

Impacts of climate change on coastal erosion

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EXECUTIVE SUMMARY

A large proportion of the coastline of the UK and Ireland is currently suffering from erosion (17% in the UK; 20% in Ireland) and of the 3,700 km coastline of England and Wales 28% is experiencing erosion greater than 10 cm per year.

The natural response of coastal systems to sea-level rise is to migrate landward, through erosion of the lower part of the nearshore profile and deposition on the upper part. The roll-over model is applicable to estuaries, barriers and tidal flats. Rocky coasts are erosional coasts by their nature and retreat even under stable sea-level conditions. Where the coast is protected by engineering structures, coasts are generally experiencing a steepening of the intertidal profile.

Coastal response to sea-level rise is strongly determined by site-specific factors and usually it is these 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 rather 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.

In the absence of a clear understanding of the coastal-change processes, and therefore a reliable predictive tool, the default position is to assume that present-day coastal change will persist; however, it is very likely that currently eroding stretches of coast will experience increased erosion rates due to sea-level rise.

The coastal management strategy (e.g., hard coastal defences, beach nourishment, managed realignment) is also a key aspect for determining the long-term response of the coast to climate change effects, including sea-level rise. Managed realignment is likely to increase in the future as a key management strategy and although this will result in increased local erosion rates, the enhanced erosion may benefit other sections of coast by reducing erosion or even causing accretion. Adaptation is emerging as the key coastal management paradigm to cope with coastal erosion.

INTRODUCTION

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, which in the worst case 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 village 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 (e.g., Poulton *et al.*, 2006). Sea-level rise is a key factor in causing coastal erosion and concerns about erosion risk have mounted in light of increased rates of sea-level rise predicted due to climate change.

Responsibility for the management of coastal erosion in the UK has recently been passed on from the Department of Food and Rural Affairs (DEFRA) to the Environment Agency (EA) (together with coastal councils). At a national level, the *Making Space for Water* initiative still 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 (<http://archive.defra.gov.uk/environment/flooding/documents/policy/strategy/strategy-response1.pdf>). 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 (<http://archive.defra.gov.uk/environment/flooding/documents/policy/guidance/smpguide/smpgvoll.pdf>).

The *Making Space for Water* philosophy has been fully incorporated into the second generation SMPs, which increasingly consider managed realignment as the preferred management strategy, leading to controversial SMPs (e.g. SMP for North Norfolk; Fletcher, in press).

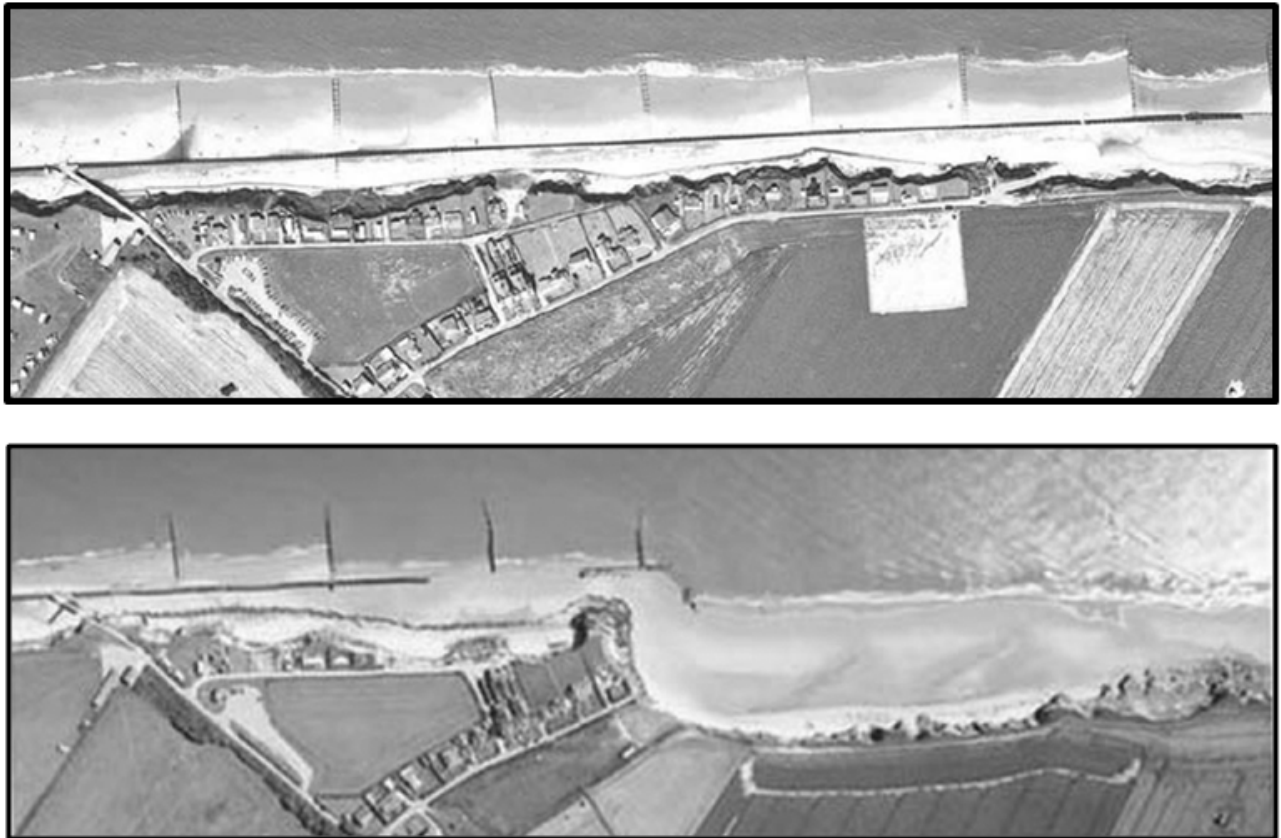


Figure 1: Coastal erosion at Happisburgh, Norfolk, from 1993 to 2003. It should be pointed out that the erosion recorded in these photographs is extreme and to a large degree the result of the removal of coastal defences.

This review will first provide an overview of current erosion rates in the UK (Section 1) and what is likely to happen in the future (Section 2). Contrary to common beliefs, coastal erosion is not solely and simply linked to sea-level rise, and the key message of this report is 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. In this respect, this report is rather different from other MCCIP reports.

Importantly, erosion of one stretch of coast is likely to cause accretion elsewhere – sediment is generally not lost from the coastal system. This notion has recently been demonstrated in a study by Montreuil and Bullard (2012) on the east coast of England. Here, the rapid erosion of the Holderness cliffs to the north of the Humber is, in part, counterbalanced with accretion on beaches along the north Lincolnshire coast to the south of the Humber. The amount of accretion in Lincolnshire corresponds to around 29% of the volume of sediment eroded from Holderness, and increased cliff recession rates of the Holderness coast as a result of sea-level rise may even lead to increased accretion and shoreline progradation along the north Lincolnshire coast (the remaining 71% of eroded sediment ends up in the Humber estuary, including the ebb tidal delta and Spurn Head spit system, or is transported furthered afield, perhaps even as far as the Dutch Wadden Sea).

Due to the complex and multi-faceted nature of coastal erosion, most of this review is concerned with describing the most relevant processes involved with coastal erosion and discussing how these processes affect different types of coastal environments. At the end of the report, management strategies that address coastal erosion problems are briefly discussed.

1. WHAT IS ALREADY HAPPENING?

According to the most recent European-wide study into coastal geomorphology and erosion (EUROSION, 2004), the UK coastline is 17,381 km long, of which 3,008 km (17.3%) 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. According to the same EU report, Ireland has 4,578 km of coastline, of which 19.9% is eroding and 7.6% is protected.

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 10 cm 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). More recently, the National

Table 1: Coastal erosion and protection in the UK (EUROSION, 2004). Islands with a surface area smaller than 1 km² and inland shores (estuaries, fjords, fiords, bays, lagoons) where the mouth is less than 1 km wide are not included in the analysis.

Region	Coast length	Coast length that is eroding	Coast length that is eroding	Coast length with defence works and artificial beaches	Coast length with defence works and artificial beaches
	km	km	%	km	%
Northeast England	297	80	27.0	111	37.4
Northwest England	659	122	18.5	329	49.9
Yorkshire and 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
UK	17381	3008	17.3	3185	18.3
Ireland	4578	912	19.9	349	7.6

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.

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 intertidal profiles in England and Wales have steepened over the past hundred years; however, a re-evaluation of these results by Dornbush *et al.* (2008), pertaining to the south-east coast of England, suggests that steepening is less common.

2. WHAT COULD HAPPEN?

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 global rate of sea-level rise estimated from (satellite) altimetry data over the 15-year period from 1993 to 2008 is 3.5 mm per year (Nicholls and Cazenave, 2010). Most global sea-level data sets suggest that the rate of sea-level rise is accelerating (Church and White, 2006; Rahmstorf *et al.*, 2012, their Figure 1); however, not all coastal locations seem to conform to this accelerating trend. For example, Haigh *et al.* (2011) found that the current rate of sea-level rise at 16 sites along the English Channel over the period 1993–2008 was considerably higher than that averaged over the complete data records, but was within the

envelope of observed change when compared with other 15-year periods since 1900. In other words, there have been several periods during the 20th Century that the rate of sea-level rise along the English Channel was similar to that at present.

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4) 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 (Meehl *et al.*, 2007). In these projections, the potential contribution of rapid changes to the Greenland and Antarctic ice sheets are not included, and the IPCC suggested an upper limit to sea-level rise during the 21st century of 0.76 m that does take into account ice sheet dynamics. Since 2007, sea-level science has progressed significantly (e.g. studies of ice sheet dynamics and interglacial periods), and, in particular, semi-empirical model projections of sea-level rise have been developed. These models use present relationships between temperature and sea-level rise combined with climate-model projections of future warming to give an alternative set of future sea-level predictions (Rahmstorf, 2007). Many of these studies suggest that the upper end of the sea-level projections by 2100 could be significantly higher than the IPCC projections (e.g. 0.75–1.90 m according to Vermeer and Rahmstorf, 2009; 0.72–1.60 m according to Grinsted *et al.*, 2009). Following their analysis of sea-level rise and its possible coastal impacts given a 'beyond 4°C world', Nicholls *et al.* (2011) suggest a pragmatic estimate of sea-level rise by 2100 between 0.5 and 2 m.

Specifically for the UK, the IPCC climate change projections have recently been updated by UKCP09 using Met Office predictions and the key elements of these for coastal erosion can be summarised as follows (<http://ukclimateprojections.defra.gov.uk/>):

- **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 by 2100, 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 (Figure 2 and 3). A low-probability, high-impact range of sea-level rise scenarios, called the H++ scenario, based on observations of the past and plausible constraints on ice sheet dynamics was also developed. The H++ sea-level rise estimate for the UK is 0.93–1.90 m by 2100.

- **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 due to increased storminess. Some support for these predictions is provided by Haigh *et al.* (2010) who showed that the increase in extreme sea-levels during the 20th century in the English Channel could almost wholly be attributed to sea-level rise.

- **Wave climate:** The primary basis of UKCP09 projections of future wave conditions is the HadCM3 AOGCM (Atmosphere Ocean Global Climate Model), with 3.75° by 2.5° horizontal spatial resolution. Alternative variants of model parameters were selected to create a ‘perturbed physics ensemble’ (PPE) and the results were also compared to results from a set of independent climate models (referred to as a multi-model ensemble (MME)) to provide insight into uncertainties. 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 due to the projected southward movement of the storm tracks (Lowe *et al.*, 2009). Changes in the maximum wave conditions are more pronounced, and the most sensitive areas are *Charting Progress Regions* 3 and 4 (Eastern English Channel, Western English Channel) and the south coast of Ireland, where an increase in the maximum significant wave height of 0.5–1 m can be expected by the end of this century. No H++ scenario has been developed yet for waves.

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) due to the combination of disequilibrium morphology (shoreline is out of equilibrium with prevailing wave direction and present sea-level) and an easily erodable coastline made of unconsolidated material (mainly clays). Such national, or even regional, predictions of coastal erosion are not very useful, however, because coastal erosion is largely a local process and coastal recession rates are spatially highly variable. Coastal scientists and managers

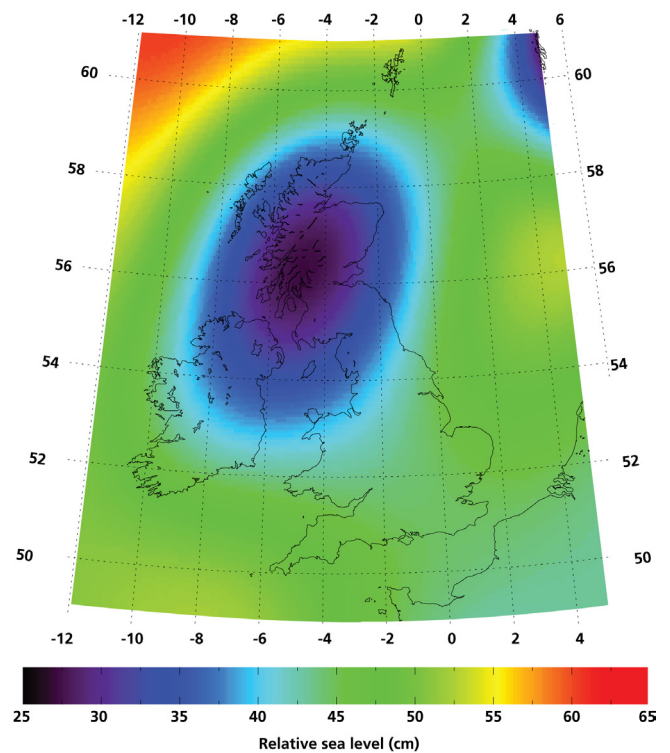


Figure 2: Relative sea-level change around the UK over the 21st century. The change combines the central estimate for the medium emissions scenario and vertical land movement, and relates to the period to 2095 (UKCP09).

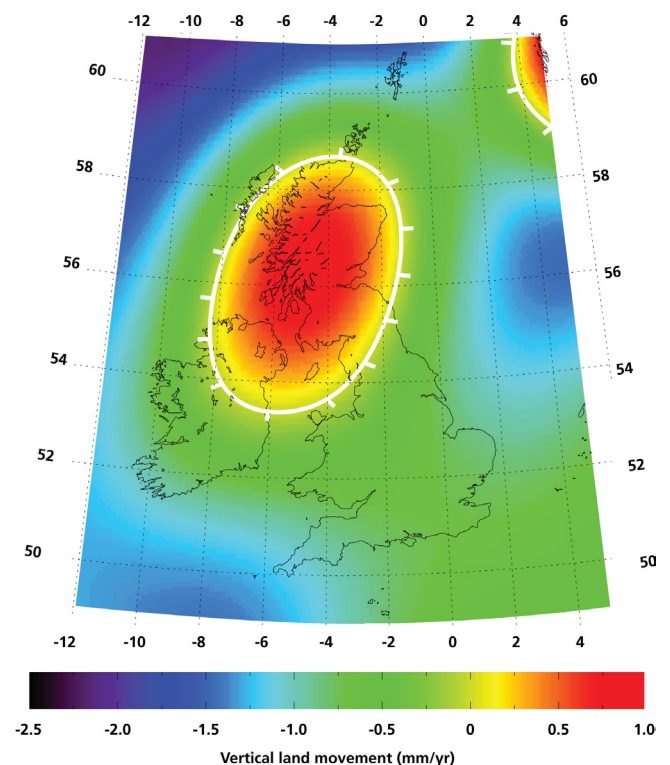


Figure 3: Glacial Isostatic Adjustment (GIA) map of the vertical land movement for the UK (UKCP09; Adapted from Bradley *et al.*, 2008). Note that there is some doubt with regards to the relatively large rate of relative sea-level in the southwest of England (Gehrels, 2006). The white circle represents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

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 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.

Predicting future coastal erosion rates remains problematic. In the absence of a clear understanding of the coastal-change processes, including past coastal change and causes of coastal erosion, and therefore a reliable predictive tool, the default position is to assume that present-day coastal change will persist; however, it is very likely that currently eroding stretches of coast will experience increased erosion rates due to sea-level rise. Moreover, the removal of coastal defences, which is likely to increase in response to anticipated and enhanced uptake of the managed realignment coastal management strategy (e.g., Happisburgh), will also increase coastal erosion rates. Therefore, the proportion of eroding coastlines, and the average coastal recession rates, in both UK and Ireland are expected to increase in the future.

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, often more important, processes are involved:

- **Sea-level history:** Coasts 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 and also Ireland. 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. For example, the Holderness coast has retreated by c. 4 km over the last 2000 years and many villages, including Roman settlements, have been lost to the sea (http://databases.eucc-d.de/files/000164_EUROSION_Holderness_coast.pdf) and along parts of the Norfolk coast there has been almost 200 m of recession since 1885 (Clayton, 1989). In both these cases, the erosion 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 coastline in the UK and Ireland must

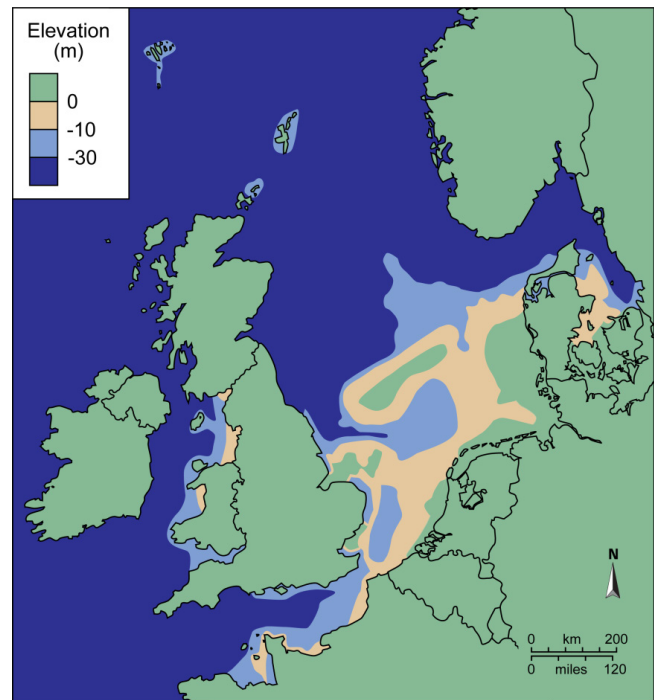


Figure 4: Coastal configuration of NW Europe 7,500 years BP (Shennan *et al.*, 2000)

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. In this context it is of interest that it has been suggested that, for the first time since the last glaciation, the eustatic sea-level rise is now outpacing isostatic rebound in Scotland (Rennie and Hansom, 2011), although this has been subject to some debate (Dawson *et al.*, 2012; Rennie and Hansom, 2012).

- **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, Northern Ireland and Ireland, and the low-relief, mainly unconsolidated coast of east England (Clayton and Sharnoon, 1998). Cliff erosion is controlled to a large extent by rock strength, with typical cliff recession rates in hard and soft rock of 0.1–1 cm yr⁻¹ and 10–100 cm yr⁻¹, respectively. The configuration of many estuaries is also largely controlled by the geology, because most are drowned river systems (Prandle, 2006). In addition, geology can also play a major role in influencing the morphology and dynamics of sandy beaches, especially in Ireland (Jackson *et al.*, 2005) and the south-west of England (Scott *et al.*, 2011).

- **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

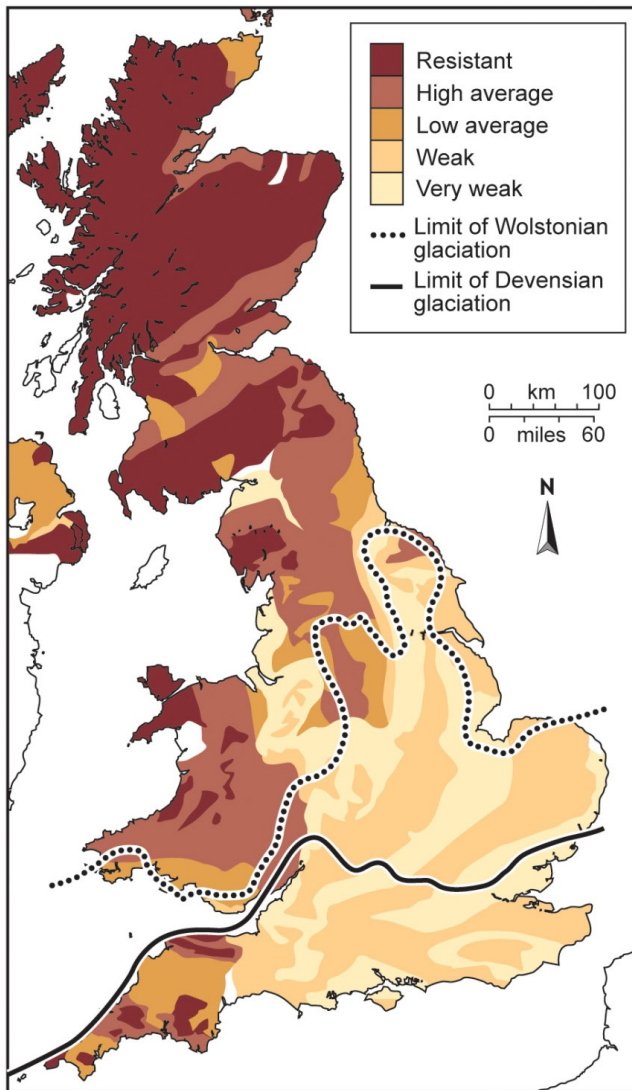


Figure 5: Map of Britain showing resistance of the geology to denudation (Clayton and Shamoon, 1998).

onshore during the post-glacial transgression and has been incorporated in dunes, beaches, barriers and estuaries (Futurecoast, 2002). It is generally assumed that 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 and Ireland, 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). On the other hand, longer waves produce larger run-up (e.g. Stockdon *et al.*, 2006) and are more important for coastal flooding. 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. For example, a study of the response of tides on the north-west European Continental Shelf (Pickering *et al.*, 2012) to a 2-m sea-level change predicts increased tidal amplitude through much of the North Sea, but significantly reduced amplitude in the Gulf of St Malo and the Bristol Channel. This study also highlighted that changes in tidal properties derived from sea-level rise can extend to alterations in the shape of the tides and alterations in the strength of the neap-spring cycle.

• **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 cusped 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 (De Alegria-Arzaburu *et al.*, 2008; De Alegria-Arzaburu and Masselink, 2010).

• **Human impacts:** Much of the coastline in the UK and Ireland, 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 (Brown *et al.*, 2011). 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, 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

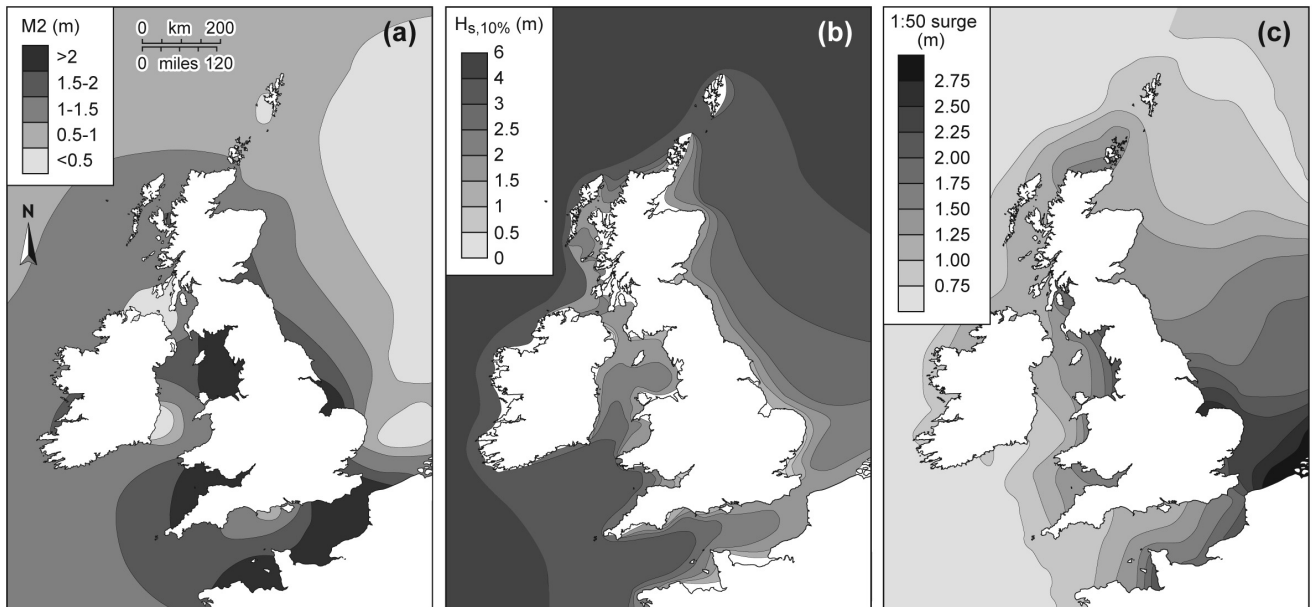


Figure 6: Map of Britain with: (a) M2 tidal amplitude (Davidson et al., 1991); (b) 10% exceedance significant wave height $H_{s,10\%}$ (Draper, 1991); and (c) 1-in-50 year storm surge level (Flather, 1987).

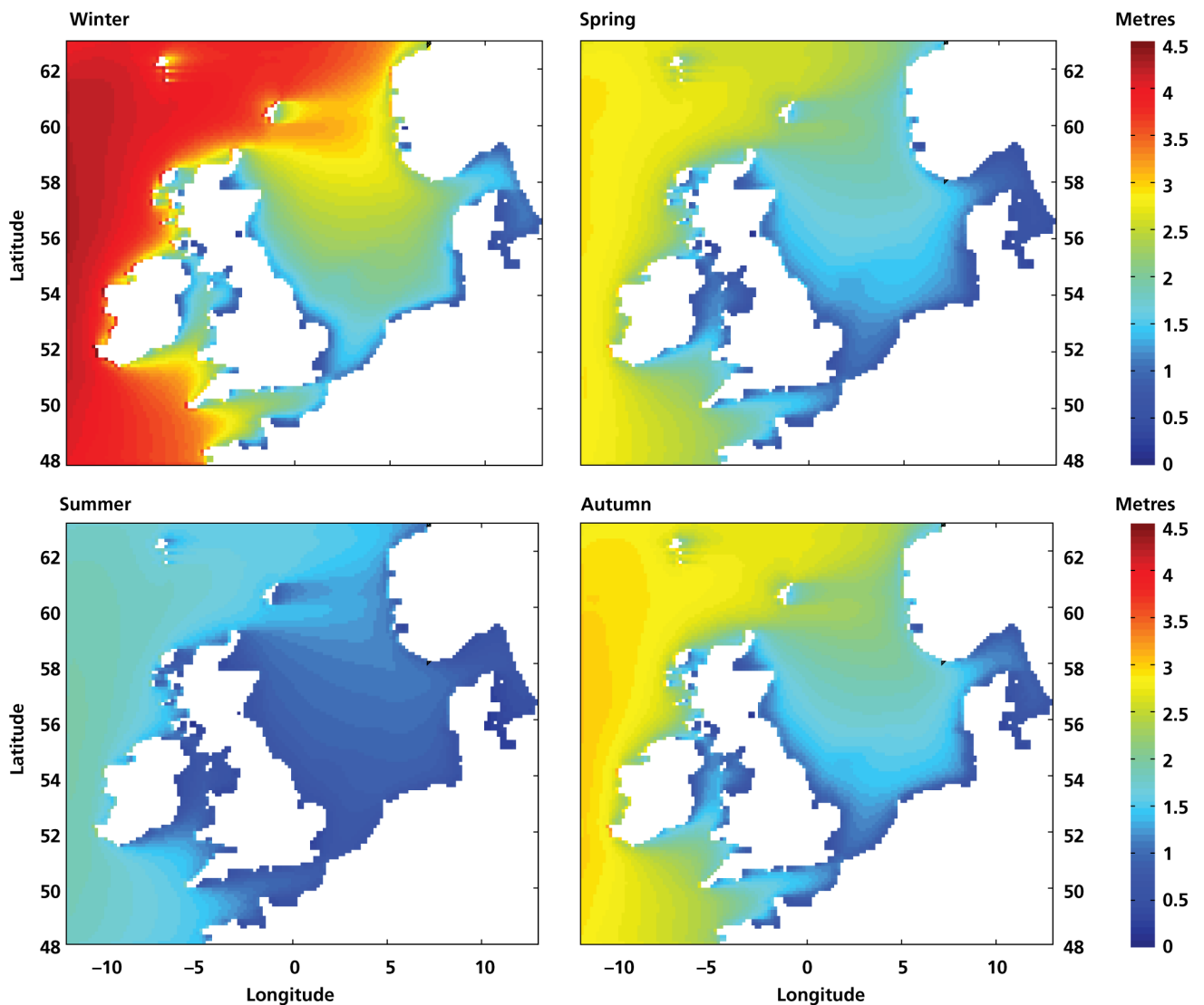


Figure 7: Modelled seasonal means of significant wave height of swell waves for 1960–1990 (UKCP09).

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 *et al.*, 2009).

- **Linkages between coastal systems:** Coastal evolution and shoreline trends, especially those occurring over long timescales (≥ 100 year), are related to process interactions and sediment linkages between different coastal landform units (Leafe *et al.*, 1998; Montreuil and Bullard, 2012). 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 saltmarshes 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.

Dominant types of coastal geomorphology

a. Hard-rock coasts

According to EUROSION (2004), about 42% in the UK and 56% in Ireland of the open coast (i.e. excluding estuarine shores) 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. Quantifying erosion rates on hard-rock coasts and increasing our understanding of the linkages between terrestrial weathering and coastal erosion processes remains problematic, but progress is being made through use of advanced remote sensing techniques that enable the collection of high-resolution data (Earlie *et al.*, 2013). Specifically, application of digital photogrammetry and terrestrial laser scanning along the North Yorkshire coast by Lim *et al.* (2010) has revealed that hard-rock cliff erosion may not be as dominated by high-magnitude and low-frequency events as hitherto thought, and that large, isolated rockfalls are in fact part of a larger, continuous magnitude-frequency relationship.

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 in the south-west of England and Wales and the Atlantic coast of Ireland where embayed beaches abound (Jackson *et al.*, 2005; Reeve and Li, 2009; Jackson and Cooper, 2010; Scott *et al.*, 2011).

b. Soft-rock coasts

According to EUROSION (2004), 18% of the open coast in the UK is soft-rock coast (only 1% in Ireland) and most of their 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. Soft cliff retreat occurs through a combination of marine erosion, shallow structural failures and mass failures, and cliff height has been identified as the principal factor controlling the failure mechanism (Quinn *et al.*, 2010).

Cliff erosion on soft-rock coasts is a highly episodic process (Dong and Guzzetti, 2005) with erosion rates varying both spatially and temporally. For example, along the Suffolk coast, Brooks *et al.* (2012) carried out annual to biannual ground survey data and applied GIS techniques to digitised records of changing shoreline position from historical maps and aerial photography. They revealed that the cliffs exhibited long-term (1883–2010) recession rates of 3.5 m per year, rising to 4.7 m per year in the period 1993–2010. The data further revealed considerable decadal-scale variations in cliff recession, within which are nested inter-annual fluctuations in rates of retreat.

Brown *et al.* (2012) studied coastal cliff retreat and the impact of coastal defences along the Holderness coast between 1845 and 2005. The analysis of three approximately 50-year periods (1854–1905, 1905–1952, 1952–2005) gives a retreat rate of between 0.8 ± 0.4 m per year and 2.1 ± 0.4 m per year with retreat varying spatially and temporally due to natural causes and human activity, especially 19th century beach mining and coastal defence construction. In particular, coastal defences were found to reduce sediment input and modify the sediment budget, usually resulting in a sediment deficit down-drift, leading to the development of a set-back. They concluded that, at the scale of Holderness, defences have changed the pattern of erosion rather than stopping it, and that accelerated retreat down-drift of defences can threaten human infrastructure and buildings and reduce the efficiency of defences.



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, Rhooose, 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 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).



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 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 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 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 per year) 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. Brooks and Spencer (2012) applied the SCAPE model to the Suffolk coast and predicted that volumes of sediment released by cliff erosion in the 21st century in response to accelerating sea-level rise will increase by about one order of magnitude above the sediment release estimates for the early 20th century under lower rates of sea-level rise.

The SCAPE 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.

c. Barrier coasts

According to EUROSION (2004), 25% in the UK and 39% in Ireland of the open coastline is backed by a (Holocene) coastal

plain, and is taken up by beaches, barriers and sandy tidal flat systems, often capped by dunes (Figure 10). There are two models of barrier response to rising sea level (cf. Masselink *et al.*, 2011). 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).

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 104–105 m³ per year. 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.

d. 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

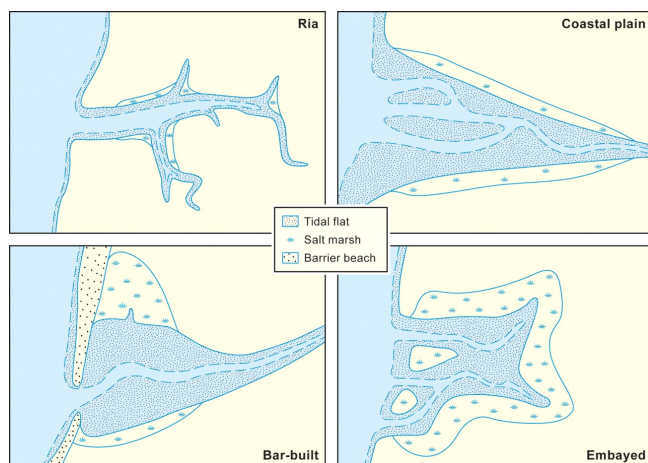


Figure 11: Four main estuarine types in England and Wales (Davidson *et al.*, 1991).

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 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.

Recently, a Boolean network approach has been applied to analyse the long-term response of estuaries to sea-level rise (Reeve and Karunaratna, 2009). This analysis supported the widely-kept notion that the nature of long-term morphodynamic response to sea-level rise depends on the type of estuary and the availability of external sediment to meet the increasing sediment demand within the system. If the estuary has an abundant influx of external sediment on

a continuous basis, then the estuary is able to maintain its geomorphology and reach a stable state. In the absence of adequate supply of external sediment, some of the prominent features such as saltmarshes and spits are likely to recede or disappear altogether during the process of morphological evolution against sea-level rise. The analysis also suggested that moderate human interference in the form of dredging and structural construction does not have a significant impact on the overall geomorphology of estuaries in the long-term.

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 saltmarshes 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. In this context the recently improved managed realignment scheme on the Steart Peninsula, near Bridgwater in Somerset, is of significant interest as it aims to create over 400 hectares of valuable natural habitats including saltmarsh and freshwater wetland, as well as providing coastal protection (<http://www.environment-agency.gov.uk/homeandleisure/floods/80793.aspx>).

Adapting to coastal erosion

Humans now represent an important factor in directly affecting coastal erosion and geomorphology, for example, through dredging, beach nourishment and construction of coastal defences, and also indirectly by influencing climate and sea level (see section 1.3). At the same time, coastal erosion has a significant impact on the human utilisation of the coastal zone, and it is appropriate to briefly discuss the management strategies available for coping with coastal erosion. One of the most important concepts to have emerged from several decades of (sustainable) coastal zone management is that of adaptation, which, in the context of this report, refers to an adjustment in natural or human systems as a means of moderating the adverse impacts of and reducing the vulnerability to coastal erosion.

There are three basic adaptation approaches: (1) protect, (2) accommodate; and (3) retreat, and each of these approaches may be pursued through the implementation of one of more complementary adaptation technologies (Linham and Nicholls, 2012; Table 2). Most of these adaptation technologies also reduce coastal flood risk (e.g. sea dykes), and some also contribute to habitat creation (e.g. wetland restoration). It is noted that the three basic adaptation strategies do not quite map onto the four policy options provided in the second generation Shoreline Management Plans (SMPs), which are hold the line, advance the line, managed realignment, and no active intervention. Nevertheless, adaptation is an important aspect of these non-statutory policy documents, as illustrated in several case studies discussed by Pontee and Parson (2012).

An important additional aspect of adaptation is to enhance understanding and awareness of coastal erosion risks through monitoring, education and policy and strategic initiatives. An example of the latter is the Pathfinder project, which is a £11M project funded by DEFRA to help local authorities and communities to develop and trial methods of coastal adaptation (<http://archive.defra.gov.uk/environment/flooding/manage/pathfinder/index.htm>). Of the 15 pathfinder projects, the North Norfolk District Council received the largest sum of money (£3M) and developed a wide range of adaptation strategies, ranging from acquisition, demolition and relocation of houses at risk of coastal erosion, to improving community infrastructure (Frew, 2012).

As pointed out by Nicholls *et al.* (2011), it is of particular importance to develop long-term strategic adaptation plans for the full range of possible climate change outcomes, both in terms of changes in sea level, extreme water level, storminess and wave climate. An example of such long-range planning is that being considered in the Netherlands and proposed by the Second Delta Commission (<http://www.deltacommissie.com/en/advies>). In the UK, the Thames Estuary 2100 (TE2100) Project which considers flood management in London and its environs is a good example (<http://www.metoffice.gov.uk/services/climate-services/case-studies/barrier>). The inclusion of a 50–100 year time horizon in the SMPs is also encouraging, but an even longer-ranging view may be appropriate.

Table 2: Commonly applied coastal adaptation technologies. This table has been modified from Linham and Nicholls (2012) to make it specific to coastal erosion (the original table was related to coastal erosion and flood management).

Adaptation approach	Technology
Hard protection	Seawall/revetments Sea dykes Groynes Detached breakwaters Land claim Raise land areas
Soft protection	Beach nourishment Coastal dune construction
Accommodate	Flood-proofing Wetland restoration Coastal aquaculture
Retreat	Managed realignment Coastal setbacks and zoning

The coastal management strategy (e.g. hard coastal defences, beach nourishment, managed realignment) is also a key aspect for determining the long-term response of the coast to climate change effects, including sea-level rise (Dawson *et al.*, 2009). The second generation SMPs increasingly advise a managed realignment policy, especially for the longer time scale (20–50 and 50–100 years). Although managed realignment will result in increased local erosion rates, especially where existing coastal defences are being removed, the enhanced erosion may benefit other sections of coast by reducing erosion or even causing accretion. Implementation of such strategy will have significant socio-economic implications and is influenced by financial, conservation, legal and social justice arguments (Cooper and McKenna, 2008; Fletcher, in press).

Conclusions

A large proportion of the coastline of the UK and Ireland is currently suffering from erosion and 28% of the coastline of England and Wales is experiencing erosion greater than 10 cm per year. The natural response of coastal systems to sea-level rise is to migrate landward, through erosion of the lower part of the nearshore profile and deposition on the upper part, and this roll-over model is applicable to estuaries, barriers and tidal flats. Coastal response to sea-level rise is, however, strongly determined by site-specific factors and usually it is these 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 rather 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. The coastal management strategy for a section of coast (e.g. hard coastal defences, beach nourishment, managed realignment) is also a key aspect for determining the long-term response

of the coast to climate change effect, including sea-level rise. Adaptation is emerging as the key coastal management paradigm to cope with coastal erosion.

3. KNOWLEDGE GAPS

a. Long-term and large-scale coastal system response to sea-level rise: Process-based models for open coastlines can at best forecast coastal change over relatively short time scales (days to a few weeks) and small spatial scales (< 1 km). There is a real need for models to be able to predict larger scale (more than 10 km) coastal system behaviour over longer time scales (more than ten years). Simple up-scaling of existing process-based model does not work, and behaviour-oriented or parametric models are not yet at the level to be able to provide reliable quantitative long-range forecasts. The Futurecoast approach of considering the coast as a series of Coastal Behavioural Systems (CBS) is a significant step forward, but our understanding of how these CBSs function remains largely conceptual and this needs to be much more quantitative. In addition, the role of coastal management will need to be incorporated in these models. Only for soft-cliff coastlines there is some predictive capability over long time scales.

b. Coastal response to extreme storms: We lack the understanding and ability to forecast the response of coastal systems to extreme storm events. This is particularly relevant for wave-dominated barrier coasts, where the sand and gravel barriers serve an important natural coastal protection role. Better understanding of and predictive tools for extreme storm response are required to assess vulnerability of coastal systems to extreme storm events and help identify critical thresholds. In combination with predicted changes in sea-level, storm surge statistics and wave climate, such tools can assist with determining coastal resilience to climate change and assist in the design of coastal protection schemes.

c. Cliff erosional processes: On the one hand, coast cliffs are the least complicated of all coastal systems: all cliffs erode. However, the processes of cliff erosion, especially the interplay between atmospheric, terrestrial and marine processes, and the controlling role of geology, are poorly understood, even though a reasonable amount of confidence may be placed on the actual cliff recession rates. This lack of understanding gets in the way of formulating reliable models of coastal cliff response to climate change effects.

4. SOCIO-ECONOMIC IMPACTS

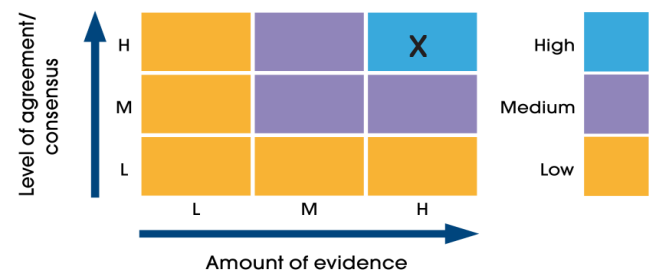
Coastal erosion is widespread in the UK. Current damage due to coastal erosion is estimated at £15 million per year which in the worst case may rise to £126 million per year by 2080 (Foresight, 2004). Increased coastal erosion due to climate change will provide significant opportunities for environmental 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. There is now increased realisation that against a back drop of rising sea level and sediment management issues, current coastal management practices, which are very much focussed on hold-the-line adaption strategies, are not sustainable in the long-term. The second generation Shoreline Management Plans increasingly advocate managed realignment as an alternative adaptation strategy, especially for less developed stretches of coast.

5. CONFIDENCE ASSESSMENT

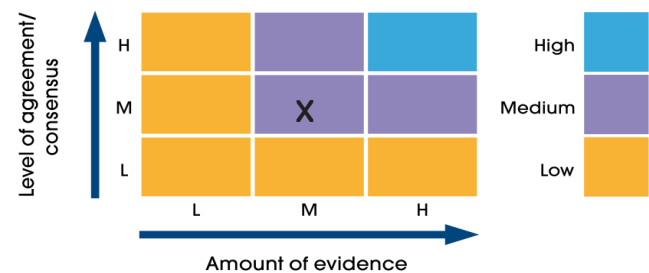
What is already happening?

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?

Coastal erosion is only partly driven by sea-level rise; therefore, medium confidence in predictions can be achieved for many regions by assuming current erosion rates (which are generally well-constrained) persist. However, coastal erosion is likely to be exacerbated by sea-level rise and coastal response is also susceptible to changes in the wave climate (storminess and wave direction). Since there are uncertainties about these climate-induced changes in coastal forcing factors, and the relation between sea-level rise and coastal erosion is highly non-linear due to the interconnectedness of coastal systems in terms of sediment fluxes and process linkages, high confidence for the future is still some way off. A further complicating factor is the coastal management, in particular the adaptation strategy used to combat coastal erosion. Nevertheless, especially for eroding soft-cliff coastlines, model predictions of coastal retreat are becoming increasingly reliable and useful for coastal zone planning and management.



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