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Nick Brooks, Robert Nicholls, Jim Hall:

Sea Level Rise: Coastal Impacts and Responses

Externe Expertise für das WBGU-Sondergutachten
"Die Zukunft der Meere – zu warm, zu hoch, zu sauer"

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Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen
Geschäftsstelle
Reichpietschufer 60–62, 8. OG.
10785 Berlin

Telefon (030) 263948 0
Fax (030) 263948 50
E-Mail wbgu@wbgu.de
Internet http://www.wbgu.de

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Expertise for WBGU on Oceans and Global Change

Sea-Level Rise: Coastal Impacts and Responses

Nick Brooks[1], Jim Hall[2], Robert Nicholls[3]

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[1] Visiting Fellow, Tyndall Centre for Climate Change Research and School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK. Email: nick.brooks@uea.ac.uk.
[2] Department of Civil Engineering, University of Newcastle, School of Civil Engineering, Cassie Building, University of Newcastle upon Tyne, Newcastle NE1 7RU, UK. Email: jim.hall@bristol.ac.uk
[3] School of Civil Engineering & the Environment, University of Southampton, Highfield, Southampton SO17 1 BJ, UK. Email: rjn@soton.ac.uk.

1 INTRODUCTION

In the 1990s it was estimated that 21 and 37 per cent of the global population lived within 30 km and 100 km, respectively, of the coast (Cohen *et al.* 1997; Gommes *et al.* 1997). Population densities in coastal areas are three times the global mean, and it is estimated that 50% of the world's population will live within 100 km of the coast by 2030 (Small and Nicholls, 2003). Human settlements, including many large cities, are also concentrated near or on coastlines, and a large proportion of global economic productivity derives from coastal areas (Turner *et al.*, 1996). Trends towards urbanisation are likely to increase population densities in low-lying coastal areas; the population living within 30 km of the coast is estimated to be growing at twice the global average reflecting coastward migration, and GDP growth in coastal areas exceeds the national average in many countries (Bijlsma *et al.*, 1996). Coastal zones are therefore of great importance as zones of settlement and play a vital role in the economic well-being of many nations.

Sea level rise (SLR) will have profound implications for many coastal populations and the systems on which they depend. The consequences of SLR for a given population in a particular locality will depend on the following factors:

- the amount of SLR locally (termed relative sea-level rise)
- the effects of this SLR on hazards such as storm surges
- the interaction of SLR with other climate change hazards such as changes in the frequency and severity of storms
- the geomorphological response of coasts to SLR, which will in turn depend upon natural geomorphological processes and human interventions in the coastal system
- the physical exposure of the population and associated systems to the immediate impacts of SLR and related coastal hazards
- the ability of the population and related systems to cope with these impacts.

While the emphasis on this paper is on exposure to SLR-related hazards (inundation, storm surges, coastal flooding) we recognise that the risk to a system is a function of both exposure to these hazards and of the resilience of that system (broadly speaking, the ability of a system to sustain itself in the face of disturbance). For coastal systems risk is heavily influenced environmental and geographical factors such as elevation above mean sea level, distance from the shoreline, and the effectiveness of artificial coastal defences or natural barriers such as wetlands, dunes, coral reefs or mangroves which can dissipate the energy of hazards such as storm surges. However, under existing management regimes such natural barriers are likely to provide little defence against long-term SLR. Risk will also depend on the resilience of systems to the immediate impacts of coastal hazards, for example the quality of physical infrastructure, the preparedness of communities, and the ability of a system to recover from damage associated with coastal hazards. Recovery will be aided by the availability of financial and other resources. In the longer term, risk will evolve according to the ability of systems to adapt to evolving hazards; this "adaptive capacity" will depend on a number of factors including the availability of resources, the availability of information on the likely evolution of coastal hazards, and the availability and cost of technology that may assist in adaptation.

This paper addresses each of the above issues at the global level, with examples from specific regions and locations where appropriate. The paper is divided into two parts, with the first section addressing the potential physical impacts of SLR on coastal areas. Issues of exposure are addressed first, based on a number of plausible SLR projections for the next millennium. Sea levels will continue to rise for many centuries, even if atmospheric greenhouse gas concentrations (which are likely to remain the principal driver of SLR for the foreseeable future) are stabilised at relatively low levels (Nicholls and Lowe, 2004; Wigley, 2005). If emissions are not stabilised, much larger rises in sea level are possible over this time span, exceeding a 10-m rise over the next millennium if the Greenland and Antarctic ice sheets disintegrate (Lenton et al., 2005; Nicholls and Lowe, 2005). A millennial timescale is therefore appropriate for studies of the physical vulnerability of coastlines based on elevation above mean sea level. Exposure to different rates of SLR covering the range of possible change from 10 cm per century to 2 m per century (i.e., 1-m up to a 20-m global-mean rise in sea level) is assessed using global datasets analysed in a GIS environment to produce "first order" calculations of exposure assuming no adaptation or coastal protection. The literature is also reviewed to develop estimates of land losses to sea-level rise including possible adaptation.

Estimates of geographic exposure are complemented by estimates of population exposure and impacts of SLR on GDP. As uncertainties in projections of population and socio-economic trends become greater with time, such projections focus on socio-economic scenarios for the 21st century. Results are compared across studies of potential increases in coastal flood risk, and are discussed in the context of research into the effects of climate change and SLR on coastal hazards. The role of erosion in coastal morphological change is addressed through literature review and using results from studies with the SCAPE model. The intrusion of salt water into fresh water aquifers as a result of SLR, and the effects of SLR on coastal and marine ecosystems, are also discussed.

The following section of the paper (Section 2: Impacts) begins with the description of a set of illustrative SLR scenarios based on plausible rates of change arising from thermal expansion of the oceans, the melting of glaciers, and the collapse of large ice sheets. These scenarios frame the discussion of impacts that follows.

Section 3 of the paper (Responses) addresses potential means of adapting to SLR. Different adaptation options are considered, and their viability discussed, including "hard" coastal protection schemes involving large-scale engineering, management of natural systems, managed retreat and relocation, and the enhancing of resilience in coastal systems. The development of "optimal" portfolios of adaptation options based on combinations of defence, retreat and abandonment is also discussed.

2 IMPACTS

2.1 Methodology

2.1.1 Sea-level rise scenarios

Projections of SLR are addressed in detail elsewhere in this volume. Here we use a number of plausible "illustrative" SLR scenarios. For the sake of simplicity and in the absence of detailed information beyond 2100, rates of SLR are assumed to be constant and are projected for the next 1000 years, although more attention is paid to the 21st and 22nd centuries, for which a higher temporal resolution is employed, than for later periods. The scenarios are thus defined in terms of average increases in global mean sea level per century, and are used to assess geographical and population exposure using in a GIS environment and a literature review. The assumed increases in global mean sea level range from 10 cm to 2 m per century, incorporating low, medium, and high values within the range of possible futures. Individual scenarios are described below, along with associated plausible driving mechanisms.

(a) 10 cm per century
A mid-range value for SLR assuming greenhouse gas (GHG) *concentrations* were to remain constant at 2000 levels, according to Wigley (2005). While this is obviously an unrealistic assumption, this value represents a reasonable lower limit on future SLR, although it should be noted the range of estimates for constant GHG concentrations extends from near-zero to 30 cm. It implies a 1-m rise by the year 3000, which is roughly consistent with projections for the same emission scenarios by Nicholls and Lowe (2004).

(b) 25 cm per century
A mid-range value (with extremes at 7 and 50 cm) for SLR assuming GHG *emissions* were to remain constant at 2000 levels (Wigley, 2005), close to the 30 cm per century upper limit for the no further emissions case. It should be noted that a SLR or 2m is emerging as a possible "guardrail" value, i.e. an upper limit that should not be exceeded. Such a SLR guardrail requires stabilisation of GHG concentrations below about 450 ppm; stabilization at or above this value (associated with a rise in global mean surface temperature of about 1.5º C (Warren, 2005)) is associated with a high risk of the slow disintegration of the Greenland Ice Sheet, which would increase sea levels by up to 7 m in total, but over an uncertain timeframe of 1000 years or even longer (Lowe and Gregory, 2005). GHG emissions are certain to rise in the immediate future, and may initially overshoot any stabilization target; this fact, coupled with the long response time of sea levels to increases in air temperature, means that Wigley's constant emissions figures are probably applicable over the coming centuries for low stabilization targets.

(c) 50 cm per century
The upper estimate for Wigley's stabilisation at current emissions levels, and in the middle of the IPCC (2001) range of estimates based on six "illustrative" emissions scenarios.

(d) 1 m per century
A plausible linear trend assuming the complete loss of the Greenland Ice Sheet over the coming millennium (Nicholls and Lowe, 2005), added to contributions from thermal expansion, the melting of terrestrial ice in other regions, and a partial collapse of the West Antarctic Ice Sheet (WAIS). The Greenland Ice Sheet (GIS) has been thinning in recent decades (Paterson and Reeh, 2001), and new data indicate that mass loss is much greater than previously thought in some sectors of the GIS (Bøggild *et al.*, 2004). A total collapse of the GIS would add some 7 m to global mean sea level, occurring over the next thousand years or so (Gregory *et al.*, 2004). A combination of ice-core data and numerical modelling indicates that melting of the GIS "plausibly contributed 4-5.5 m to the [higher] sea-level" during the last interglacial (some 120 thousand years ago) (Cuffey and Marshall, 2000). Simulations of warming associated with atmospheric CO_2 concentrations of 450 ppm and greater indicate that "the Greenland ice-sheet it likely to be eliminated by anthropogenic climate change unless much more substantial emission reduction are made than those envisaged by the IPCC", with collapse of the GIS resulting from increases in *local* temperatures of some 3° C (Gregory *et al* 2004). The nature of sea level rise over the coming centuries will be heavily influenced by the rate and nature of the likely disappearance of the GIS, assuming that action is not taken to keep greenhouse gas concentrations below about 450 ppm.

(e) 1.5 m per century
A plausible linear trend until around assuming contributions to SLR as in (d) with an additional 0.5 m per century from the loss of the WAIS (Vaughan and Spouge, 2002). It should be noted that Oppenheimer (1998) suggests a more rapid SLR from the WAIS, stating that the loss of the WAIS could contribute some 60-120 cm per century to SLR over the course of a collapse occurring over some 500 - 700 years. Oppenheimer (1998) suggests that we may disregard the possibility of a sudden collapse of the WAIS leading to a 4 – 6 m sea-level rise in the twenty first century, due to the lack of any convincing model for such a process, but that the likelihood of collapse increases substantially thereafter. Vaughan and Spouge (2002), after extensive expert consultation found considerable disagreement, particularly with regard to the longer term prospects of a collapse of the WAIS; however, they also describe evidence that the WAIS has collapsed in the past, illustrating the its potential instability. Nicholls *et al.* (2006) examine the impacts of a WAIS collapse, based on scenarios in which this process results in additional SLR ranging from 0.5 to 5 m per century from 2030.

(f) 2 m per century
A plausible but extreme linear trend until for the next millennium, based on the loss of the Greenland Ice Sheet as in (d) and (e) combined a high-end estimate of a contribution of 1 m per century from the WAIS (Vaughan and Spouge, 2002).

2.1.2 Calculation of land at risk, population exposure and economic assets

A first-order estimate of potential losses of land to SLR was arrived at by integrating digital elevation data with the above sea-level rise scenarios using a geographical information system (GIS). Elevation data are from the SRTM Enhanced Global Map developed by ISciences (2003). This analysis also used tidal range data from the map of Davies (1980) as contained in the LOICZ typology dataset (Maxwell and Buddemeier, 2003), and administrative unit boundaries from the GIS dataset of 1095 first-level sub-national administrative boundaries included in the Digital Chart of the World (DCW) (ESRI, 2002; Deichmann et al., 2001). In the first step average tidal range values were estimated for all coastal administrative units. Then, based on these values and using the elevation dataset, land area loss as a function of sea-level rise was calculated for each administrative unit and for the various scenarios of sea-level rise listed above. In this step, low-lying inland areas and water bodies were masked out.

First-order estimates of population exposure to SLR were calculated by combining the above data with data from version 3 of the Gridded Population of the World dataset (GPW3: CIESIN and CIAT, 2004) and from the 2003 Landscan dataset (see also Dobson et al., 2000). These datasets were used to calculate resident coastal population counts for the areas lost based on 1995 data. Population projections were used to calculate future potential population exposure, assuming stabilisation of coastal populations by 2080.

Economic impacts were evaluated in terms of the proportion of global GDP in exposed areas, and on the basis of literature review.

2.2 Potential land lost due to SLR

2.2.1 Land at risk of inundation

Figure 2.2.1 shows global estimates of land elevations above present high water as a function of elevation. The detailed methods and the datasets used are outlined by Nicholls et al (in review) and comprise the best global datasets currently available. Figure 2.2.1 illustrates that there are large areas within 1-m elevation of present high water, partly reflecting the extensive areas of natural and claimed intertidal habitat around the world's shores. Above 1-m elevation, land area is an almost linear as a function of elevation, although the threatened area does diminish slowly with elevation. Figure 1 shows that over 5×10^6 km^2 lies within 10 m of mean high-water levels and 8×10^6 km^2 lies within 20 m of mean high-water levels across the globe. This illustrates the large areas that are threatened by the high-end sea-level rise scenarios considered in the previous section.

Figures 2.2.2 - 2.2.6 show potential coastal land lost from inundation only, in the event of an increase in global mean sea level of 20 m, assuming no protection and neglecting erosion, for the European region, south and east Asia, North America, South America and Africa. This SLR assumes the complete collapse of the GIS and WAIS, with additional contributions from thermal expansion and the melting of glaciers and terrestrial ice sheets, and would occur over a timescale of the order of a millennium. This scenario represents an extreme worst case, but is plausible in the absence of stringent mitigation of GHG emissions. While the threatened areas are distributed widely, a large part of these areas are concentrated in a few extensive coastal lowlands, as illustrated in Figures 2.2.2 - 2.2.6.

In Europe, the greatest potential losses are in the east of England, the Po Delta Plain of northern Italy, and along a swathe of coast extending from Belgium through the Netherlands and northwestern Germany into western and northern Denmark (Figure 2.2.2). Significant potential losses also occur along the coasts of northeast Germany, Poland and the Baltic states, western France, eastern Sweden, and Ukraine and Russia at the northern edge of the Black Sea (particularly around the sea of Azov) (Figure 2.2.2). It is estimated that 9% of European coastal zones, defined as a extending 10 km inland, lie below 5 m amsl. This figure rises to 12% for EU member states, 22% for Denmark, 30% for Poloand, 50% for Germany and Romaina combined, and 85% for the Netherlands and Belgium combined (European Environment Agency, 2005).

In North America, the greatest potential losses of land occur in the Yukon delta, Alaska, the Frazer delta, Canada, and along the Mexican and US coast of the Gulf of Mexico, and the eastern seaboard of the USA south of Cape Cod, and especially in Florida (Figure 2.2.3). Approximately half the land area of the Florida Pan Handle is below 13 amsl and it is highly threatened by large rises in sea level as recognised in early climate change analyses (Schneider and Chen, 1980). In South America, the Orinoco delta is threatened as is the Amazon delta (Figure 2.2.4). The mouth of the Parana is also highly exposed, particularly on the southern side south-east of Beunos Aires, and north of Buenos Aires along the Parana valley. The low-lying coastal region between Porto Alegre in Brazil and Montevideo in Uraguay are also at risk.

In North Africa and the Middle East, much of the Nile Delta is threatened and large areas of land could be lost at the head of the Persian Gulf in the Tigris-Euphrates delta of southern Iraq and the adjacent regions of southwestern Iran (Figure 2.2.5). In this case impacts extend up to 500 km inland. Much of the Libyan and Tunisian coasts, and the Atlantic coast of north-eastern Morocco, are also at risk.

Much of the West African coast is threatened (Figure 2.2.5) In the Gulf of Guinea region the Niger Delta is at risk, as is the coast extending westwards along the coast to Ghana. Other “hot-spots” in Africa occur along the coast of Mozambique, particularly in the central zone around Beira, and in the region spanning the borders of Kenya and Somalia, where exposure is greatest around Kismaayo. Sections of the west-central African coasts are also threatened, particularly along the coast of Gabon.

In south and east Asia, the nine heavily-populated major deltas are threatened (Figure 2.2.6): the Indus, the Ganges-Brahmaputra-Meghan (GBM), the Irawaddy, the Chao Phraya, the Mekong, the Red River, the Pearl River, the Chianjiang and the Huanghe – these areas are presently home to 250 million people with over half (129 million people) in the GBM delta (Woodroffe et al., 2005). These populations are currently dominantly rural, but this is likely to change and each of the deltas is associated with at least one large and rapidly growing “megacity”. Thus even as a result of urbanisation alone, the delta populations are likely to grow much further.

Hence, many of the threatened areas are deltaic plains, but with varying degrees of human exposure from very low in the Frazer and Yukon, to very high in the Po and the Nile and the deltaic regions of south and east Asia. Other coastal lowlands include deltas, such as the southern North Sea (the Rhine) and the USA East and Gulf Coasts (the Mississippi), but the threatened areas shown in Figures 2.2.2 - 2.2.8 are much more extensive.

Figures 2.2.7 and 2.2.8 show land below 2m amsl for the northern European costal and North Sea region, and the Ganges-Brahmaputra plain.

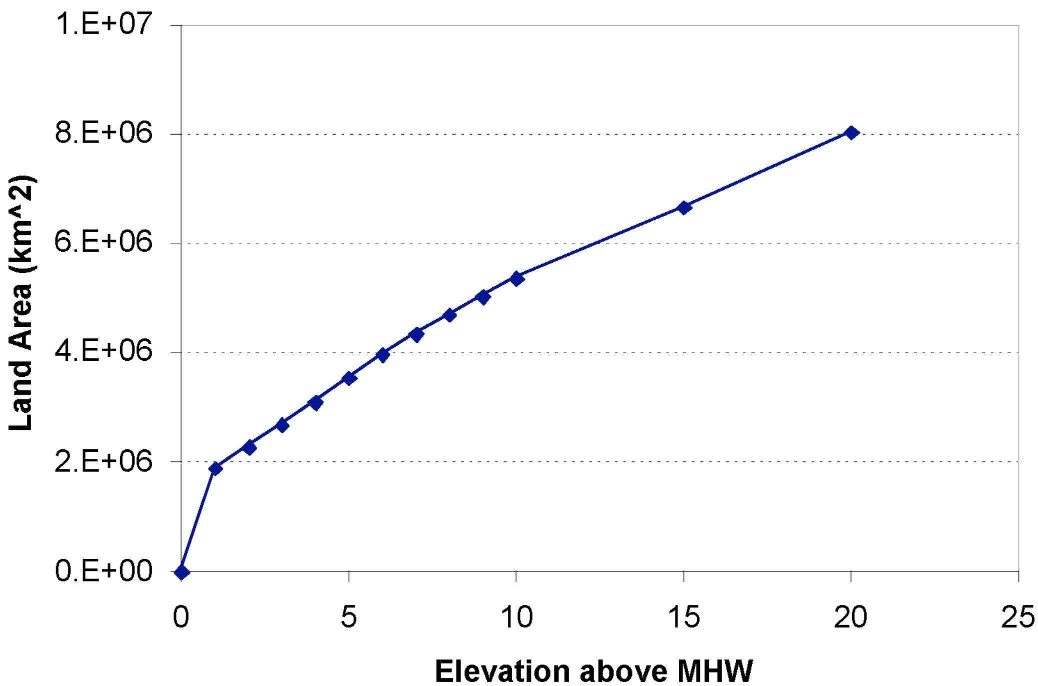


Figure 2.2.1. Land area as a function of elevation above present mean high water, excluding Antarctica, from the SRTM Enhanced Global Map (ISciences, 2003).

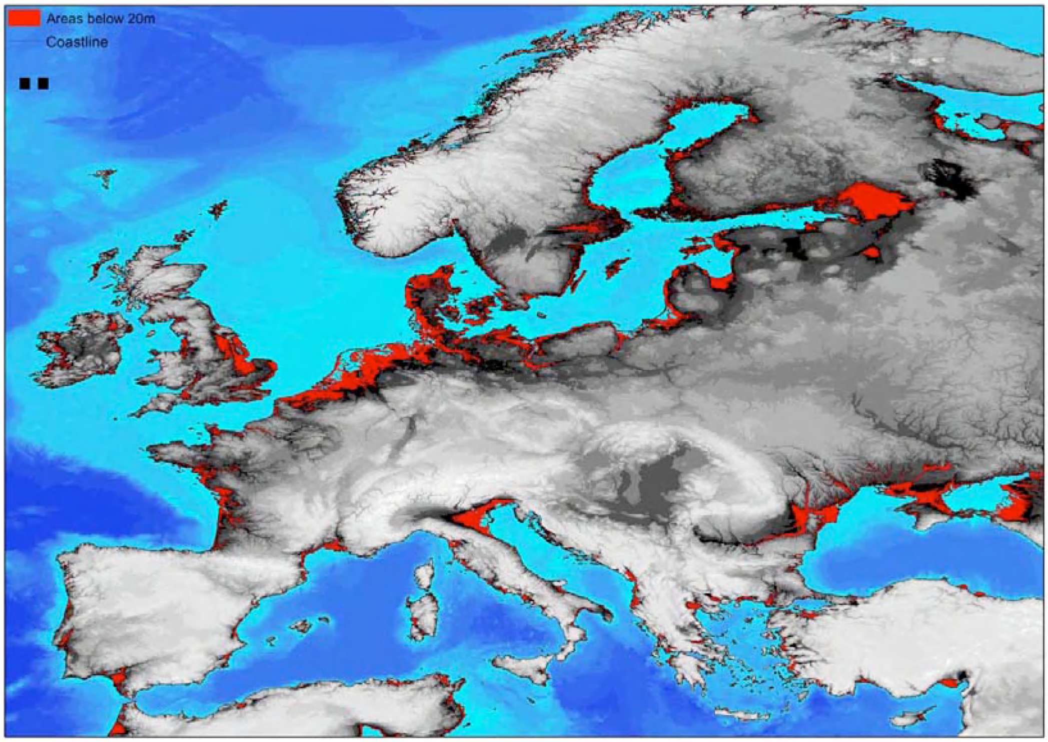


Figure 2.2.2. Land area below 20m elevation amsl for Europe.

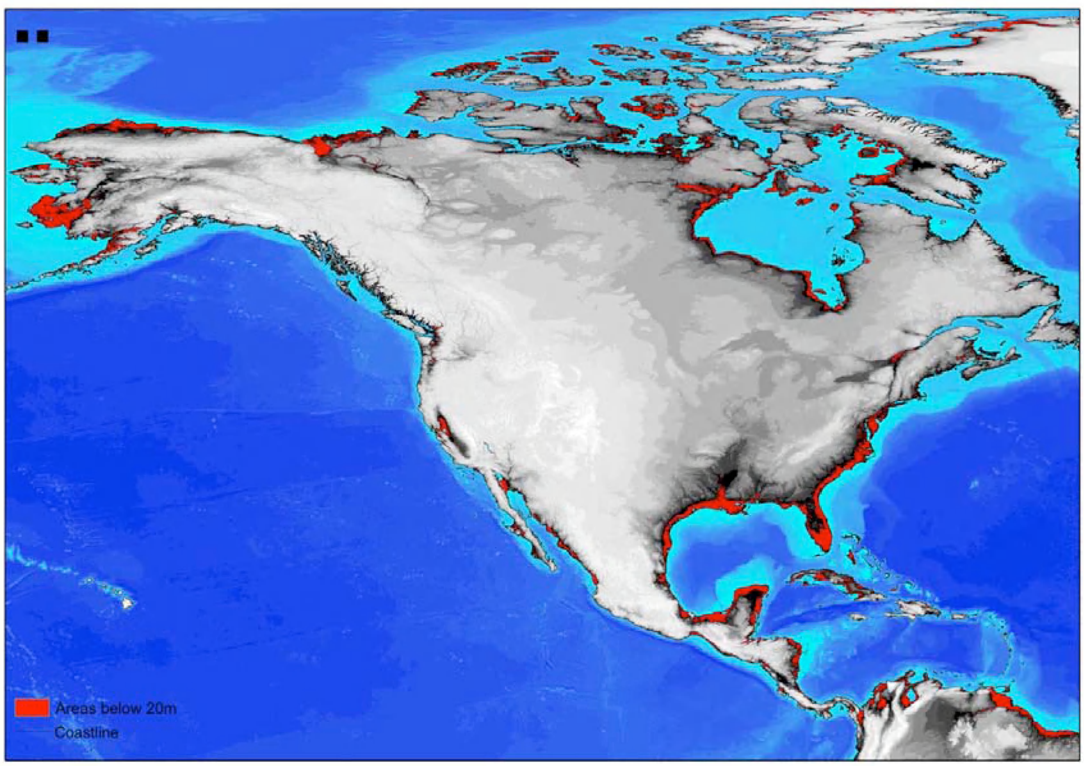


Figure 2.2.3. Land area below 20m elevation amsl for North America

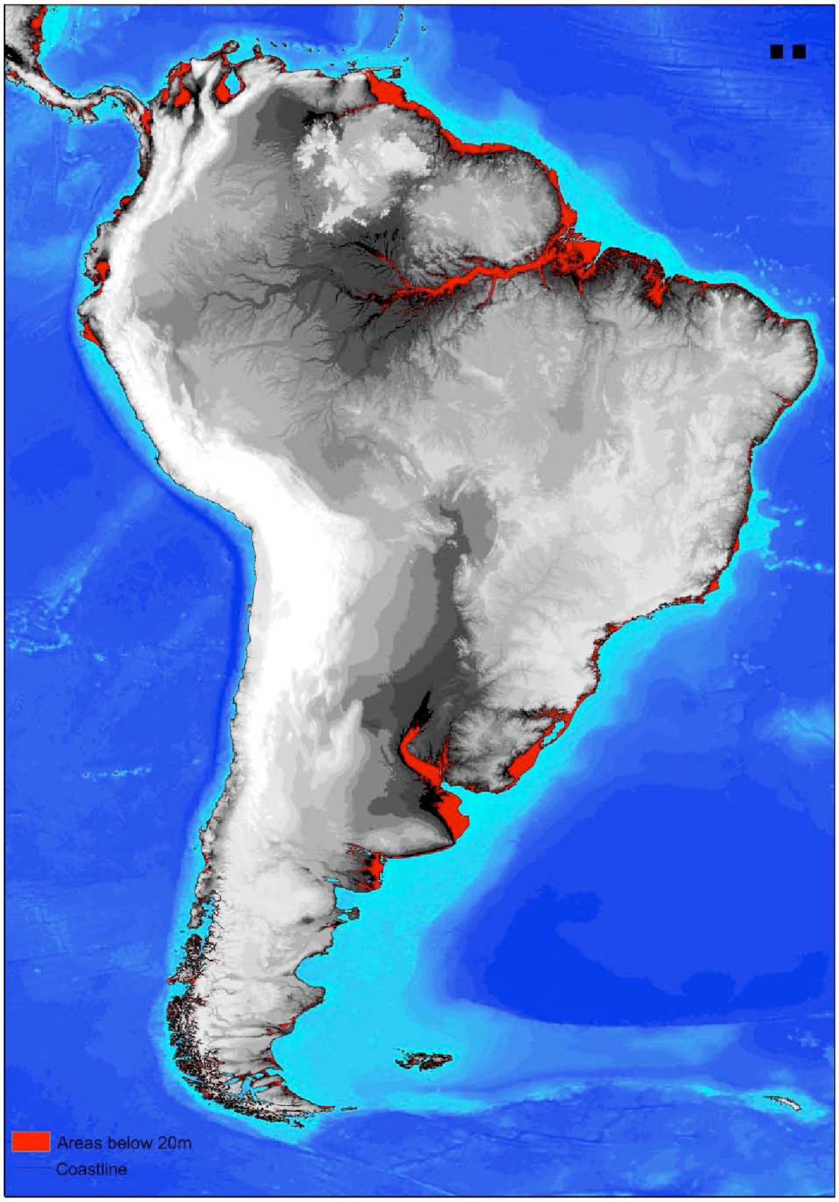


Figure 2.2.4. Land area below 20m elevation amsl for South America.

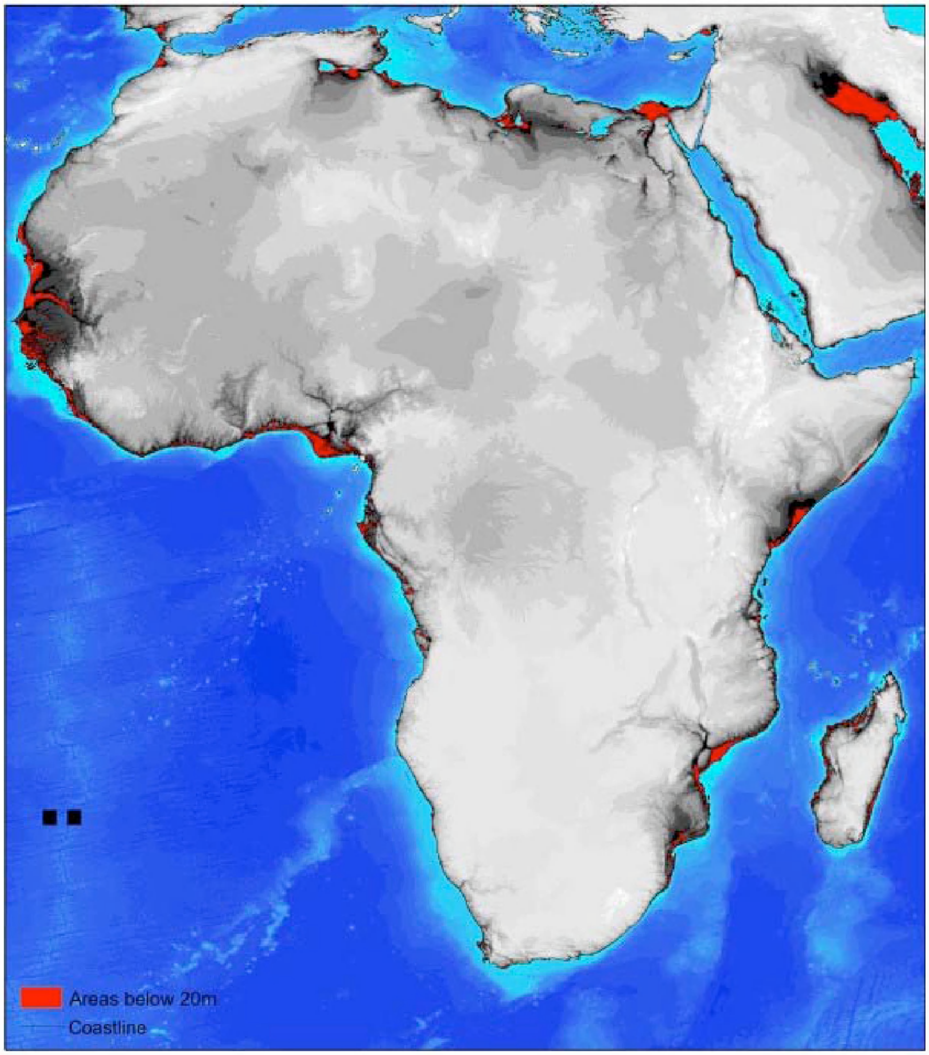


Figure 2.2.5. Land area below 20m elevation amsl for Africa and parts of western Asia.

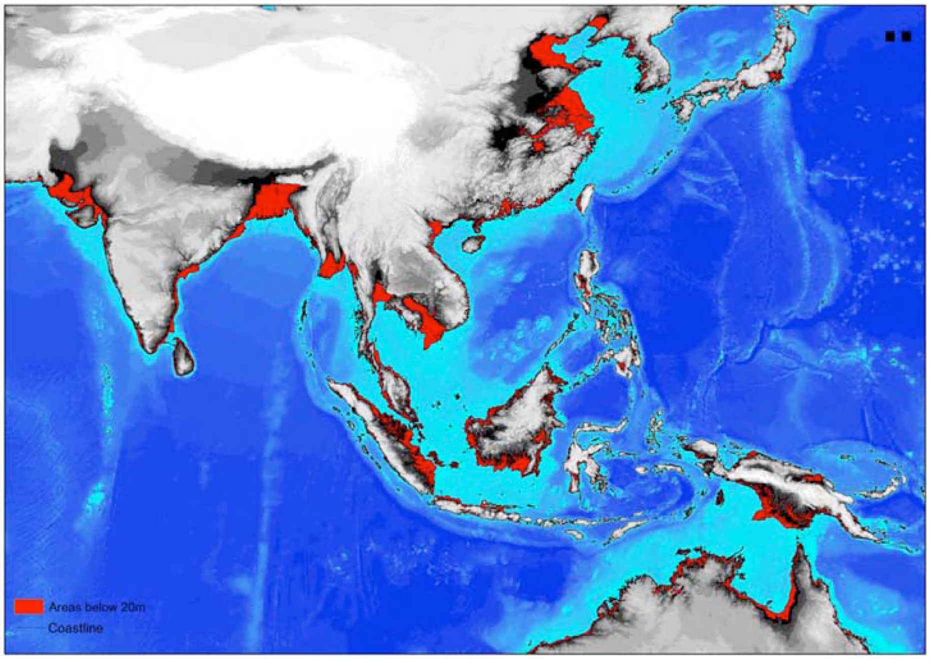


Figure 2.2.6. land area below 20m elevation amsl for South -east Asia.

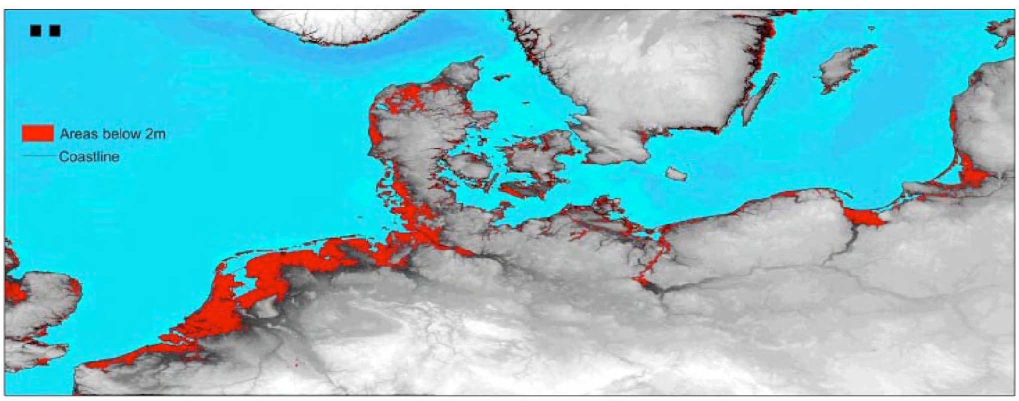


Figure 2.2.7. Land area below 2m elevation amsl for the North Sea Region.

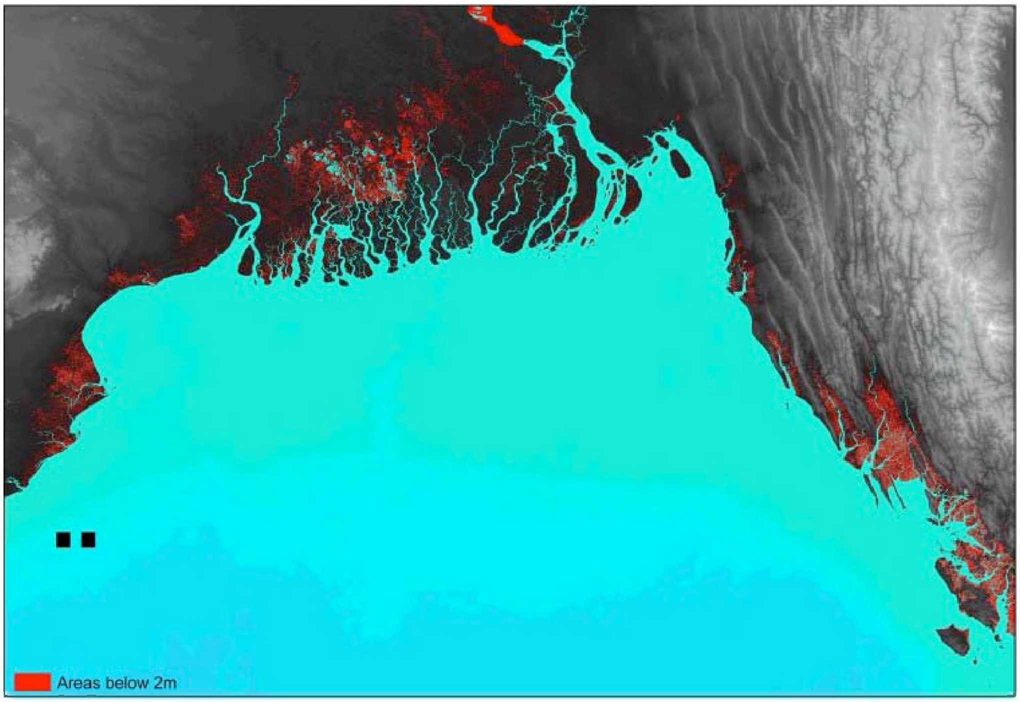


Figure 2.2.8. Land area below 2m elevation amsl for the Ganges-Brahmaputra plain.

2.2.2. The role of erosion

The results described above do not take account of adaptation in the form of coastal protection. Such protection may result in a considerable reduction in land lost, although it is costly and the protection of one stretch of coastline may have adverse impacts on adjacent coastal areas, as discussed in Section II.

Furthermore, the areas at risk of inundation represented in Figures 2.2.2 - 2.2.8 are simply a function of land elevation relative to sea level, and do not take account of the role of erosion - the physical removal of material from coastal areas, which is likely to increase as a result of SLR (Stive, 2004). The simple 'rule of thumb' from the Bruun Rule (Zhang et al., 2004) suggests that erosion is rough 100 times the rise in sea level (Nicholls, 1998). If it is assumed that about half the world's coasts could erode, a 10-m rise in sea level translates into a loss of 500,000 km^2, or about 10% of the area threatened by inundation. While this is a gross simplification of how coastal profiles respond to sea-level rise (Cowell et al., 2003a; 2003b; Walkden and Hall, 2005), it illustrates the important point that excluding adaptation, inundation is likely to be a more important process than erosion. New developments in geomorphology include models of the effect of sea-level rise on salt marshes (French, 1993), sand shores (Stive, 1995), and cliff/shore platform erosion (Walkden and Hall, 2005). Another approach has been to adopt a 'Behavioural' approach to the prediction of coastal evolution and response to climate change, where the coast is classified into regions expected to exhibit similar behaviour. Such approaches may be largely descriptive (e.g. Hosking & McInnes, 2002) or translated into numerical form (e.g. Hanson et al. 2003).

The manifestation of erosion due to sea level rise is rather different to that of inundation. The damaging effects of inundation will be manifested in occasional flood events, including rare but potentially devastating flooding disasters. Whilst erosion can also usefully thought of as being an episodic process (Hall et al. 2002) it is in the long term strongly regulated by shore platform response to sea level rise (Dickson et al. 2005), so impacts are fundamentally less variable than those of flooding. Nonetheless, erosion rates will vary with location, and in some places erosion will represent a significant hazard, particularly where it leads to the undercutting and subsequent collapse of soft cliffs or existing sea defences. Smith and Lazo (2001) conclude that the role of erosion is significant, and likely to be of greater relative importance for smaller and slower increases in sea level.

Figure 2.2.9 shows an example output from the SCAPE model, comparing annual average cliff recession rates along the Norfolk coast in the UK, in metres per annum, for three different sea level rise scenarios, corresponding to 1.2m, 0.4m and 0.2m net slr by 2100, assuming natural coastal processes (i.e. no coastal protection measures). Whilst for most of the site the predicted recession rate is highest for the high sea level rise scenario, this is not universally the case, and between kilometres 12 and 18 in the model, the high sea level rise scenario is associated with lower recession rates. The results illustrate the complexity of coastal responses to sea level rise (Dickson et al. 2005). While for most of the model domain sea level rise results as expected, in coastal recession, the increase in sediment supply generated by erosion in the northern area of the model results in net *accretion* of the coast between kilometres 12 and 18. Thus while rules of thumb like the Brunn rule provide some indication of coastal erosion losses, more complete understanding of the coastal processes is required in order to make authoritative predictions (Stive 2004).

Rates of sea level rise are also important for coastal morphology. Van Goor et al. (2003) address the potential for constant SLR to prevent tidal inlets reaching a state of morphodynamic equilibrium, as a result of the rate of SLR exceeding sediment import. They conclude that the intertidal areas in the western region of the Netherlands would be submerged as a result of SLR of 80 cm to a few m per century.

It is important to note that the deltas can maintain land area by sedimentation: this is the process that has developed these areas through the Holocene. Sea-level rise will trigger increased sedimentation on the delta plain, and not all the areas shown would be lost by the implied scenario of relative sea-level rise. However, sedimentation occurs during flood events, and the land areas that are maintained would become more hazardous for habitation given the sea-level rise scenario. Further, river management has generally reduced sediment inputs to deltas through the 20th Century, and this trend is expected to continue to intensify through the 21st Century. A relevant analysis of seven of the big heavily-populated Asian deltas with a collective population of 250 million people (the ‘megadeltas’) is presented by Woodroffe et al. (2006). For the other coastal areas, morphological changes will also be important, and it is hard to generalise about this effect – it will certainly depend on the available sediment supply.

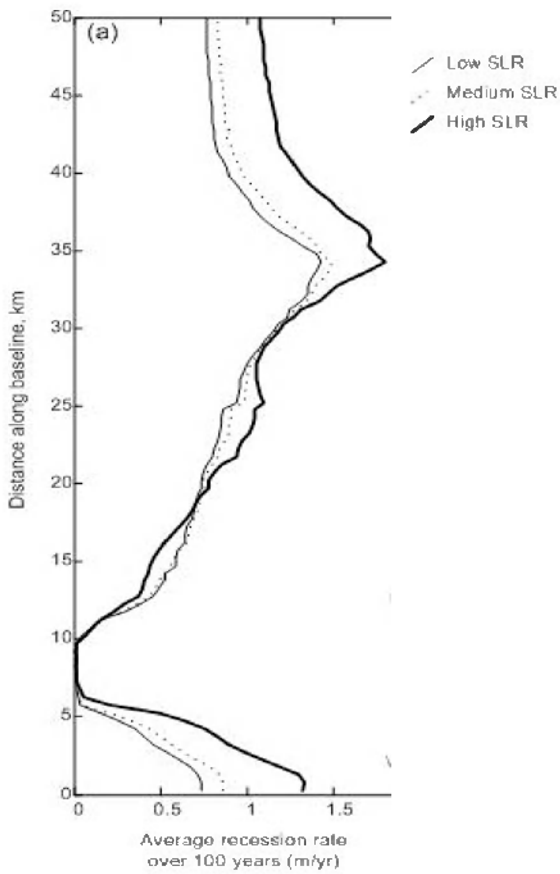


Figure 2.2.9. Cliff recession rates along the Norfolk coast, UK, for different SLR scenarios, derived from the SCAPE model. No coast protection. (after Dickson et al. 2006)

2.3 Increases in coastal flood risk

In addition to the direct threat of inundation where coasts are not defended, SLR will increase the exposure of coastal populations to storm surges and storm waves. The destructive power of such events will increase as a consequence of higher mean sea-level: higher waves will be capable of reaching the original shoreline (defined as the shoreline prior to the rise in sea level) and areas further inland will become exposed to wave action (Jiménez and Sánchez-Arcilla, 1997). In a study reported by Sutherland and Gouldby (2003) waves and surge water levels were hindcast from time series output from the ECHAM4 model, run for an IS92A scenario. The results were input to cross-shore wave transformation and overtopping models to predict overtopping rates at five sites round the coast of England. They calculated that in 2075 overtopping rates would increase by an average factor of 1.5 for a typical embankment and 1.8 for a typical shingle beach. A raise in crest elevation roughly equal to the net sea level rise was necessary to reduce overtopping rates to their base line values. In analysis of long-shore sediment transport

Sutherland and Gouldby found that the variation due to changing wave climate was less than the current levels of uncertainty in sediment transport calculations.

The area around the southern North Sea has been threatened by flooding for centuries (Lamb, 1995). Major floods occurred in eastern England/Netherlands in 1953 (McRobie et al., 2005) and in the German Bight in 1962, triggering massive investment in better flood defences, and operational flood warning systems. While benefiting from excellent flood defences, sea-level rise increases these flood risks and flood defence is planning for a significant rise in sea level in the 21st Century. Retreat via managed realignment is also being seriously considered and implemented at small scales, representing a fundamental shift in society's relationship to the sea (e.g., Rupp-Armstrong and Nicholls, accepted).

The scenario of a 2-m rise in sea level raises interesting questions, as this exceeds the typical design allowance, currently being allowed for sea-level rise. The rate of sea-level rise may be important: the faster the rise in sea level, the more likely that society cannot cope (Tol et al., 2005). However, a slower rise would allow dike raising, but at the expense of intertidal areas and coastal squeeze. This loss of natural protection will mean that the upgrade would need to exceed a 2-m rise in elevation, to maintain safety standards.

Burgess and Townend (2004) have observed that the majority of the UK's sea defence 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 though, 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. Burgess and Townend (2004) predicted the costs of maintaining coastal defence structures in England and Wales by coupling shoreline trend predictions with information on defence structures drawn from the UK National Flood and Coastal Defence Database and the Sea Defence Survey. Costs were found to increase due to both climate change and background processes associated with transgression, such as foreshore steepening. Future annual costs of lowering structure foundations, and increasing their mass and height in order to maintain their stability and function, were estimated for the 2050s and 2080s. It was estimated that by the 2080s the annual cost of coastal defence structures will be between 150% and 400% of the current levels (depending on the emissions level). 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 defence 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.

Storms may increase in destructiveness as a result of climate change, regardless of considerations of SLR. For example, while there is no evidence that the frequency of tropical storms will increase as a result of anthropogenic climate change, observational and modelling studies point to an increase in the destructiveness of such storms associated with greater wind speeds and rainfall intensities as a result of anthropogenic greenhouse warming (Emmanuel, 2005; Trenberth, 2005; Webster *et al.*, 2005). Such an increase in destructiveness will be amplified further by higher mean sea levels as discussed above.

Changes in oceanic and atmospheric currents and wind speeds may also contribute to local or regional changes in storm activity and destructiveness (Jiménez and Sánchez-Arcilla, 1997; Lowe *et al.* 2001), while changes in fluvial activity and sedimentation associated with land management and changes in rainfall may affect coastal geomorphology, exacerbating or ameliorating erosion and flood risk.

Lowe *et al.* (2001) model changes in the occurrence of storm surges around the United Kingdom by the end of the 21st century. The results indicate a reduction in the return period of extreme events. Increases in surge height are driven by meteorological forcing as well as increases in sea level, with the relative importance of these factors varying with location. At the location of Immingham in the east of England, a storm surge model driven by the Hadley Centre regional climate model predicts that the return period of an extreme water height of 1.9 m (relative to mean sea level and the tide) will be reduced from 500 years in the control case to 120 years due to meteorological forcing alone, and to 12 years due to a combination of meteorological forcing and a SLR of 0.5 m by 2100. The 500 year water level is increased to 2.2. m for meteorological forcing alone, and to 2.7 m when SLR is taken into account.

2.4 Exposure of human populations to SLR hazards

2.4.1 Population at risk from inundation

Currently (based on 1995 figures) some 60 million people live within 1m, and 275 million live within 5m, of mean sea-level. These figures are projected to increase to some 130 and 410 million respectively by the end of the 21st century (Nicholls *et al.*, 2005). Over longer periods, mean sea-level is likely to exceed 5m if no action is taken, as outlined earlier in this paper. Figure 2.4.1 shows 1995 population as a function of elevation above mean sea-level based on the Global Population of the World Version 3 (CIESIN and CIAT, 2004).

Considering higher values of SLR, there are 500 million people below a 10-m elevation and 800 million people below a 20-m elevation, based on 1995 data. Therefore, assuming a constant population or spatially uniform population growth, roughly 10% of the world's population could be displaced by a 10-m rise in sea level, and 15% of the world's population could be displaced by a 20-m rise in sea level. When trends in population growth are extrapolated to the 2080s and fixed thereafter, some 0.9 to 2.6 billion people might have to be relocated away from land threatened by inundation within 500 years, for a high but plausible SLR of 10 m over the same period (Table 2.4.1).

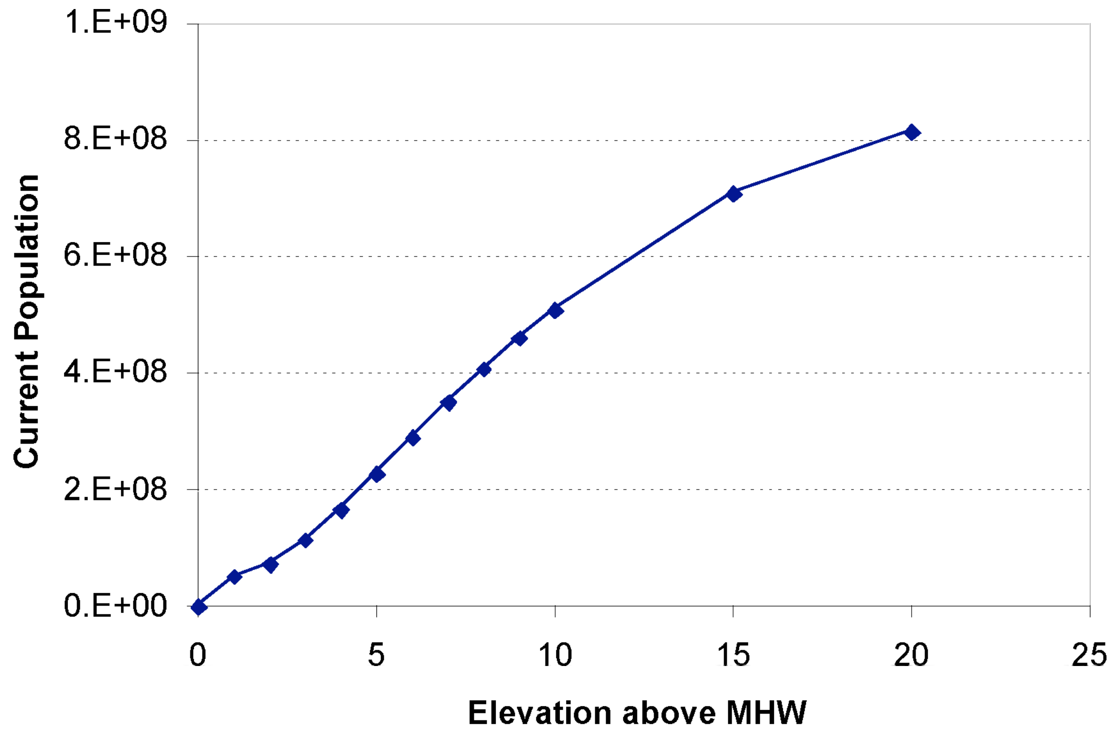


Figure 2.4.1. Population as a function of elevation above present mean high water, based on 1995 data. Antarctica is excluded (extended analysis using the methods in Nicholls et al (in review).

	Uniform Population Growth		Coastward Migration at double global growth	
Elevation above MHW	10	20	10	20
Today (2000)	500	800	500	800
A1/B1 (2080s)	900	2560	1200	1920
A2 (2080s)	1600	2560	2600	4160
B2 (2080s)	1150	1840	1700	2720

Table 2.4.1. Possible changes in the exposed population based on the SRES scenarios

The responses of coastal populations to SLR rise will of course be complex and dynamic. People are likely to migrate away from threatened coastal areas as the result of economic decisions, resulting in a slow depopulation of some regions as coastal livelihoods become less viable. However, this gradual migration is likely to be augmented by the episodic displacement of large numbers of people by catastrophic events such as tropical storms. People evacuated from their homes as a result of such events may decide not to return, and the survivors of such events may decide to move to less exposed areas. The movement of people away from coastal areas threatened by inundation or catastrophic erosion (for example by single extreme events) will be incremental, and mediated by the extent and success of coastal protection schemes. Local and national governments, through the measures they take to communicate risks and to enable or discourage (or even prohibit) return to evacuated areas, have a crucial and sometimes deciding role in the management of displaced peoples. The immediate aftermath of a flooding disaster is not the best time to make decisions about reconstruction or resettlement, which should form part of pre-existing disaster recovery plans.

To talk of a given number of people being "displaced" by a SLR of, say 2m, therefore may be somewhat misleading. Such an increase in sea level would not occur instantaneously, and migration away from threatened coastal areas less than 2 m above sea level would occur over many years. Nonetheless, coastal populations in such areas will ultimately need to be accommodated elsewhere, whether as refugees or migrants. The additional global or regional "population burden" deriving from the loss of coastal areas as a result of SLR by a given date may therefore be defined as the potential population in those areas based on existing trends by that date, assuming no SLR. The impact of this additional population burden will depend on the rate and nature of migration away from threatened areas and on the ability of host communities to absorb new members.

SLR is likely to necessitate the phased relocation of some coastal populations over the medium to long term, even for if a 2m guardrail value is successfully implemented. For example, four sovereign states (Kiribati, the Maldives, the Marshall Islands and Tuvalu) and one dependent territory (Tokelau) are comprised entirely of low-lying atolls, with a mean height above sea level of 2m. These countries, home to over 400,000 people, are in danger of disappearing entirely due to sea-level rise and the resulting combination of permanent inundation, salinisation, and increased storm and flood risk (Barnett and Adger, 2003).

Some coastal towns and cities are also threatened within the 2m guardrail. For example, the entire Gambian capital of Banjul lies below 2m amsl: without large-scale coastal protection, even an increase in sea-level of 1 m is expected to displace its 42,000 inhabitants (Jallow *et al.*, 1996). An analysis by El-Raey *et al.* (1999) based on current population values suggests that in the Alexandria and Port Said governerates of Egypt, a SLR of 50 cm would displace some 1.5 million people, including over half the population of the city of Alexandria, if no action is taken. According to the European Environment Agency (2005), a 1m rise in sea-level would affect 13 million people in five European countries, based on the population in coastal floodplains.

The impacts of SLR on coastal populations in terms of displacement or forced migration as a result of inundation will depend on rates, as well as magnitudes, of change. Using the FUND model, Nicholls *et al.* (2006) examine the consequences of a collapse of the WAIS and a resulting additional 5 m SLR, commencing in 2030 and unfolding over a range of timescales, from 100 to 1000 years. The FUND model estimates the extent of coastal protection based on cost-benefit analysis calculations. In all the scenarios, even the slowest, forced migration peaks between about 2030 and 2060. For the most rapid collapse (complete within 100 years), forced migration peaks at around 350,000 people per year, and remains at that level for a decade, with some 15 million people being displaced in total. However, numbers displaced are only 2-3% of the total exposed, as a result of the implementation of coastal protection.

2.4.2 Increases in exposure to flood risk

Increases in coastal flood risk and population growth mean that in many parts of the world larger human populations will be exposed to more severe flooding, where improvements in coastal protection are absent or do not keep pace with increases in flood risk. Figure 2.4.2 shows the number of people who might be flooded including evolving protection.

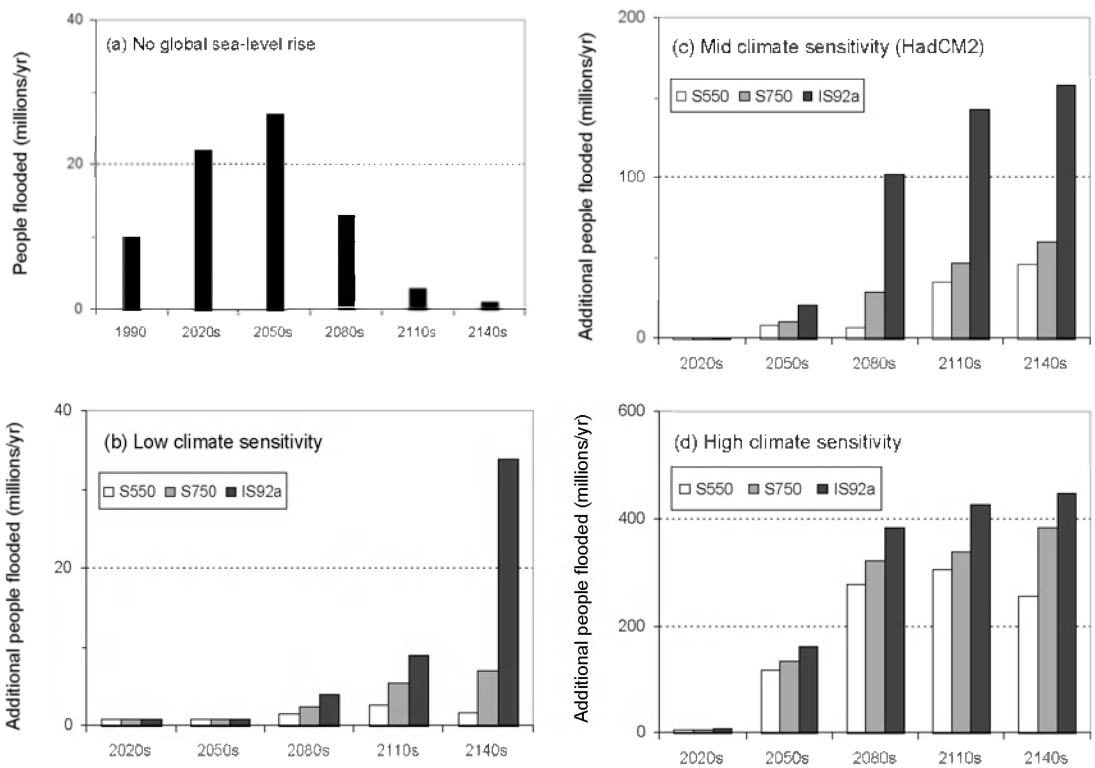


Figure 2.4.2. Coastal flooding under the IPCC 'S' Stabilisation experiments from 1990 to the 2140s, which compares unmitigated (IS92a) impacts with those under the S750 and S550 stabilisation scenarios. (a) People flooded/year without any global sea-level rise; (b) Additional people flooded/year due to sea-level rise assuming low climate sensitivity; (c) as (b) for mid climate sensitivity (HadCM2); (d) as (b) for high climate sensitivity. Note the varying scale of the y axis. (from Nicholls and Lowe, 2004).

An increase in the frequency of *severe* tropical storms may render some regions less habitable and encourage migration in the absence of permanent inundation, due to return periods being shorter than the time taken to recover between events, the costs of protecting communities against such events becoming prohibitive, or catastrophic changes in landscapes associated with individual severe storm events. Whether or not communities are abandoned will depend to a large extent on the resilience of those communities and their ability to adapt to changes in the frequency of severe storms (Adger *et al.* 2005).

Hall *et al.*, 2005 examine the evolution of flood risk in the UK and conclude that by the 2080s the number of people exposed to flood events with a return period of 75 years doubles relative to 2002, from 0.9 to 1.8 million, for the A1 and A2 SRES scenarios. Smaller increases are seen for other scenarios (Table 2.5.1).

2.5 Economic impacts of SLR

Figure 2.5.1 shows economic assets as a function of elevation above sea-level, in the form of GDP versus elevation, along with area and population. On the one hand the concentration of economic activity (and assets) in coastal zones may be expected to increase due to the concentration of both population and economic activity in coastal areas, so these figures might be viewed as representing a minimum value of assets at risk. However, given the long timescales required for SLR in excess of 1m to occur, and the finite lifetimes of the systems that make up a large proportion of these assets, it might realistically be anticipated that economic activity might gradually migrate away from areas at risk from the SLR in excess of 1m without severe economic losses on these longer timescales. The window of most concern should be that over which existing and projected near-term assets are directly threatened by lower values of SLR.

Economic impacts of SLR will be much wider and more complex than the costs of relocating property, people, industry, agriculture and transport infrastructure from areas threatened by inundation. Relocation costs may be offset by coastal protection, although the costs of coastal protection are high. To the costs of adaptation through coastal protection, relocation or resilience building (see Section 3) must be added the costs of residual, unavoided damages, including:

- Loss of productive land that it is not deemed economically viable to protect
- Costs of relief and reconstruction after coastal storm and flood events
- Loss of livelihoods resulting from SLR
- Impacts on trade and markets

While it may cost more in economic terms to protect certain areas than is gained from keeping them, the loss of such areas will still constitute an economic loss. Countries may wish to protect certain areas for non-economic reasons, event if they are not strictly economically viable when subjected to a cost-benefit analysis (CBA). For example, it may be seen as desirable to protect stretches of coast that are deemed of cultural or historical importance, or to protect or relocate valued ecosystems. Furthermore CBA may not capture all of the potential economic costs of losing or relocating certain systems, and the non-economic costs may be seen as unacceptable.

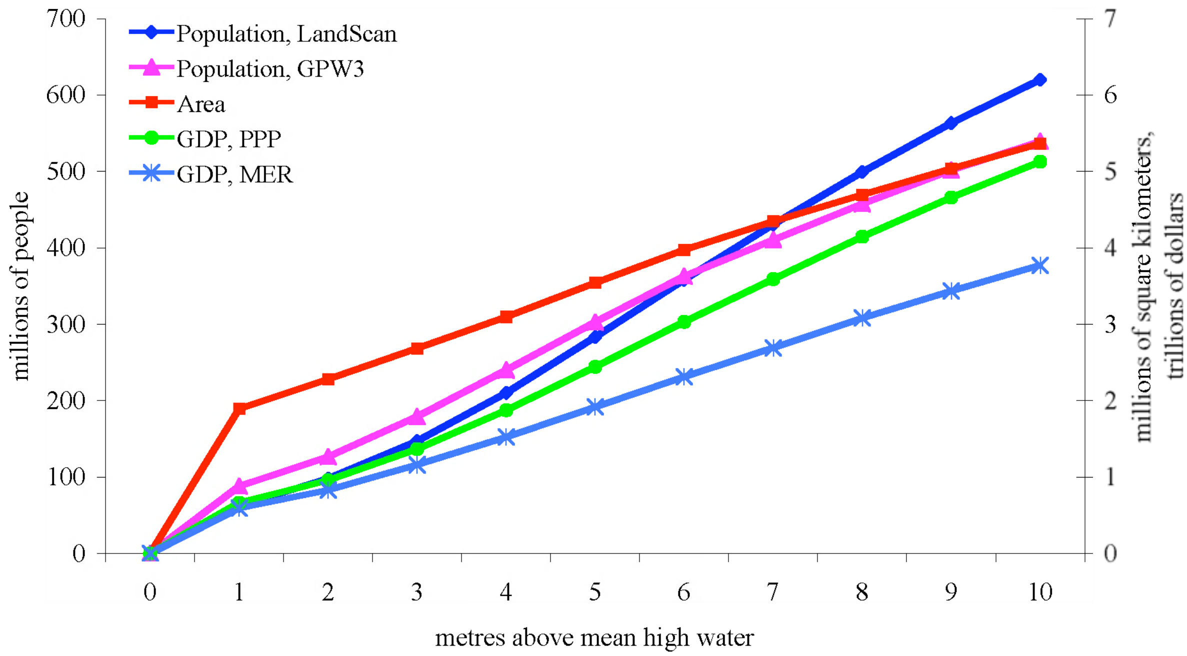


Figure 2.5.1. GDP as a function of elevation above present mean high water, also showing land area (excluding Antarctica) and population, from the SRTM Enhanced Global Map (ISciences, 2003).

2.5.1 Economic costs associated with inundation and protection

Tol (2004) estimates costs of SLR associated with dryland and wetland losses as a proportion of GDP, using the FUND model driven by the IPCC SRES A1/B1 scenario, in which the atmospheric CO_2 concentration rises to 870 ppm and global mean surface temperature to 3.5° above the pre-industrial value, resulting in a SLR of 0.66 m, by 2100. Tol (2004) finds that potential dryland loss by 2100, as a proportion of GDP and assuming no protection, is highest for the Maldives (122%), Micronesia (12%), Macau (10%), Vietnam (8%) and Bangladesh (5%). Measured in the same way, the largest economic impacts resulting from wetland loss are in the Bahamas (4.8%), Papua New Guinea (3%), Belize (1.4%), Malaysia (0.5%) and Senegal (0.4%). Tol (2004) also calculates economically "optimal" levels of coastal protection, concluding that such an optimisation would result in most countries opting for full protection land that would otherwise be lost. The costs of protection differ by seven orders of magnitude, and are highest in terms of proportion of GDP in 2100 for Micronesia (0.36%), Palau (0.30%), Tuvalu (0.07%), Kiribati (0.06%) and the Marshall Islands (0.04%), with costs falling over time.

Examining different world regions using the FUND model, Tol (2002) estimates the costs of coastal protection and the total costs of a 1 m SLR over the coming century. Protection and total costs are greatest for South and South-east Asia, where they are calculated at \$305 billion (in total) and \$3.3 billion (per year). As Tol (2002) points out, these figures are significantly lower than some earlier estimates, as a result of different assumptions about protection strategies: Tol assumes optimal protection strategies whereas earlier studies are based on arbitrary protection strategies. Tol (2002) calculates global costs of a 1 m SLR as \$13 billion per year, compared with the estimate of Frankhauser (1995) of \$47 billion per year. Tol's estimate of \$2 billion per year for the USA contrast with earlier estimates ranging from \$7 to \$12 (Tol, 2002).

Locally and regionally, the potential costs of SLR are high. For example, El-Raey *et al.* (1999) estimate that, in the absence of further coastal protection, SLR will cause the loss of 195,000 jobs and economic losses of \$3.5 billion in Alexandria governorate in Egypt by 2100 (in addition to the displacement of almost 2 million people). In Gambia, a 1m rise in sea-level is would result in the loss of \$217 milllion worth of land in the capital Banjul; more importantly, with no coastal protection Banjul is expected to be entirely lost to erosion and inundation by the middle of the 21st century (Jallow *et al.*, 1996). The loss of major ports has the potential to disrupt regional trade and transport networks at the sub-continental scale, with major economic impacts over a wider area.

2.5.2 Economic costs of increased flood risk

Hall *et al.* (2005) analysed the economic assets at risk of coastal flooding in England and Wales, using a pre-existing flood risk analysis model (Hall et. al. 2003). The analysis combined relative sea level rise scenarios of between 26cm and 86cm in south eastern England with the four socio-economic scenarios used in the UK Foresight project (Evans et al. 2004), which were derived from the SRES analysis (IPCC, 2000). The results in Table 2.5.1 for the number of people living in coastal flood plains reflects differing projections for the UK population as a whole (UKCIP, 2000) and for its location in coastal flood plains. The figures for the number of people at risk reflect these demographic factors, sea level rise, best estimates of changing storminess and the mediating effect of coastal defences, assuming those defences are kept in the same condition as present. The risk analysis method incorporated a simple flood defence reliability model, but in the first instance it was assumed that the flood defences were maintained as present i.e. there would be no engineering adaptation to increasing flood risk. The increase in expected annual damage reflects both the probability of flooding and the economic vulnerability of coastal assets. Hall et al. (2005) estimated that the proportion of economic risk due to fluvial and coastal flooding England and Wales that is attributable to coastal flooding would increase from roughly 50% at present to between 60% and 70% in the 2080s, because of the relentless effect of sea level rise, as compared to the more variable effects of climate change on fluvial flooding. The contribution that agricultural damages make to the total flood risk is small on the coast, as it is inland, especially in the more globalized socio-economic scenarios that are expected to rely more upon agricultural imports. The final row in Table 1 provides an indication of the severity of coastal flood risk as a proportion of GDP under the different scenarios, as an indication of the affordability of mitigation actions. While risks grow fastest in the high growth (and high emissions) Global Markets scenario, so too does the wealth that may be used to adapt to the changing risks. The most demanding situation is where climate change is combined with lower growth and less effective governance measures to reduce vulnerability,

	2002	World Markets 2080s	National Enterprise 2080s	Global Sustain-ability 2080s	Local Steward-ship 2080s
Number of people within the indicative floodplain (millions)	2.5	3.4	3.2	2.6	2.5
Number of people exposed to flooding (depth > 0m) with a frequency > 1:75 years (millions)	0.9	1.8	1.8	1.4	1.3
Expected annual economic damage (residential and commercial properties) (£billions)	0.5	13.5	10.1	3.1	1.0
Expected annual economic damage (agricultural production) (£millions)	2.2	20.7	74.0	18.9	35.8
Expected annual economic damage (as % of GDP)	**0.05**	**0.09**	**0.21**	**0.04**	**0.04**

Table 2.5.1 Summary of scenario analysis of coastal flood risk for the UK (assuming no adaptation)

Relief and reconstruction costs following coastal storms and floods may increase as a consequence of SLR. These may be reduced by adaptation strategies based on making settled areas more resilient in the face of coastal hazards, although it is unlikely that relief and reconstruction costs will be reduced to zero. Even where it is more economically viable to relocate coastal populations, such a course of action may be socially or culturally unacceptable. Strategies to increase resilience will take time to implement and may have to go through several revisions before they are truly effective.

Coastal hazards can have a significant impact on national economies, as apparent from the economic fallout from Hurricane Katrina in late 2005. Katrina caused massive destruction in a major urban centre, disrupted vital transport networks (specifically the Mississippi River), and compromised US energy production, leading to higher energy costs. In the short-term, these impacts acted to depress US GDP, with forecast decreases in GDP of 0.7 % and 0.4 % in successive quarters according to an article in Business Week. However, the article concludes that the economic impacts of Katrina are likely to be mixed, with economic activity associated with reconstruction adding to GDP in later quarterly periods. Regionally, insurance pay-outs led to increased spending, particularly in the rental market. To these impacts must be added the billions of Dollars promised by the Federal government for reconstruction; where revenues need to be raised for such purposes by central government, higher taxes may be one consequence of such disasters.

Other studies of economic impacts are described in the UK Foresight project (Evans et al., 2005), which estimates current annual combined losses from riverine and coastal flooding in the UK as approximately one billion pounds, and projects that this figure will increase by between £1 billion and £27 billion by the 2080s, with the range of figures reflecting different amounts of climate change and different increases in the value of assets at risk and new development in flood prone areas associated with different socio-economic scenarios. Post-Foresight results from Hall et al. (2005) which look specifically at coastal flood risks using the same scenarios framework and quantified risk analysis method, have been summarised above. Erosion contributes a small fraction of this figure: up to £126 million.

Many coastal livelihoods may be threatened by SLR. Changes in coastal marine ecosystems associated with SLR, other manifestations of climate change and other forms of human impact may affect key marine resources on which local communities depend. The destruction of marine habitats may undermine livelihoods based on fishing and other marine resources, increasing poverty and food insecurity and requiring economic intervention from government, as well as depressing local economic activity. The destruction of either marine or terrestrial coastal habitats and / or beaches may reduce income from tourism.

In addition to costs associated with the construction of new or improved coastal defences, costs of maintaining groundwater levels at manageable depths will increase in some area. Certain low-lying coastal catchments, for example in eastern England, depend on pumping to prevent inundation and to keep water levels low, to permit agriculture. A rise in sea-level would affect the water levels in these catchments, increasing pumping costs (Arnell, 1998).

2.6 Impacts of SLR on Freshwater Resources

The Ghyben-Herzberg relationship states that in the coastal zone, a one metre height of the free water table above is associated with a depth of freshwater below sea level of

40m, indicating that a 50 cm SLR will result in approximately a 20m reduction in the thickness of the freshwater layer (Sherif and Singh, 1999). However, this relationship assumes a sharp, well-defined interface between sea and fresh water and must be treated as approximate. Relationships between sea-level and groundwater are modified by pumping and recharge activities, and the impacts of SLR on freshwater resources via saline intrusion into coastal aquifers will vary considerably with depending on geography, topography, and the geological and geomorphological characteristics of coastlines.

On the basis of modelling studies, Sherif and Singh (1999) conclude that a 50 cm increase in sea-level in the Mediterranean will cause an additional intrusion of saline water of some 9 km in the Nile Delta, while a similar rise in the Bay of Bengal would cause an additional intrusion of 0.4 km. In contrast, Clark *et al.* (1992) conclude that the impacts of a SLR of 0.6m on freshwater resources in the UK will be small, with a reduction in yield of coastal boreholes of 1-2%, and few intakes close to current tidal limits being at risk. In the UK, the costs of relocation of boreholes would be small relative to annual maintenance and operational costs, and the impact of SLR on intakes near to tidal limits would be small compared to the impacts from extreme tidal events.

Any impacts on the availability of freshwater in coastal areas will interact with other factors, for example changes in runoff and recharge rates resulting from land management and climate change, as well as changes in demand resulting from population growth, urbanisation, industrialisation, the expansion of agriculture and increased affluence. Most of these factors are likely to increase water stress, compounding even modest decreases in freshwater availability (Vörösmarty *et al.*, 2000). Water stress resulting from a combination of all of these factors is likely to be greatest in the rapidly growing coastal megacities of the developing world. Small island states are also particularly vulnerable to salinisation due to their limited arable land, with implications for both export earnings and food security (Tompkins, 2005).

2.7 Impacts of SLR on Ecosystems

SLR will have significant impacts on a number of marine and terrestrial ecosystems, many of which are already threatened by human activities (Jackson *et al.*, 2001). Coastal wetlands are particularly at risk where coastal flood barriers and human settlement prevent their migration inland. Nicholls (2004) assesses the sensitivity of the coastal system to flooding under the different SRES scenarios using the HadCM3 model, and finds that coastal wetlands are lost in all scenarios, although these losses are small compared with the potential for non-climatic anthropogenic destruction. Nicholls (2004) concludes that differences in attitudes towards the environment (as captured by the "storylines" of the different SRES scenarios) have a greater impact on the future extent of coastal wetlands than differences in the direct effect of varying magnitudes of sea level rise between such scenarios. However, inundation of coastal wetlands and their ability to migrate inland are not the only issues. Schallenberg *et al.* (2003) find that even minor saline intrusions into coastal lakes can cause severe perturbations of zooplankton community structure and abundance, and that "…even relatively small increases in salinity can drive such systems to a state of depleted biodiversity and abundance, altering ecosystem functioning." Even in the absence of complete inundation, SLR may therefore compromise existing coastal lake ecosystems via increases in the frequency and severity of saline intrusions. Coastal marine and estuarine ecosystems will be affected by changes in tidal height and tidal range, which will alter water depth, available light, current velocities, and temperature and salinity distributions. Short *et al.* (1999) review the potential impacts of these manifestations of SLR for seagrasses, keystone species for many marine habitats. The mechanisms through which SLR will affect seagrasses are complex; for example, changes in tidal ranges will affect the positions of the landward and seaward extremities of seagrass beds, changes in water motion will affect biomass, pollination and larval recruitment, and changes in water velocity will impact the health of beds through the increased or decreased sediment suspension (affect light levels and photosynthesis), and more or less flushing of macroalgal biomass which may be overtaking seagrass beds. Short *et al.* (1999) conclude that seagrass distributions will be altered, with the nature of these alterations depending on the local manifestations of SLR, which in turn will depend on topography and geomorphology as well as the role of human activity and local manifestations of climate change. Jackson *et al.* (2001) Describe mass mortality of seagrasses in recent decades due to human disturbance; SLR will interact with other anthropogenic factors that have decreased the resilience of seagrass beds.

Coastal mangroves, which dissipate the energy of storms and thus offer a form of physical protection to coastal systems and populations, are also likely to be affected by SLR. The impact of global SLR on mangroves will vary with local increases in sea-level and with the availability of sediment, as well as with the ability of the mangroves themselves to adapt to SLR, which is likely to vary from species to species (Field, 1995).

All coastal and marine ecosystems will be subject to multiple stresses from climate change and other forms of disturbance resulting from human activity. For example, many coral species survive only in shallow water, and coral reefs across the globe have undergone significant decline in recent decades (Gardner *et al.*, 2003; Bellwood *et al.*, 2004).Changes in water depth will interact with other factors such as the effects of physical disturbance from human activity and tropical storms, predation, disease, an increased frequency of bleaching episodes resulting from high sea-surface temperatures, and pollution to adversely affect coral reefs in the future (Aronson *et al*, 2000; Gardner *et al.*, 2003; Hughes *et al*,, 2003). Gardner *et al.* (2003) conclude that "The ability of Caribbean coral reefs to cope with future local and global environmental change may be irretrievably compromised."

SLR will be one of many factors, and in many cases a minor or even negligible factor, affecting other coastal and marine ecosystems. Changes in ocean currents may result from changes in atmospheric circulation and wind speeds and directions, as well as from geomorphological change triggered or accelerated by SLR and associated inundation or erosion. Recent intrusions of hypoxic water off the Oregon coast have led to widespread mortality of marine organisms, and have been tentatively attributed to changes in wind regimes (Service, 2004). In contrast, Goes *et al.* (2005)find that warming of the Eurasian landmass is resulting in enhanced upwelling and increased biological productivity in the Arabian Sea.

SLR will interact with other manifestations of climate change, exploitation of resources such as fish stocks, and habitat destruction to have a complex impact on coastal and marine ecosystems. The impacts of SLR on ecosystems therefore cannot be considered in isolation from other factors.

3 RESPONSES

3.1 Options for responding to SLR

Evans et al. (2005b) describe four broad physical approaches to managing coastal flood risks under conditions of sea level rise, as follows:

1. Coastal Defences: Construction or raising of physical barriers to flooding and coastal erosion e.g. dikes and flood barriers
2. Realigment of coastal defences by relocation landwards
3. Abandonment (managed or unmanaged) of flood defences:
4. Measures to reduce the energy of nearshore waves and currents, including beach nourishment, offshore barriers, energy converters (that may also be used for renewable energy generation) and nearshore morphological modifications.
5. Coastal morphological management by allowing or encouraging changes in the coastline to accommodate the forcing processes

Further details are provided in Palmer and Townend (2006) and Nicholls et al. (2006).

To the above list of responses should be added resilience-building strategies based on the modification of existing, exposed settlements and infrastructure, and on the reduction of socio-economic vulnerability. Such approaches are conceptually less straightforward and more difficult to evaluate economically, but may be important elements in response strategies where coastal systems face increased levels of risk rather than existential threats.

3.2 Engineering responses to sea level rise

The construction of large-scale coastal defences such as sea walls to physically protect vulnerable areas is one option for addressing SLR. While such schemes can be extremely costly, the immediate costs of construction are often more than offset by the value of productive land and infrastructure that would otherwise be lost to erosion or inundation, or the costs associated with relocating threatened settlements. In many instances, including the entire coastlines of Poland and Uruguay, the Estonian cities of Tallin and Pärnu, and the Zhujian Delta in China, protection benefit-cost ratios have been calculated in the range 2.6 to around 20 for a SLR of 0.3 - 1.0 m (Smith and Lazo, 2001). However, comparable ratios for the vulnerable coastline of Dar es Salaam and for the entire populated coastline of Tanzania are less than 0.2 and around 0.1 respectively (Smith and

Lazo, 2001). Stolwijk and Verrips (2000) estimated that the total annual costs of protection against foreseen climate change, sea level rise and land subsidence are in the order of €600 million, or about 0.15% of GDP, while the benefits (avoided annualised damage) exceed the costs by a factor of about 5.

For simple inundation losses, benefit-cost ratios are typically calculated as the value of the protected systems that would otherwise be lost divided by the cost of constructing the necessary defences. However, flood defences are typically designed to protect against infrequent extreme events, in which case the benefits are calculated in terms of the expected annual reduction in flood risk compared to some 'base case' which is typically a 'no protection' scenario. The residual flood risk (expressed in terms of expected annual damage) that persists even in the presence of the flood defence must be factored into the analysis.

Evans et al. (2005b) quote typical prices for sea wall construction and beach nourishment but do not comment upon how these prices may change in future conditions of increased demand for coastal defences. Some economies of scale and specialisation (for example the development of more specialised plants) are to be expected. On the other hand material and fuel costs can be expected to increase. Already some materials (for example rock armour) have to be imported long distances to some sites (e.g. from Scandinavia to sites round the southern North Sea). Suitably graded sediments for beach nourishment are already scarce in some locations. Increases in fuel costs will impact significantly on construction processes that involve transporting large volumes of material, be it rock or dredged sediments, and also in construction using cement. This assumes that construction of coastal defences will continue to be a material-intensive process and, with the exception of tidal barriers, which can be monuments of technology, based upon fairly basic construction processes (though the technologies for analysis, design and monitoring are bound to improve). While it may be possible to make projections of sea level rise over centuries or more, discussion of engineering-based adaptation on this timescale is much more problematic. Modern coastal engineering dates from the end of the Second World War, so has existed for just 60 years. While the core engineering techniques associated with coastal structures and beach recharge are quite mature, it is possible that novel engineering solutions may emerge in future, perhaps combining renewable energy production from waves and/or tides with coast protection. Enhanced understanding of the broad scale and long term responses of the coast, for example using the type of model described by Dickson et al. (2005) will lead to more efficient targeted investment of resources in the adaptation to sea level rise.

While the material and construction costs of flood defences are relatively straightforward to evaluate, they may be associated with costs in addition to those of their construction. Coastlines are dynamic systems, and decisions to implement coastal protection in one location will have impacts on down-drift locations. Because of their potential environmental harm, the construction of coastal defences is subject to increasingly stringent environmental regulation in some countries. These regulations now provide major constraints on the extent to which some types of engineering protection can be implemented and implementation of statutory compensatory measures can add considerably to the costs.

3.3 Management of natural systems and managed realignment

The careful management of natural systems can play an important role in reducing coastal risk. Systems such as coral reefs, mangroves and intertidal areas such as saltmarshes act to dissipate wave energy, reducing flood risk (e.g. Spencer and Moeller, 1996). Given the multiple stresses often experienced by these systems, their preservation in the face of SLR is likely to be increasingly difficult. Existing policies and practices often mitigate against the preservation of such natural systems, for example in south-east Asia where economic liberalisation has resulted in the conversion of mangroves to shrimp farms, removing the natural protection against the impacts of coastal storms (Adger, 1999). In many parts of the world overfishing and declining water quality have made coral reefs more vulnerable to the impacts of tropical storms and led to their physical deterioration, potentially increasing future storm risk along adjacent coasts (Hughes *et al.*, 2003; Adger *et al.*, 2005). Reductions in pollution, for example by management of runoff, and more sustainable fishing practices will help to sustain valuable coastal protection systems in such cases.

Climate variability and change may place additional stresses on coastal ecosystems regardless of the impacts of SLR, and these stresses may combine with other factors to compromise natural coastal protection. In the south-eastern United States severe drought has been identified as the primary cause of massive die-off of salt marshes, exacerbated by increased grazing of salt marsh by snails (Silliman *et al*, 2005). While the factors behind the occurrence of high-density "grazing fronts" of snails remain unconfirmed, the suggestion that this is due to observed reductions in numbers of blue crabs which predate on the snails (Silliman *et al*, 2005) highlights the potential for disturbances in food chains to have dramatic impacts on coastal ecosystems. Salt marshes are the most ecologically and economically important shorelines along the eastern seaboard and Gulf Coast, and their die-off and replacement of mudflats has implications for coastal erosion and storm and flood risk. Careful management of ecosystems, avoiding reductions in the populations of key species through human predation, might help to avoid ecosystem collapse. Such management requires, a minimum of human disruption, a detailed understanding of ecosystem functioning in order to inform the exploitation of ecosystems, or possibly active intervention in order to increase the resilience of ecosystems in the face of external stresses.

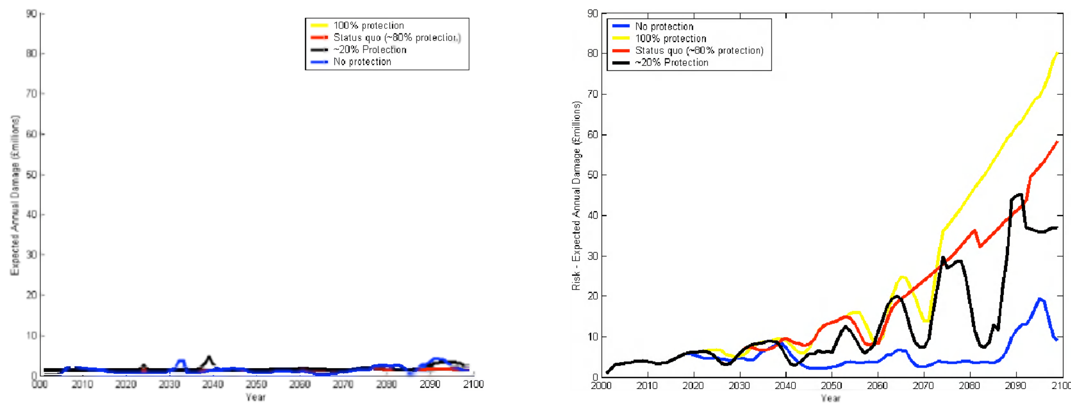
The exploitation of natural systems as physical barriers to the impacts of coastal storms and surges requires that such systems exist as a buffer between the shoreline and the areas requiring protection. Where SLR is likely to inundate existing natural buffer zones, ecological and geomorphological systems may be permitted or assisted to migrate in land in order to serve a protective function. This will require the displacement of coastal populations and infrastructure in many instances, and may also involve habitat creation where existing systems are unable to migrate naturally over the timescale associated with

SLR. Such “managed realignment” will enable the preservation of valued (economically or otherwise) ecosystems and will reduce the exposure of settlements and associated infrastructure, and is likely to be less costly than the construction of coastal defences in many instances, at least in the medium to long term. Managed realignment will be required in European countries in order to conform with the EC Habitats and Species Directive. However, this will be associated with “potential conflict between maintaining the favourable conservations status of intertidal areas and avoiding the degradation and loss of freshwater areas” (Lee, 2001). Lee (2001) predicts that in England and Wales there could be a net loss of freshwater and brackish habitat of around 4000 hectares, and a net gain of intertidal saltmarsh and mudflat/sandflat habitats of around 770 hectares, as a result of SLR and associated management strategies. The latter figure results from the balance between losses of existing intertidal areas and the creation of some 12,500 hectares of new intertidal zones. Lee (2001) estimates that replacement of lost freshwater and brackish habitats would cost in the region of £50-60 million.

3.4 Development of “optimal” response strategies: a portfolio approach

In practice coastal management will incorporate multiple approaches, including “hard” defences, managed realignment and abandonment. For example, Hall *et al.* (2005) use climate scenario data and the Soft Cliff and Platform Erosion (SCAPE) model to assess the impacts of different management strategies along a stretch of the Norfolk coast in the UK, and find that increasing the level of coastal defence in certain areas results in diminished beach volume and increased erosion in down-drift areas. Figure 3.4.1 illustrates, on the same axes of direct financial risk, the expected annual damage from cliff erosion and coastal flooding on a section of the East Anglian coast in the UK, based on SCAPE projections over the 21st Century, under different coastal management scenarios (Hall et al. 2005). First, it is clear that the economic value of the erosion risk, even in the scenario in which all of the coastal defences are abandoned, is small when compared with the flood risk on the neighbouring coast. In scenarios in which the up-drift cliffed coast is protected from erosion, the flood risk on the down-drift flood-prone coast increases rapidly through the 21st Century, due to sea level rise and a reduction in sediment supply. The resulting lowering of beaches reduces the stability of sea walls and increases their probability of failure. Investment in coastal protection along sections of coastline may thus increase losses in adjacent areas; in other words, the reduction of vulnerability to coastal erosion and SLR in one location can exacerbate vulnerability elsewhere. The flood risk remains more stable, even given sea level rise, if the neighbouring cliffs are allowed to retreat, providing protective sediments to the beaches. Permitting coastal erosion, or indeed encouraging it by removing defences at sediment-rich locations, can have down-drift benefits in terms of risk reduction that more than off-set the losses of land due to erosion.

The fluctuations that are evident in the graphs reflect long period fluctuations in beach level in the model. The simulations demonstrate that careful attention must therefore be paid to the time and space scales for which benefit-cost ratios are calculated.



a. Erosion b. Flood risk

Figure 3.4.1. Evolution of erosion and flood risk (on same economic scale) on the East Anglian coast, for different coastal management policies (after Hall et al. 2005)

The type of analysis illustrated in Figure 3.4.1. may be used to construct optimal spatial-temporal portfolios of coastal management measures. The optimisation problem is usually framed in the following terms

$$\min_{S} E(PV(C_i)+PV(R_i)-PV(R_0))$$

where S is a set of coastal management options, often simplified to a space $X \times T$ i.e. a single continuous dimension along the coast on which protections may be located and a dimension through time. C_i is the cost of some $i \in S$, R_i is the erosion or flood risk associated with option i, and R_0 is the risk associated with the (zero cost) base case. The function PV denotes the present value of a stream of costs or risks through time. Finally the function E denotes that it is the expected value of net cost that is to be minimised, reminding us that future costs and risk are all uncertain.

The determining process in this optimisation are the rates of costal change under the base case and for different coastal management options in S, which are determined through simulation under a range of different loading conditions and climate scenarios. Figure 3.4.2. illustrates one such analysis, where the costal response for three different management options is compared under three different management scenarios. The patterns of coastal erosion and accretion are complex, and the solution to the optimisation problem will also depend critically on the location of coastal assets and the costs of coast protection.

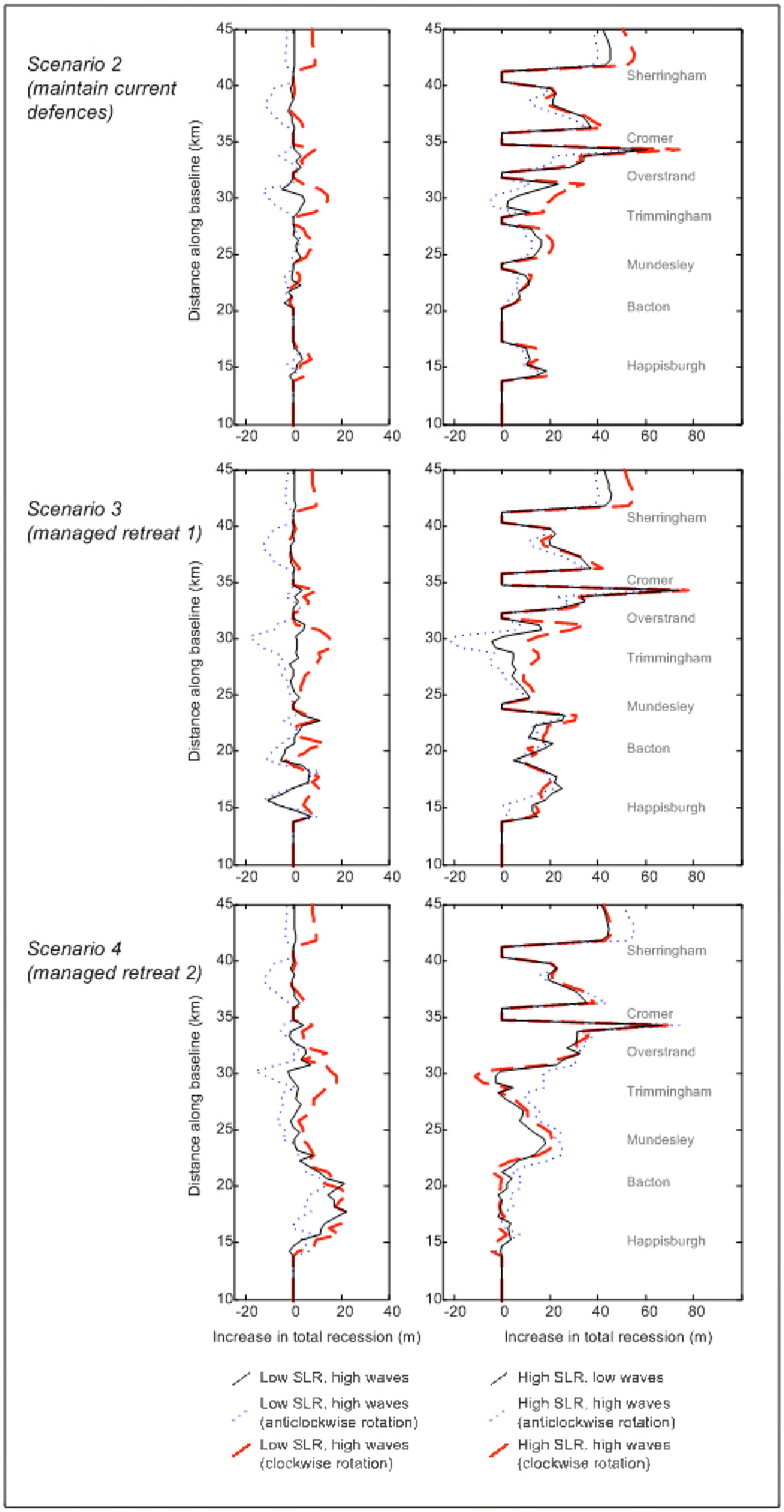


Figure 3.4.2. Coastal evolution under different coastal management and climate scenarios (after Dickson et al. 2005)

The deficiencies of optimisation approaches as outline above are well known. The solution is influenced by the choice of discount rate, which is a value-laden problem. So too is the problem of valuing the various dimensions of risk (to people, cultural heritage and the environment as well as to capital goods and economic activities) and the environmental losses often associated with the construction of coastal protection schemes. These may include the loss of wetlands which are unable to migrate inland. Benefit-cost ratios may therefore depend on the value placed on such systems, which may not generate significant economic wealth but which might be highly valued in a subjective sense, for example for cultural or recreational reasons. Systems such as wetlands may, however, be of significant economic value if they sustain tourism; the impact of coastal protection on these systems should therefore be carefully considered.

Inclusion of an expectation function to integrate out the uncertainties assumes that all of the uncertainties can be unambiguously specified as probability distributions, which is hardly the case for many of the uncertainties associated with climate change, coastal modelling and economic valuation over extended time frames. Under these circumstances it may be desirable to seek options that are robust to uncertainties rather than representing any notional optimum, as we have argued elsewhere (Hall et al, 2006).

3.5 Enhancing social resilience

In the short to medium term, coastal risks will increase in many areas in the absence of costly protection or relocation schemes. Where the consequences of SLR stop short of permanent inundation, the risk from SLR will not simply be a function of exposure to SLR-related hazards, measured in terms of areas of low-lying coastal land and the population in the coastal zone. Some countries with large low-lying coastal land areas and associated populations will find it economically feasible, in terms of both cost effectiveness and ability to pay, to protect coastlines against storms and flooding. However, other countries, perhaps with smaller low-lying coastal areas and populations, will be unable to afford costly coastal protection measures, meaning that population exposure to the impacts of SLR may be higher than in countries with greater potential exposure. Where this is the case, risk to coastal populations will depend on their vulnerability as determined by developmental factors and socio-economic status - in other words, how capable these populations are of coping with and adapting to increased coastal risks.

Where big-budget, large-scale coastal management strategies are absent, coastal risk may be reduced through the building of resilience and the reduction of socio-economic vulnerability at smaller scales, for example at the community level. Adger *et al.* (2005) define resilience as "the capacity of linked social-ecological systems to absorb recurrent disturbances such as hurricanes or floods so as to retain essential structures, processes and feedbacks… [reflecting] the degree to which a complex adaptive system is capable of self-organization and the degree to which the system can build capacity for learning and adaptation".

Vulnerability reduction and resilience building will be achieved through the actions of a variety of bodies, including government agencies, non-governmental organisations, and community-based organisations, with some adaptation occurring autonomously as the result of individual action. Vulnerability is closely related to development and strongly related to factors such as poverty, inequality, marginalisation and access to resources. Brooks *et al.* (2005) assessed relationships between mortality from climate-related disasters and a variety of socio-economic variables at the national level, and concluded that mortality risk (and by extension vulnerability) exhibited statistically significant relationships with indicators of health, education and aspects of governance. There was no statistically significant relationship with GDP; risk and vulnerability do not map simply onto poverty at the national level. As well as being influenced by the national developmental context, vulnerability is also strongly related to a variety of factors specific to the local context (Brooks *et al.*, 2005). Prospects for vulnerability reduction and adaptation are strongly influenced by the wider socio-economic and political environment at a variety of scales, which provide constraints on and opportunities for adaptation (Brooks and Adger, 2005).

Social resilience can be enhanced by strong and effective formal and informal institutions, robust governance systems, efficient early warning systems, diversity in resource use and livelihood strategies and other risk-spreading measures (Adger *et al.*, 2005). Coupled social-ecological resilience is also mediated by the economic environment. Adger (1999) recounts how a shift to a more market-based economy and a move from communal labour to taxation led to a deterioration in coastal protection Vietnam, making coastal communities physically more vulnerable to coastal storms. This occurred as a result of a decline in the maintenance of defensive dikes, which used to be undertaken collectively by coastal communities, and through the destruction of mangroves to make way for commercial shrimp farms in the growing private sector. An absence of severe storms during the late 1980s and 1990s also fostered complacency regarding coastal protection.

In Honduras, Nicaragua and El Salvador, economic policies exacerbated the impacts of Hurricane Mitch; Adger *et al.* (2005), citing Holt-Giminez (2002), claim that "Farmers who had adopted modern management practices suffered greater losses than those who had more traditional agro-ecological practices." The impacts of Hurricane Mitch were also amplified by widespread poverty and poor-quality housing in physically vulnerable areas such as floodplains and steep slopes, coupled with widespread deforestation that increased runoff (Russel, 1999). The experiences of Mitch and other tropical storms demonstrate that vulnerability to the impacts of coastal storms might be reduced a wide range of actions, including, but not limited to:

- improvements in physical infrastructure (including transport infrastructure)
- watershed management that avoids deforestation
- stabilisation of slopes with vegetation

- the prevention of the encroachment of settlements onto flood plains and unstable slopes the provision of safe housing and agricultural land for the very poor and marginalised
- policies that support rural livelihoods, thus reducing the growth of informal settlements in vulnerable areas at the periphery of cities, which are often situated in highly exposed coastal areas

These "adaptations" should be incorporated into disaster recovery and reconstruction programmes, but should also be implemented in anticipation of future hazards prior to the occurrence of complex disasters resulting from the interaction of physical hazards and socially constructed vulnerability. Adaptation in the form of vulnerability reduction or resilience building will be most successful if it is strongly stakeholder-driven, with stakeholders being represented from all sections of society, including the poor and marginalised, rather than being pursued in a top-down fashion through the imposition of policies developed by central or regional governments (Glantz and Jamieson, 2000; Brooks and Adger, 2005).

Lessons may also be learnt from the impacts of Hurricane Katrina. Flood waters in New Orleans after the hurricane contained sewarage contamination and a wide range of chemicals, including dangerous levels of lead and coliform bacteria. The submergence of vehicles (some 150,000) and houses is likely to have resulted in the leaking of petrol, oil, antifreeze, asbestos, pesticides, solvents and other household chemicals. Landfill sites were also sited in submerged areas, while the Gulf Coast is home to much of the US petrochemical industry (Marris, 2005). Recovery from events such as Katrina, which may be more common in the future due to both higher baseline sea-levels and increased ocean surface temperatures, will be made easier if the potential for water-borne pollution and disease is reduced. This may be achieved by relocating landfill sites, sewage works, chemical and other industrial plants, by phasing out potentially toxic chemicals in domestic and other products, and by developing cleaner fuel technologies. These actions would reduce cleanup costs and enable displaced persons to return to their homes more quickly, helping to reduce recovery times and increasing resilience.

Tompkins (2005) describes changes in the regulatory environment in the Cayman Islands that have altered exposure to storm risk, resulting from the introduction of an enhanced Building Codes and alterations to Development and Planning Regulations to improve construction standards and increase set-back of waterfront properties. These innovations have been supported and guided by several policy and planning documents, including the National Hurricane Plan, which promote anticipatory adaptation and vulnerability reduction. The Hurricane Plan is supported by the National Hurricane Committee, which engages a wide range of civil society groups in order to "mainstream" hurricane preparedness into forward planning at a variety of scales (e.g. household, business, government). Responsibility for risk management has also been encouraged by decentralisation and substantial investment in storm preparedness by the tourism sector (Tompkins, 2005). This is echoed by the conclusion of the UK Department for the Environment, Food and Rural Affairs (DEFRA) that a lack of clarity and transparency in the ownership of sewerage and drainage systems mitigates against the development and maintenance of sustainable drainage systems, and that extending the responsibility of sewerage undertakers to the management of surface water and drainage systems might lead to improved management of flood waters (DEFRA, 2005).

4 SUMMARY AND CONCLUSIONS

The potential impacts of sea-level rise are great, and unevenly distributed across the globe. Many regions exhibit high exposure to the primary impacts of SLR, namely inundation and accelerated erosion, and to secondary impacts such as increased storm and flood risk. This paper examined exposure to SLR of up to 20 m, a high but plausible value that may be realised within 1000 years in the absence of dramatic and immediate action to reduce greenhouse gas emissions. However, lower values of SLR, of 2 m and below, were also considered based on assessment of exposure and literature review for specific regions.

A large number of low-elevation "hot-spots" is evident on the global 20m exposure maps. In Europe these include the northern coastal region extending from Belgium to eastern Germany, the coastlines of the Baltic States, eastern England, the west coast of France the northern coast of the Black Sea, and the Po Plain. Many of these regions remain significantly threatened even for a 2m increase in sea-level. In North America the highest exposure is seen along the eastern seaboard, Gulf coast and Florida Pan Handle, the Yukon Delta and Alaska. In South America the mouths of the Amazon, Orinoco and Parana are threatened, along with the low-lying coastal regions between Porto Alegre and Montevideo, and south-east of Buenos Aires. Much of the West African coast is at risk, and exposure is high along parts of the North African coast, in the Nile Delta, and in the coastal zones of Nigeria (the Niger Delta), Gabon, Mozambique, Kenya and Somalia. However, perhaps the region of most concern is south and east Asia, where exposure is extremely high in terms of both area and population: nine heavily populated major deltas are threatened.

Inundation (whether permanent or temporary) will be augmented by erosion, whose role may be of greater relative importance for smaller and slower increases in sea-level. Erosion will be offset by sediment transport, which in turn will depend on factors such as river management, the existence and extent of upstream coastal defences, and climate change impacts on fluvial processes and runoff.

SLR will increase the exposure of coastal populations to episodic flooding, and a 2m increase in sea-level exceeds the typical design allowance for coastal flood defences. Rapid increases in sea-level are more likely to result in the capacity of societies to adapt through the construction of flood defences being exceed. However, dike raising to keep pace with slower increases will result in the loss of buffer zones such as salt marshes, mudflats and estuaries through coastal squeeze, which will mean that coastal defences will have to account for enhanced flood severity. Flood risk may increase in some regions as a result of non-SLR climate change impacts, such as increased destructiveness of tropical storms and changes in atmospheric and ocean circulation. Return periods of extreme water levels will decrease due to SLR, and may decrease even further due to changes in meteorological forcing. In the UK, the population exposed to flood events with a return period of 75 years doubles by the 2080s for the A1 and A2 SRES scenarios.

The 60 million people living within 1m, and the 275 million living within 5m of mean sea-level are projected to increase to 130 million and 410 million respectively by 2100. Approximately 10% of the world's population live within 10m, and 15% within 20m, of mean seal-level. Assuming a constant distribution of population, an eventual SLR of 10m (plausible in the event of the collapse of large ice sheets) could displace 900 million people, rising to 2.6 billion if coastward migration continued at double the global population growth rate. In the shorter term and in the absence of coastal protection, a SLR of 2m would result in the displacement of 400,000 people from four low-lying atoll nations. A rise of 1 m would affect 23 million people in five European countries and displace the populations of vulnerable coastal cities such as Banjul (where such a rise would displace 42,000 people). In the absence of further coastal protection, a rise of just 50 cm would displace 1.5 million people along the Mediterranean coast of Egypt. In the event of a collapse of the West Antarctic Ice Sheet commencing in 2030, some 15 million people would be displaced even with economically optimal coastal protection, with displacement peaking between 2030 and 2060 for all scenarios (based on rates of collapse ranging from 0.5 to 5m per century).

The costs of coastal protection vary by seven orders of magnitude between countries, although Tol (2004) concludes that most countries would opt for full coastal protection based on economic optimisation. Estimates of the total costs of coastal protection against a 1m SLR range from $13 billion to $47 billion per year over the 21st century, with the lower figure based on the assumption of "optimal" protection strategies. Without protection the local costs associated with loss of land, jobs and housing are potentially large. The costs associated with increased flood risk vary, with the most pessimistic scenario for the UK (based on the SRES A2 scenario) associated with a four-fold increase in economic damage as a proportion of GDP by the 2080s.

SLR will have impacts on freshwater resources and ecosystems, causing saline intrusion and altering the composition of ecosystems. The severity of saltwater intrusion will vary significantly with location, being most problematic for small islands with limited areas of agriculturally productive land. Inundation will affect the ecology of coastal wetlands, while increases in water depth and changes in turbidity will impact on coastal marine ecosystems such as seagrass beds. The ability of coastal systems to accommodate the impacts of SLR will depend on their management, the extent to which coastal protection inhibits their migration, and the existence of other stresses, for example resulting from other manifestations of climate change.

Human responses to SLR will vary, and will include coastal protection, managed retreat or realignment, abandonment, measures to reduce wave and current energy, morphological modification of coasts, and resilience building and vulnerability reduction measures. In practice no one response is likely to be pursued in isolation, with coastal management strategies instead being based on a portfolio of options, with the mixture of responses depending on economic, social, ecological and dynamical considerations. For example, the impact of sea walls on sediment transport and downdrift beach nourishment must be considered if protection of one area is not to increase exposure and vulnerability in another area. The management of existing natural systems, and measures to increase their physical and ecological resilience, will play an important role in minimising the exposure of coastal populations. The reduction of socio-economic vulnerability and changes in governance and institutional structures will also play an important role in enabling coastal communities to absorb and recover from the impacts of coastal hazards.

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