Marine Climate Change Impacts Partnership

Topic

Coastal erosion and coastal geomorphology

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Executive summary

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). Almost two-thirds of the intertidal profiles in England and Wales have steepened over the past hundred years, a process which is particularly prevalent on coasts protected by hard engineering structures (this represents 46% of England's coastline; 28% of Wales; 20% of Northern Ireland and 7% Scotland). Both coastal erosion and steepening of intertidal profiles 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.

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. 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. Therefore any predictions of coastal response due to climate change will have a low confidence, unless a detailed study is conducted and long-term coastal change data are available.

Full review

Introduction

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). The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) predicts that the rise in global sea level by 2100 will be in the range of 18–38 (lower level) to 26–59 cm (upper level), depending on the emissions scenario, but there appears to be less certainly with regards to changes in the wave climate (IPCC, 2007).

According to a recent Europe-wide study into coastal geomorphology and erosion (*EUROSION*; http://www.eurosion.org), the UK coastline is 17,381 km long, of which 3,008km 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:*

http://www.foresight.gov.uk/Previous_Projects/Flood_and_Coastal_Defence

estimated present and future (next 100 years) coastal erosion rates for the coast of England and Wales. According to their analysis, 28% of the coast is experiencing erosion rates in excess of 0.1 m yr^{-1} (Evans *et al.,* 2004). 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. In England and Wales, almost two-thirds of the intertidal profiles have steepened over the past hundred years (Taylor *et al.,* 2004). The *Foresight Project* also estimated future coastal erosion rates and compared these to the benchmark present condition (20–67m 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 175m, with the most severe erosion occurring in the east of England (Evans *et al.,* 2004).

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 1a shows the sea level at 7,500 Before Present (BP), when global mean sea level was c.15m 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 10km 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 200m 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.
- **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 & Horton, 2002). 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 1b), 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 2) 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 & Shamoon, 1998). Cliff erosion is controlled to a large extent to 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 the geology, because most are drowned river systems (Prandle, 2006)
- **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 (Figure 3) 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.
- **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.
- **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 groynes 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 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.

- **Linkages between coastal systems** – Coastal evolution and shoreline trends, especially over long time scales (≥ 100 year), are related to process interactions and sediment linkages between different coastal landform units. 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.

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 4). 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, because cliff erosion is an episodic process (Dong & Guzzetti, 2005).

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.

Soft-rock coasts

About 20% of the open coast in the UK is soft-rock coast and most of their morphology is characterised by a beach fronting either a cliff or non-cliffed higher ground (Figure 5). In common with hard-rock coasts, these coasts are eroding (Lee & Clark, 2002), but, in contrast to their hard-rock counterparts, there is usually an abundance of sediment present in the coastal zone. 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.

Walkden & Hall (2005) developed a model that considers the cliff-platform-beach system and realistically accounts for positive and negative feedback processes, as well as littoral drift. The model was used to model cliff retreat of 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 also applied to the Norfolk coastline, where it was run for a number of climate change and management scenarios (Dickson *et al.,* in press). 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.

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 6). 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 *barrier translation 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 & Pilkey, 2004). There is much stronger evidence for the barrier translation model, which is especially appropriate for gravel barriers, strongly wave-dominated barriers and on relatively gentle substrate slopes. Barrier translation 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.

The Bruun rule and the barrier translation 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 & French, 2004). 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).

Estuaries

There are 106 estuaries in Great Britain (UK, excluding Northern Ireland) and the majority of the estuaries fall into five groups (Figure 7; 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.

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 of 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 & 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.

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 & 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.

Tables and Figures

Table 1 – Coastal erosion and protection in the UK (http://www.eurosion.org/index.html). 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.

Region	**Coast Length**	**Coast length which is eroding**		**Coast length with defence works & artificial beaches**	
	km	km	%	km	%
Northeast England	297	80	26.9	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	68.8
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

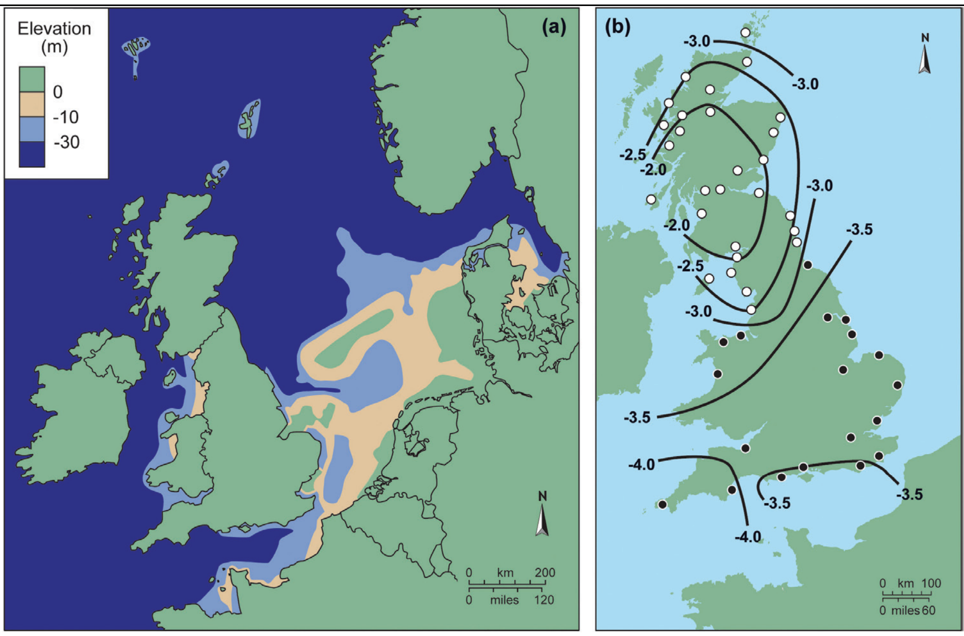

Figure 1 – (a) Coastal configuration of NW Europe 7,500 years BP (Shennan et al., 2000) and (b) estimated current relative sea-level changes in England and Wales obtained by combining relative sea-level change (Shennan & Horton, 2002) with a current eustatic sea-level rise of 3 mm yr^{-1} (Church & White, 2006) and assuming that eustatic sea-level has been constant over the last 4,000 years. The open and solid circles indicate rising and falling land levels, respectively. Note that there is some doubt with regards to the large rate of relative sea-level change in the southwest of England (Gehrels, 2006).

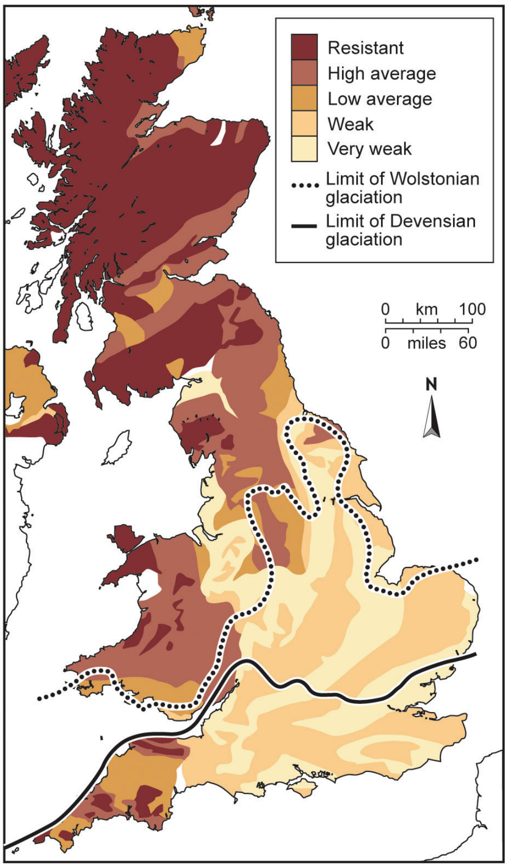

Figure 2 – Map of Britain showing resistance of the geology to denudation (Clayton & Shamoon, 1998).

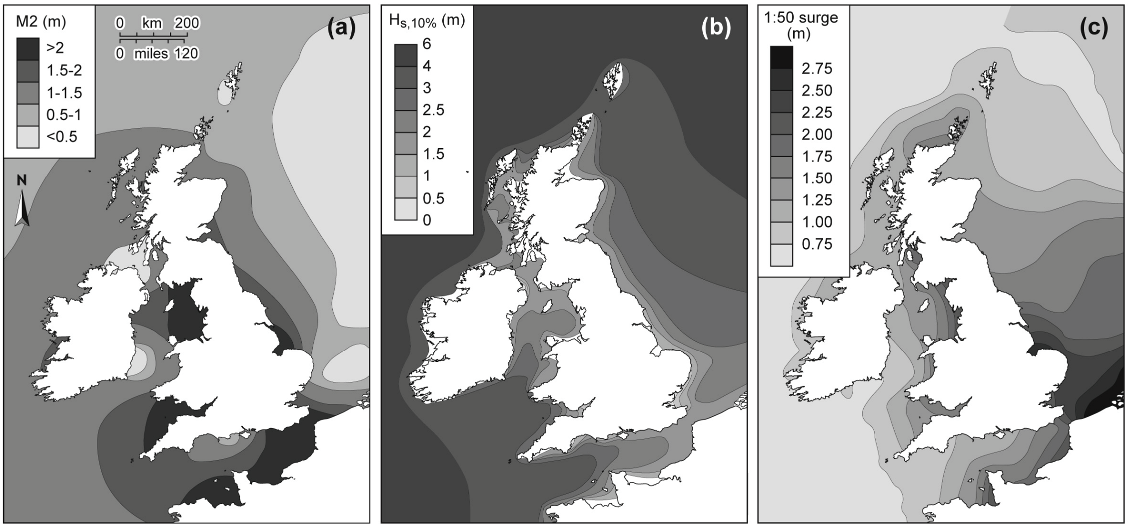

Figure 3 – Map of Britain with: (a) M2 tidal amplitude (Davidson et al., 1991); (b) 10% exceedence significant wave height Hs,10% (Draper, 1991); and (c) 1-in-50 year storm surge level (Flather, 1987).

Figure 4 – 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).

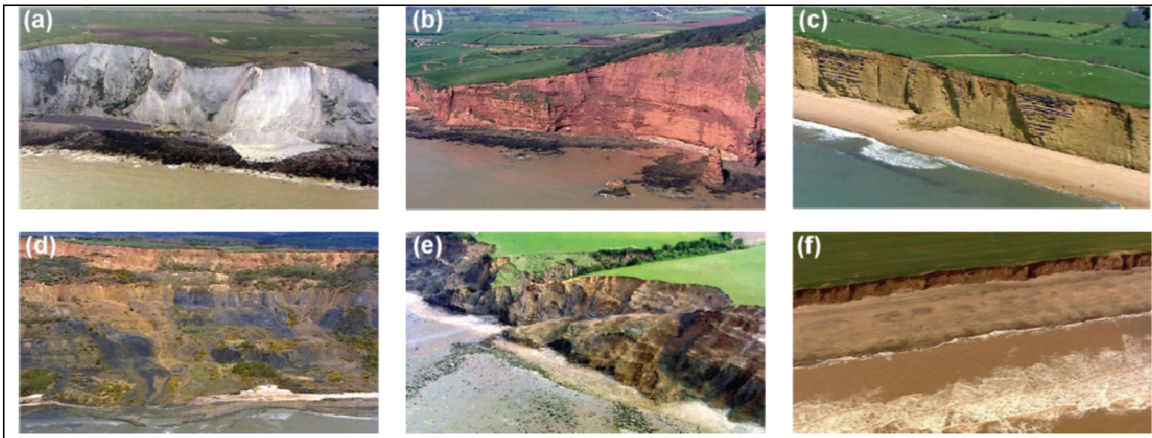

Figure 5 – Examples of soft-rock coasts: (a) chalk cliff fronted by shore platform, Dover, Kent, SE England; (b) cliff fronted by small beach and shore platform, Sidmouth, Devon, south England; (c) cliff fronted by sandy beach, Burton Bradstock, Dorset, south England; (d) Black Ven landslide complex 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).

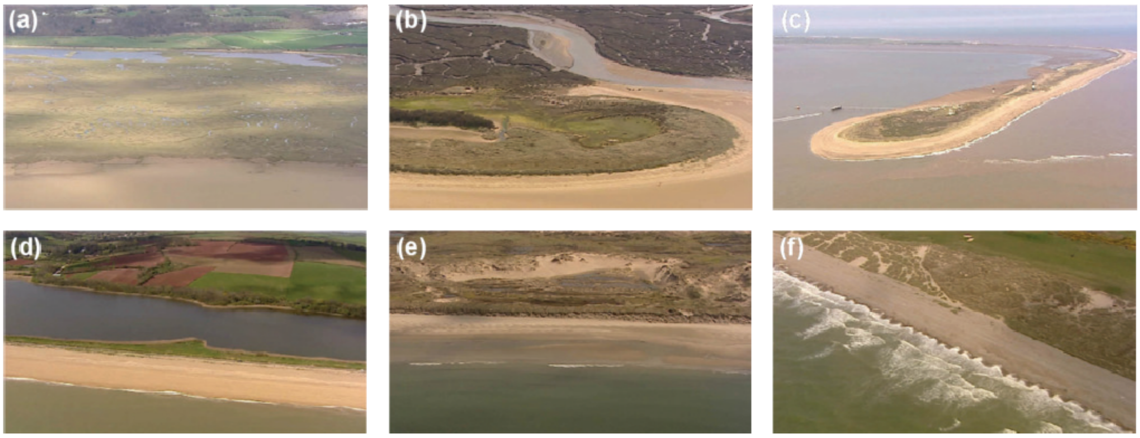

Figure 6 – Examples of barrier coasts: (a) tidal flat and salt marsh, Morecambe Bay, Cumbria, NW England; (b) barrier system fronting an estuary with extensive salt marshes, Titchwell, Norfolk, east England; (c) barrier spit stretching several kms into the Humber estuary, Spurn Head, Lincolnshire, east 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).

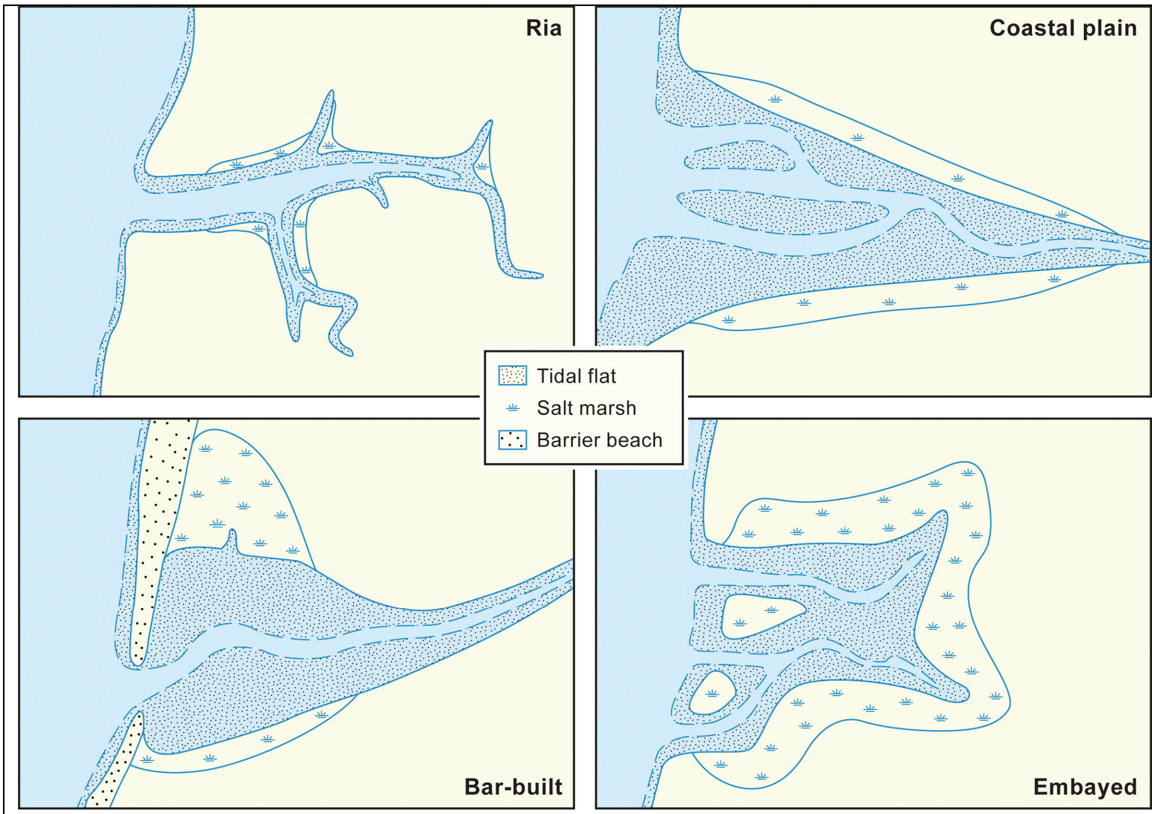

Figure 7 – Four main estuarine types in England and Wales (Davidson *et al.,* 1991).

Confidence assessments

'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 in the future' - 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.

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 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, at present our understanding of how these CBSs function is largely conceptual and this needs to be much more quantitative.

Commercial impacts

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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