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Coastal Erosion

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EXECUTIVE SUMMARY

Coastal erosion is a complex process that has a variety of causes, with rising sea level being only one of them. Most importantly, whereas climate change and relative sea-level rise are global and regional phenomena, respectively, coastal erosion is a local process. A large proportion of the UK coast is currently suffering from erosion (17% in the UK; 30% in England; 23% in Wales; 20% in Northern Ireland; 12% in Scotland). Where the coast is protected by engineering structures, coasts are generally experiencing a steepening of the intertidal profile. Both coastal erosion and steepening effects are expected to increase in the future due to the effects of climate change, especially sea-level rise and changes to the wave conditions. Management of coastal erosion in the UK is the joint responsibility of Defra and coastal councils, and Shoreline Management Plans (SMPs) are an important non-statutory instrument to assist with coastal management at a local and regional level.

The natural response of coastal systems to sea-level rise is to migrate landward according to the roll-over model, through erosion of the lower part of the nearshore profile and deposition on the upper part. This process is accompanied by the onshore transport of sediment. The roll-over model is applicable to estuaries, barriers and tidal flats, and the rate of coastal recession is likely to increase with the rate of sea-level rise. Rocky coasts (hard and soft) are erosional coasts and retreat even under stable sea-level conditions. Their retreat rates are expected to increase as a result of sea-level rise and increased storminess, but along soft-rock coasts, the introduction of cliff material into the nearshore zone may slow down local erosion rates through the formation of beaches. Coastal erosion can also have a beneficial effect: the introduction of eroded sediment into the nearshore sediment system and the subsequent deposition can reduce the risk of coastal flooding. Human activities, such as land reclamation, the building of hard coastal defences and the construction of jetties and marinas significantly impair the ability of coastal systems to respond naturally to changes in the forcing by restricting the free movement of coastal sediments.

It is very important to consider, however, that the coastal response to sea-level rise is very much determined by site-specific factors. These include relative sea-level history, isostatic land-level change, solid and drift geology, wave/tide conditions, longshore sediment transport, human impacts and the interactions between different coastal systems. More often than not, it is these site-specific factors that determine the coastal response, rather than a global change in sea level or a regional change in wave climate. Any predictions of *general* coastal response due to climate change are therefore relatively meaningless and will have a low confidence. However, if a detailed study is conducted and long-term coastal change data are available, then *local* or *regional* predictions of coastal response to climate change can have medium confidence.

FULL REVIEW

Coastal erosion is widespread in the UK and the *Foresight Flood and Coastal Defence Project* estimates current damage due to coastal erosion at £15 million per year, and in the worst case this figure may rise to £126 million per year by 2080 (Foresight, 2004). An extreme illustration of erosion risk is shown in Figure 1 for the case of the town of Happisburgh in Norfolk. Here, the coastline position has been artificially maintained for decades using hard coastal defence structures and their part removal has resulted in rapid coastal erosion. Coastal erosion is generally attributed to sea-level rise and concerns about erosion risk have mounted in light of increased rates of sea-level rise predicted due to climate change.

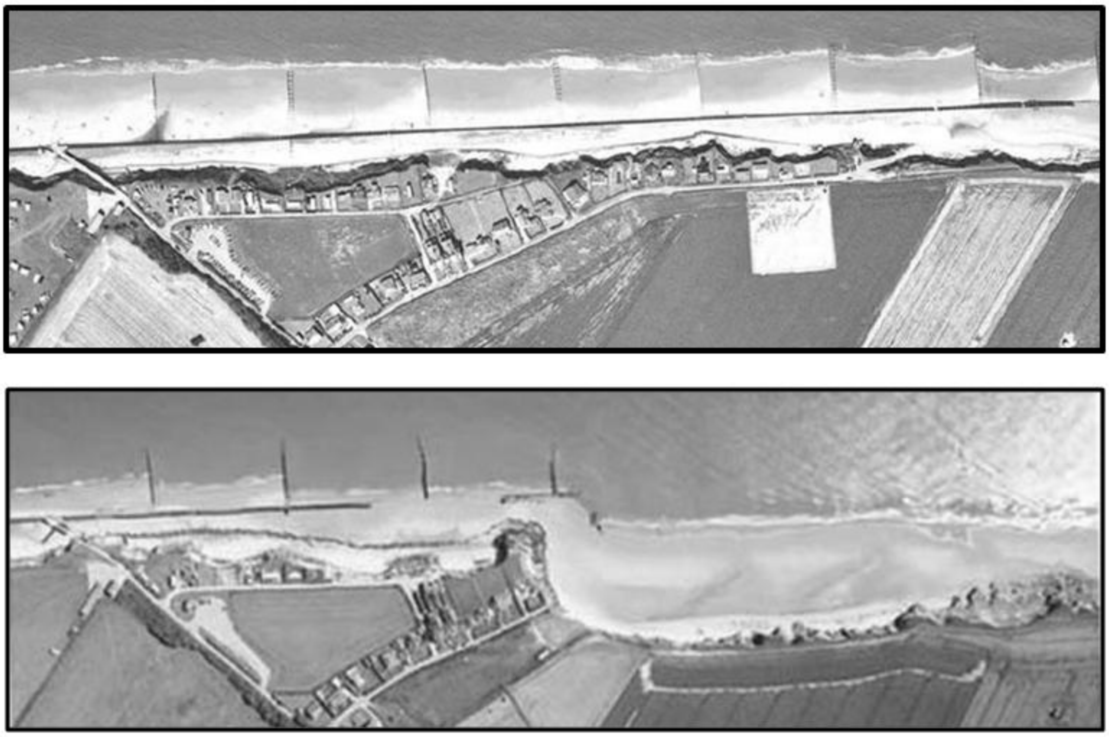


Figure 1 *– Coastal erosion at Happisburgh, Norfolk, from 1993 to 2003. It should be pointed out that the erosion recorded in these photographs is extreme and to a large degree the result of the removal of coastal defences.*

Management of coastal erosion in the UK is the joint responsibility of Defra and coastal councils. At a national level, the *Making Space for Water* initiative provides important strategic guidance for dealing with coastal (and river) management. The key aspect of the strategy is that sustainable development should be firmly rooted in all flood risk management and coastal erosion decisions and operations (defra.gov.uk/environment/flooding/policy/strategy/index.htm). At a local and regional level, strategic guidance for coastal management is provided through (non-statutory) Shoreline Management Plans (SMPs). The plans provide a large-scale assessment of the risks associated with coastal processes and present a long term policy framework to reduce these risks to people and the developed, historic and natural environment in a sustainable manner (defra.gov.uk/environment/flooding/documents/policy/guidance/smpguide/smpgvol1.pdf). The *Making Space for Water* philosophy is currently being incorporated into the second generation of SMPs, which increasingly consider managed realignment as the preferred management strategy, leading to controversial SMPs (e.g. SMP for North Norfolk).

This review will provide an overview of current erosion rates in the UK (Section 1) and what is likely to happen in the future (Section 2). However, sea-level rise is only part of the story and the key message will be that coastal erosion is a complex process that has a variety of causes, with rising sea level being only one of them. Most importantly, whereas climate change and relative sea-level rise are global and regional phenomena, respectively, coastal erosion is a local process. Erosion of one stretch of coast is likely to cause accretion elsewhere – sediment is not lost from the coastal system. Therefore, most of this review is concerned with describing the most relevant processes involved with coastal erosion (Section 2.1) and discussing how these processes affect different types of coastal environments (Section 2.2).

1. What is already happening?

Region	Coast length	Coast length which is eroding	Coast length which is eroding	Coast length with defence works & artificial beaches	Coast length with defence works & artificial beaches
	km	km	%	km	%
Northeast England	297	80	27.0	111	37.4
Northwest England	659	122	18.5	329	49.9
Yorkshire & Humber	361	203	56.2	156	43.2
East Midlands	234	21	9.0	234	99.8
East England	555	168	30.3	382	68.9
Southeast England	788	244	31.0	429	54.4
Southwest England	1379	437	31.7	306	22.2
England	4273	1275	29.8	1947	45.6
Wales	1498	346	23.1	415	27.7
Scotland	11154	1298	11.6	733	6.6
Northern Ireland	456	89	19.5	90	19.7
Total	**17381**	**3008**	**17.3**	**3185**	**18.3**

Table 1 *– Coastal erosion and protection in the UK (EUROSION, 2004). Islands with a surface area smaller than 1 km^2 and inland shores (estuaries, fjords, fjards, bays, lagoons) where the mouth is less than 1 km wide are not included in the analysis.*

According to a recent Europe-wide study into coastal geomorphology and erosion (EUROSION, 2004), the UK coastline is 17,381 km long, of which 3,008 km are currently experiencing erosion (Table 1). The coastline of England is most affected, with 29.8% of its coastline suffering from erosion. The coastline of England is also the most protected with 45.6% of its length lined with coastal defence works (seawalls, groins) or fronted by artificial beaches. The Foresight Flood and Coastal Defence Project provides estimates of present and future (next 100 years) coastal erosion rates for the coast of England and Wales (Foresight, 2004). According to their analysis, 28% of the coast is experiencing erosion rates in excess of 0.1 m yr-1 (Evans et al., 2004; Burgess et al., 2007). A large proportion of the coastline is held in position artificially, however, and a more realistic estimate of potential erosion is that 67% of the coastline is under threat (Futurecoast, 2002). Where the coast is protected by engineering structures, the rising sea level results in a steepening of the intertidal profile, known as coastal squeeze. According to Taylor et al. (2004) almost two-thirds of the intertidal profiles in England and Wales have steepened over the past hundred years; however, a re-evaluation of these results pertaining to the southeast coast of England suggests that steepening is less common (Dornbush et al., 2008). More recently, the National Coastal Erosion Risk Mapping project (Rogers et al., 2008) has suggested that 42% of the coast of England and Wales is at risk from erosion, of which 82% is undefended. However, this project is only concerned with cliffed coastlines and does not consider coastal floodplains, beaches, barriers and intertidal areas.

2. What could happen in the future?

The two main consequences of climate change that have an impact on coastal erosion and coastal geomorphology are sea-level rise and changes to the wave climate (storminess and prevailing wave direction). Currently, global sea level is rising at a rate of c. 3 mm per year and the rate is accelerating (Church and White, 2006). The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change predicts that the rise in global sea level by 2100 will be in the range of 18–38 to 26–59 cm, depending on the emissions scenario, but there appears to be less certainty with regards to changes in the wave climate (IPCC, 2007).

The IPCC climate change projections have recently been updated for the UK by the UKCP09 (ukclimateprojections.defra.gov.uk/) and the key elements of these for coastal erosion can be summarised as follows:

- **Relative sea-level rise** – During the 21st century, relative sea level (i.e., change in sea level relative to the level of the land) in the UK is expected to rise by 30–50 cm, depending on emissions scenario. Because of differences in land-level changes due to the glacial isostatic adjustment (GIA), the projected relative sea-level rise in south England is larger than in north England and Scotland (Figures 2 and 3)
- **Storm surge levels** – If the predicted sea-level rise is disregarded, there seems to be only a very modest increase in predicted storm surge levels.
- **Wave climate** – Projected changes to the wave climate range widely depending on the sensitivity of the model used. Overall, changes in the seasonal mean significant wave height are modest, generally < 0.1 m. Some regions might actually experience a reduction in wave height. The most sensitive area appears to be the *Charting Progress Regions* 2 and 3 (Southern North Sea, Eastern English Channel), where an increase in the seasonal mean significant wave height of 0.1 m is predicted.

The *Foresight Project* estimated future coastal erosion rates and compared these to the benchmark present condition (20–67 m erosion over 100 years). Depending on the emissions scenario, the amount of erosion predicted to occur over the next 100 years ranges between 82 and 175 m, with the most severe erosion occurring in the east of England (Evans *et al.*, 2004). It is questionable, however, whether such national, or even regional, predictions of coastal erosion are very useful, because coastal erosion is largely a local process and coastal recession rates are spatially highly variable. Coastal scientists and managers are aware of the importance of geographical variability in coastal change; therefore, a Geographical Information System (GIS) framework is usually adopted to quantify current and projected coastal changes, and assess societal risk of coastal erosion. Examples of such initiatives include Esteves *et al.* (2008) at the local scale, Nicholls *et al.* (2008) on the regional scale and Rogers *et al.* (2008) at the national scale. The latter project, due to finish in 2009, is of particular relevance to coastal managers, because it combines existing coastal recession rates with a probabilistic method for assessing the hazard and risk of coastal erosion (resulting from the Risk Assessment of Coastal Erosion project; Halcrow, 2006) to determine coastal erosion risk at the local scale 20, 50 and 100 years into the future.

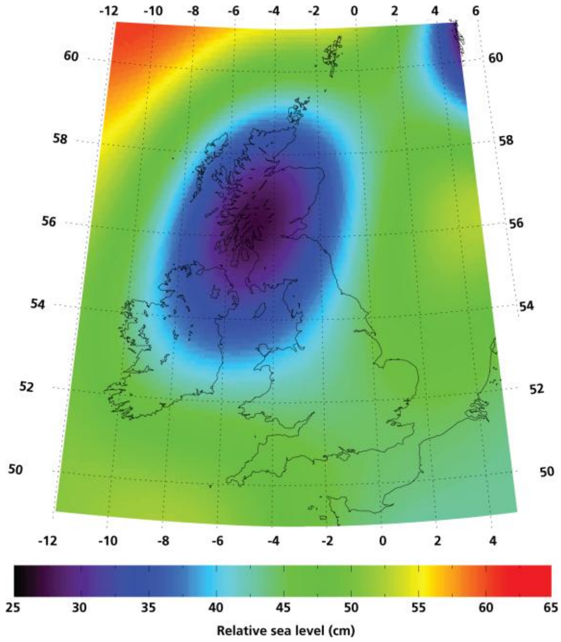


***Figure 2 –** Relative sea-level change around the UK over the 21st century. The change combines the central estimate for the medium emissions scenario and vertical land movement, and relates to the period to 2095 (source: UKCP09).*

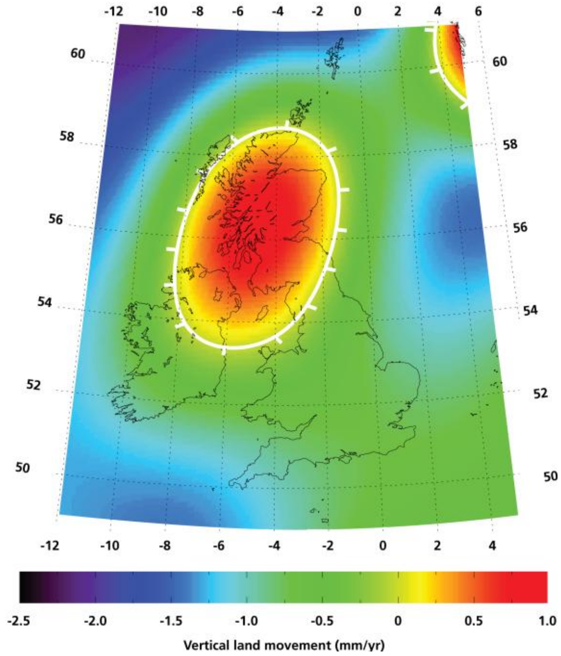


***Figure 3** – Glacial Isostatic Adjustment (GIA) map of the vertical land movement for the UK (source: UKCP09; Adapted from Bradley et al., 2008). Note that there is some doubt with regards to the relatively large rate of relative sea-level rise in the southwest of England (Gehrels, 2006).*

2.1 Factors involved with Coastal Erosion and Geomorphology

It is tempting to attribute the coastal erosion in the UK to rising sea level; however, this is a serious over-simplification, as several other processes are involved:

Sea-level history – Coastlines do not respond instantaneously to changing sea levels, but evolve over time scales ranging from centuries to millennia. Present-day trends in shoreline position (erosion/accretion) are therefore often better explained in terms of the sea-level history, than contemporary sea-level change. In this context, the sea-level history of the last 10,000 years has been particularly influential. Figure 4 shows the sea level at 7,500 BP, when global mean sea level was c. 15 m below present (Shennan *et al.*, 2000), and highlights the contrast between the east coast of England and the rest of the UK. At this time, the coastline of east England had a very different shape and was located more than 10 km seaward of the present coastline. The implication is that this coast is very young, and is unlikely to have adjusted to present sea-level. The erosion rates along the east coast of England are amongst the largest in the UK (e.g. on parts of the Norfolk coast there has been almost 200 m of recession since 1885; Clayton, 1989), and this has nothing to do with the present-day sea-level rise, but is largely attributed to their sea-level history.

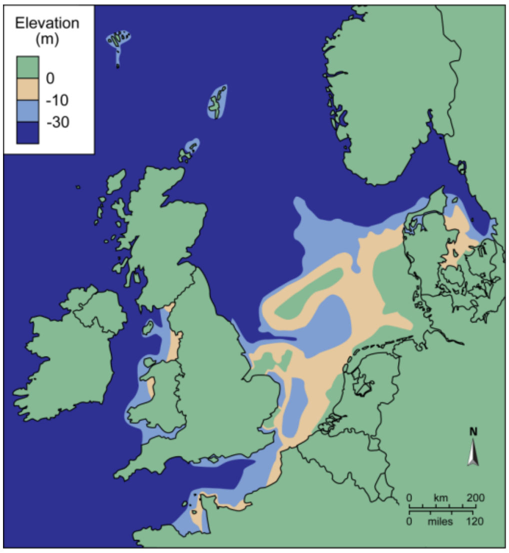


Figure 4 *– Coastal configuration of NW Europe 7,500 years BP (Shennan et al., 2000)*

Relative sea-level change – The effect of eustatic (global) sea-level rise on the UK coastline must be considered in combination with the changes in the land level associated with glacio-isostatic effects, in particular isostatic rebound of the formerly glaciated areas in the north, and collapse of the forebulge of areas near the ice margin in the south (Shennan and Horton, 2002; Figure 3). There is considerable regional variation in the estimated relative sea-level change, with relative sea level in the south rising faster than in the north (Figure 2), and this will have a significant effect on the coastal response.

Geology – The geology exerts its control on coastal erosion mainly through the resistance of the rocks to denudation (Figure 5) and provides the explanation for the contrast between the high-relief, mainly rocky coast of west England, Wales, Scotland and Northern Ireland, and the low-relief, mainly unconsolidated coast of east England (Clayton and Shamoon, 1998). Cliff erosion is controlled to a large extent rock strength, with typical cliff recession rates in hard and soft rock of 0.1–1 cm yr-1 and 0.1–1 m yr-1, respectively. The configuration of many estuaries is also largely controlled by their geology, because most are drowned river systems (Prandle, 2006)

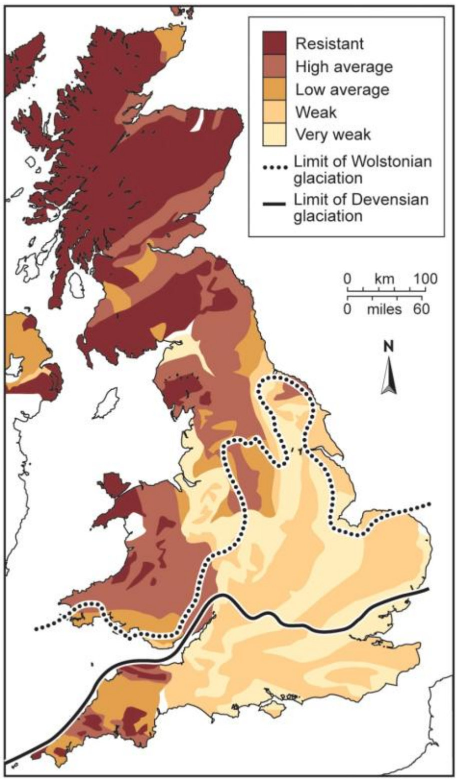


Figure 5 *– Map of Britain showing resistance of the geology to denudation (Clayton and Shamoon, 1998).*

Sediments – During deglaciation, large quantities of sediments, comprising the full spectrum of sediment sizes from mud to boulders, were left in front of the retreating glaciers. Most of the coarser material that was deposited on what is now the continental shelf has been transported onshore during the post-glacial transgression and has been incorporated in dunes, beaches, barriers and estuaries (Futurecoast, 2002). This sediment source is now more or less depleted and offshore sediment supply to the coast by natural processes, as opposed to beach recharge, is currently very limited. However, large amounts of glacial material are still present on the land and represent an important sediment source to the nearshore system through cliff erosion (Bray, 1997). The deposition of clay and silts onto salt marshes and tidal flats is particularly important, because it may enable these environments to 'keep up' with rising sea levels (Adam, 2002).

Waves, tides and storm surge – Coastal sediment transport processes are mainly the result of tide- and wave-driven currents, particularly during storm conditions. The tidal regime, wave climate and storm surge exhibit a large spatial variability (Figures 6 and 7) and this plays an important role in explaining the diversity in coastal landforms in the UK, as well as having an effect on coastal erosion. The potential for coastal erosion increases with wave height, but wave period is also important, because steep waves (wind waves with short wave periods) are known to be more destructive than long waves (swell waves with long wave periods). The North Sea and the Irish Sea are characterised by the highest storm surges and the shortest wave periods, and their coastlines are likely to be most sensitive to changes in storminess. Changes to tides and tidal currents due to climate change are expected to be minimal in the foreseeable future, but can become significant in the long-term when the rising sea levels start affecting the configuration of tidal basins and estuaries.

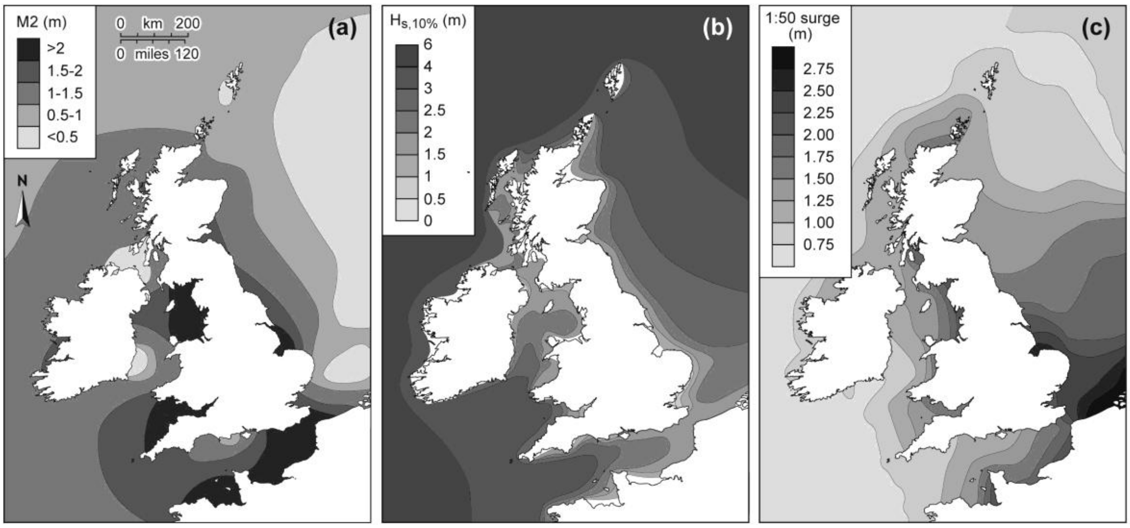


Figure 6 *– Map of Britain with: (a) M2 tidal amplitude (Davidson et al., 1991); (b) 10% exceedence significant wave height* H^{s}*,10% (Draper, 1991); and (c) 1-in-50 year storm surge level (Flather, 1987).*

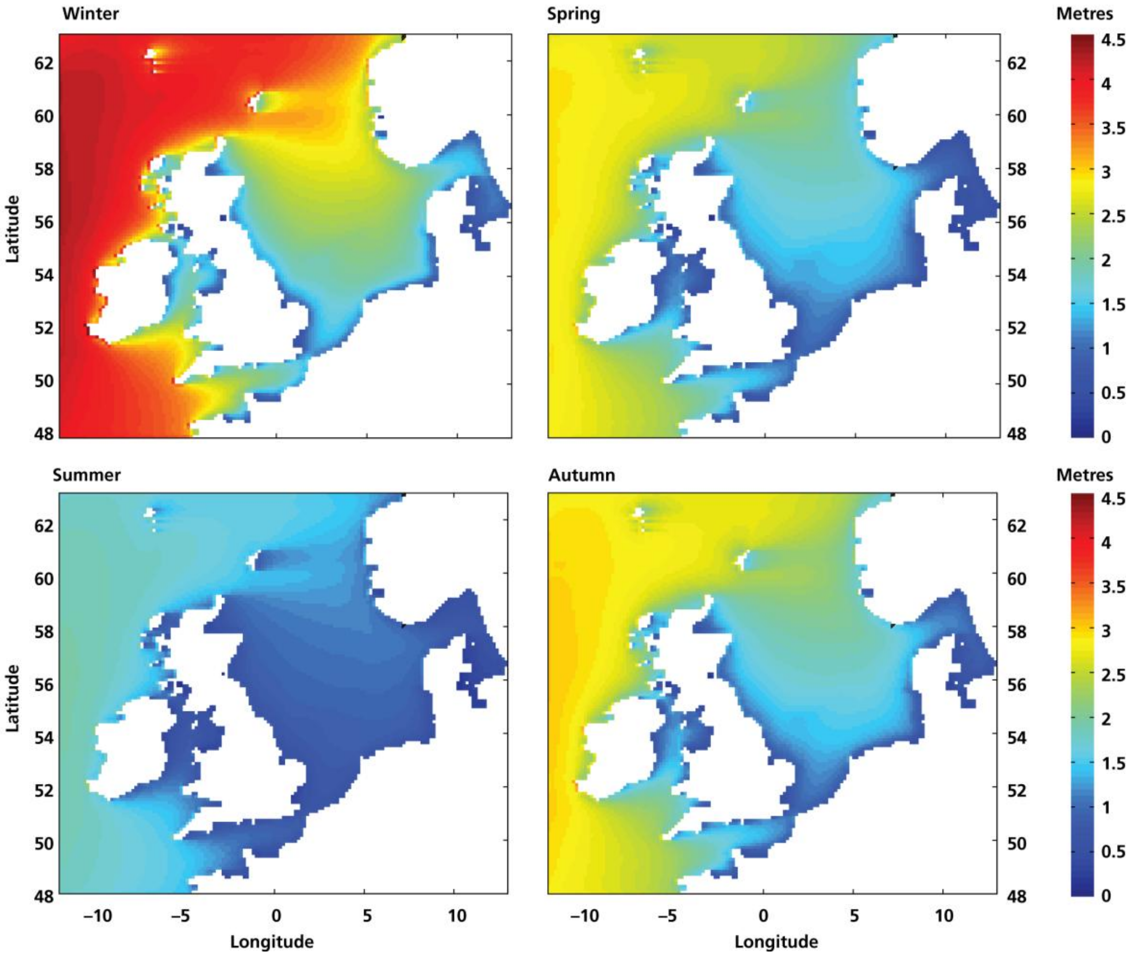


Figure 7 *– Modelled seasonal means of significant wave height of swell waves for 1960–1990 (UKCP09).*

Longshore sediment transport – Many beaches and barrier systems are so-called drift-aligned systems, meaning that their configuration, dynamics and stability are largely controlled by longshore sediment transport processes (Orford et al. 2002). Classic examples of such systems are spits (e.g., Spurn Head) and cuspate forelands (e.g. Dungeness). Even small changes to the net littoral drift rate (or direction), for example, due to a change in wave climate, will have major implications for the shoreline position. Embayed beaches, which are generally aligned according to the prevailing wave direction, are also susceptible to changes in the wave climate and may exhibit rotation, characterised by erosion at one end of the bay, and accretion at the other end. Annual or decadal changes in the prevailing storm wave direction can induce changes in the littoral drift direction over the same time scale, which in turn can cause pronounced changes in the beach width (Alegria et al., 2008).

Human impacts – Much of the UK coastline, especially that of England and Wales, is developed (Table 1) and human activities significantly affect coastal erosion (French, 2001). Coastal protection works such as breakwaters, seawalls and groins are designed to halt coastal erosion, but the resulting fragmentation of the coast interrupts the longshore transport and exacerbates, or even causes, downdrift erosion problems. Protection of the base of eroding cliffs stops erosion, but prevents the introduction of eroded cliff material into the nearshore sediment system, which may also have a deleterious effect on downdrift beaches. Land reclamation has been very widespread in the UK (Davidson et al., 1991), mainly in estuarine environments, but this reduces the natural resilience of these environments to sea-level rise. Coastal defences significantly impair the ability of coastal systems to respond naturally by restricting the free movement of coastal sediment. Only beach nourishment (or recharge) has a positive influence on the coastal sediment budget, but the sediment required for recharge will have to come from elsewhere (usually the continental shelf). The sediment volumes required to maintain our beaches are considerable and questions have been raised with regards to the sustainability of this method of coastal protection. For example, since 1995, the Sussex and Kent coast has been nourished with 4.1M m3 of sediment, mainly gravel, at a total cost of at least £62M (Moses and Williams 2009).

Linkages between coastal systems – Coastal evolution and shoreline trends, especially that over long time scales (≥ 100 years), are related to process interactions and sediment linkages between different coastal landform units (Leafe *et al.*, 1998). An important and useful concept arising from this notion is that of *Coastal Behavioural Systems* (CBS), which attempt to integrate coastal geomorphological units, such as cliffs, beaches, dunes and salt marshes that are spatially contiguous into a single entity (Burgess *et al.*, 2002). A CBS is generally defined by long-term regional evolution, the wider-scale interactions or drivers of change, and/or common characteristics of shoreline features. A good example of a CBS is the west Dorset coast. The characteristics of this coast are a continual supply of terrestrial sediments to the nearshore system through cliff erosion, a large net eastward longshore sediment transport and the presence of a large gravel beach barrier at the end of the longshore transport corridor (Bray, 1997). Depending on the balance between terrestrial sediment supply and marine removal, beaches fronting the cliffs either grow or shrink, and interruptions to the longshore drift system, for example through engineering structures, have major implications for shoreline stability. Clearly, the west Dorset coast is quite diverse on the small scale, and may have alternating eroding and accreting sections, but on the larger scale, and in the longer term, it behaves as one unit.

2.2 Dominant types of Coastal geomorphology

Hard-rock coasts

About 60% of the open coast (i.e. excluding estuarine shores) in the UK is hard-rock coast, characterised by cliffs, shore platforms and embayed beaches (Figure 8). Little is known about the impact of climate change on hard-rock coasts, but erosion rates are likely to increase, both as a result of more energetic wave action at the cliff base due to rising sea level and increased storminess, as well as increased mass-wasting processes due to more precipitation. However, recession rates will generally remain low, on the order of several metres over 100 years, except perhaps very locally.

The effect of climate change on embayed beaches is probably more significant. These beaches are backed by cliffs or higher ground and generally have very limited back-beach accommodation space. They also tend to be closed systems with no, or very limited net import of sediment due to their embayed settings. Rising sea level will attempt to push these beaches landward, but, with no space to move into and not sufficient time to create new space through erosion, coastal squeeze will result in a progressively diminishing beach volume until no beach is left. Climate change may also result in the rotation of embayed beaches due to changes in the wave climate, especially the wave direction, causing alterations in the littoral drift rate and/or direction. The narrowing and widening of beaches at opposite ends of embayments has been documented for several locations in the world (e.g., Klein *et al.*, 2002; Ranasinghe *et al.*, 2004), and may become significant along the coastline of England and Wales.

Figure 8 *– Examples of hard-rock coasts: (a) plunging cliffs, Great Orme Head, Conwy, North Wales; (b) cliffs fringed by narrow shore platform, St Bees Head, Cumbria, NW England; (c) rocky, coast with shore platform, Port Eynon, Gower, south Wales; (d) extensive shore platform, Rhoose, Vale of Glamorgan, south Wales; (e) cliff fronted by sandy beach and shore platform, Saltburn, Cleveland, NE England; and (f) sandy beach between cliffed headlands, Caldey Island, Pembrokeshire, south Wales (images from Futurecoast, 2002).*

Soft-rock coasts

About 20% of the open coast in the UK is soft-rock coast and most of it's morphology is characterised by a beach fronting either a cliff or non-cliffed higher ground (Figure 9). In common with hard-rock coasts, these coasts are eroding (Lee and Clark, 2002), but, in contrast to their hard-rock counterparts, there is usually a significant amount of sediment present in the coastal zone. Cliff erosion on soft-rock coasts is a highly episodic process (Dong and Guzzetti, 2005) with erosion rates varying both spatially and temporally. The presence of well developed beaches along an otherwise eroding coast is a paradox, but soft-rock coasts are generally drift-aligned and the beaches represent the morphological expression of the longshore transport system, rather than stable depositional features. In fact, the source of the beach material is cliff erosion, and the beaches would not exist were it not for the eroding cliffs.

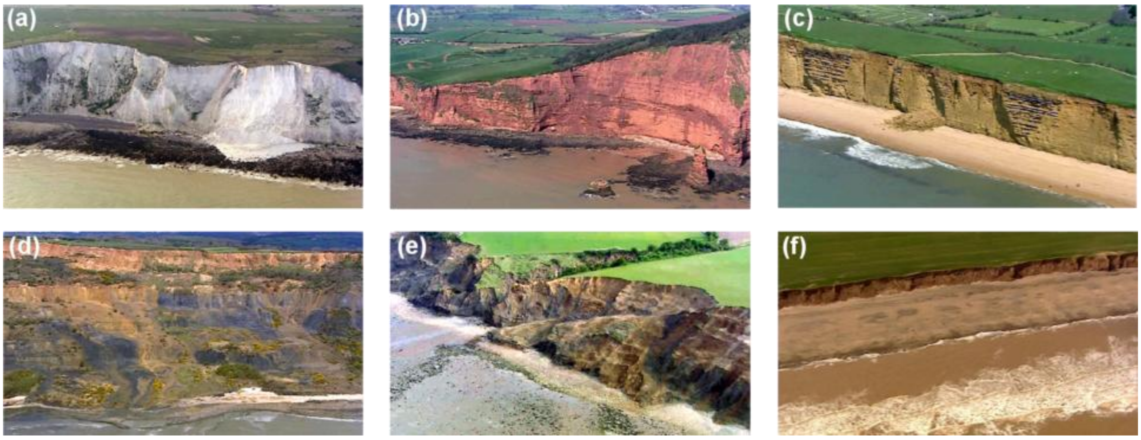


Figure 9 *– Examples of soft-rock coasts: (a) chalk cliff fronted by shore platform, Dover, Kent, SE England; (b) cliff fronted by small beach and shore platform, Sidmouth, Devon, south England; (c) cliff fronted by sandy beach, Burton Bradstock, Dorset, south England; (d) Black Ven landslide complex fronted by mixed sand/gravel beach, Lyme Regis, Dorset, south England; (e) clay cliff fronted by sandy beach and unconsolidated shore platform, Isle of Sheppey, Kent, east England; and (f) cliffs in glacial deposits fronted by sandy beach, Holderness, Lincolnshire, east England (images from Futurecoast, 2002).*

Walkden and Hall (2005) developed a model that considers the cliff-platform-beach system and realistically accounts for positive and negative feedback processes. The model was used to model cliff retreat of single cross-shore sections on the Naze peninsula, Essex, and it was found that a three-fold increase in the rate of sea-level rise (from 2 to 6 mm yr^{-1}) only resulted in a 15% increase in cliff recession rate. The model was extended by adding a one-line model to link the different cross-shore sections and was applied to the Norfolk coastline, where it was run for a number of climate change and management scenarios (Dickson *et al.*, 2007; Walkden *et al.*, 2008). Model output was found to be relatively insensitive to an increase in the offshore wave height and moderately sensitive to changes in the wave direction, but the most important effects were due to accelerated sea-level rise. A complex suite of responses were predicted, however, and for some sections along the coast, the model actually predicted shoreline progradation with increased rate of sea-level rise owing to the delivery of sediment from eroding cliffs updrift.

This morphodynamic model has recently been linked to hydrodynamic, reliability and socio-economic models by Dawson *et al.* (2009) to provide an integrated analysis of coastal flooding and cliff erosion under different scenarios of coastal management, climate and socio-economic change, and has been applied to a 72-km stretch of the East Anglian coastline (coastal sub cell 3b in UK coastal management planning). The two key findings of the modelling efforts are: (1) sediment released from cliff erosion plays a significant role in protecting neighbouring low-lying land from flooding; and (2) flood risk in the area studied is expected to be an order of magnitude greater than erosion risk. A very significant finding of this research is that it can make economic sense to allow coastal erosion to take place, and thereby sacrifice properties and land, because the costs associated with the coastal erosion can be offset by the benefits of achieving improved defence against coastal flooding. The modelling also demonstrates that, provided the coastal system is reasonably well understood, some confidence can be obtained in predicting the effects of climate change, both physically (flooding and erosion) and in terms of socio-economics.

Barrier coasts

About 20% of the open coastline in the UK is backed by a (Holocene) coastal plain, and is taken up by barriers and tidal flat systems, often capped by dunes (Figure 10).

There are two models of barrier response to rising sea level. According to the *Bruun rule*, the shoreface profile moves upward by the same amount as the rise in sea level, through erosion of the upper shoreface and deposition on the lower shoreface. According to the *roll-over model*, the barrier migrates across the substrate gradient without loss of material, through erosion of the shoreface and deposition behind the barrier in the form of washovers and/or tidal inlet deposits. The Bruun rule is widely used for predictive purposes, but there is actually very limited support for its validity and some argue it should be abandoned altogether (Cooper and Pilkey, 2004). There is much stronger evidence for the roll-over model, which is especially appropriate for gravel barriers (Pye and Blott, 2006), strongly wave-dominated barriers and on relatively gentle substrate slopes. Barrier migration is not a steady process, however, but occurs episodically when extreme water levels, often in combination with large waves, result in overwashing of the barrier (Orford *et al.*, 2003). Therefore, in addition to sea-level rise, changes in extreme water levels and storminess are also important for the stability of barrier coasts (Pye and Blott, 2008).

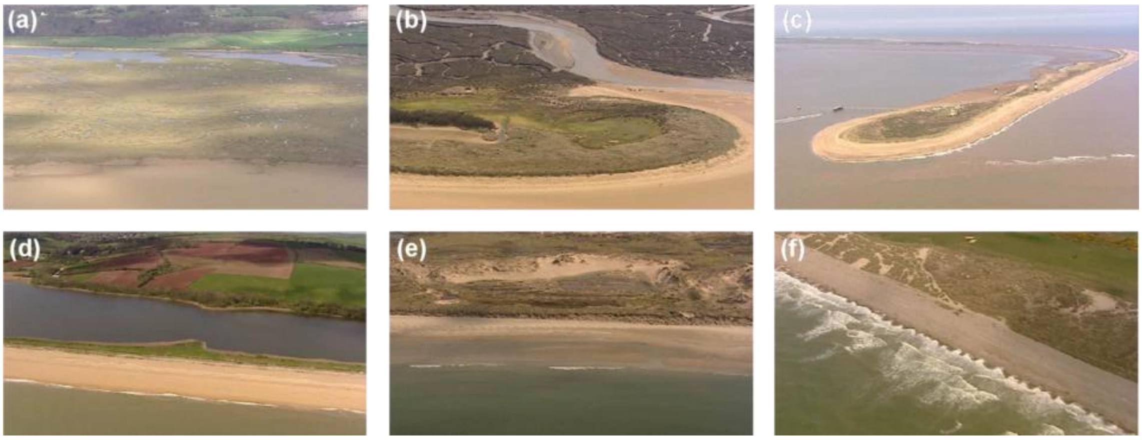


Figure 10 *– Examples of barrier coasts: (a) tidal flat and salt marsh, Morecombe Bay, Cumbria, NW England; (b) barrier system fronting an estuary with extensive salt marshes, Titchwell, Norfolk, east England; (c) barrier spit stretching several km's into the Humber estuary, Spurn Head, Lincolnshire, east England; (d) gravel barrier with back-barrier lagoon, Slapton Sands, Devon, south England; (e) sandy barrier with extensive dune development, Morfa Dyffryn, Gwynydd, Wales; and (f) gravel beach capped by sandy dunes, Littlehampton, Sussex, south England (images from Futurecoast, 2002).*

The Bruun rule and the roll-over model are essentially two-dimensional models of shoreline response to sea-level rise that ignore the contribution of longshore sediment transport processes and the presence of additional sources and sinks. Most UK barriers are drift-aligned systems and characterised by relatively high net littoral drift rates of the order of 10^4–10^5 m^3 yr^{-1}. In such settings, modifications to the longshore transport system (e.g., due to changes in wave climate or coastal engineering structures) can be more important in driving coastal change than sea-level rise (Chadwick *et al.*, 2005). The interaction between tidal inlets and the adjacent open coasts also requires consideration (Burningham and French, 2006). The type of interaction will depend on the tidal asymmetry of the inlet: when the inlet is ebb-dominant (flood-dominant), sea-level rise may cause an export (import) of sediment, countering (promoting) retreat of the adjacent coast (Stive, 2004).

Recently, longer-term modelling of barrier coasts has adopted the so-called 'coastal-tract' approach, which considers that shoreline evolution over centuries to millennia must be linked to the behaviour of the continental shelf and coastal plain (Cowell et al., 2003a, b). In this approach, coastal evolution is modelled using behaviour-orientated coastal change models constrained by sediment mass conservation. The key factor that controls the rate of coastal change is governed by the balance between the change in sediment accommodation space caused by sea-level rise and sediment availability. The coastal-tract modelling approach has not yet been applied to the UK coast.

Estuaries

There are 106 estuaries in Great Britain (UK, excluding Northern Ireland) and the majority of the estuaries fall into five groups (Figure 11; Davidson *et al.*, 1991): (1) rias, or drowned river valleys, are short, deep and steep-sided with small river flows; (2) coastal plain estuaries are long and funnel-shaped with extensive intertidal zones; (3) bar-built estuaries are short and shallow with small river flows and tidal range, and are located along coasts with plentiful supplies of sediment; (4) embayed estuaries are large shoreline indentations with a relatively small amount of fresh water input; and (5) fjords and fjards, which occur mainly in Scotland and represent drowned glacial valleys. Estuaries interact with the adjoining coast and can be a sediment source or sink: highly-stratified, short and ebb-dominant estuaries (i.e., bar built estuaries) are likely to be sediment sources, whereas partially-mixed, longer and flood-dominant estuaries (i.e., coastal plain estuaries) and embayed estuaries tend to be sediment sinks (Burgess *et al.*, 2002). Net import/export of sediments in estuarine environments is often a very small difference between two very large numbers. For example, Townend and Whitehead (2003) presented a sediment budget of the Humber estuary and found that the sediment import per tide (100 tonnes) is only 0.08% of the total amount entering and exiting the estuary at each tide.

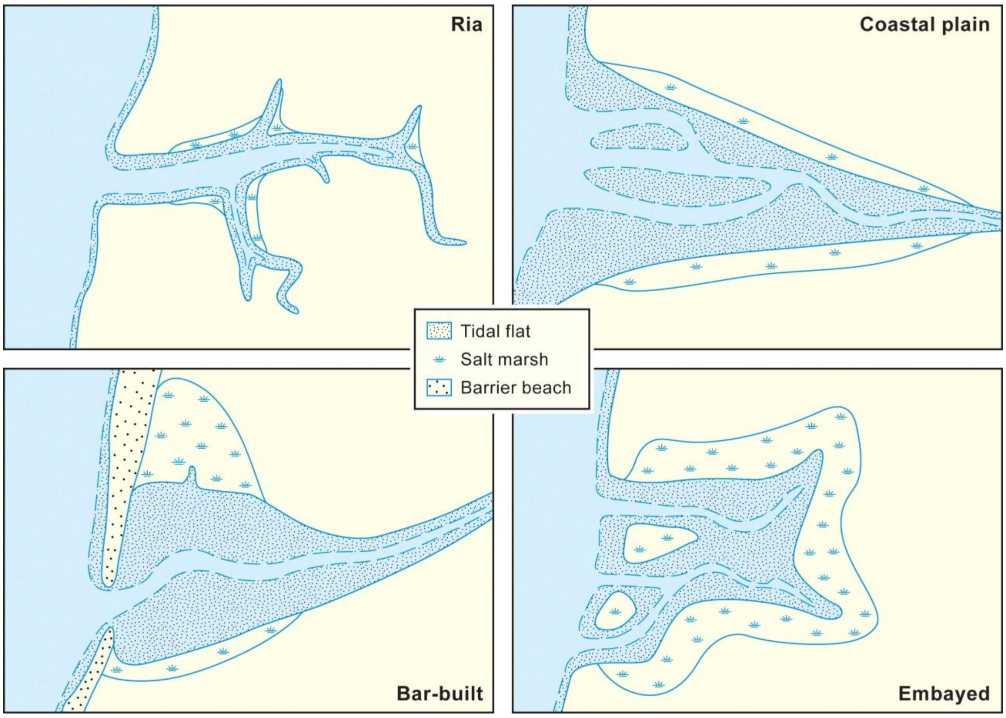


Figure 11 *– Four main estuarine types in England and Wales (Davidson et al., 1991).*

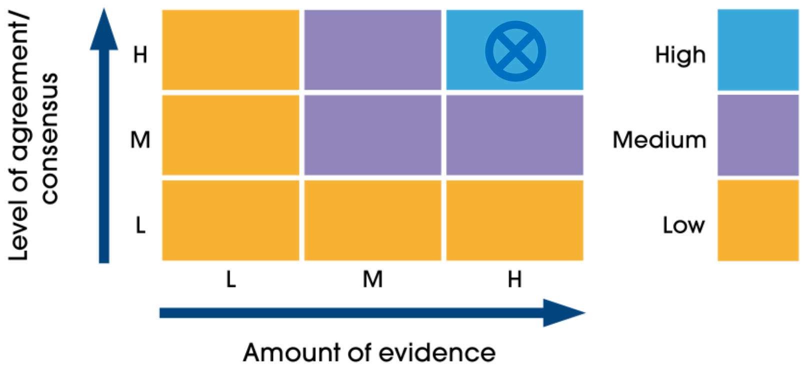
Process-based models are not able to reliably predict estuarine evolution, and conceptual, behaviour-oriented models are more appropriate for predicting the long-term response of estuaries to sea-level rise. Several such models have been applied to predict the long-term response of UK estuaries to sea-level rise, and these have been based on estuarine roll-over (Allen, 1990), tidal asymmetry (Townend and Pethick, 2002) and tidal regime theory (Pethick, 1998; Townend, 2005). Generally, these models propose that estuaries migrate landward and upward with rising sea level through a redistribution of sediment within the estuarine system from outer to inner estuary, accompanied by a widening of the tidal channels, especially in the outer estuary.

A more holistic approach for predicting the response of estuaries to sea-level rise is the ASMITA model (Aggregated Scale Morphological Interaction between Inlets and Adjacent coast; Stive *et al*, 1998). This approach represents the estuary as a series of morphological elements, such as tidal flat, channel and ebb tidal delta. Each element evolves towards an empirically derived equilibrium volume and interacts with adjacent elements by sediment exchange. The ASMITA model has been applied to several UK estuaries and results for the Thames estuary, for example, suggest that for the period 2000 to 2100 under accelerated sea-level rise scenarios, the estuary will experience accretion. However, because the accretion is predicted to be at a slower rate than sea-level rise, intertidal profiles may be up to 0.5 m lower with respect to high water, resulting in a deepening of the estuary (Rossington and Spearman, 2009).

The natural response of estuaries to sea-level rise – landward migration – is inhibited by coastal defence structures. Erosion of the seaward edge of salt marshes and the lower part of the intertidal zone nevertheless occurs, resulting in a narrowing of the intertidal zone, or coastal squeeze. The best management solution from a geomorphological perspective would be to relocate the line of defence landwards of its existing position to allow salt marsh and intertidal mud flats to develop landward of those already in existence. This management option is referred to as managed realignment and ideal estuaries for successful realignment schemes are those with extensive reclaimed areas, where restoration of the outer estuary produces the sacrificial area for sediment erosion, and restoration of the head of the estuary will act as a sink for these sediments allowing the estuary to transgress (Townend and Pethick, 2002). It follows that any restoration policy must incorporate a plan for the entire estuary, since restoring the sink without the source, or vice versa, would result in even greater problems of sediment balance in the estuary than those the plan is trying to combat. Small realignment schemes, such as are currently being carried out (French, 2004) may be useful for habitat generation and as scientific experiments, but are unlikely to contribute significantly to the longer-term management of sea-level rise in estuarine environments.

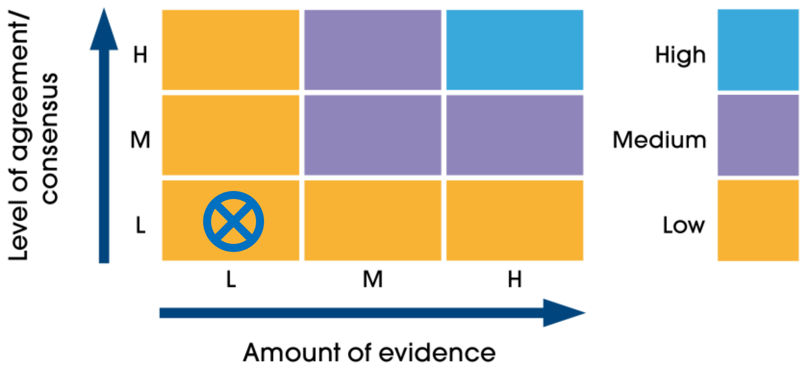
3. Confidence in the science

What is already happening: **High**



High confidence for the present statement is derived from the detailed and comprehensive studies that have been carried out to assess current coastal erosion rates (EUROSION, Futurecoast and ForeSight projects).

What could happen: **Low**



Low confidence for the future stems firstly from uncertainties about the effect of climate change on the rate of sea-level rise and, especially, the wave climate (storminess and wave direction), and secondly from the highly interconnected nature of coastal systems and the complex and not very well understood coastal response to changing sea-level and wave conditions. Medium confidence for the future can only be achieved for certain coastal locations.

4. Knowledge gaps

Apart from uncertainties about the effect of climate change on sea-level and wave climate, the coastal response to these changing boundary conditions is complex due to the connectivity between coastal sub-environments (cliff, beach, dune, estuary), the non-linear nature of nearshore sediment transport processes and the scale of human interference. The Futurecoast approach of considering the coast as a series of Coastal Behavioural Systems (CBS) is a significant improvement to previous approaches, because it acknowledges these connections, and also the need to consider coastal evolution over long time scales. However, our understanding of how these CBSs function remains largely conceptual and this needs to be much more quantitative.

5. Socio-economic impacts

Coastal erosion is widespread in the UK. Current damage due to coastal erosion is estimated at £15 million per year and in the worst case this figure may rise to £126 million per year by 2080. Increased coastal erosion due to climate change will provide significant opportunities for environmental engineers (mainly coastal engineers) to develop additional, or redesign existing, coastal protection measures, whether in the form of hard engineering structures, or soft engineering practices (beach recharge and managed realignment). Increased implementation of beach recharge schemes will have a considerable commercial effect on the aggregate industry. Depending on how society responds to increased coastal erosion, there can also be a very significant effect on the tourist industry through the loss of beach frontage and recreational beach area.

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