b) bold marsh cliff, (c) marsh ramp with wave-scoured spurs and furrows (after Allen, 1993)

A1.2.3 Protected marshes

In sheltered locations, defined as regions which are inaccessible to open sea wave propagation, the statistical distribution of wave heights at high water exhibits a finite upper limit. This is a response to the fixed fetch length at this tidal stage and means that waves larger than a given height will not be experienced. The mudflat/saltmarsh transition in these areas, therefore, develops a permanent boundary, the location of which is determined by the capacity of the mudflat to dissipate the energy of the maximum wave height.

A1.3 Estuary and bay processes

Tides are very long period waves generated by the gravitational attraction of the moon and sun in association with the earth's gravitational force. The earth and moon have known orbits that combine to produce predictable gravitational forces, causing a rhythmical rise and fall of sea level. As the earth spins about its axis, the centrifugal force results in slightly deeper water near the equator and shallower water at the poles.

The alignment of the moon and sun relative to the earth controls the tidal cycle of spring and neap tides. When all three are in line, the gravitational effect of the moon and sun act together, producing a large tidal bulge and, therefore, spring tides. When the angle between the sun, the earth and the moon is 90o, the gravitational effect of the moon and sun counteract each other and the bulge is at a minimum, producing neap tides approximately one week later. This is why spring tides occur at full and new moon phases, and neap tides occur at the first and last quarter moon phases.

During spring tides, high tide is higher than average and low tide is lower than average, whereas during neap tides, high tide is lower than average and low tide is higher than average. The tidal bulge created by the moon and sun does not have an instantaneous movement, due to inertial and frictional effects. For example, this may cause a lag of up to 36 hours in the spring tides after the full moon.

Because of their large scale, tidal waves are affected by the Coriolis force due to the earth's rotation. In the northern hemisphere this causes the tide to rotate in an anticlockwise direction about a nodal point, called an amphidromic point. At the amphidromic point the tide has little height but increases with distance radiating out from the point. Figure A1.3 shows the six amphidromic points that encircle the United Kingdom and how the co-tidal lines radiate from them. The co-tidal lines represent lines of equal tidal phase, thus each 30o section represents a movement in the tidal phase of approximately 1 hour.

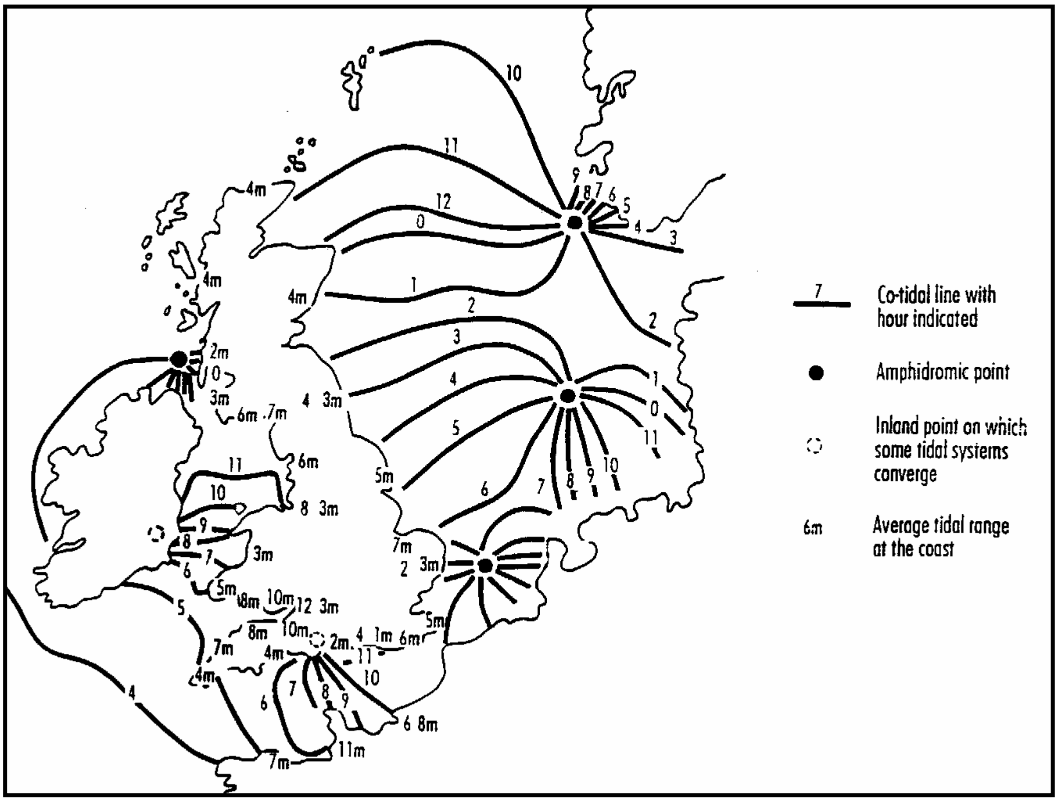

Figure A1.3 Amphidromic points and tidal range around the coast of Britain (from Toft et al., 1995)

The anticlockwise rotation causes a north to south tidal progression along the east coast of England, while on the Irish Sea coast it moves from south to north. In the English Channel the tidal system progresses eastward (Figure A1.3). The direction of movement of these tides is important as it effects the source of the sediments and the large scale sediment transport mechanisms which feed estuaries/bays and, ultimately, mudflats and saltmarshes.

A1.3.2 Tides in estuaries and bays

It is important to consider tides in estuaries (and bays) as extremely long period waves travelling up the estuary and not simply as changes in water level (i.e. they should be considered in terms of both horizontal and vertical water movements). As the tidal wave passes into the shallow waters of an estuary or bay, the frictional effect of the bed slows its passage. If the path taken by a single water drop within the tidal wave is followed it would describe an elliptical course. In the open sea this water pathway is in phase with the water surface elevation in the wave so that maximum currents occur at high and low water and the direction of flow changes at half tide. In an estuary or confined bay, the reflection of the tidal energy from the bed and banks causes this pattern to be altered so that maximum current flows at half tide and zero velocity (and direction change) takes place at high and low water (Figure A1.4). This is fundamental to the development of saltmarshes, since the occurrence of zero velocities during the change in flow direction at high tide means that the deposition of fine grained sediments through the water column can take place.

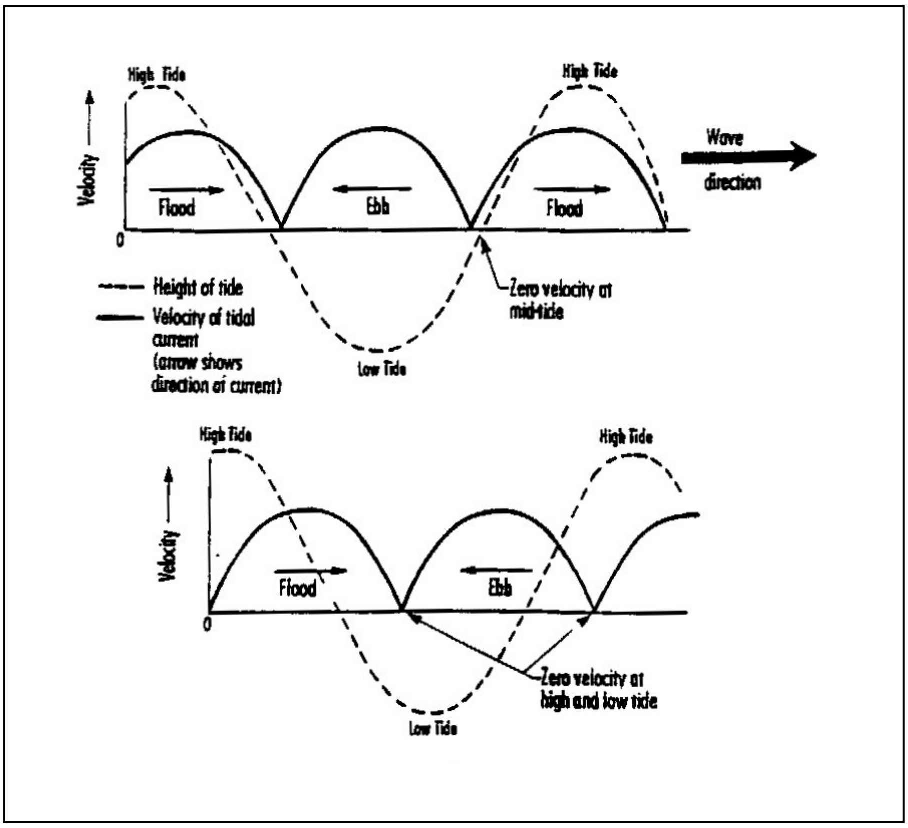

Figure A1.4 The relationship between tidal stage and velocity at the mouth of an estuary (top) and the head of an estuary (bottom) (from Toft et al., 1995)

The speed of tidal wave propagation is controlled by water depth. The peak and trough of a tidal wave travel in different water depths and so move at different speeds, resulting in an asymmetric wave form within estuaries. The asymmetry means that tidal current velocities will be different on the flood and the ebb. If the flood velocities are higher (the more common situation in English and Welsh estuaries) the estuary is referred to as being flood dominant. Conversely, if the ebb tidal current velocities are higher, the estuary is referred to as being ebb dominant. Flood dominance will mean a greater quantity of sediment will be driven into the estuary on the flood than is driven back out on the weaker ebb tide, and the estuary is likely to be accretionary. Ebb dominance will mean more sediment is transported out of the estuary on the ebb than is driven back in on the relatively weaker flood tides and, as a result, the estuary is likely to be erosional.

This is a simplified view of tidal dominance and how it affects the transfer of sediment into and out of the estuary and, in reality, many other factors will complicate this balance. For example, the morphology and depth of the subtidal channel is fundamental to understanding the tidal dynamics. In estuaries with shallow subtidal channels, there is increasing drag between tidal movements and the bed, and short term variations in tidal stage and longer term variations in tidal range are major controls of the depth. Since the water is significantly deeper at high tide than at low tide, a flood tide asymmetry is set up.

A1.3.3 Waves in estuaries and bays

Waves which affect estuaries and bays may be sub-divided into two main categories: open sea waves and internally generated wind waves. Wave generation is governed by four factors: wind speed, wind duration, fetch and water depth. In the open sea all of these factors are important and the largest waves will develop when high wind speeds blow over a large distance of sea (fetch) for extended time periods. However, in the open sea, water depths and fetch are rarely limiting since very large sea distances and depths are involved. This means that wave height is governed by wind speed and duration. Since both of these factors are variable in time, so are wave conditions. Small waves are more frequent than large waves, with the result that the return intervals increase progressively with wave height.

Open sea waves can enter the mouths of estuaries and bays and play a major role in modifying the morphology of their shorelines. Shorter period waves can penetrate further upstream in an estuary than longer period waves since they are less affected by the shallow water conditions they meet in the estuary. Conversely, longer waves refract more markedly than short waves and, therefore, tend to enter confined estuary/bay mouths or those protected by spits or bars more easily than short waves. As a result, the effect of waves within estuaries/bays differs greatly depending on physiographic setting and degree of exposure. For example, the estuaries of the Camel in north Cornwall or the Dovey in Wales are affected by long Atlantic swell waves which can penetrate their outer parts, resulting in the formation of extensive sandy intertidal flats with restricted saltmarsh development and a characteristic wide, flat channel. By contrast, the estuaries of East Anglia are affected only to a much smaller extent by open sea waves from the North Sea, which lack the oceanic swell component and tend to be shorter and steeper.

The second type of wave is generated within the confines of the estuary system itself. Since the fetch distances here are normally very short, usually no more than 10 to 20km, wind speed and duration are not critical and only fetch length and water depth are limiting. Thus the height of waves generated within estuaries and confined bays is controlled almost entirely by fetch, so that a given shoreline with a fixed fetch across the estuary/bay to the far bank, and which is remote from the influence of sea waves, can only experience waves of a fixed maximum height. However, it should be noted that, in most estuaries, both fetch length and water depth vary with tidal stage, so that the largest waves generally occur at about high water. This is important when considering the development of both mudflats and saltmarshes in estuaries, since the existence of an upper limit to wave height means that these shorelines can develop in response to this fixed upper limit, whereas shorelines facing open sea waves are forced to respond to the continually increasing wave heights associated with longer return intervals.

It should not, however, be assumed that because waves generated within estuaries are relatively small they have little geomorphological impact. Small waves are active for a high percentage of the time and can produce a significant cumulative effect.

A1.3.4 Sediments in estuaries and bays

Erosion

The initial movement of sediment begins when the shear stress becomes sufficiently great to overcome the frictional and gravitational forces holding the particles on the bed. This value is known as the critical shear stress (τc) and can be determined for any given particle size.
The relationship between particle size and critical shear stress is not linear, but is complicated by the cohesiveness of the sediment. Cohesion mainly results from the presence of platy clay minerals in the sediment, which are held together by a combination of electrostatic attraction and the surface tension of the water surrounding the particles (see Flocculation below). Non-cohesive sediments contain a majority of coarser particles, which are often more near-spherical than cohesive sediments. They lack the physico-chemical interactions that exist between clay particles, and so are free to move independently.

Erosion is more rapid under accelerating or decelerating currents, such as those set up within waves, as compared to steady tidal currents. Initial erosion caused by wave generated currents followed by transportation of the eroded sediment by tidal currents usually produces the most rapid bed erosion.

Deposition

In the case of bedload, particles of a certain size will be deposited once the bed shear stress (τo) falls below the critical shear stress (τc) that was needed to start them moving.

The settling velocity (ws) (the rate at which a particle settles out of suspension), and a process known as settling lag, control deposition from suspension back to the bed. As the flow carrying the sediment begins to slacken, the particles begin to settle from suspension as soon as the forces due to upward and stream-wise components of turbulence fall below those associated with downward components of turbulence and gravity acting on the particle mass. However, at this stage, the particles do not settle vertically through the water but continue to be carried as they sink, by the still-moving flow. This means the particles may not reach the bed until some time after the flow transporting them has dropped below the critical shear stress. This process enables the mud to be deposited at some distance inland of the point at which the critical settling velocity is reached. Assuming that the ebb tide and flood tide show a similar time-dependent velocity distribution, when the tide turns the deposited sediments will not be re-suspended until much later in the flow, since they have gained some distance due to the settling lag.

For particles smaller than 0.1 mm, the settling velocity is proportional to the square of the particle diameter:

$$w_s \propto d^2$$

where d = particle diameter where the particle is a perfect sphere in an infinite volume of fluid.

This means that for only a small change in diameter there is a significant change in the settling velocity, and so the smaller the particle size the more significant the process of settling lag becomes. For particles greater than 0.2 mm, the settling velocity is proportional to the square root of the particle diameter:

$$w_s \propto d^{1/2}$$

This means that large changes in diameter will only result in a small change in settling velocity. For particle sizes between 0.1 and 0.2 mm, the settling velocity is proportional to gradually decreasing powers of the diameter, from d2 to d1/2.

Flocculation

The process by which clay particles stick together is known as flocculation. Each clay platelet contains attractive and repulsive forces, known as van der Waals Forces and Coulombic Repulsive Forces, respectively. In fresh water, the attractive forces equal the repulsive forces and there is no net effect in terms of particles being attracted to each other or repelled from each other. However, in saline fluids, such as sea water, the repulsive forces reduce and the attractive forces become dominant. The strength of the attractive forces is increased as the clay particles get closer together, the net result being they stick together, or *flocculate*.

Flocculation is an important process in areas where fresh water and saline water mix, such as estuaries. For example, clay particles being transported down a river and into an estuary are brought close together during the mixing process and at the same time are introduced to saline water, where they flocculate. The zone of high suspended sediment concentration is known as the turbidity maximum.

This process is relevant to the settling velocity of particles, which is dependent on the particle diameter, with larger diameters settling faster. That is, the process of flocculation will result in larger particles which will settle faster. Indeed, since individual particle settling rates are in many cases so slow as to prevent their deposition within a tidal period, flocculation is essential for the formation of intertidal mudflats and, ultimately, saltmarshes.

A1.4 Mudflat and saltmarsh processes

A1.4.1 Mudflats

Net deposition on a mudflat is not only a matter of sediment particles settling from suspension on the surface, it also depends upon a complex of factors which increase the shear strength of the sediment after deposition and prevent the particles being re-entrained on the succeeding tide. An important process is the dewatering of the deposited particles, giving them cohesion to resist re-erosion. Biological processes, such as their invasion by algae, can bind sediment together and thus impart considerable strength. These biological processes are generally regarded as fundamental to mudflat development, so any factor (such as chemical contamination) which may impair the biological viability of the sediment must be avoided.

Wave erosion of the mudflat surface provides the ultimate control of mudflat morphology. The shear stress developed at the bed as a wave passes over the mudflat depends on wave height, wave period and water depth; shear stress increases for higher waves and shallower depths. In relation to wave activity, erosion rates are controlled by the ratio between wave shear stress and mud shear strength and the length of time the surface is affected by waves. As the mudflat surface rises due to deposition and mean water depths decrease, so the bed shear stress increases until sediment deposition is balanced by erosion; a spatial balance between deposition and erosion forces which alters for each wave event. This balance is also controlled by the length of time the mudflat is affected by a wave and here the tidal amplitude is a critical factor. A large tidal range means that the residence time for water at high tide is much shorter than that for a small tidal range. Thus, extensive fine grained mudflats tend to be located in macrotidal (tidal range >4m) rather than mesotidal estuaries (range 2-4m). The more protracted wave effects within mesotidal estuaries tends to result in sandier and lower elevation intertidal flats.

A1.4.2 Saltmarsh

The physical effects of saltmarsh vegetation on the processes of the intertidal zone are complex but all depend on one principal mechanism, vegetation acts as a form of frictional roughness on the surface and consequently causes changes in the flow of water and sedimentation patterns over it (Shi *et al*., 1996). However, field monitoring studies have shown that the relationship between vegetation characteristics and long-term marsh accretion rates is complex (Boorman *et al*., 1998).

The velocity profile of the flowing water over a mudflat without vegetation describes a characteristic logarithmic curve as velocity reduces towards the bed (see Figure A1.5). Indeed, immediately above the bed (usually less than 1mm), velocity reduces to zero. Under saltmarsh vegetation this zone of zero velocity is increased in depth to over

100 cm in some cases, thus protecting the bed from the erosive action of tidal and wave driven currents (Figure A1.5).

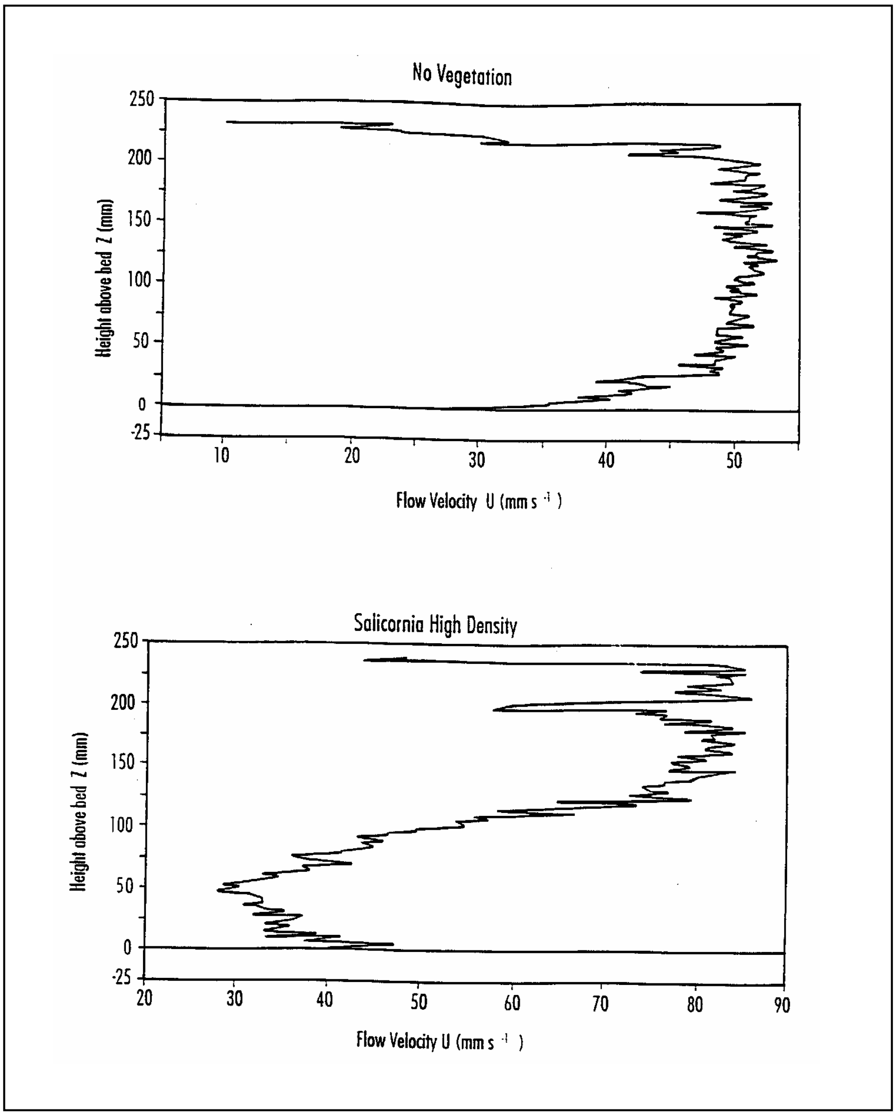

Figure A1.5 Velocity profiles over a bare mudflat (top) and within saltmarsh vegetation (bottom) (from Toft et. al, 1995)

Elevation relative to the tidal frame to a large extent determines how saltmarshes function geomorphologically. Neap tides merely enter and are confined to the creeks, leaving the saltmarsh surface dry, whereas spring tides generally rise above the creek banks, drowning the saltmarsh for a period. These are known as undermarsh tides and overmarsh tides respectively (see Figure A1.6).

There are significant differences in flow velocities in tidal creeks between undermarsh and overmarsh tides (Figure A1.7). Generally, undermarsh and bankfull tides tend to yield weak flows in the order of 0.1 to 0.2 ms^{-1}. During overmarsh tides, the saltmarsh platform exerts a dominant role as a geomorphological threshold. The velocity of the flow in the channel is low, so long as the stage is below but not too close to bankfull. However, during overmarsh tides the huge storage capacity of the saltmarsh platform (overmarsh tidal prism) causes flows to peak at an order of magnitude greater, during both flood and ebb. Typically, the maximum ebb flow in the channel is stronger and peaks at a slightly lower stage than the flood. However, there is also frequently a short velocity 'surge' on the flood as the level exceeds that of the marsh surface and there is a sudden reduction in frictional resistance to the incoming flow (Healey *et al*., 1981).

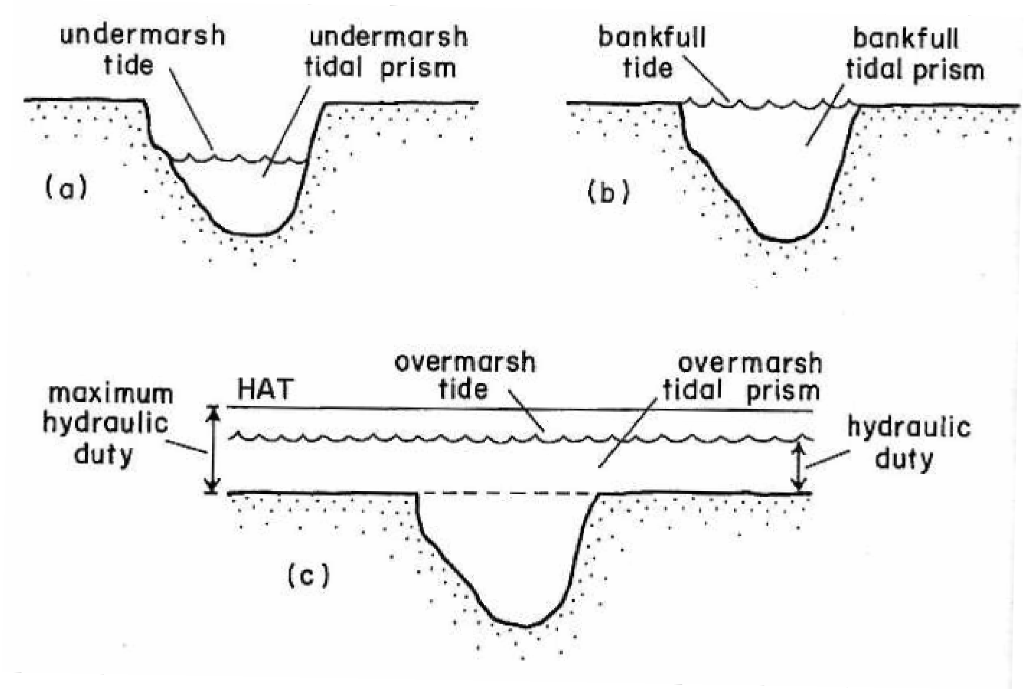

Figure A1.6 A classification of tides and tidal prisms affecting saltmarshes; hydraulic duty is the height difference between the saltmarsh surface and the level of high water (after Allen, 2000)

The lower velocities of undermarsh tides may allow sediment to settle on the bed and banks, but during overmarsh tides, erosion of bed and bank sediments may take place, sometimes leading to undercutting and toppling or sliding failure. This is a major process by which creek enlargement is accomplished, for example in response to lateral erosion of the marsh front and a shortening of the channel network length due to a rise in relative tidal levels.

Sediment supply to the saltmarsh surface is crucial to the deposition process. As on mudflats, the rate of deposition is controlled by the concentration of suspended sediment in the tidal waters covering the surface. As deposition occurs immediately inside the vegetated area, sediment concentration is reduced inland. Thus, areas further into the saltmarsh experience lower deposition rates than those at the edge of the creeks or bordering the open mudflats. Areas of saltmarsh which are more than a critical distance from a creek system may not receive any sediment inputs. These areas then fail to accrete and become marsh hollows, eventually forcing an extension of the creek network to develop.

This process of suspended sediment depletion with distance in to the saltmarsh also means that the largest particles are deposited at its leading edge and only fine grained sediment travels further into the vegetated zone. These changes in the rate and type of deposition mean that the saltmarsh surface gradually flattens and widens over time and the particle sizes in the sediment column tend to fine upwards as each location becomes relatively distant from the sediment inputs. This process means that careful examination of the horizontal and vertical distribution of sediment particle sizes in a saltmarsh can yield important information about its history and, therefore, allow predictions to be made about its future (Allen, 1996).

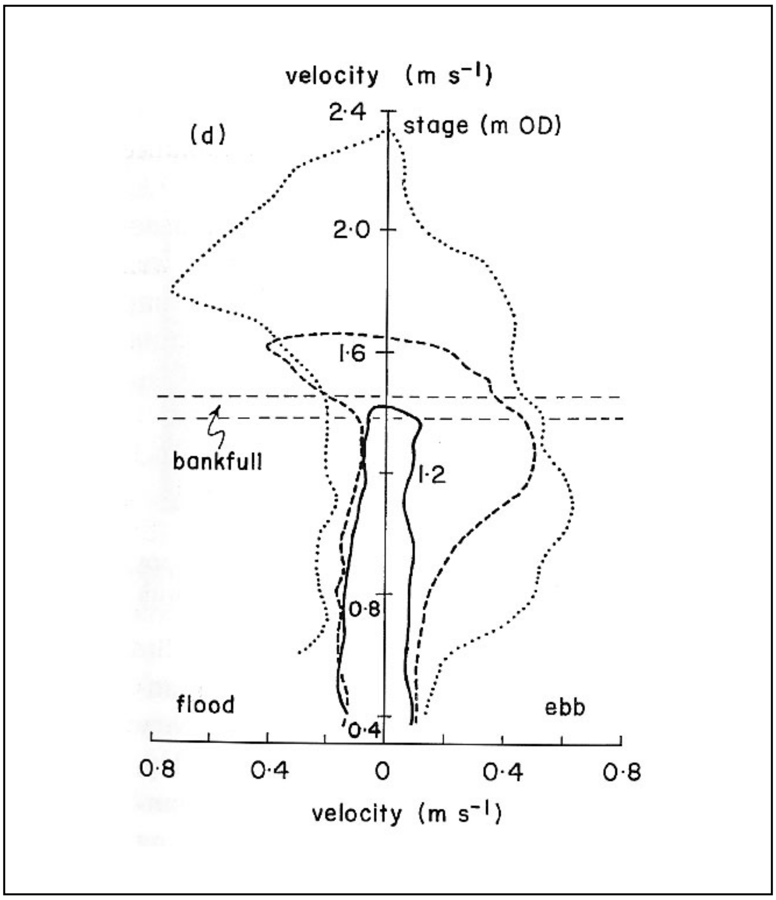

Figure A1.7 Example of a velocity-stage curve measured within creeks for undermarsh (solid line), bankfull (dashed line) and overmarsh tides (dotted line) (after Allen, 2000)

Saltmarshes are not, however, totally protected against erosion of their surfaces. In exposed areas, large waves can pass into the vegetated zone. The rotational movement of water in a wave means that the horizontal component of the current is constantly accelerating and decelerating. Under these conditions the zone of zero velocity near the bed fails to develop under the vegetation and the surface may be eroded. However, on wide saltmarshes, wave energy dissipation can be as high as 82% (Moller et al., 1999), and erosion of the bed under vegetation is a relatively rare occurrence. As in the case of mudflat erosion, the erosion threshold is a critical balance between wave shear stress and saltmarsh sediment shear strength. Water depth during a wave event is crucial to the critical threshold so that the joint probability of wave and tide events provides the return interval for erosional processes.

A1.4.3 Sea level changes

Sea level changes can change saltmarsh accretion rates. In areas of net sea level rise, accretion rates are accelerated due to the increase in water depth and tidal inundation. Provided adequate supplies of sediment are available to the saltmarsh, accretion rates will continue to increase until they equal the rate of sea level rise when a dynamic equilibrium is established. Examination of a saltmarsh accretion curve for a period of years can help to predict the outcome of sea level rise (Figure A1.8). An exponentially increasing curve indicates that water depths are deepening over the saltmarsh surface and suggests that the sediment supply is inadequate to compensate for sea level rise; under these conditions the saltmarsh may theoretically eventually 'drown'. However, evidence from Holocene sedimentary sequences has shown that saltmarshes are able to keep pace with rates of sea level rise of up to several tens of centimetres per year, if sufficient sediment is available. A decreasing rate of measured accretion (i.e. vertical elevation change) over time suggests that sedimentation is outpacing sea level rise and will eventually result in a balance being achieved between the two.

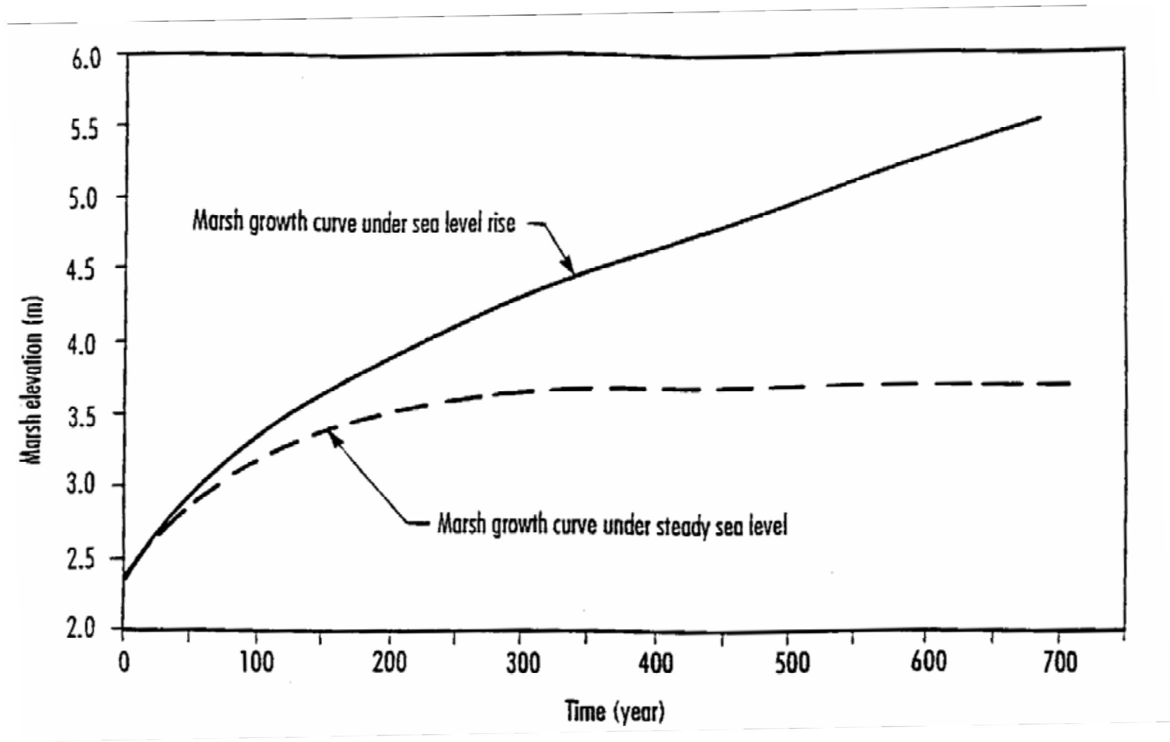

Figure A1.8 Theoretical saltmarsh growth curves under rising and steady sea level conditions in the Humber Estuary (from Toft et al., 1995)

A1.5 Wave attenuation over the saltmarsh

A1.5.1 Introduction

At Stiffkey, on the north Norfolk coast, an average wave height reduction of 61% has been measured over saltmarsh, which is approximately four times the 15% reduction observed over an equivalent width of adjacent sand flat (Möller et al., 1999). Total wave energy reduction over the saltmarsh of 82% was nearly three times that over the unvegetated sand flat (average 29%). On the Dengie Peninsula, at Tillingham, wave height attenuation of 21% was measured over the mudflats and 87% over saltmarsh, while at Bridgewick, offshore wave heights actually increased across mudflats by 24% and decreased by 44% over a much narrower (10 m) strip of saltmarsh (Möller and Spencer, 2002). Associated decreases in wave energy were observed over the saltmarsh at Tillingham (35%) and Bridgewick (79%). In The Wash, overall wave energy attenuation over saltmarsh of between 72% and 97% has been measured, with associated decreases in wave height of between 64% and 91% (Cooper, 2001). Results from these three studies are summarised in Tables A1.1 and A1.2.

Table A1.1 Measured levels of wave attenuation across UK saltmarshes and intertidal flats Möller *et al.* (2001)

	Mud/sand flat wave height attenuation	Mud/sand flat wave energy attenuation	Saltmarsh wave height attenuation	Saltmarsh wave energy attenuation
North Norfolk				
Stiffkey	15%	29%	61%	82%
Dengie				
Tillingham	21%	35%	87%	99%
Bridgewick	24% increase	55% increase	44%	79%
The Wash				
Wrangle Flats	16%	10%	91%	97%
Butterwick Low	23%	36%	64%	72%
Breast Sand	36%	56%	78%	91%

There are a number of factors that influence the extent of wave attenuation by saltmarsh, including water depth, bed roughness and marsh edge characteristics and vegetation characteristics (see Figure A1.9).

A1.5.2 Water depth

In shallow water areas, water depth is the key control on the extent of wave attenuation. Although the relative level of wave attenuation afforded by saltmarsh is highly dependent on the water depth, the extent of wave attenuation over saltmarsh is greater than can be accounted for by water depth alone. The relationship between water depth and wave attenuation is stronger and less variable over vegetated saltmarsh than over unvegetated sand or mud flats, as illustrated in Figure A1.10.

In water depths of less than 1.1m, Möller *et al.* (2001) observed reductions in wave energy by an average of 87% over saltmarsh (37% over an equivalent width of sand flat); while in deeper water the average wave energy reduction was less at 72% and 27% over saltmarsh and sand flats respectively.

The results in Tables A1.1 and A1.2 confirm the potential for saltmarsh to contribute to coastal defence. In considering this value, it is important to understand variations in the attenuating efficiency of saltmarsh under different water depths. Over a certain water depth (estimated at 3.7m by Möller *et al.*, 2001), the relationship between wave attenuation and water depth becomes the same as over unvegetated mud or sand flat. In many areas, it is likely that during very large storm surge events, the water level over saltmarsh areas would be increased above this threshold. This means that in the case of very large surge events, the level of protection against wave energy and overtopping at the landward margin of the saltmarsh may be the same as if it were fronted by unvegetated sand or mud flat. In contrast, Möller *et al.* (2001) showed that saltmarsh is very effective at mitigating small to medium energy wave events that still may cause damage to structures. The extent to which saltmarsh is able to aid in protection from very large events will, therefore, be site specific and dependent on the elevation of the saltmarsh and the magnitude of surge generated in the area.

Table A1.2 Measured wave attenuation rates across UK saltmarshes and intertidal flats Möller et al. (2001)

	Mud/ sand flat width (m)	Mud/sand flat wave height attenuation rate (%/m)	Mud/sand flat wave energy attenuation rate (%/m)	Salt-marsh width (m)	Saltmarsh wave height attenuation rate (%/m)	Saltmarsh wave energy attenuation rate (%/m)
North Norfolk						
Stiffkey	197	0.08	0.15	180	0.34	0.46
Dengie						
Tillingham	147	0.14	0.24	163	0.53	0.61
Bridgewick	102	0.23 increase	0.54 increase	10	4.4	7.9
The Wash						
Wrangle Flats				425	0.21	0.23
Butterwick Low				542	0.12	0.13
Breast Sand				387	0.20	0.24

A1.5.3 Saltmarsh width and edge characteristics

Assuming a constant rate of wave attenuation, the overall width of saltmarsh fronting a shoreline would be related directly to the total extent of wave attenuation. However, the results in Table A1.2 show that the level of wave attenuation is not proportional to the width of saltmarsh. This is because the rate at which wave energy is attenuated across saltmarsh is not consistent across the whole salt marsh width. Field measurements on the Dengie Peninsula indicate that more than 40% of the wave energy arriving at the saltmarsh edge is attenuated across the first 10m of the permanently vegetated saltmarsh with, on average, the following 28m of saltmarsh attenuating a further 60% of the remaining energy. The importance of the saltmarsh margin in attenuating wave energy is shown particularly clearly in results from Dengie (Table A1.2), where a saltmarsh width of just 10m attenuated 79% of wave energy at Bridgewick. The morphology and vegetation of the saltmarsh margin are, therefore, particularly important in determining the nature and extent of total wave energy attenuation.

The morphology of the saltmarsh and intertidal flat boundary can vary considerably and will influence the way that wave energy is dissipated across the critically important saltmarsh margin. The nature of the saltmarsh margin depends on whether the saltmarsh is undergoing erosion or accretion, and is also influenced by the exposure of the area to wave energy. A gradual sloped margin typical of an accretionary saltmarsh will dissipate wave energy in a very different way to a bold saltmarsh cliff, normally associated with an erosional system.

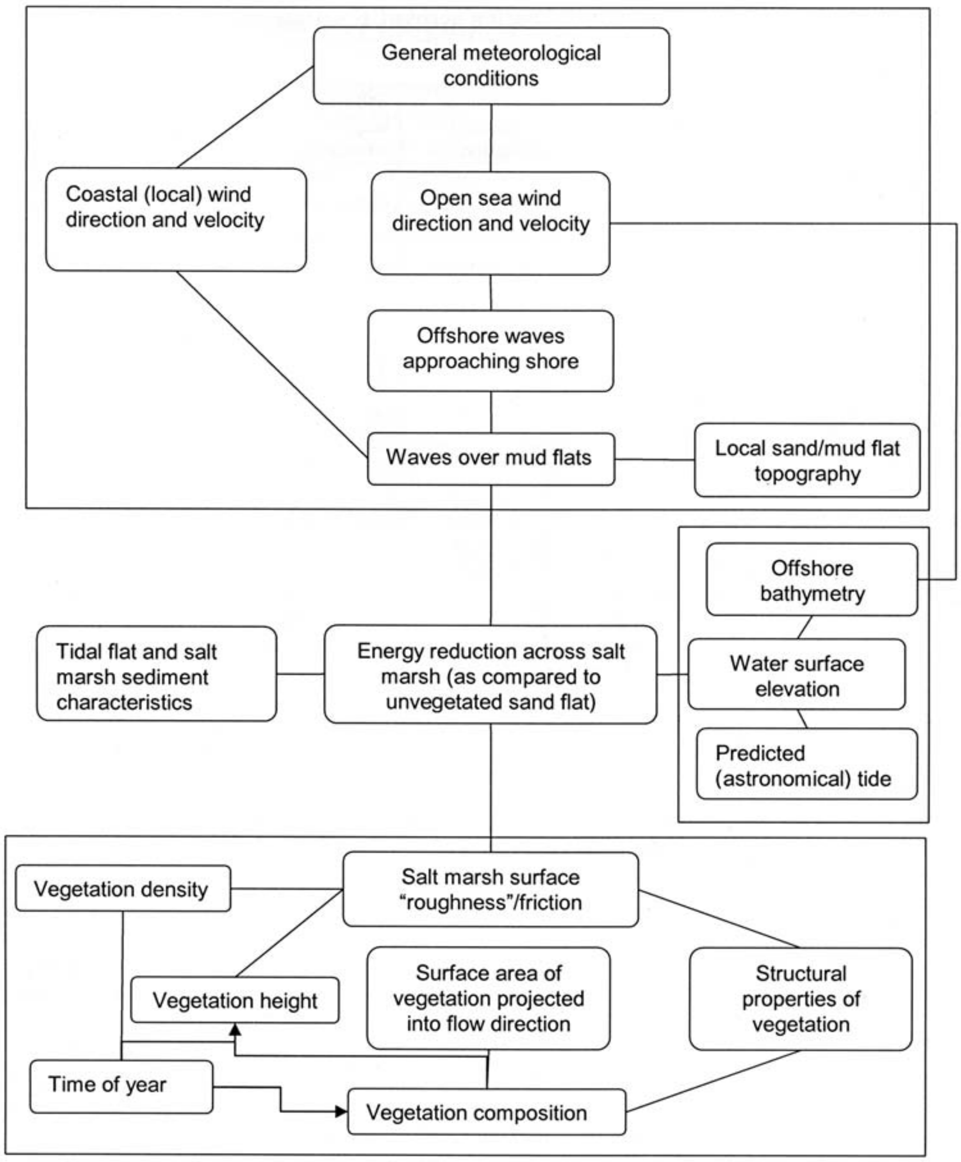

Figure A1.9 Factors influencing wave energy dissipation over saltmarshes (from Möller *et. al.*, 2002)

Möller and Spencer (2002) investigated the difference in wave attenuation patterns across two contrasting saltmarsh margins on the Dengie Peninsula. The two sites were a low angle ramp at Tillingham and a steep cliffed saltmarsh frontage at Bridgewick. Wave attenuation rates at the saltmarsh margin were twice as high at the cliffed site compared with the low angle smooth transition at Tillingham, with an average energy dissipation of approximately 8%/m and 4%/m, respectively.

Steep saltmarsh boundaries impact on the nature as well as the extent of wave energy dissipation. Steep faced saltmarsh boundaries reflect wave energy and cause rapid shoaling, increasing wave energy immediately fronting the cliffed frontage (Möller and Spencer, 2002).

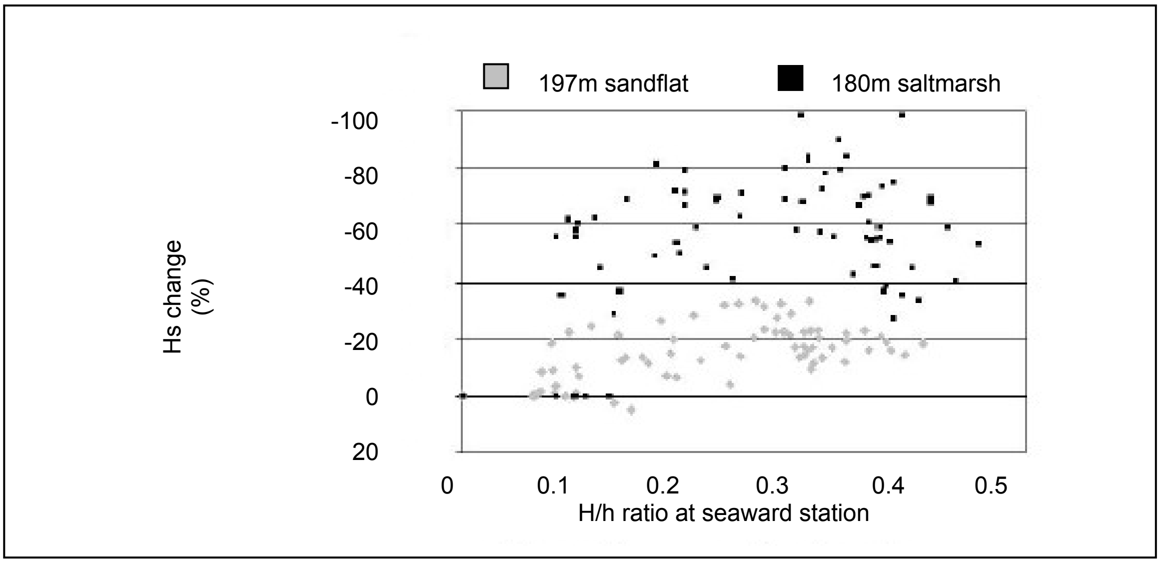

Figure A1.10 Relationship between wave energy attenuation and water depth for the sand flat and saltmarsh areas at Stiffkey, north Norfolk (from Möller et al., 1999)

Although the increased attenuation rate at a steep margin protects the saltmarsh and shoreline further landward, it is likely to generate ongoing erosion of the cliffed face, and progressive reduction in saltmarsh width. In contrast, wave attenuation rates over a ramped saltmarsh edge are more consistent, with an initially high level of wave reduction, followed by a steady attenuation rate of approximately 0.5%/m after approximately 80 m of saltmarsh. This configuration is much less likely to experience ongoing erosion caused by wave action.

A1.5.4 Topography and bed friction

In addition to water depth and topography, wave attenuation over intertidal flats and saltmarsh is generated by a wide range of other influencing factors, including viscous friction, percolation and sea bed boundary layer friction. Sea bed friction is the most significant of these factors in terms of the increased effect of saltmarsh on wave transformation.

Numerical model results indicate that the main factor responsible for increased wave attenuation across saltmarsh is an increase in the bed surface friction factor due to the roughness of the vegetation (Möller *et al*., 1999). Results of field studies and numerical modelling at Stiffkey have been used to estimate values for the “friction factor” f_{mod} to reflect surface roughness over saltmarsh and sand flat areas. Möller *et al*. (1999) quoted values of less than 0.02 over the sand flat increasing to over 0.07 over saltmarsh (Table A1.3).

Table A1.3 Friction factors for sand flat and saltmarsh environments, calculated from the wave attenuation model by Möller *et al*. (1999)

	Modelled friction factor, f_{mod}	
	Sand Flat	Saltmarsh
Mean	0.010	0.240
S.D.	0.003	0.060
Median	0.011	0.234
Min.	0.003	0.077
Max.	0.018	0.383

These results indicate that if saltmarsh areas were lost and replaced by sand or mud flat, average wave heights would increase at the backing land or sea defences. Möller *et al*. (1999) estimated that if the saltmarsh at Stiffkey was lost completely, it would cause a two-fold increase in wave heights at the shore, due to the reduction in the surface friction factor. This effect would vary depending on the site, in particular the elevation of the saltmarsh and the nature of the vegetation.

In addition to saltmarsh vegetation, other factors can increase sea bed friction and increase energy dissipation across an area of salt marsh. Landward of the marsh edge, wave energy dissipation is affected by marsh surface micro-topography, including presence/absence of salt pans and creek systems, and the nature and density of the vegetation cover. Quantifying the influence that these factors have on the extent of wave attenuation is very difficult, due to their highly variable and dynamic nature. The relative level of wave attenuation by unvegetated sand flats can also be highly variable, due (in part) to the presence of ripple bedforms.

A1.5.5 Vegetation density

The extent of wave attenuation across saltmarsh areas is also influenced by the nature and density of the saltmarsh vegetation. Differences can be due to spatial variability in vegetation density, the species composition and seasonal variability in the vegetation characteristics (see Appendix A2).

The area of saltmarsh immediately landward of the permanently vegetated edge is most significant in terms of attenuating wave energy, so vegetation changes in this area are likely to have the greatest influence. Möller and Spencer (2002) observed a correlation between lowered wave attenuation and seasonal decreases in vegetation density over a gradually sloping saltmarsh edge. The same study observed no such relationship over a steep cliffed saltmarsh margin, suggesting that the dominant effect on wave dissipation at this type of site is the cliffed topography rather than the vegetation.

The vegetation community type can also influence wave attenuation rates, due to the different physical structure of the plants. Across Dengie, Möller *et al*. (1999) identified a possible link between vegetation density, wave attenuation and the type of vegetation, with the flexible grass *Puccinellia* spp. in the upper saltmarsh having less effect on wave attenuation than the saltmarsh dominated by *Salicornia* and *Suaeda* spp.