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Impacts of climate change on built structures (onshore and coastal)

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EXECUTIVE SUMMARY

The UK has for some time been adapting to changing risks of erosion and flooding, caused by natural and anthropogenic changes. Many past (and some current) coastal management practices are, however, increasingly recognised as unsustainable, and future approaches that have implications for coastal structures will very much depend upon the rate of sea-level rise, and actual events (which may trigger drastic responses). However, the rates of various aspects of climate change are highly uncertain, as are the associated responses of human and coastal systems. Since the previous version of this report, new sources of information have been developed to help understand potential impacts; although the continued use of datasets to monitor actual changes should be intensified, and where possible continually integrated with methods that maintain a contemporary understanding of the changing risks and feasible options for the management of coastal structures.

1. WHAT IS ALREADY HAPPENING?

This report card supersedes a previous version by Hunt and Rees (2010), which reviewed the potential impacts of climate change upon both coastal and offshore structures. This updated version focuses only upon coastal structures, defined as structures attached to or landward of the shoreline and within the zone potentially affected by extreme flooding and the tidal influence of rivers, including:

- property and infrastructure associated with floodplains;
- flood and coastal erosion protection assets (sea walls, breakwaters, beach control structures, etc.); and,
- large-scale infrastructure on the coast (power stations, roads, railway, etc.) potentially impacted by erosion or flooding.

Issues relevant to the current state and future of coastal structures are primarily changing trends in flooding and erosion (including the loss of intertidal habitats), and are therefore the main focus of this report. Air and sea water temperature changes may also impact on UK infrastructure in many ways, for example influencing the cooling efficiency of power stations; whilst changes to sea water pH and salinity have a range of implications for coastal structures (e.g. corrosion rates).

Coastal erosion is associated with less widespread consequences than coastal flood events (which can often threaten human life) but localised economic and social consequences can be as serious when land is permanently lost. In this report it is assumed that flooding and erosion are mainly controlled by: (1) mean sea level, (2) fluctuating still water levels, mainly caused by tides and storm surges (the latter is when sea water levels are raised above normal tidal water levels), and (3) waves. Erosion and flooding can be interrelated (e.g. erosion may expose flood defences to greater wave energy). Other drivers of coastal flood and erosion risk include winter precipitation and storm rainfall intensity, which may compound marine effects (e.g. water draining to the sea from flood events may damage coastal structures, whilst rainfall may saturate and weaken cliffs). The primary climate change risk for flood and coastal erosion is sea-level rise (SLR). SLR is mainly caused by eustatic effects (which include the amount of water in the oceans, water temperature, and oceanic circulation patterns), although isostatic effects (vertical land movements caused by compression and decompression of the Earth's crust) may exert small spatial differences upon relative sea level changes across the UK over the coming century.

The UK Coast

The seas around the UK have been responding to changes in global mean sea level since the end of the last ice age. Global mean sea level is linked to climate change through the thermal expansion of the ocean waters as they warm, the melting of glaciers and ice caps and changes in the freshwater exchange between land and sea. In addition, mean sea-level rise is further modified regionally by changes in large-scale ocean circulation, and locally by land movements (relative sea level observed at any given location around the coast of the UK has been influenced by unloading of ice sheets since the last glaciation approximately 18,000 years ago). Sea-level rise has been slightly faster since the early 1990s than previous decades (Cazenave and Llovel, 2010), with global sea levels rising by 3.3 mm per year (± 0.4 mm) between 1993 and 2007; approximately 30% was due to ocean thermal expansion due to ocean warming and 55% due to melting of land ice (Defra, 2012). The current approximate lengths of coastline of the UK (defined by the mean high water mark in Ordnance Survey maps, (e.g. OS, 2008) are:

• England: 10,000km (inclusive of the Isle of Wight, Lundy and the Scilly Isles);

• Wales: 3000km (inclusive of the islands of Anglesy, and Holyhead),

• Scotland: More than 18,000 km if including the islands of Arran, Islay and Jura, Shetland and Orkney, and the Western Isles); and,

• Northern Ireland: 650km.

Since at least Roman times the British coast has been heavily modified by flood and coastal defences to protect human activities, and land has been claimed for agricultural, industrial, port and residential development. Defences are present on approximately 44% of the English and Welsh coastline, and between 5-6% of the Scottish and Northern Irish coastlines. Various estimates indicate that more than 2,500km of these defences comprise structures, of which approximately half this length is primarily for protection against erosion, the remainder for protection against coastal flooding. 26km of Northern Ireland's 650km of coastline has hard engineering features designed to prevent erosion (Arkell *et al.*, 2007). Coastlines which offer more natural resistance to destructive coastal processes (e.g. rocky cliffs and platforms, and gravel shores) are mostly situated in Scotland, Wales, and south-west England. Softer coastal types, such as sand dunes and beaches, sand and mud flats, and saltmarshes are more prominent on the eastern and southern coasts; whilst gravel barrier beaches are widespread around the UK, and can serve as flood defences.

The UK coast is mostly meso-tidal (2 to 4m range between high and low tide) and macro-tidal (>4m), with the highest tidal ranges experienced along the west coast. The mean spring tidal range on the Severn Estuary is about 12 m, which is the one of the largest in the world; hence the relative timing of storm surges and high tide can be crucial to the occurrence of flooding. The tidal range around the majority of Scotland's coastline is between 3-4 m. In some areas, however (for example the Solway Firth), the tidal range may exceed 6 m. Superimposed upon tides, storm surges can cause flooding and/or rapid erosion events. Surges tend to be largest on the east coast where the propagation path of low-pressure weather systems and the bathymetry of the North Sea allow surges elevations of greater than 3m. Surges of 1-2m frequently occur on the west coast, whilst surges rarely exceed 1m on the south coast. On all coasts, surges may be enhanced by coastal orientation and local bathymetry. Waves are the main source of energy in the coastal zone, and oceanic swell waves (characterised by large periods and wavelengths) in particular cause greater overtopping, flooding and damage to coastal defences. All UK open coasts are subject to a significant storm-wave climate, with oceanic swell capable of impacting the western coasts and areas of the south coast. Direct measurements of wave heights in UK waters (1960s to present) together with inferences drawn from pressure and tide gauge data, (1880 to present) have indicated substantial variability in wave height, depending on season and location.

In the UK, many existing hard structures (seawalls and drainage systems) were built more than a century ago and it is increasingly recognised that many of these are unsustainable, with costs of protection exceeding benefit/costs of the assets being protected. The unsustainability of hard structures is exemplified by 'coastal squeeze', where a beach or intertidal area is trapped between a fixed landward boundary, such as a sea wall, and cannot respond naturally to changing water level or wave conditions, and therefore becomes narrower or submerged. The decline in the natural protection offered, and loss of habitat has resulted in policy and practice shifting towards more adaptive measures that utilise natural coastal processes. For example, beaches and dunes attenuate wave affects prior to contact with structural defences (or act as a line of defence in their own right) whilst offshore barriers, breakwaters, reefs, saltmarshes and mudflats are known to dissipate wave energy, with implications for coastal flooding and erosion.

Understanding risk

To approximate how often an extreme water level or wave event may be expected to occur, 'return periods' are often generated using probabilistic calculations applied to observations (or model simulations) that span a number of years. Return periods estimate the probability that a given water level or wave height, or the joint probablity of both, will occur in any one year. For example an extreme event defined as having a 1 in every 200 year return period may be considered as having a 0.05% chance of occurring in any given year (it is possible that extremes may actually occur more closely together in time than expected, due to the variability inherent in climate driven processes). With risk defined here as the product of probability and consequences of flooding or erosion; knowing the return periods of water levels and waves is vital for assessing threats to coastal communities, and for indicating costs of protection. For example an uncertainty of 1 m in setting defence crest levels might cost £1500–2000 per metre length (e.g. Allsop *et al.*, 2005). In the UK, return period analysis is often used in conjunction with indicative targets set for flood protection. For example the Environment Agency aims to manage urban coastal defences in England and Wales so that they can protect against a 1 in 200 year storm event (a 1 in 100 year standard is used for river flood defences, reflecting the greater consequences associated with large coastal flood events). Lower indicative standards are generally accepted for rural areas and higher targets for important infrastructure (e.g. nuclear power stations). In terms of regional coastal defence characteristics in the UK, the largest structures are usually seen on the east coast to protect large low-lying floodplains against extreme North Sea storm surges.

Coastal Flooding

Flooding can arise from 'functional' failures when wave and water level conditions exceed those for which the defence was designed, or structural failure where some element or components of the defence do not perform as intended. Functional failures arise from society's need to compromise between the cost of the defence and the consequences of a flood, and can feature waves overtopping or still water levels overflowing defences. These may progress to structural failures known as breaching, where the crest of the defence is lowered or an aperture forms. Once other processes (such as overtopping) become replaced by significant breaching; the volume of water that passes onto the floodplain can increase by several orders of magnitude, and this can be dangerous to floodplain inhabitants. Most sea defences are designed to accommodate a tolerable amount of overtopping during storms, although wave overtopping at seawalls has been known to disrupt transport infrastructure, and cause structural damage to roads and railway track. The causes of structural defence failure in the UK can be due to direct damage caused by water levels and waves, or may be exacerbated by weaknesses such as toe scour, geotechnical loads, and local irregularities. Currently, coastal and flood defences in England and Wales are routinely inspected and maintained to reduce the risk of breaching, although localised flooding quite frequently occurs due to overtopping.

Coastal Erosion

There are three principal types of coastal erosion which affect risk to coastal structures, as described below.

Cliff erosion: cliffs can erode due to hydraulic action of waves and water levels, coupled with sub-aerial processes such as high pore pressure within the cliff itself (e.g. caused by heavy rainfall).

Beach morphology: beaches are themselves effective coastal protection structures, and are often in place to protect against flooding and erosion of cliffs or bedrock. They can also be valuable tourist attractions.

Habitat loss: historical evidence (e.g. maps and aerial photos) has extensively indicated that areas of the UK are undergoing progressive loss of intertidal habitat (e.g. Gardiner *et al.*, 2008). This is often directly caused by land claim, although many existing natural intertidal saltmarshes and mudflats are retreating, due to shifting positions of offshore banks and channels, reductions in alongshore sediment supply and changes in the wind–wave climate.

New information sources

Since the previous version of this report, a number of key datasets and sources of information have been developed:

• *National guidance on extreme water levels and waves*: return period waves and water levels are available for around the UK coast (McMillan *et al.*, 2011a,b).

• *Climate Change Risk Assessment (CCRA)*: this study has quantified the possible impacts of climate change, published by the Government on 25 January 2012 and is the first assessment of its kind for the UK and the first in a 5 year cycle. The CCRA reviewed the evidence for over 700 potential impacts of climate change in a UK context. Detailed analysis was undertaken for over 100 of these impacts across 11 key sectors, on the basis of their likelihood, the scale of their potential consequences and the urgency with which action may be needed to address them (Defra, 2012).

• *Shoreline Management Plans (SMPs)*: SMPs provide large-scale assessments of coastal processes over the coming century for the coastline in England and Wales, and the framework for dealing with flooding and erosion. More have been completed, and many have completed a second review.

• *Living With Environmental Change (LWEC) and the National Flood and Coastal Erosion Risk Management (FCERM)*: the LWEC partnership coordinated a steering group (consisting of the main flooding research funding organisations) in March 2012 to oversee delivery of the FCERM strategy covering the whole of the UK (England, Wales, Scotland and Northern Ireland). This is intended to cover the period from 2011-2030, and aims to facilitate future research collaboration and exchange of knowledge between researchers and practitioners, and provide guidance to all organisations involved in flood and coastal erosion risk management (including local authorities, internal drainage boards, water and sewerage companies, highways authorities, and the Environment Agency). The outcomes of the strategy are likely to have implications for coastal structures in the near future.

• *National Coastal Erosion Risk Mapping (NCERM)*: in 2006, the Environment Agency and Defra commissioned a project to map the whole of the English and Welsh coastline susceptible to erosion and instability from natural processes such as wave attack, whilst taking account of the current defences and management activities (Halcrow, 2011).

These developments are accompanied by ongoing updates to indicative flood maps. Refer to the Environment Agency (EA), Scottish Environmental Protection Agency (SEPA) and Defra websites for further details.

Infrastructure impacted by flooding

Approximately 6 million people in the UK (about 10% of the population) are considered at risk of tidal and fluvial flooding (Defra, 2012). The total numbers of properties within this broad definition of flood risk are:

• 2.4 million in England (Environment Agency 2009);

• 220,000 in Wales (Environment Agency Wales, 2009);

• 125,000 in Scotland (SEPA, 2011);

• 46,000 in Northern Ireland (HR Wallingford, 2007).

Of these, currently 560,000 properties are viewed as exposed to a significant risk (an annual probability of 1.3% or 1 in 75 years on average of flooding). These amalgamated numbers (inclusive of river and coastal flooding) are relevant because fluvial and coastal flood sources can interact. However, specific to tidal flood risk, it has been estimated that 2.5 million people live in coastal areas below 5m Ordnance

Datum in England and Wales, including one million in London (de la Vega-Leinert and Nicholls, 2008), which approximates to between 1 - 1.5 million UK properties at risk of tidal flooding alone. The CCRA (Defra, 2012) suggests that 170,000 properties in England and Wales are at significant risk of an exclusively tidal (i.e. storm surge) flooding event; and SEPA (2011) estimate that 21,000 properties are at risk of tidal flooding in Scotland.

The need for robust and well maintained coastal defence infrastructure was highlighted through the disaster of the coastal floods on 31st January – 1st February 1953. This event saw 1,200 flood defences breaches, 150,000 acres of land inundated, and 307 people killed in the UK (RMS, 2003). Since 1953 flood defences and forecasting have been improved, but risk is greater because of the increased dependence upon these measures. For example, the cost of the damage caused by the 1953 North Sea flood event to the UK equates to approximately £1 billion based on 2003 values (de la Vega-Leinert and Nicholls, 2008), whereas an equivalent flood could now cause at least £10 billion of damage due to the increased assets at risk and impacts such as disruption (Muir Wood *et al*., 2005). Hence prevention of breaching remains a critical factor in managing flood hazards for coastal communities; and risk-based management of coastal structures in the UK is constantly reviewed and improved.

One of the World's most iconic flood defences is the Thames Barrier which is closed in response to storm surge warnings. The barrier (and associated defences) protect the nation's capital and was completed in the 1970s as a direct response to the 1953 event, providing protection against a storm surge and tide combination equivalent to a 1 in 1000 year event. Since 1953 severe coastal flooding events have occurred on the English west coast, including Fleetwood (1977), the Bristol Channel (1981) and Towyn, Wales (1990). Although these events did not result in the direct loss of human life, amongst the consequences were extensive damage to property and distress to those affected. In Scotland, January 2005, during an exceptionally severe storm, a causeway in Uist was overtopped resulting in five fatalities. In other locations around the UK there is a risk of extreme flood events, although these have not occurred in living memory. Historically, the worst known flood on the UK west coast was in the Bristol Channel on 30 January 1607, when between 500 and 2000 people were drowned by a 2 m storm surge and high tide (Horsburgh and Horrit, 2006; RMS, 2007). Defences and warning systems would now play a much greater role, although Bristol, Gloucester, Cardiff and Swansea are within floodplains containing a total of £32 billion worth of property, if threatened by a repeat of this event (RMS, 2007). The south coast is exposed to smaller storm surges but frequent floods (e.g. Ruocco *et al*., 2011). Historical records suggest that much more severe flood events occurred prior to the 20th century (e.g. Lamb, 1991). Low lying urban areas rely on both sea defences and pumping facilities to manage flood risk. The UK cities which contain the greatest amount of property at risk from coastal flooding (aside from London) are Portsmouth and Kingston-upon-Hull (RIBA and ICE, 2009). Both cities have experienced failure of drainage infrastructure during high rainfall events, which would be exacerbated in combined with a storm surge. More than 750 properties flooded on the 15th September 2000 in Portsmouth due to failure of pumping systems; whilst in June 2007 Hull experienced unusually high rain fall which flooded over 7200 residential properties and 1300 businesses. Since the original draft of this report, late 2013 to early 2014 has seen a succession of coastal (and river) flood events due to intense storminess and high tides. These events, including the 5-6 December 2013 North Sea storm surge, appear to have in places exceeded previously recorded sea level extremes; whilst the clustering in time of these events has placed unprecedented pressure upon coastal communities and structures (e.g. destruction of the railway at Dawlish and the promenade at Aberystwyth). These events will require further analysis to be placed into context with past extremes and climate change.

Energy: The energy sector is already vulnerable to extreme weather events that have an immediate impact on the ability to supply energy (Defra, 2012). For example, the (non-coastal) flooding of infrastructure during the 2005 Carlisle floods resulted in over 63,000 customer interruptions to electricity supply. As a result of the Pitt Review, the sector has been tasked with increasing the resilience of energy infrastructure to flooding. The main risk posed by flooding from the sea is to power stations (electricity transmission and primary distribution substations are at greater risk of river flooding). There may be opportunities to increase resilience to flooding as current energy infrastructure reaches the end of its lifetime and is replaced.

Road and Rail: Currently 12,000 km of UK transport infrastructure is considered to be at risk of flooding (Defra, 2012). Notoriously, the railway line at Dawlish in Devon is known to overtop during storms, as well as routes in Cumbria and Scotland. In the south of England, numerous key transport routes are within coastal floodplains. For example, the Bristol Channel floods in December 1981 reached the M5 motorway, although more than £100 million has since been spent upon defences in the region. Road networks in Scotland are vulnerable to flooding include low-lying coastal areas in Scotland in the Outer Hebrides and Orkney (CREW, 2012).

Wastewater treatment: It is often necessary to locate waste water treatment plants in the coastal zone, and over 50% of the UK's water and sewage pumping stations and treatment works are already in the floodplain (Defra, 2012). When these are structurally damaged or flooded there is the potential for the release of untreated waste, causing significant damage to the environment and people. Flood waters are often polluted by sewage, which leads to additional risks to health, higher repair costs and longer periods of disruption.

Coastal Erosion

Progressive depletion of nearshore sediment supplies are well known to have taken place throughout the Holocene (c. 12,000 years until the present). However, in some locations human activities have exacerbated the decline in sediment availability (e.g. cliff protection, land claim, interruption of longshore drift by coastal defence structures). Approximately 3,000 km of the UK coastline is thought to be eroding (Defra, 2012); with around 12% of Scotland's coastline recognised as in a state of erosion, compared to 30% of the coastlines in England and Northern Ireland and 20% in Wales (CREW, 2012). Notorious examples of cliff erosion include the village of Happisburgh, on the Norfolk coast, and the town of Lyme Regis on the Dorset 'Jurassic' coast. At Happisburgh, historical records indicate that over 250 m of land were lost between 1600 and 1850, and the coast here is experiencing rapid erosion as defences deteriorate and the sea cuts through the soft glacial till cliffs. At Lyme Regis, a £20 million project is underway to protect 480 homes and the main road that leads into the east of the town. In the case of beaches, focus has, in many places, shifted from structural maintenance of sea walls to maintenance of a healthy beach (although sediment retaining features such as groynes are widely utilised). For example during the winter of 2005/2006, 1.1 million cubic metres of sand was dredged from Poole Harbour channels and pumped onto the beaches of Swanage, Poole and Bournemouth to protect them from erosion as part of a £5 million coastal protection project.

The exact cause of intertidal habitat loss in many locations has not been determined, but significant losses are likely to continue even without climate change, and loss rates are likely to be exacerbated by accelerated sea-level rise (e.g. Nicholls *et al*., 1999). In some places, habitat loss has been reversed by 'managed realignment' and 'regulated tidal exchange' projects, where the line of actively maintained defences is set back to a new line or the original line of defences, promoting the creation of intertidal habitat between the old and new defences. This is often achieved by removing or creating artificial breaches in sea walls. For example, it has been estimated that an 80 m wide zone of intertidal habitat fronting sea walls can save £2600-4600 per metre in sea defence costs (King and Lester, 1995). The recent SMPs placed an emphasis upon identifying locations where this was feasible, and numerous schemes are underway or foreseen over the coming century. However, it is estimated that there are about 32,000 ha (320 km^2) of coastal freshwater habitats within designated sites that are at risk of inundation by the sea.

2. WHAT COULD HAPPEN?

The latest UK climate projections from the United Kingdom Climate Impacts Programme (UKCP09) were released on 18th June 2009. Climate science and computer modelling have advanced significantly since the UK produced its first climate change information. UKCP09 presents what is considered to be current best understanding of how the climate system operates, and how it might change in the future. However, no climate model can provide a definitive answer to what the future climate will look like. Present climate models are capable of outputting information on the following:

- Observed climate data (20th and 21st century historical information about temperature, precipitation, storminess, sea-surface temperatures and sea level).
- Future climate projections (for temperature, precipitation, air pressure, cloud and humidity).
- Future marine and coastal projections (for sea level rise, storm surge, sea surface and sub-surface temperature, salinity, currents, and waves).

Current knowledge of sea level trends from statistical analyses of historical water level datasets suggest that SLR is occurring, and is increasing the probability of extreme events in a number of coastal regions (e.g. Menéndez and Woodworth, 2010; Haigh *et al*., 2011; Wahl *et al*., 2011). The main climate drivers of flood risk (storms, precipitation) are also expected to increase, leading to an increase in the risk of coastal flooding and erosion. Mean sea-level rise (MSLR) is expected to be the most influential of these changes, and likely to overshadow the changing frequency and magnitude of storm surges and wave climate over the next 100 years (Horsburgh *et al*., 2011). The mean estimates of sea-level rise have remained steady over the past decade, and low-high probabilities for medium emission climate change scenarios suggest approximately half a metre can be expected by the end of the 21st century. However, the original UKCP09 work was based upon estimates which excluded climate-carbon cycle feedbacks and the possibility of future rapid dynamical changes in ice sheet flow, i.e. the biggest source of uncertainty in sea level projections is the response of the large ice sheets of Greenland and west Antarctica. Consequently the UKCP09 marine report provided an additional high-plus-plus (High++) scenario. The H++ scenario for possible SLR for 2100 (compared to 1990) gives a lower estimate (0.93m) obtained from the maximum global mean sea-level rise value given by the Intergovernmental Panel for Climate Change's 4th Assessment Report (IPCC AR4), whilst the top of the range (1.9m) is derived from indirect observations of sea-level rise in the last interglacial period. Although considered unlikely, various other studies acknowledge even larger changes are theoretically possible. In a study which combines global climate model simulations and mitigation scenarios, Meehl *et al.* (2012) suggest that sea-level rise cannot be stopped for at least the next several hundred years, although with aggressive mitigation it can be slowed down (which would buy time for adaptation measures to be adopted).

UK waters have warmed over the last 50 years at least partly driven by anthropogenic climate change. The longest continuous time-series of sea-surface temperature in the UK (for Dover, Eastbourne and the Isle of Man) show an increase in annually-averaged temperature of about 0.6°C over the last 70 to 100 years and 2006 was the second-warmest year in UK coastal waters since records began in 1870 (Defra, 2012). Seven of the 10 warmest years have occurred in the last decade. The observed warming was strongest in the southern North Sea and weakest to the north and west of Scotland. The salinity of the upper ocean (0 - 800 m) to the west and north of the UK has been generally increasing since a 'fresh' period in the 1970s, reflecting a pattern of change in the wider North Atlantic. Within the shelf seas (e.g. the North an Irish Seas), trends in salinity are less clear and there is high inter-annual variability. There is some evidence of a recent trend to earlier stratification and onset of the spring plankton bloom in UK seas, largely in response to warming air temperatures. However, this report mainly focuses upon the impacts of changing sea levels.

Since the last version of this report, climate change science has continued to develop methods to reduce the uncertainty in the long-term outlook, whilst gaining a better understanding of shorter-term natural variability (e.g. Hawkins and Vidale, 2012). It is recognised that higher resolution of the atmosphere and ocean are required to achieve this, and it is probable that the UKCP09 climate change projections will in the future be superseded by modelling systems which represent fundamental weather and climate processes more completely (e.g. PRACE, 2012). As noted above, on-going monitoring and analysis of mean sea level (and subsequent revisions to extreme event and coastal flooding probabilities) are amongst the most relevant research areas to benefit the design of coastal defences and plan investment into other climate change mitigation measures at the coast. However, there is growing recognition of the need to understand the temporal clustering of weather events (Mailer *et al.*, 2006; Vitolo *et al.*, 2009; Villarini *et al.*, 2012) (which have implications for damage and recovery times for coastal structures and flood event impacts) and understanding of existing variability and future changes in storm tracks and weather patterns (e.g. Burningham and French, 2012).

Infrastructure impacted by coastal flooding and erosion

Properties on the coast and in the floodplain: The CCRA (Defra, 2012) summarises that across the UK, residential and non-residential properties with a significant likelihood of flooding are likely to increase from the current figure of 560,000, to between 770,000 and 1.3 million by the 2050s, rising to between 980,000 and 1.5 million by the 2080s. Annual damage to these properties due to flooding is expected to reach between £1.7 and £4.5 billion by the 2050s, rising to between £2.1 and £6.2 billion by the 2080s (current figure: £1.2 billion). These figures incorporate river and tidal flooding (a large proportion of these increases are attributed to increased rainfall). A separate indication of the impacts relating only due to changes to tidal flooding is summarised in Table 1.

Table 1: Number of properties at significant risk of tidal flooding at present sea levels and with SLR (source: Defra, 2012).

Scenario	Estimated number of properties at risk (tidal flooding only, not accounting for socio-economic scenarios)
Significant likelihood of tidal flooding: Present day	170,000
Significant likelihood of tidal flooding: 2080s Low to high probability sea level rise UKCP09 scenarios	450,000 - 620,000
UKCP09 High ++ (2080s)	1,250,000

At present, the east coast of England contains the most extensive and well understood regions affected by coastal flooding and erosion, including a high proportion of the UK property at risk of tidal flooding. SLR and other climate-induced changes are likely to increase the risk of defence failures unless defences are upgraded. However, a national study of future flood risk identified that some of the largest 21st century increases in UK coastal flood risk could occur on the south coast (Foresight, 2004). Despite being associated with smaller storm surges and floods than the east and west coasts, defence standards in some south coast regions are currently more variable, and depending upon how much time SLR allows for the building of new defences or relocation of communities and infrastructure, there are likely to be large changes to the consequences of coastal flood events.

There are an estimated 200 homes at risk of complete loss to coastal erosion in the next 20 years, and it is possible 2,000 more could become at risk over this period (Defra, 2012). The Foresight (2004) study suggested that due to 21st century SLR coastal erosion losses in England and Wales represented only 3% of the total risk (based upon an average estimation of property numbers valued at £7.7 billion at year 2000 prices). However, in the context of broader coastal zone management issues and also the viability of coastal settlements on eroding coastlines, coastal erosion merits serious attention (Hall *et al.*, 2006). It has been suggested that over the coming century there will be habitat gains from managed realignment and accretion, whilst losses will continue in some locations. There could be a net loss of coastal dry land, wetland and open water habitat of approximately 4,000 hectares from protected sites in England and Wales accompanied by 2,220 ha gain from managed realignment programmes over the next 50 years (Defra, 2011). The future publication of the National Coastal Erosion Risk Mapping (NCERM) results is likely to provide a better understanding of what is currently happening, and what could happen in the future.

Coastal defences: SLR will prompt shifts in flood risk management, although the nature of these changes is uncertain. Options include building new coastal defence structures, and it is likely that a substantial amount of costly engineering work will take place, particularly on the south and east coasts of the UK. The Environment Agency (EA) estimates for maintaining the flood threat to existing standards suggest that by 2035, in England the investment in building and maintaining of flood defences will need to almost double to £1billion a year (compared to £570million now). In Wales, the equivalent figure is around £135 million a year (compared to approximately £44 million now) by 2035. Non-structural measures such as changes to land use spatial planning, insurance and flood resilient construction may yet prove to reduce the burden of expectation placed upon traditional sea wall and embankment construction. Furthermore, efforts to reduce coastal squeeze and intertidal ecosystem loss may be increasingly used, although how successfully natural systems will respond to rapid SLR is uncertain.

The total cost of engineering works in relation to climate change and socio-economic scenarios depends greatly upon the rate of the increase of risks. Burgess and Townend (2004) estimated that by the 2080s the annual cost of coastal dyke structures will be between 150 and 400% of the current levels (depending on the emissions scenario). However, these costings did not incorporate 'non-structural' flood risk reduction measures. Costs were less sensitive to geographic location than to emissions scenario, and predicted to increase because structures are vulnerable to increases in water depth. This is because the design wave condition for most UK coastal dyke structures is depth limited, hence wave heights reaching structures increase linearly with water depth. Furthermore, raising crest levels may often have to be accompanied by re-engineering of entire structures to mitigate scour around the toe, resulting in an overall substantial increase in costs (of two to four times the present cost to provide a similar level of performance).

In the independent review of the 2007 summer (Pitt, 2008), it was recommended that locally-funded flood defences should become a bigger feature of flood and coastal risk management. However, whether this prompts further construction of hard defences or adoption of the aforementioned approaches is uncertain. In view of the structural integrity required for new structures, there will be little room for compromise. Potential consequences of coastal defence failures (particularly breaches) will grow as the elevation difference between sea level and the floodplains increases; and there will be an increasing reliance upon pumping systems as well as sea walls and embankments. Improvements to the existing Thames barrier and defences are feasible for sea level increases in the region of 1 m; although more extreme and costly works would be required beyond this, with construction of an outer estuary barrage an option.

Energy: The main risk posed by coastal flooding in this sector is to power stations. The energy industry has a relatively high awareness of the risks posed by climate change, but risk may be exacerbated by interdependencies with other sectors (e.g. disruption to transport infrastructure and therefore to the movement of supplies of some fuels). This may have a major impact on the UK's energy industry, which aside from sea-level rise is notably affected by other climate influences, e.g. higher summer temperatures may result in a rise in energy demand for cooling (particularly in the south). Cooling of buildings (air conditioning, refrigeration, cooling of information technology and communications infrastructure) currently accounts for around 4% of total UK electricity use and demand is already increasing (Defra, 2012). Although currently well protected, sea-level rise may gradually reduce the standard of protection unless defences are raised and upgraded.

A preliminary qualitative analysis of the monetary impacts of flood risks has been estimated to be between £10 and £100 million per year by the 2050s and over £100 million by the 2080s (for all types of energy infrastructure). However, there is not significant information about the vulnerability of gas and coal energy infrastructure to permanent inundation by sea-level rise, and current assessments do not incorporate the latest erosion mapping data. An area of significant concern is nuclear power. There are eight proposed new stations, 12 waste stores and 16 nuclear power station decommissioning sites at a total of 19 locations around the UK coast (Defra, 2012). Because of the importance of these sites, regulations require flood protection to a 1 in 10,000 year standard, and it is likely that it will be costly to enhance defences to maintain this level of protection over the coming century.

Table 2: Flood costs to transport: expected annual damage (£million/year), considering a medium emissions scenario, and no socioeconomic change (from the CCRA by Defra, 2012).

Transport	2020s	2050s	2080s
Rail	0.09	0.21	0.32
Motorway	0.04	0.10	0.14
A-Road	0.09	0.23	0.35
TOTAL	0.22	0.54	0.81

Road and Rail: Defra (2012) estimate that the length of road exposed to significant likelihood of flooding will be between 13,000 km and 18,000 km by the 2050s, rising to between 14,000 km and 19,000 km by the 2080s (the current figure is 12,000 km) although due to the datasets used, current day estimates and future risk estimates are quite uncertain and likely to be overestimated. However, coastal rail tracks are not easily moved and may require complex and costly adaptation (RAE, 2011). Recent SMPs identified various transport-related issues. For example on the west coast of Wales near Porthmadog, the UKCP09 H++ scenario highlights a major impact on transport systems, such as the Cambrian railway, and coastal roads in Pembrokeshire, potentially over the next 50 years.

Wastewater treatment: As well as potentially more frequent impacts to water infrastructure through flooding, SLR will also cause saline intrusion into coastal aquifers and sewers. New sea-water desalination plants and more water storage may be necessary to maintain supply during periods of drought. Water infrastructure is also dependent upon electricity to power its facilities (pumping, water treatment, IT systems). During a heavy storm, valves are opened and untreated effluent is sometimes released from outfalls around the coast. It is possible that future climate change might increase the frequency of incidents during which untreated sewage is discharged into the marine environment through a combined sewer overflow (Knights, 2007). Increased runoff due to climate change, and any lack of capability for wastewater structures to adapt will also result in increased pollution of coastal waters. Some 80% of substances that find their way into the world's oceans and seas come from land-based activities via riverine or atmospheric inputs. Changes in flow regimes in estuaries and rivers could also result in reduced dilution of pollutants (because of hotter, drier summers), or pulsed release from diverse sources reaching the marine environment (Knights, 2007).

Infrastructure impacted by changes in water temperature

The vast majority of nuclear or coal-fired power stations around the UK coast require large inputs of sea-water for cooling. Where cooling water is extracted from, and discharged into estuarine or marine waters it is important that potential impacts on receiving water temperature are carefully assessed. European and national legislation requires that specific standards are not exceeded. The EU Water Framework Directive specifically regulates on thermal inputs and national standards have been developed for application to UK water bodies.

Intake structures may need to be located further offshore in the future, in order to accommodate access to cooler (usually deeper) waters that are needed to ensure efficient operation. Outflows may also need to be located offshore, to ensure that the heat-balance of coastal or estuarine waters is not too adversely impacted. For example, Cefas (2008) undertook modelling of the Blackwater Estuary, Essex, taking into account long-term climate change scenarios. The simulations suggested that by the 2080s sea surface temperature would rise 'naturally' to the extent that the estuary would be impacted and fail to meet 'good environmental status' regardless of any thermal inputs from a new power station. In addition, the predicted 'background' rise in temperature of ~2-4°C may well exclude the species that such regulations are designed to protect (migratory fish and shellfish).

3. KNOWLEDGE GAPS

a. The rate of 21st century sea-level rise: this is highly uncertain and affects the knowledge of tipping points in time for when SLR and other climate change effects will trigger sharp increases in erosion and the impacts of extreme flood events (and hence decisions upon the management of coastal structures).

b. Understanding interactions of many other flood system variables within assessments of coastal flooding impacts (sediment transport processes, drainage, interactions between groundwater, fluvial and surface water flooding).

c. Socio-economic impacts associated with increased flooding and erosion, and the resultant implications for coastal structures.

4. SOCIO-ECONOMIC IMPACTS

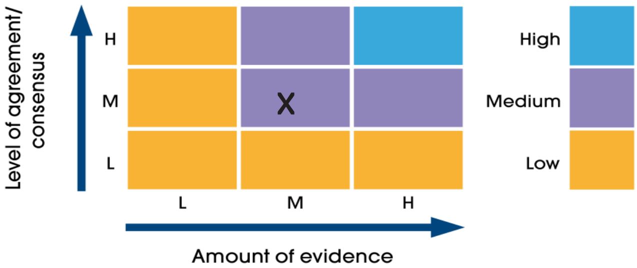
The impact of sea-level rise and other climate change influences on coastal structures are manifested as a threat to coastal communities, particularly those reliant upon the immediate coastal area for their residence, communications and economic and social activity. The SMP studies suggested that there is increasing, genuine acceptance that SLR will really happen although not everyone can come to terms with the notion that coastal structures will no longer be maintained to protect them from flooding and erosion. With central government policy encouraging a shift to localism, there is an ever-increasing onus on communities to help themselves to become more resilient. However, the way climate change is communicated (e.g. as a future risk) and lack of awareness of impacts and what actions are needed may be causing apathy in some communities (Zsamboky *et al.*, 2011). Coastal local authorities with areas of high deprivation may not prioritise or be able to afford adaptation activities, nor can the residents. Awareness, acceptance and adaptation to climate change are greatest amongst communities that have experienced flood or erosion events in living memory. Table 3 summarises socio-economic and ecological implications relating to climate change and UK coastal structures.

Table 3: Predicted socio-economic and ecological consequences of changes in storm intensity and in relative sea-level rise (based on UKCP09 outputs and Defra, 2012). With level of confidence (H = High, M = Mid, L = Low).

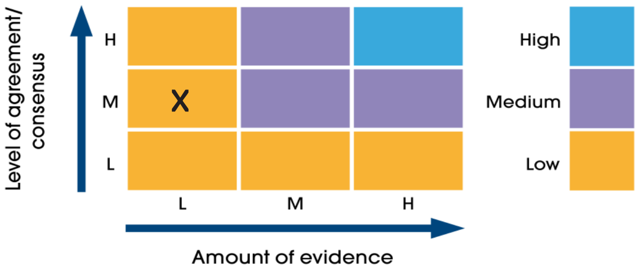
Risk	Ecosystem impacts	Impacts on human activity
Changes in storm intensity (L)	• Higher flood risk (L) • Coastal geomorphology changes, e.g. shifts in sandbanks (L) • Coastal inundation (L) • Increased release of contaminated sediment or storm water containing untreated sewage (L)	• Acute damage to ports and coastal infrastructure (L) • Damage to aquaculture sites and offshore cabling (L) • Safety at sea (shipping, spillages, etc) • More difficult to access offshore resources (e.g. aggregates) • Risks but also opportunities for marine recreation • Health risks, e.g. storm discharge of untreated sewerage • Change in specifications required to be resilient to say 50 year storm event (or 1 in 10,000 year event for nuclear power stations). • Opportunities for wind farms (if stronger winds) • Increased insurance premiums • Conditions more conducive for Harmful Algal Blooms (HABs)
Relative sea-level rise (H)	• Increased frequency of extreme high-water-level events (L) • Coastal erosion / undermining / squeeze • Saltation of coastal aquifers / river catchments • Flooding of coastal habitats	• Sustainability and viability of coastal infrastructure (e.g. towns / power stations) • Loss of agricultural land (e.g. grazing marsh) • Change in planning laws – impacts on coastal communities (including insurance premiums) • Fragmentation / loss of rural communities (e.g. impacts on eco-tourism)

5. CONFIDENCE ASSESSMENT

What is already happening?



What could happen?



Numerical modelling and data collection are increasingly important to support the management and design of coastal structures, by improving understanding of natural processes and to simulate given scenarios. However, much uncertainty remains, and the protection of high risk areas of flooding and erosion is increasingly complicated by economic and environmental constraints and future uncertainty over sea-level projections. With regard to the marine scenarios in the latest UK climate projections (UKCP09), it was noted that it was not possible to quantify the probability of changes to these. As an analogy, the state of modelling of the marine environment in 2009 is similar to where modelling of the atmospheric and terrestrial climate change was at the time of the previous UKCIP assessment in 2002. There are a number of reasons for this apparent discrepancy:

• knowledge gaps in our understanding of marine processes (e.g. deep ocean mixing, which affects ocean circulation) mean that current models may not simulate the full range of possible futures;

• even where it might be possible to estimate the range of futures, there is an insufficient number of model simulations (e.g. of climate driven changes in waves) to credibly fill in the range between projected highest and lowest values;

• insufficient work has been carried out in the maritime community on suitable observational constraints for projections of global and local marine and coastal climate change.

For the 'What is already happening' assessment, we have altered our confidence in science and amount of available evidence since our assessment in 2010. Improved extremes analysis and ongoing climate research have increased the knowledge and theory previously available. Further integration of coastal process knowledge with drainage and surface water processes would be highly beneficial. A consistent body of information about intertidal habitat loss around the UK coast and climate change impacts is currently lacking. The magnitude of sea-level rise beyond UKCP09 projections, and the nature of human responses to such scenarios are also highly uncertain.

At present, confidence in the wind projections from Global Climate Models (GCMs) and down-scaled Regional Climate Models (RCMs) is very low. Thus the current confidence in predictions of winds and storms from the models underlying UKCP09 were also considered very unreliable and uncertain. Therefore, UKCP09 did not provide wind field changes within its package of model outputs. For important applications that depend on wind, such as the prediction of future waves and extreme water levels, this uncertainty is acknowledged and tackled with a somewhat cruder sensitivity approach.

The frequency of occurrence and size of extreme waves are generally expected to increase slightly in the south-west of the UK, reduce to the north of the UK and experience little change in the North Sea. There are large uncertainties especially with the projected extreme values and no High ++ scenario has been attempted in this case. Changes in the winter mean wave height are projected to be between –0.35 m and + 0.05 m. Changes in the annual maxima are projected to be between –1.5 m and +1 m (Defra, 2012).

Wave heights around the UK depend on winds and storms both locally and in the wider Atlantic. Wind-driven waves and storms are seen as primary drivers of short-term coastal processes on many European coasts. Higher waves together with increased storm-surge elevations (a result of increased sea level and high tides) would have important potential consequences such as enhanced/accelerated erosion and more frequent flooding in estuaries, deltas and embayments.

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