Impacts of climate change on coastal flood risk in England and Wales: 2030-2100

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Abstract

Coastal flood risk is a function of the probability of coastal flooding and the consequential damage. Scenarios of potential changes in coastal flood risk due to changes in climate, society and the economy over the 21st Century have been analysed using a national-scale quantified flood risk analysis methodology. If it is assumed that there will be no adaptation to increasing coastal flood risk, the expected annual damage in England and Wales due to coastal flooding is predicted to increase from the current £0.5 billion to between £1.0 billion and £13.5 billion, depending on the scenario of climate and socio-economic change. The proportion of national flood risk that is attributable to coastal flooding is projected to increase from roughly 50% to between 60% and 70%. Scenarios of adaptation to increasing risk, by construction of coastal dikes or retreat from coastal floodplains are analysed. These adaptations are shown to be able to reduce coastal flood risk to between £0.2 billion and £0.8 billion. The capital cost of the associated coastal engineering works is estimated to be between £12 billion and £40 billion. Non-structural measures to reduce risk can make a major contribution to reducing the cost and environmental impact of engineering measures.

Introduction

The coast of England and Wales contains a concentration of population and industry, together with environmental and recreational assets. Large urban areas, including London, and significant proportions of high grade agricultural land are located in coastal floodplains. In addition to the risk of flooding in the coastal lowlands the UK has many eroding coastlines, the total length of which has recently been estimated to be over 3000 km long (Eurosion 2004). The UK vulnerability is indicated by the fact that it has around 2300 km of artificially protected coast, the longest in Europe (Eurosion 2004).

Using results from the Hadley Centre's HadCM3, Hulme et al. (2002) predict that by the 2080s and depending on greenhouse gas emissions scenario, relative sea level may be between 2cm below and 58cm above the current level in South West Scotland and between 26 and 86cm above the current level in South East England. For some coastal locations a water level that at present has a 2% annual probability of occurrence may have an annual occurrence probability of 33% by the 2080s for Medium-High emissions. These estimates do not account for uncertainty in regional assessments of sea level rise or for any change in the frequency of storm surge residuals.

In 2004 the UK government published the results of a two year Foresight project on flood and coastal defence (Evans et al. 2004*a,b*). The aim of the project was to analysis the risk that flooding and coastal erosion poses to the UK over a timescale of 2030-2100. The analysis proceeded through a combination of consultation, structured expert elicitation and quantified risk analysis. The Foresight project dealt with flooding from rivers and the sea in an integrated analysis framework. In this paper we make use of the modelling conducted as part of Foresight to present new analysis specifically of coastal flood risk and vulnerability to climate change. The quantified analysis is restricted to England and Wales because it makes use of the Environment Agency's National Flood and Coastal Defence Database, which does not include Scotland and Northern Ireland.

The focus of the work is on flood risk, but the Foresight study and other research has highlighted the influence of coastal erosion on modifying flood risk both locally and on down-drift coasts. The Foresight study confirmed previous analysis (Halcrow 2000) that on its own coastal erosion is not a major economic issue. Coastal erosion losses represent only just over 3% of the total risk, although this is based upon an average estimation of property numbers (value £7.7 billion in 2000 prices). Even taking the extreme property number estimates, for which asset values vary between £2.7 billion and £12.2 billion, this still only represents 2% to 6% of the total capital value of assets at risk (Halcrow 2000). 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.

This paper begins with a review of the evidence relating to marine climate change on the UK coast. The coastal flood risk analysis method is introduced, which was in the first instance used to estimate the total expected annual damage due to coastal flooding in England and Wales, based on data for 2002. The parameters in this flood risk analysis method were then perturbed to reflect the effects of scenarios of future climate and socio-economic change. This method was first applied in the Foresight study (Evans et al. 2004*a*,*b*), but new results are presented that have been generated subsequent to the Foresight study, based on the same analysis methodology, scenarios and datasets. The scenarios analysis first deals with the base line situation in which it is assumed that there is no adaptation to climate or socio-economic change. In other words, current coastal management practices were projected into the future more or less unchanged. Flood risk estimates, again in terms of expected annual economic damage, are presented for four scenarios and compared with the present day risk estimate. Then scenarios of future coastal management are presented, which were implemented by modifying the coastal defences, land use and other variables in the flood risk model to investigate the potential for adaptation to future changes. We conclude by reflecting on the usefulness of the methodology and the implications of the results.

Marine climate change in the UK

It is estimated that by the 2080s the global average sea level will have risen above present day levels by between 90 and 690 mm, depending on emissions scenario (Hulme et al. 2002). Such predictions require translation to provide regional estimates of sea level rise. Tsimplis et al. (in press) provide multiplication factors for doing this. They also include a means of accounting for the effect of fluctuations in the North Atlantic Oscillation (NAO).

The risk posed by ongoing sea level rise depends on the magnitude and frequency of surge events. Hulme et al. (1998) provide a design method in which the net sea level rise is added to water level-frequency curves calculated from historic data. This approach assumes stationary surge statistics, whilst some evidence suggests that extremes are increasing (e.g. Langenberg et al., 1999). It also does not account for the effects of increased sea level on tide and surge propagation and on surge generation. Lowe et al. (2001) modelled storm surge for both existing conditions and the climate in 2100, using a 35km resolution model of the North West continental shelf region. The results show an increase in 1:50 year return period events for the majority of the British coast. The increase ranged up to 0.24 m. Debernard et al. (2002) conducted a similar analysis of wind, wave and storm surge climates in the northern North Sea. Present day and future (2030-2050) conditions were modelled, driven with output from regional climate models. The results showed relatively small changes, but rougher autumnal maritime climates.

It is widely held that there has also been a significant growth in wave conditions in the North Atlantic over the last few decades. Bacon & Carter (1991) demonstrated recent growth in North Atlantic (NA) mean wave height of about 2% per year. Subsequently Bacon and Carter (1993) related wave observations to the North Atlantic Oscillation (NAO) and were then able to tentatively hindcast wave conditions back to 1873 for the North East Atlantic. These results indicated that the observed growth in wave height began in the mid 1960s and had not been exceeded during the hindcast period. Gulev & Hasse, (1999) calculated similar increases in wave height of between 100 and 300 mm/decade. Carretero et al. (1999) studied the apparent rise by analysing 40 years of wind records and using them to hindcast wave conditions, concluding that the storm and wave climate in the North Sea and most of the northeast Atlantic has shown significant variability at decadal timescales and has become more energetic in recent decades. However, recent storm intensity is similar to that experienced at the start of the 20th century, so present storminess may simply be an expression of natural climate variability. There is some evidence that the period of wave height growth may be coming to an end. Langenberg et al. (1999) found storms Baltic sea storms to have calmed in recent years. Carretero et al. (1999) explored the relationship between climate variability and the NAO. More recent work (Wolf et al., 2002) investigated the relationship between recent wave heights and the NAO. This link is useful in that it provides a means of linking wave predictions with large scale climate changes. Tsimplis et al. (in press) discuss this in some depth, and stress the uncertain nature of wave predictions, but are able to provide scenarios of future wave conditions around the British Isles for the 2080s in terms of growth in significant wave height.

Hargreaves et al. (2002) explored the coastal wave conditions around the British Isles resulting from a continued increase in offshore wave conditions and sea-level rise. It was found that the relationship between offshore and inshore waves was complicated by bathymetry, tidal range and wave angle. Sutherland and Gouldby (2003) used GCM and surge model data to demonstrate the relative effects of increased mean sea level, future wave climates, raising the crest height of a seawall and coastal steepening on overtopping. Burgess and Townend (2004) have observed that the majority of the UK's sea dike structures have depth-limited design wave conditions, which implies that the largest nearshore waves will not necessarily increase if offshore waves do. It should be noted, however, that larger waves are likely to drive coastal morphology at a greater rate, so over the medium to long term any growth in offshore wave heights may well be expressed at the coast.

Quantified national-scale analysis of coastal flood risk

Flood risk is conventionally defined as the product of the probability of a given flood event and the consequential damage, integrated over all possible flood events. It is often quoted in terms of an expected annual damage, which is sometimes referred to as the 'annual average damage'. Significant progress has been made in recent decades in the development of probabilistic flood risk analysis methods for the coast at the scale of Dutch dike ring systems (Vrijling 2001, Voortman et al. 2003). However, these methods are limited by the availability of data, in particularly relating to the configuration of sea dike systems. The analysis presented in this paper is based on an approximate national-scale methodology (Hall *et al.*, 2003) developed to make use of the following GIS databases for all of England and Wales:

1. *Indicative Floodplain Maps (IFMs)* are the only nationally available information on the potential extent of flood inundation. The IFMs are outlines of the area that could potentially be flooded in the absence of defences in a 1:200 year return period flood for coastal floodplains.
2. *1:50,000 maps with 5m contours.* The methodology has been developed in the absence of a national topographic dataset of reasonable accuracy. Topographic information at 5m contour accuracy has only been used to classify floodplain types as it is not sufficiently accurate to estimate flood depths.
3. *National Flood and Coastal Defence Database* provides a national dataset of dike location, type and condition.
4. *National database of locations of residential, business and public buildings*.
5. *Land use maps and agricultural land classification*

An essential aspect of flood risk analysis is to assess the reliability of the sea dikes. These infrastructures must be dealt with as systems if the flood risk is to be accurately estimated. In the absence of more detailed information on flood extent, the Indicative Floodplain is adopted as the maximum extent of flooding and is further sub-divided into Impact Zones, not greater than 1km × 1km. Each flood Impact Zone is associated with a system of sea dikes which, if one or more of them were to fail, would result in some inundation of that zone.

Reliability analysis of coastal dikes potentially requires a huge quantity of data, which are not available for all of the dikes in England and Wales. An approximate reliability method has therefore been developed that makes use of the so-called Standard of Protection (SoP), which is an assessment of the return period at which the dike will significantly be overtopped. Dike is addressed by estimating the probability of failure of each dike section in a given load (relative to SoP) for a range of load conditions. Generic versions of these probability distributions of dike failure, given load, have been established for a range of dike types for two failure mechanisms: overtopping and breaching.

Having estimated the probability of failure of individual sections of dike, the probabilities of failure of combinations of dikes in a system are calculated. To do so, it is assumed that the probability of hydraulic loading of individual dikes in a given dike system is fully dependent. The probabilities of failure of each of the dikes in the system, conditional upon a given load, are assumed to be independent. For each failure combination an approximate flood outline, which covers some proportion of the IFM, is generated using approximate volumetric methods. These methods estimate discharge through or over the sea dike and inundation characteristics of the floodplain.

In the absence of water level and topographic data, estimation of flood depth has been based on statistical data. These data were assembled from seventy real and simulated floods for a range of floodplain types and floods of differing return periods. These data were used to estimate flood depth at points between a failed dike and the floodplain boundary, in events of a given severity. Flood depth estimates from a range of floods were used to construct an estimate of the probability distribution of the depth of flooding for each Impact Zone.

The numbers of domestic and commercial properties and area of agricultural land in each Impact Zone were extracted from nationally available databases. These data were combined with relationships between flood depth and economic damage that have been developed from empirical analysis of past flooding events (Penning-Rowsell et al. 2003). For a given Impact Zone the expected annual damage R is given by

$$R = \int_0^{y_{\max}} p(y)D(y)dy$$

where y_{max} is the greatest flood depth from all flooding cases, $p(y)$ is the probability density function for flood depth and $D(y)$ is the damage in the Impact Zone in a flood of depth y metres. The total expected annual damage for a catchment or nationally is obtained by summing the expected annual damages for each Impact Zone within the required area.

Figure 1 is based on the Indicative Floodplain Maps and illustrates how coastal floodplains in England and Wales are concentrated on the south and east coast. Several areas of Britain's main metropolitan areas, most notably the financial districts of London, are located within this floodplain. Large areas of high grade agricultural land in the east of England are located in the coastal floodplain. The floodplains are identified as being liable to coastal flooding on the basis of the Environment Agency classification. Some areas classified as being fluvial (so not appearing in Figure 1), notably the Fens of East Anglia, might also be liable to coastal flooding, especially under sea level rise scenarios.

Based on the methodology outlined above, the Expected Annual Damage due to coastal flooding in England and Wales was estimated to be £0.5 billion. This represents roughly half of the flood risk due to fluvial and coastal flooding combined, estimated in 2002. Highest economic risk is located in floodplain areas of high economic value, notably central London (despite very high standards of flood protection) and Hull (Figure 1). The expected annual coastal flood damage to agriculture, which is small copared to damage to buildings and contents, is estimated to be £2.2million, representing 37% of the total expected annual damage to agriculture.

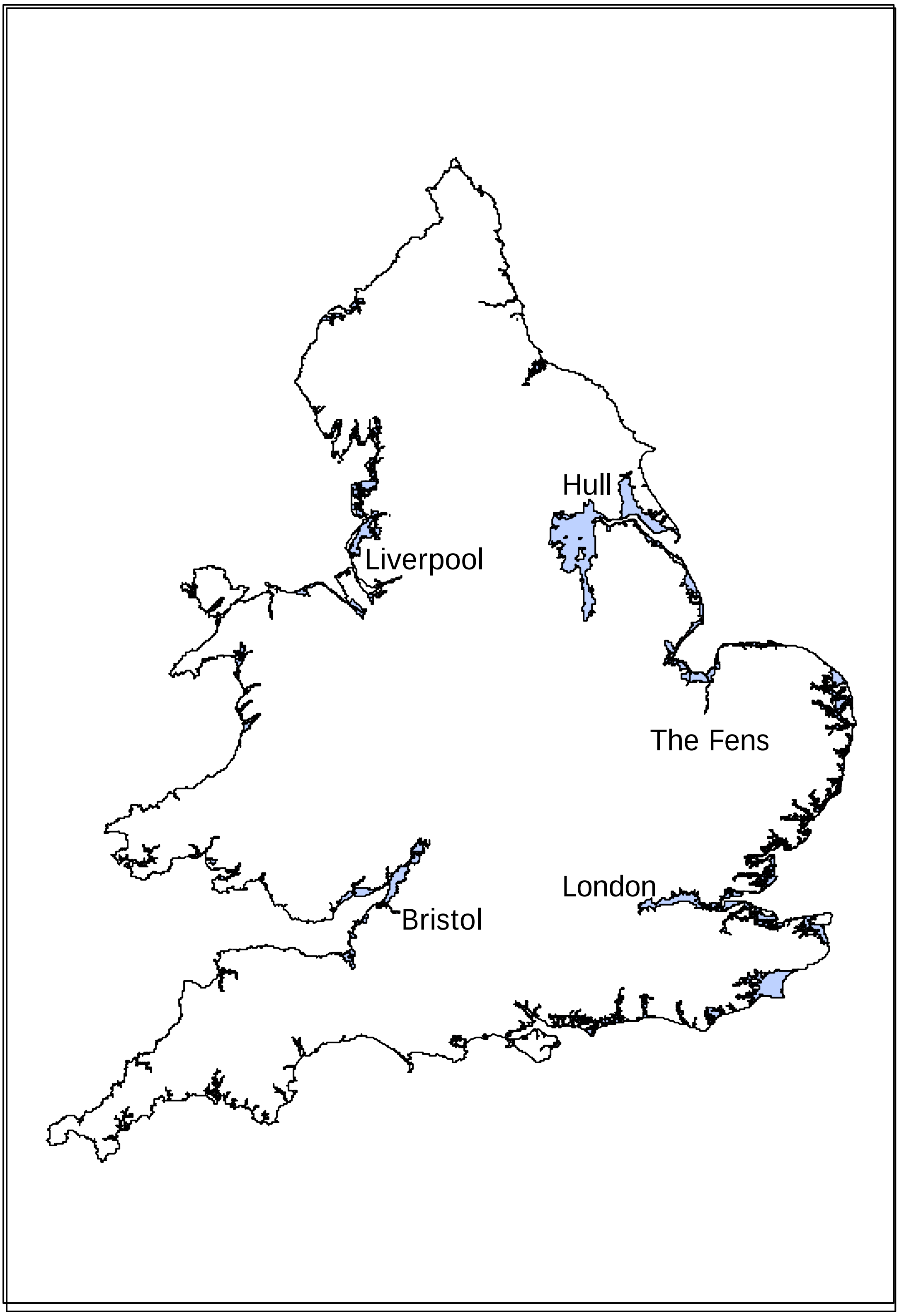

Figure 1 Location of the 1:200 year coastal floodplains according to Environment Agency classification in England and Wales

Table 1 UKCIP02 sea level rise scenarios for the UK

SRES[1] scenario	UKCIP02[2] scenario	Foresight Futures[4]	Global average sea level rise (2080s)[3]	Relative sea level rise in London[2]	Relative sea level rise in SW England[2]	Relative sea level rise in NW Scotland[2]
B1	Low emissions	Global Sustainability	23 (9-48) cm	26cm	16cm	-1cm
B2	Medium-low emissions	Local Stewardship	26 (11-54).cm	-	-	-
A2	Medium-high emissions	National Enterprise	30 (13-59) cm	-	-	-
A1FI	High emissions	World Markets	36 (16-69) cm	86cm	76cm	59cm

Notes:

1. Special Report on Emissions Scenarios (IPCC, 2000)
2. UK Climate Impacts Programme 2002 scenarios (Hulme et al. 2002).
3. UK Climate Impacts Programme 2002 scenarios (Hulme et al. 2002). Figures in brackets are IPCC ranges associated with same SRES emissions scenarios
4. DTI (2002)

Scenarios of future coastal flooding

The use of scenarios for policy analysis far into the future has been stimulated by the long-term nature of climate change and the socio-economic uncertainties surrounding greenhouse gas emissions and projections of societal vulnerability. Coastal flooding is an interesting application of the scenarios-based approach because it involves integrated use of two different types of scenario:

- Climate change projections are based on *emissions scenarios*.
- *Socio-economic scenarios* provide the context in which coastal management policy and practice will be enacted and influence the vulnerability of the coast to climate change.

The climate impacts analysis has been based upon the UKCIP02 climate scenarios for the UK (Hulme *et al*., 2002) (Table 1). These scenarios are based on runs of the Hadley Centres HadCM3 GCM, dynamically downscaled to the UK using the HadRM3 regional climate model. The UKCIP02 scenarios are presented in terms of four emissions scenarios: Low emissions, Medium-low emissions, Medium-high emissions and High emissions corresponding to the IPCC's SRES (IPCC, 2000) scenarios B1, B2, A2 and A1FI respectively. Of most relevance to the coastal analysis are projections of sea level rise. No conclusive patterns of spatial variability are detectable in comparisons of GCM predictions of sea level rise. Therefore, projections of absolute mean sea level rise, globally averaged have been super-imposed upon rates of land subsidence/emergence measured for the UK.

The Foresight Futures socio-economic scenarios (SPRU *et al*., 1999; DTI, 2002) are intended to suggest possible long term futures, exploring alternative directions in which social, economic and technological changes may evolve over coming decades. The four Foresight Futures are summarised in Table 2.

Table 2 Summary of Foresight socio-economic scenarios (DTI 2002)

	World Markets	National Enterprise	Global Sustainability	Local Stewardship
Social values	Internationalist, libertarian	Nationalist, individualist	Internationalist, communitarian	Localist, co-operative
Governance structures	Weak, dispersed, consultative	Weak, national, closed	Strong, co-ordinated, consultative	Strong, local, participative
Role of policy	Minimal, enabling markets	State-centred, market regulation to protect key sectors	Corporatist, political, social and environmental goals	Interventionist, social and environmental
Economic development	High growth, high innovation, capital productivity	Medium-low growth, Low innovation, Maintenance economy	Medium-high growth, high innovation, resource productivity	Low growth, low innovation, modular and sustainable
Structural change	Rapid, towards services	More stable economic structure	Fast, towards services	Moderate, towards regional systems
Fast-growing sectors	Health & leisure, media & information, financial services, biotechnology, nanotechnology	Private health and education, Domestic and personal services, Tourism, Retailing, Defence	Education and training, Large systems engineering, New and renewable energy, Information services	Small-scale manufacturing, Food and organic farming, Local services
Declining sectors	Manufacturing, agriculture	Public services, civil engineering	Fossil fuel energy, Traditional manufacturing	Retailing, tourism, financial services
Unemployment	Medium-low	Medium-high	Low	Medium-low (large voluntary sector)
Income	High	Medium-low	Medium-high	Low
Equity	Strong decline	Decline	Improvement	Strong improvement

There is no direct correspondence between the UKCIP02 scenarios and the Foresight Futures 2020, not least because the Foresight Futures are specifically aimed at the UK whereas the emissions scenarios used in UKCIP02 are *global* emissions scenarios. However, an approximate correspondence can be expected, as shown in Table 1. This is not the only conceivable correspondence and several alternatives are explored by the UK Climate Impacts Programme (2000), Arnell et al. (2004) and Holman et al. (2005*a*,*b*).

The coastal flood risk analysis outlined above was used to calculate the effects of climate and socio-economic change by making appropriate modifications to the model parameters to reflect the time and scenario under consideration. The input data required by the coastal flood risk analysis did not correspond exactly to the information provided in either in climate change or socio-economic scenarios. It was therefore necessary to construct approximate relationships between the variables for which scenarios information was available and the variables required for flood risk analysis. A summary of the relationships adopted in the analysis of risks from coastal flooding is provided in Table 3. A quantified estimate was made of the effect in each scenario that a given change, for example urbanisation, would have on the relevant variables in the risk model. The cumulative effect of each of the changes in the given scenario was then calculated. Where feasible, regional variation was applied to these adjustments in order to take account of, for example, regional differences in climate or demographic projections. For example, Table 4 illustrates variation in the effective standard of protection of different types of sea dikes under scenarios of climate change.

Future coastal risk is greatly influenced by coastal management policy and practice, perhaps more so than it is by changes outside the control of the coastal manager, such as climate change or economic growth. In the first instance current sea dike alignment and levels of investment in maintenance and renewal were kept the same across all scenarios. In other words it was assumed that there would be no adaptation to climate or socio-economic change or in response to increasing flood frequency. Scenarios of adaptation are examined later in this paper.

Table 3 Representation of future scenarios in risk model

Variable used in risk model	**Explanation**	**Changes that may be represented with this variable**
Standard of Protection (SoP) of flood dikes	The return period at which the flood dike is expected to overtop.	Climate change* Morphological change
Condition grade of flood dikes	An indicator of the robustness of the dikes and their likely performance when subjected to storm load.	Maintenance regimes
Location of people and properties in the floodplain	Spatially referenced database of domestic and commercial properties. Census data on occupancy, age etc.	Demographic changes Urbanisation Commercial development
Flood depth-damage relationships	Estimated flood damage (in £ per house or commercial property) for a range of flood depths	Changes in building contents Changes in construction practices
Agricultural land use classification in the floodplain	Agricultural land grade from 1 (prime arable) to 5 (no agricultural use)	Changed agricultural practices Agricultural land being taken out of use
Damage reduction factors	Measures that will reduce total flood damage, e.g. flood warning and evacuation can be reflected by factoring the estimated annual average damage	Flood warning (including communications technologies) and public response to warning Evacuation Community self-help

*For example a scenario in which if climate change is expected to increase water levels by 20% is represented by reducing the SoP of coastal dikes by an appropriate increment

Table 4 Reduction in coastal dike Standard of Protection (expressed as return period in years) in 2080s due to climate change: Example for South-East of England (Sutherland & Gouldby 2003)

Present SoP	World Markets	National Enterprise	Global Sustain-ability	Local Steward-ship
Vertical Wall				
2	<2	<2	<2	<2
5	<2	<2	<2	<2
10	<2	<2	<2	<2
20	<2	<2	<2	<2
50	<2	<2	2	2
100	3	3	4	4
200	7	8	10	9
Embankment				
2	<2	<2	<2	<2
5	<2	<2	<2	<2
10	<2	<2	<2	<2
20	<2	<2	<2	<2
50	<2	<2	2	2
100	2	2	3	3
200	4	4	5	5
Shingle Beach				
2	<2	<2	<2	<2
5	<2	<2	<2	<2
10	<2	<2	<2	<2
20	<2	<2	<2	<2
50	<2	<2	2	2
100	2	2	3	3
200	4	4	5	5

Table 5 Summary of scenarios analysis of coastal flood risk (no adaptation)

	2002		World Markets 2050s		World Markets 2080s		National Enterprise 2080s		Global Sustainability 2080s		Local Stewardship 2080s	
	Coastal	Coastal and fluvial	Coastal	Coastal and fluvial	Coastal	Coastal and fluvial	Coastal	Coastal and fluvial	Coastal	Coastal and fluvial	Coastal	Coastal and fluvial
Number of people within the indicative floodplain (millions)	2.5	4.5	3.1	6.2	3.4	6.9	3.2	6.3	2.6	4.6	2.5	4.5
Number of people exposed to flooding (depth > 0m) with a frequency > 1:75 years (millions)	0.9	1.6	1.6	3.3	1.8	3.5	1.8	3.6	1.4	2.4	1.3	2.3
Expected annual economic damage (residential and commercial properties) (£billions)	0.5	1.0	10.6	14.5	13.5	20.5	10.1	15.0	3.1	4.9	1.0	1.5
Expected annual economic damage (agricultural production) (£millions)	2.2	5.9	28.6	41.6	20.7	34.4	74.0	135.7	18.9	43.9	35.8	**63.5**
Expected annual economic damage (as % of GDP)	**0.05**	**0.09**	**-**	**-**	**0.09**	**0.14**	**0.21**	**0.31**	**0.04**	**0.06**	**0.04**	**0.05**

Results of the scenarios analysis, assuming no adaptation

The results of the flood risk scenarios analysis are summarised in Table 5, which compares the new analysis of coastal flood risk with the Foresight results for combined fluvial and coastal flooding. No discounting or inflation is applied to economic risks. Risk is estimated at time points in the future using today's prices.

Large increases in the number of people occupying coastal floodplains in the UK are envisaged in the relatively loosely regulated World Markets and National Enterprise scenarios. Most of this increase is predicted to occur by the 2050s, representing predictions of very rapid growth in the first half of this century which is envisaged to approach a limit associated with a fairly stable population and spatial constraints. Floodplain occupancy is kept stable in the Global Sustainability and Local Stewardship scenarios. However, increasing coastal flood frequency, primarily due to climate change means that even with stable numbers of people in the floodplain, the number of people at risk from flooding more frequently than 1:75 years will increase in all scenarios, assuming that there is no adaptation in response to this increasing flood frequency. Greater climate change by the 2080s, together with the increased floodplain occupancy noted above mean that the World Markets and National Enterprise scenarios will see a doubling of the number of people at risk from coastal flooding more frequently than 1:75 years.

In all scenarios annual economic damage from coastal and river flooding is expected to increase considerably over this century assuming no adaptation. The magnitude of the increase is highly scenario-dependent and greatest in the World Markets scenario, which is attributable to a combination of much increased economic vulnerability (higher floodplain occupancy, increased value of household/industrial contents, increasing infrastructure vulnerability) together with increasing flood frequency.

The risk of coastal flooding will increase more than fluvial flood risk. Whilst at present coastal flood risk is about the same as the economic risk from fluvial flooding, by the 2080s, 60-70% of the total risk will be attributable to coastal flooding, assuming no adaptation. More intensive rainfall is predicted for winter months in the UK, increasing fluvial flood risk (Evans et al. 2004). However, the combined effects of sea level rise and increased storminess mean that the effectiveness of flood protection systems on the coast will decline more rapidly. This increase in the probability of flooding is combined with a relative increase in coastal floodplain occupancy in most scenarios.

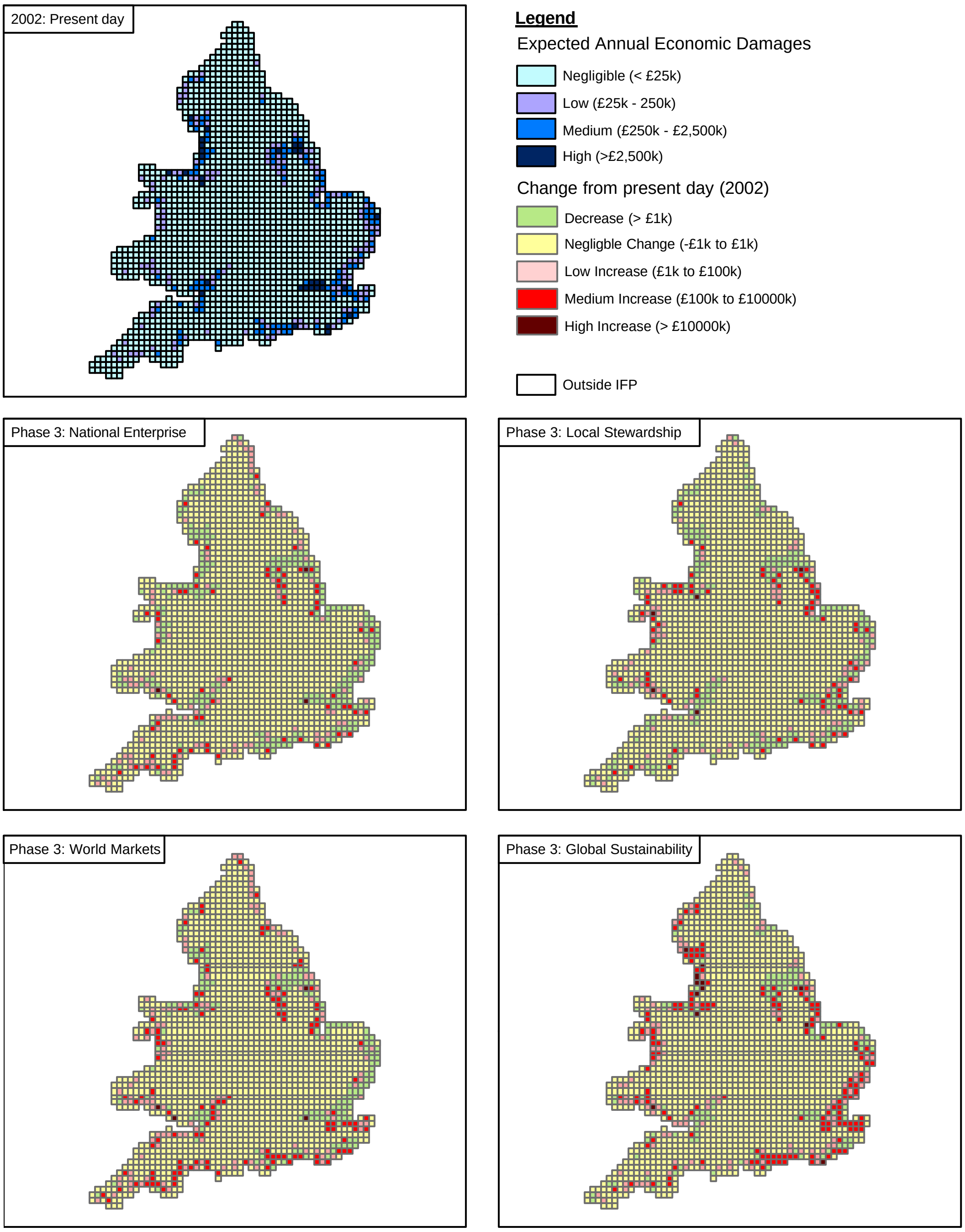

Figure 2 Coastal flood risk (expected annual damage) in the 2080s compared to present day (no adaptation)

Figure 2 shows the distribution of the increase in expected annual economic damage for the 2002 analysis and the four scenarios for the 2080s, relative to the estimated risk in 2002. Increasing risk is predicted to be concentrated in broadly the same areas as where it is currently highest, but without the added influence of higher relative sea levels in the south-east of England. The sensitivity of the low-lying Humber estuary to sea level rise is also noticeable.

Adaptation scenarios

The analysis described in the previous section was based upon the assumption that present day coastal management practices and standards of coastal flood protection are continued in future. In fact these practices and standards will be modified in response to changing risks and society's expectations for risk reduction. In other words, coastal management policies and practices are scenario-dependent. In order to analyse the amount by which the risk estimates presented above may be reduced, a set of coastal management scenarios were established. These represent portfolios of policies and practices intended to manage the probability and consequences of coastal flooding and erosion. Table 6 summarises the approaches to coastal management under the four scenarios. These scenarios are not policy prescriptions. They are merely intended to illustrate in an internally consistent way alternative plausible futures in order to inform long term decision making.

The World Markets scenario is the wealthiest of the scenarios: by the 2080s GDP could be ten times (in real terms) its present value. This therefore is a wealthy society that can afford to protect against the risks to which it is exposed. There will be a tendency to provide coastal management (and many other services) through markets rather than through government. This means that protection against the risks of flooding will to a great extent be determined by ability to pay. Protection of the environment will also be increasingly privatised, with those environmental assets and services that generate economic rents being protected and enhanced. An emphasis on economic efficiency and relative neglect of environmental considerations means that in the World Markets scenario flood management will be dominated by hard engineering measures. These will be combined with the fruits of technological progress, for example in the field of communications.

Table 6 Coastal management scenarios

	World markets	Global sustainability	National enterprise	Local stewardship
Summary	*Free market provision of measures to reduce impacts of flooding and hedge risks. Major engineering measures to keep pace with increasing risk.*	*Strategic regulation of development, management of runoff and reduction of impacts. Strategic soft coastal engineering. Universal protection through public-private schemes*	*Low regulation and limited emphasis on the environment. Piecemeal engineering measures to reduce risk, centrally-managed with limited local capabilities*	*National wealth does not keep pace with increasing risk. Abandonment of coastal floodplains. Reinstatement of natural systems. Diversity of approaches across UK regions*
Coastal management	Lack of economic justification for coast protection results in collapse of some schemes and an increase in sediment supply. New hard dikes in high value areas. Measures to improve amenity, mainly privately-funded.	Strategic coastal management, regionally and nationally coordinated Some improvement in sediment supply to beaches. Strategic attempts to modify morphology linked to environmental and conservation goals	Piecemeal approaches to coastal management result in continued reduction in sediment supply to beaches. Measures to improve amenity.	Natural coastal processes reinstated.
Managed retreat	In areas of abandoned agricultural production	Strategic managed retreat in rural and some isolated urban areas	Parochial pressures limit opportunities for managed retreat	Widespread retreat
Estuary barrages	Barrage construction as flood protection and to reduce energy insecurity towards 2050s.	Thames barrier upgrade on present alignment. No new barrages.	Barrage construction to reduce dependency on gas imports.	Thames barrier upgrade on present alignment. No new barrages.
Vulnerability to flooding and coastal erosion	Increasing urbanisation in floodplains (15% to 22% by 2050). Weak building regulations mean new construction is vulnerable to flooding. Vibrant market for flood proofing products. Ad hoc provision by wealthy. Vibrant unregulated insurance market. Non-universal availability. Weak role of local authorities in recovery, except in wealthier areas.	Stable urban extent (but increasing density) in floodplains. National and European building regulation and dissemination of best practice. Subsidy for flood proofing. National negotiation/regulation of insurance arrangements. Risk sharing (public/private). Fairly strong role of local authorities in recovery.	Increasing urbanisation in floodplains (15% to 19% by 2050). Weak building regulations mean new construction is vulnerable to flooding. Limited progress in flood-proofing of vulnerable buildings. Some private provision. Local setting of insurance premiums. Non-universal availability. Weak role of local authorities in recovery	Limited urban development in rural areas. Emphasis on sustainability in building regulations. Community involvement in insurance provision. Strong role of local authorities in recovery
Managing flood events	Limited efforts to coordinate flood event management Private subscription flood warning services (making use of new ICT). Limited/no provision for vulnerable.	Concerted flood awareness raising National (and European) provision of flood forecasting, flood fighting, warning and evacuation.	National provision of flood forecasting, flood fighting, warning and evacuation. Localised use of temporary flood defence measures	Localised provision of flood forecasting, flood fighting, warning and evacuation. Localised use of temporary flood defence measures

The National Enterprise scenario is less wealthy than the World Markets scenario and more inward in its outlook. However, it is still a consumerist-oriented scenario with economic development rated as more important than environmental quality of coasts. It will be characterised by piecemeal and reactive coastal engineering measures. Emphasis will be upon protection of strategic industries, including agriculture.

In the Global Sustainability scenario Government plays a leading role in providing a range of structural and non-structural measures for coastal management, ranging from regulation of development to measures to help recovery after flooding, particularly for more vulnerable sectors of society. Society is willing to forgo some economic benefits, for example in terms of unlimited urban development, in order to reduce risks and share them more equitably. Flood dike engineering is employed, particularly in dense urban areas, but there is an emphasis on soft engineering to work with, and where possible restore, natural processes. There is emphasis upon monitoring of and adaptation to change and implementation measures that are resilient to future uncertainties.

The Local Stewardship scenario is characterised by regionally devolved and, at the same time, environmentally conscious approaches to coastal management. A variety of approaches is envisaged across different regions of the UK. Growth in national wealth is lowest in the Local Stewardship scenario, and is not expected to keep pace with the rate of increase of coastal flood risk. A consequence will be abandonment of some coastal floodplains, with communities working to reinstate natural systems. At the same time there is an emphasis on agricultural self-sufficiency, so some key agricultural land will be preserved regionally.

The adaptation scenarios described above and in Table 6 were implemented by modifications to the database of coastal dikes and floodplain use and occupancy, representing the effect of structural and non-structural measures. Structural measures vary in importance according to scenario, but are included to some extent in each scenario and were implemented in terms of changing Standards of Protection provided by coastal dikes. The starting point was the current standards, which are expressed in terms of an indicative range (Table 7). A land use band A* has been added to the customarily used land use bands (A to E) to reflect the particularly high standard of tidal flood protection in London.

Table 7 Scenarios of standards of coastal flood protection (expressed as return period, in years, at which significant overtopping is expected to occur)

Land use Band	Comment	**Present**	**World Markets**	**National Enterprise**	**Global Sustainability**	**Local Stewardship**
			Above present in urban areas. No new protection for agricultural areas.	Above present in urban areas. Improved standard for agricultural areas.	As present, apart from highest value urban areas. No new protection in low grade agri. areas.	General reduction in standard, apart from highest value urban areas, where standard is maintained.
A*	Exceptional urban areas (i.e. London)	1000	10000	1000	1000	500
A	Typically large urban areas at risk from flooding	100 - 300	500	500	200	100
B	Typically less extensive urban areas with some high grade agricultural land	50 – 200	200	200	100	50
C	Typically large areas of high grade agricultural land at risk from flooding and impeded drainage with some properties also at risk from flooding	10 – 100	25	50	25	25
D	Typically mixed agricultural land with occasional, often agricultural related, properties at risk from flooding. Agricultural land may be prone to flooding or waterlogging.	2.5 - 20	No new protection	10	No new protection	10
E	Typically low grade agricultural land, often grass, at risk from flooding or impeded land drainage, with isolated agricultural properties at risk from flooding	1 - 5	No new protection	5	No new protection	No new protection

The baseline analysis showed that economic damage, assuming no adaptation will be greatest in the World Markets and National Enterprise scenarios because of increasing probability of flooding, the growth in value of areas at risk of flooding and because of the more flood-vulnerable nature of development. However, taking the scenarios as a starting point, we also believe that social and individual expectations for risk reduction in these more consumerist-orientated scenarios will be higher. Balanced against this is the question of affordability. For instance, under the National Enterprise scenario the resources available for flood protection are likely to be smaller due to lower economic growth (GDP growth per annum in the 2050s is taken as +1.75% as opposed to +3% for World Markets (UKCIP 2001)), and this will feed through into lower Standards of Protection. Resources for coastal management will be further stretched in the National Enterprise scenario by the need to protect strategic industries, including agriculture.

In the Global Sustainability scenario and, in particular, the Local Stewardship scenario coastal flood risk is projected to increase at a slower rate so there will be less societal expectation for risk reduction. On the other hand, the Global Sustainability scenario will be characterised by government efforts to manage risks to people and the environment in a concerted and pre-emptive way. Standards of flood protection in the Local Stewardship scenario may show a great deal of national variation, reflecting local decision-making, a feature that is impossible to represent in Table 7.

In the globalised scenarios (World Markets and Global Sustainability) there will be much less emphasis on agricultural production than in National Enterprise and Local Stewardship. This is reflected in a withdrawal of flood protection from agricultural land other than of a high grade. The mechanism of this withdrawal will however be different, and is envisaged to occur in an unmanaged fashion in the World Markets scenario whilst it will be managed and accompanied by environmental restoration measures in the Global Sustainability scenario.

The changed coastal management practices and Standards of Protection were implemented in the databases of coastal dikes. Table 8 presents the statistics of how coastal dike standards were modified in the adaptation analysis. The one-off capital costs of these modifications were estimated using typical present day capital costs of works (Evans et al. 2004) so do not reflect changes in future productivity of the construction industry, which will be scenario-dependent. The costs represent the typical total capital cost of constructing a new coastal dike and include design and supervision costs but exclude costs associated with land purchase, compensation or significant environmental mitigation measures. Maintenance costs are also excluded. The costs are presented as one-off upgrade costs and no consideration is given to the timing or phasing of these works. Recall also that these are costs only of dike raising and costs of the other measures listed in Table 6, for example the opportunity cost of restricting development in floodplains, have not been evaluated.

Costly engineering work is expected to take place on the south and east coasts of the UK. The total cost of engineering works (Table 8) is about three times greater in the World Markets and National Enterprise scenarios than it is in the Global Sustainability and Local Stewardship scenarios. This reflects the greater rate of increase in risk in these scenarios and the increased reliance on engineering measures as opposed to non-structural flood risk reduction measures, which are not included in the costing.

Table 8 Scenarios of coastal dike upgrades

Coastal dike standards (total lengths of dikes in km)	World Markets	National Enterprise	Global Sustainability	Local Stewardship
>1000	173	2	2	0
200-1000	10761	10386	7351	2
50-200	0	1023	864	8187
5-50	729	160	1829	2891
No new protection	772	864	2389	1355
Total cost (£million, today's prices)	40,030	38,440	12,880	12,170
Coastal proportion of total (fluvial and coastal) upgrade costs	53%	50%	58%	55%

Further evidence of increasing costs of coastal flood protection was provided by Burgess & Townend (2004) who estimated that by the 2080s the annual cost of coastal dike structures will be between 150% and 400% of the current levels (depending on the emissions scenario). Costs were less sensitive to geographic location than to emissions scenario. The costs were predicted to increase because structures were found to be very vulnerable to increases in water depth. This is because the design wave condition for the majority of UK coastal dike structures is depth limited. This means that raised water levels, or steeper foreshores, result in an immediate change in the design condition. This problem is amplified because the growth in energy of the design wave increases with the square of the increase in water depth.

The results of the coastal flood risk analysis including adaptation are given in Table 9. Both the probability of flooding and the associated flood risk have been substantially reduced. The magnitude of the reduction is greater in the World Markets and National Enterprise scenarios, reflecting the higher investment in engineering works under these scenarios. Despite withdrawal of flood protection from some agricultural areas, the proposed scenarios also show much reduced agricultural damage, compared with the baseline.

A sensitivity analysis reported by Evans et al. (2004*b*), which relates to fluvial and coastal flooding, but is based on the same methodology as presented here, indicated that if the non-structural measures in the Global Sustainability scenario were not implemented and replaced by engineering measures, the cost of engineering works would almost double. This illustrates the amount by which non-structural measures could potentially contribute to reducing flood risk.

Table 9 Results of coastal flood risk analysis including adaptation

	Present day	World Markets	National Enterprise	Global Sustainability	Local Stewardship
Number of people exposed to flooding (depth > 0m) with a frequency > 1:75 years (millions)	0.9	0.09	0.08	0.4	0.6
Expected annual economic damage (residential and commercial properties) (£billions)	0.5	0.36	0.23	0.81	0.32
Expected annual economic damage (agricultural production) (£millions)	2.2	1.3	1.5	3.5	8.4

Conclusions

Scenarios analysis can form the basis for long term planning and decision making, for example in relation to coastal management, by illustrating a range of possible futures. Building on the analysis of risks from fluvial and coastal flooding conducted in the Foresight project (Evans et al. 2004*a*,*b*), in this paper we have developed scenarios of future coastal flood risk. Socio-economic and climate scenarios have been used in combination in order to generate self-consistent projections of potential future variation in coastal flood risk. In all scenarios the frequency of coastal flooding and associated economic risk is set to increase. The increase is greatest in high-emission scenarios, particularly in the latter half of the 21st century. The risk of coastal flooding is strongly modified by societal vulnerability and the scenarios analysis demonstrates how widely that vulnerability may vary according to the trajectory of socio-economic change.

Calculated in real terms, a major driver of increasing flood risk is the increasing value of domestic and commercial buildings and their contents. However, all of this loss may not be perceived to be real, in that damage due to flooding as a proportion of total wealth will grow much more slowly. The extent to which losses are perceived to be harmful will determine willingness to pay to reduce risk through taxation or measures provided by the market (insurance, subscription flood protection, flood proofing *etc.*).

In the absence of adaptation, coastal flooding makes an increasing contribution to flood risk from rivers and coasts combined, increasing from roughly 50% in 2002 to 60-70% in the 2080s. This reflects the effect of sea level rise on the coast, and the continuing development of coastal floodplains under some scenarios.

The risk analysis described in this paper has not estimated the risks of loss of life due to flooding. The increasing economic risks in the absence of adaptation are likely to be accompanied by increasing risk of loss of life, though this will be mitigated depending on the effectiveness of flood warning and evacuation measures. The effects of flood damage and disruption to coastal infrastructure such as ports and railway lines are difficult to estimate. However, it is projected that unless specific measures are taken to reduce the vulnerability of infrastructures then flood damage will be significant and could impact upon a large proportion of the population, including many who do not live in coastal floodplains.

Potential adaptation to climate and socio-economic change by engineering of flood dikes or retreat from coastal floodplains was implemented spatially in a GIS covering all of England and Wales for four future scenarios. The analysis indicates that engineering works with a one-off capital cost of £12-£40 billion in today's prices could reduce coastal flood risk to a factor of 0.4-1.6 times its current level. These cost estimates are believed to low. Non-structural measures, such as land use planning and flood warning, could also make a considerable contribution to reducing this risk, though no attempt has been made to estimate the cost of these measures.

Analysis of environmental and socio-economic phenomena over a timescale of 30-100 years in the future involves formidable uncertainties. Changes in some climate variables, for example extreme sea levels are particularly difficult to predict. Socio-economic change, which on a global scale leads to changing greenhouse gas emissions trajectories and on the UK scale also determines economic and social vulnerability to flooding, is even more difficult to predict and, it is argued, succumbs only to a scenarios-based approach that can merely illustrate some of the potential range of variation between different futures. Precise results have been quoted for the quantified risk analysis but they should be interpreted merely as providing an indication of the magnitude, rate and spatial distribution of potential change rather than being firm predictions.

Notwithstanding the uncertainties in the analysis, it provides important new insights for policy-makers. 'Business as usual' in coastal management over the next century will be accompanied by large increases in flood damage, the magnitude of which will depend on the trajectory broader socio-economic change. Climate change makes a contribution to this process but the severity of its impacts are modulated by socio-economic context and the degree of adaptation to change.

Attempts to control the increase in coastal flood risk will need to address these multiple drivers in an integrated manner. There are clear spatial patterns to the distribution of flood risk and the location of its projected increases. Packages of policy response need to be tailored to reflect the characteristics of particular localities.

At many coastal sites (including major industrial and infrastructure facilities) there is very limited scope to retreat inland without major economic and/or social implications. The increasing frequency and severity of loading of coastal flood dikes means that they will be increasingly costly to repair or replace. Continued reduction in sediment supply to coasts will be reflected in a narrowing of beaches and deterioration in amenity and ecological value of coasts. Avoidance of these losses requires a long term strategic approach to coastal zone management.

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References

Alexandersson, H., Tuomenvirta. H., Schmith. T. and Iden. K. 2000 Trends of storms in NW Europe derived from an updated pressure data set. Climate research 14(1) 71-73.

Arnell, N.W., Livermore, M.J.L., Kovats, S., Levy, P.E., Nicholls, R.J., Parry, M.L. & Gaffin, S.R. 2004 Climate and socio-economic scenarios for global-scale climate change impacts assessments: characterising the SRES storylines. Global Environmental Change 14(1) 3-20.

Bacon, S. and Carter, D.J.T. 1991 Wave climate changes in the North Atlantic and North Sea, International Journal of Climatology 11 545-558.

Bacon, S., and D.J.T. Carter, D.J.T. 1993 A connection between mean wave height and atmospheric pressure gradient in the North Atlantic, International Journal of Climatology 13 423-436.

Burgess, K. & Townend, I. 2004 The impact of climate change upon coastal defence structures. In proc. 39th Defra flood and coastal management conference, 14 pages.

Carretero, J. C., Gomez, M., Lozano, I., de Elvira, A. R., Serrano, O., Iden, K., Reistad, M., Reichardt, H., Kharin, V., Stolley, M., von Storch, H., Gunther, H., Pfizenmayer, A., Rosethal, W., Stawarz, M., Schmith, T., Kaas, E., Li T., Alexandersson, H., Beersma, J., Bouws, E., Komen, G., Rider, K., Flather, R., Smith, J., Bijl, W., De Ronde, J., Mietus, M., Bauer, E., Schmidt, H., Langenberg, H. 1998 Changing Waves And Storms In The Northeast Atlantic? Bulletin of the American meteorological society 79(5), 741-760.

Debernard, J., Sætra, Ø. and Røed, L. P. 2002 Future wind, wave and storm surge climate in the northern North Atlantic. Climate research, 23, 39-49.

DTI, 2002, Foresight futures 2020: revised scenarios and guidance, Department of Trade and Industry, London. DTI/Pub 6123/1k//6/02/NP, URN 02/1038.

Eurosion, 2004. Living with coastal erosion in Europe: sediment and space for sustainability. major findings and policy recommendations of the EUROSION project. European Commission, Directorate General Environment, Service contract B4-3301/2001/329175/MAR/B3.

Evans, E.P., Ashley, R., Hall, J.W., Penning-Rowsell, E.C., Saul, A., Sayers, P.B., Thorne, C.R., and Watkinson, A. *Foresight Flood and Coastal Defence Project: Scientific Summary: Volume I, Future risks and their drivers*. Office of Science and Technology, London, 2004*a*. 366pp.

Evans, E.P., Ashley, R., Hall, J.W., Penning-Rowsell, E.C., Saul, A., Sayers, P.B., Thorne, C.R., and Watkinson, A. *Foresight Flood and Coastal Defence Project:*

Scientific Summary: Volume 2, Managing future risks. Office of Science and Technology, London. 2004*b*. 416pp.

Gulev S., K, and Hasse, L. 1999 Changes of wind waves in the north Atlantic over the last 30 years. Int. J Climatology 19(10), 1091-1117.

Hall, J.W., Dawson, R.J., Sayers, P.B., Rosu, C., Chatterton, J.B. & Deakin, R.: 2003, A methodology for national-scale flood risk assessment. Water and Maritime Engineering, 156(3), 235-247.

Halcrow Group Ltd, HR Wallingford & John Chatterton Associates, 2001. National appraisal of assets at risk from flooding and coastal erosion, including the potential impact of climate change. Defra Flood Management Division, 64 pages.

Hanson, H., Aarninkhof, S.G. J., Capobianco, M., Jimenez, J., Larson, M., Nicholls, R. J., Plant, N. G., Southgate, H. N., Steetzel, H., Stive, M. J. F. & Vriend, H. J. de 2003 Modelling of coastal evolution on yearly to decadal timescales. J. of coastal research, 19(4), 790-811.

Hargreaves, J.C., Carter, D.J., Cotton, P.D., & Wolf, J. 2002 Using the swan wave model and satellite altimeter data to study the influence of climate change at the coast. The global atmosphere and ocean system, 8(1), 41–66.

Holman, I.P., Rounsevell, M.D.A,. Shackley, S., Harrison, P.A., Nicholls, R.J., Berry, P.M. & Audsley, E. 2005*a* A regional, multi-sectoral and integrated assessment of the impacts of climate and socio-economic change in the UK: I Methodology. Climatic change, in press.

Holman, I.P., Nicholls, R.J., Berry, P.M. Harrison, P.A. & Audsley, E. 2005*b* A regional, multi-sectoral and integrated assessment of the impacts of climate and socio-economic change in the UK: II Results. Climatic change, in press.

Hosking, A. & McInnes, R. 2002 Preparing for the impacts of climate change on the central south coast of England: a framework for future risk management. J. of coastal research, special issue 36, 381-389.

Hulme, M., Jenkins, G. J., Lu, X., Turnpenny, J. R., Mitchell, T. D., Jones, R. G., Lowe, J., Murphy, J. M., Hassell, D., Boorman, P., McDonald, R., Hill, S. 2002 Climate change scenarios for the UK: UKCIP02 scientific report, Tyndall Centre, 112pp.

Langenberg H., Pfizenmayer A., von Storch H and Sundermann, J.1999 Storm-related sea level variations along the North Sea coast: natural variability and anthropogenic change. Continental shelf research 19, 821-842.

Lowe, J. A., Gregory, J. M. and Flather R. A. 2001 Changes in the occurrence of storm surges around the United Kingdom under a future climate scenario using a dynamic storm surge model driven by the Hadley Centre climate models. Climate dynamics 18, 179-188.

Penning-Rowsell, E.C., Johnson, C., Tunstall, S.M., Tapsell, S.M., Morris, J., Chatterton, J.B., Coker, A. and Green, C., 2003. The Benefits of Flood and Coastal Defence: Techniques and Data for 2003. Middlesex University Flood Hazard Research Centre.

SPRU, CSERGE, CRU, PSI, 1999. Socio-economic futures for climate impacts assessment, Final Report. Science and Technology Research, University of Sussex.

Sutherland, J and Gouldby, B. 2003 Vulnerability of coastal defences to climate change. Water and Maritime Engineering, ICE, 156(WM2), 137-145.

Tsimplis M. N., Woolf, D. K, Osborn, T. J, Wakelin, S, Wolf, J, Flather R, Shaw, A. G. P, Woodworth, P, Challenor, P, Blackman, D, Pert, F, Yan, Z and Jevrejeva, S. (in press) Towards a vulnerability assessment of the UK and northern European coasts: the role of regional climate variability. Phil. Trans. R. Soc. A. Lond.

UK Climate Impacts Programme, 2000. Socio-economic scenarios for climate change assessment: a guide to their use in the UK Climate Impacts Programme. UKCIP, Oxford.

Voortman, H.G., Van Gelder, P.H.A.J.M, and Vrijling, J.K. (2003) Risk-based design of large-scale flood defence systems. In: J. McKee Smith (ed) Coastal Engineering 2002, Proceedings of the 28th International Conference, Cardiff UK, July 8-12, 2002. New Jersey: World Scientific, vol.2: 2373- 2385

Vrijling, J. K. (2001) Probabilistic design of water defence systems in The Netherlands. Reliability Engineering and System Safety 74: 337–344

Woolf, D.K., Challenor, P.G. & Cotton, P.D, 2002 Variability and predictability of the North Atlantic wave climate. J. of geophysical research-oceans 107(10), art. no. 3145.

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