Chapter 4. THE LIKELY PHYSICAL IMPACTS OF FUTURE CLIMATE CHANGE ON INLAND WATERWAYS AND THE COASTAL ENVIRONMENT IN IRELAND

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4.1 Introduction

While increasing temperatures in Ireland are projected to occur in all seasons and time periods, it is likely that projected changes in the seasonal and spatial distribution of rain will present a much greater challenge, particularly during the summer months in the south and east of the country. Reductions in summer precipitation, leading to significant decreases in water availability and quality will result in increased competition between municipal, agricultural, and commercial interests, including tourism. Decreases in summer precipitation, together with increased evaporative losses are also likely to affect terrestrial ecosystems, particularly water dependant systems such as turloughs and fens.

Changes in seasonal water levels and the occurrence of extreme high and low flow events will directly impact on river navigability, cultural heritage, and the plant and animal communities of the riparian zone. Inland waterways also provide an important resource for potable water extraction and effluent removal, in addition to providing a tourism and recreational resource.

Climate change will also result in changes in sea level, wave energy and storm surges with consequent impacts on the coastal environment, particularly for coastal heritage. These impacts are likely to be further exacerbated due to 'non-climate' pressures arising from increasing population and development within the coastal zone.

In order to determine the likely impacts of climate change on inland waterways and the coastal environment in Ireland, this chapter will present a review of recent research as it applies to impacts in these areas in Ireland.

Figure 4.1 Seasonal changes in streamflow for selected catchments (Murphy & Charlton, 2008)
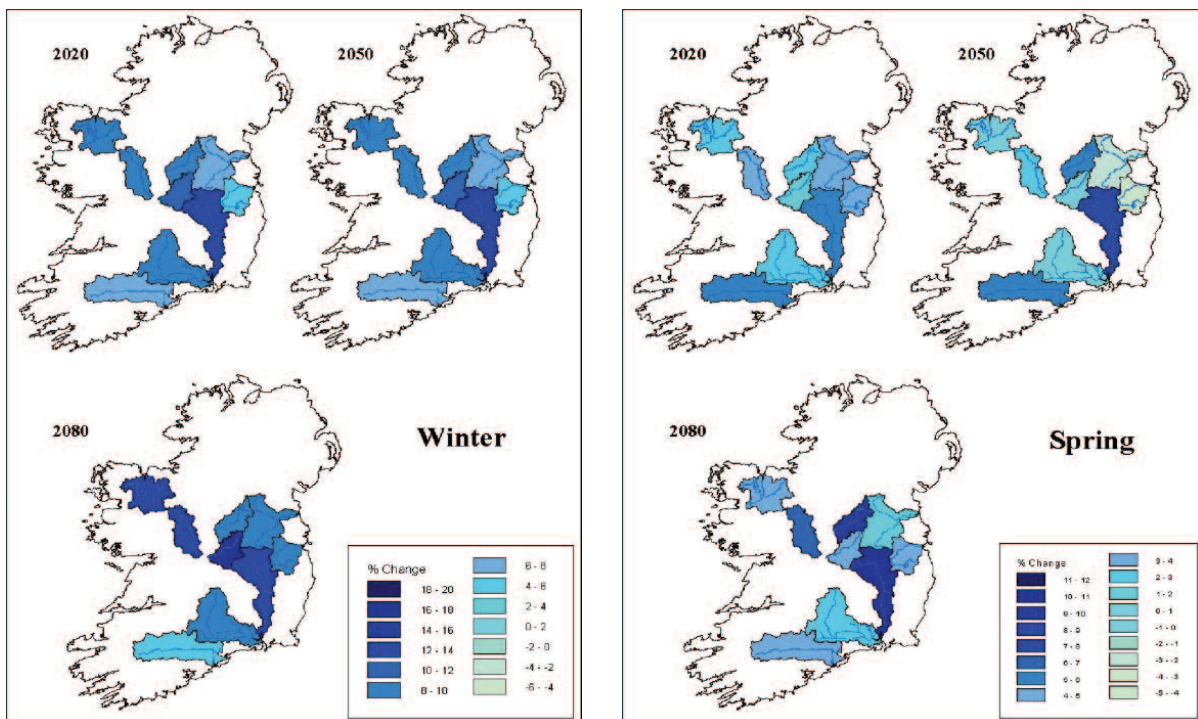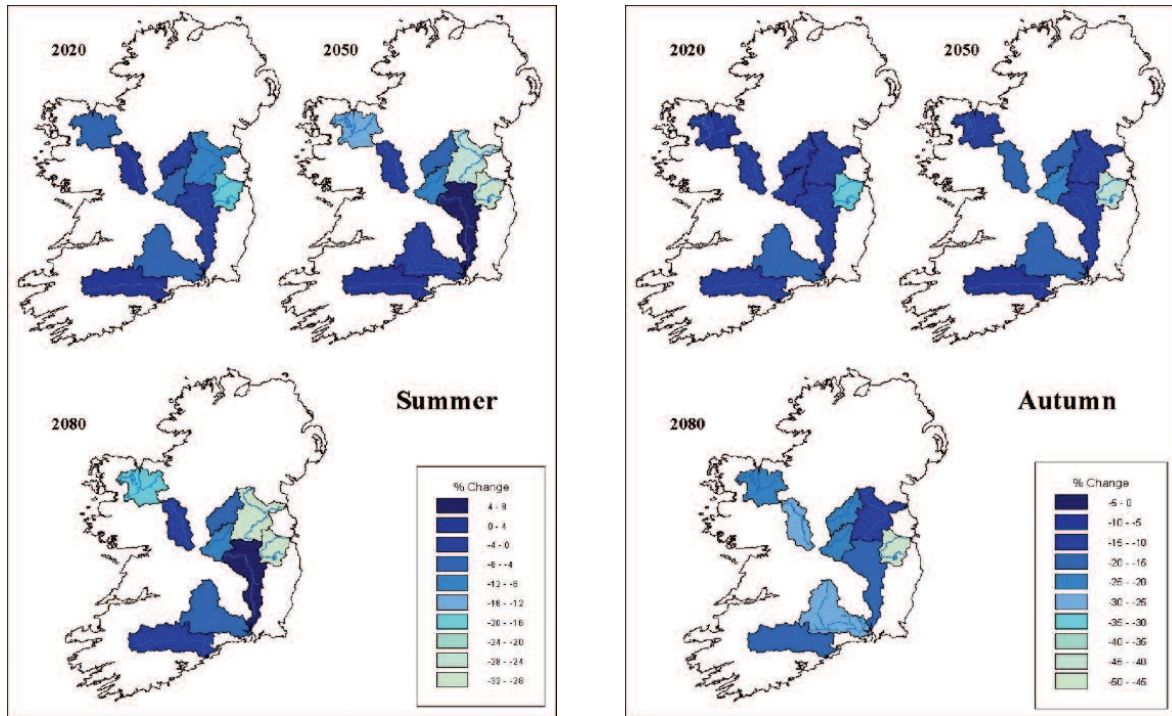
## 4.2 The likely impact of climate change on inland waterway hydrology

While little, if any, research exists with regard to assessing the direct impacts of climate change on inland waterways in Ireland, recent research has been undertaken by Murphy and Charlton (2008) on the projected changes in stream flow in a number of river catchments and sub-catchments. These include the Rivers Suir, Blackwater, Boyne, Moy, Barrow, Brosna, Inny, Suck, and Ryewater.

In their analysis, Murphy and Charlton employed a multi-model average of climate scenarios, as outlined in Chapter 3, to assess changes in mean streamflow conditions, while individual models and emissions scenarios were employed to illustrate the range of uncertainty. The use of individual models was also employed to assess changes in extremes such as flood magnitude or low flow events, occurrences which could otherwise be muted by the averaging of climate simulations.

4.2.1 Projected changes in streamflow

Changes in stream flow result from an interaction between inputs, in the form of precipitation, and outputs through evaporative losses and catchment characteristics relating to soil type, infiltration and porosity. Murphy and Charlton, in their analysis of the impact of climate change on selected catchments in Ireland, identified two distinctive catchment response types to climate change depending on whether a catchment has groundwater storage capacity or is surface water dominant (Figure 4.1 and 4.2).

Figure 4.2 Percent change in monthly streamflow in the (a) Boyne (surface water dominant) and (b) Suir (ground water dominant) catchments for each future time period for the ensemble climate simulation and the A2 (Medium-high) and B2 (Medium-low) emissions scenario (vertical bars indicate the uncertainty associated with the monthly projections of the mean ensemble. (Murphy & Charlton, 2008).
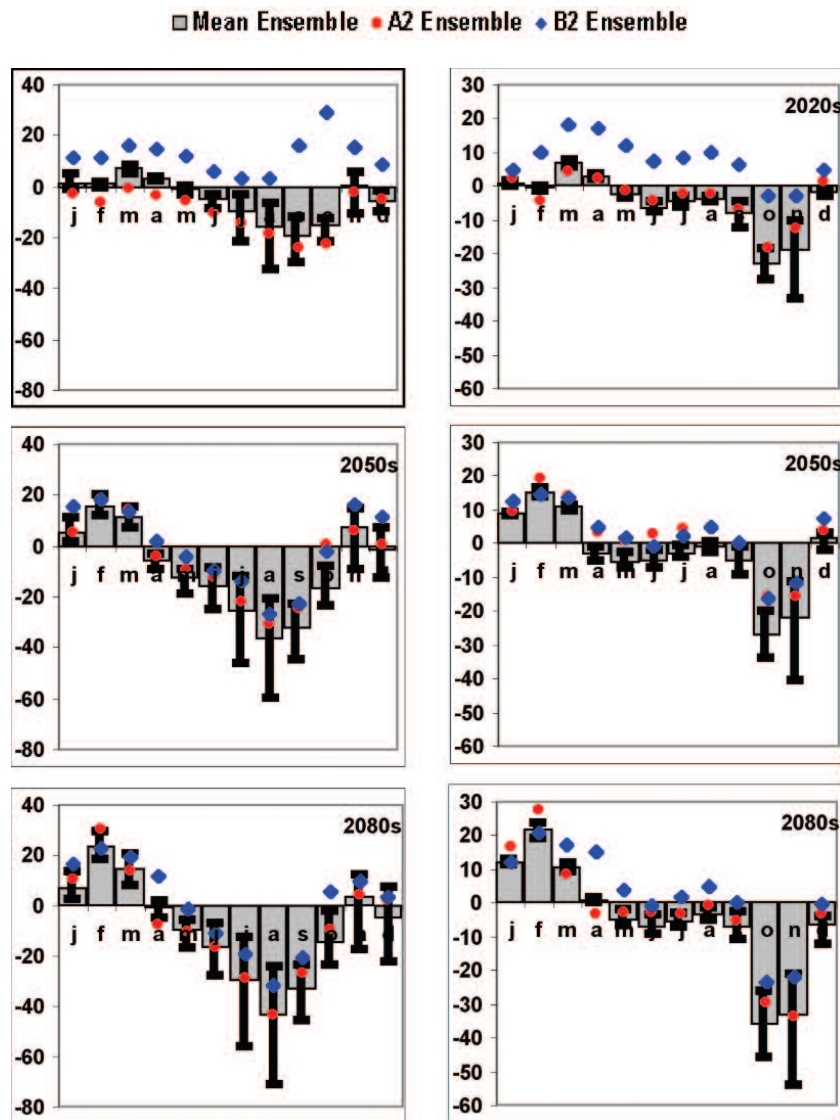
Groundwater dominant catchments like the Suir display lower reductions in summer streamflow due to a compensatory contribution to base flow, in comparison to the more pronounced changes evident in surface dominant catchments (Figure 4.2). However, catchments experienced greatest reductions during the autumn due to the cumulative effect of precipitation reductions in the preceding season, reduced contributions from groundwater to base flow and greater evaporative losses during the autumn months.

Murphy and Charlton suggest that increased flows during the winter and spring are likely, with extended periods of low flows during the summer and autumn months. The result would be increasing seasonality and variability in streamflow (Table 4.1).

Table 4.1 Percentage change in seasonal stream flow for selected catchments and time periods based on the ensemble climate simulations (after Murphy & Charlton, 2008).

Year	Season	Barrow	Moy	Suir	B'water	Boyne	Ryewater	Inny	Brosna	Suck
2020	Winter	0.5	2.7	-0.6	0.4	-1.2	-2.0	0.3	1.6	2.8
2020	Spring	5.3	2.0	2.6	5.1	3.1	4.5	2.9	1.9	3.3
2020	Summer	-0.8	-5.8	-4.9	0.5	-10.4	-18.6	-2.7	-5.7	0.4
2020	Autumn	-12.8	-6.3	-16.7	-10.3	-11.3	-33.6	-12.6	-12.2	-11.4
2050	Winter	12.2	8.6	8.5	6.2	6.5	4.7	8.1	10.9	8.3
2050	Spring	7.7	0.1	0.7	5.4	-2.2	-3.4	5.6	-0.9	2.5
2050	Summer	4.7	-14.0	-2.9	2.8	-25.7	-30.7	-7.3	-11.9	-2.2
2050	Autumn	-10.5	-14.2	-18.1	-9.5	-13.7	-41.2	-19.5	-23.9	-19.7
2080	Winter	13.9	12.2	9.1	5.1	8.6	9.0	9.9	16.8	12.2
2080	Spring	10.5	3.2	2.1	3.9	1.4	3.3	10.0	3.1	6.3
2080	Summer	4.5	-19.6	-5.2	-0.3	-29.8	-30.1	-5.5	-9.8	-0.1
2080	Autumn	-18.8	-21.1	-25.4	-18.3	-14.5	-48.8	-22.9	-21.9	-27.1

4.2.2 Changes in flood frequency and magnitude

For selected catchments, using the A2 and B2 emissions scenarios, Murphy and Charlton also assessed the likely changes in frequency and magnitude for four typical flood events of the kind that could be expected every 2 (frequent), 10, 25, and 50 years.

Table 4.2 illustrates the projected changes in flood magnitude based on the A2 (Medium-high emissions) scenario for selected catchments for the three future time periods (refer to Section 3.3). These suggest that the frequency of flood events of given magnitudes is likely to increase as a consequence of climate change. By the 2020s, nearly all catchments display an increase in the frequency of flood events that have hitherto tended to occur once every two years (T2). For example, for the River Barrow, such an event is likely to occur every 1.8 years by the 2020s, while an event hitherto associated with a 50 year return period (T50), is likely to occur with a return period of 12.6 years.

Table 4.2 Changes in the frequency of floods of a given magnitude for each future time period. Results are based on the HADCM3 (Medium-high) emissions scenarios (Murphy & Charlton, 2008).

		Barrow	Blackwater	Boyne	Brosna	Inny	Moy	Ryewater	Suck	Suir
	20s	1.8	1.8	1.9	2.1	2.5	1.6	1.6	1.5	1.8
T2	50s	1.6	1.5	1.4	1.5	1.4	1.5	1.4	1.4	1.7
	80s	1.3	1.4	1.2	1.3	1.2	1.3	1.5	1.2	1.5
	20s	12.6	6.5	26.8	85.1	26.4	12.3	7.6	8.8	8.4
T50	50s	18.3	11.1	8.2	6.4	10.6	13.9	8.1	17.8	34.4
	80s	11.5	7.3	2.9	3.8	3.3	4.0	10.2	4.0	6.2

Based on A2 scenario from HadCM3

In addition, simulations based on the same medium-high emissions scenario suggest that the magnitude of flood events is also likely to increase (Figure 4.3) (Murphy & Charlton, 2008). Increases in the future magnitude of floods are significant for most catchments and time periods. The largest increases are projected to occur for the Rivers Blackwater, Moy and Suck.

Figure 4.3 Projected change in the magnitude of flow associated with floods of a given return period (T2- 2-year return period; T50- 50-year return period) under the A2 emissions scenarios(Cumecs cubic metres/second). Confidence limits are shown as dashed lines (Murphy & Charlton, 2008)
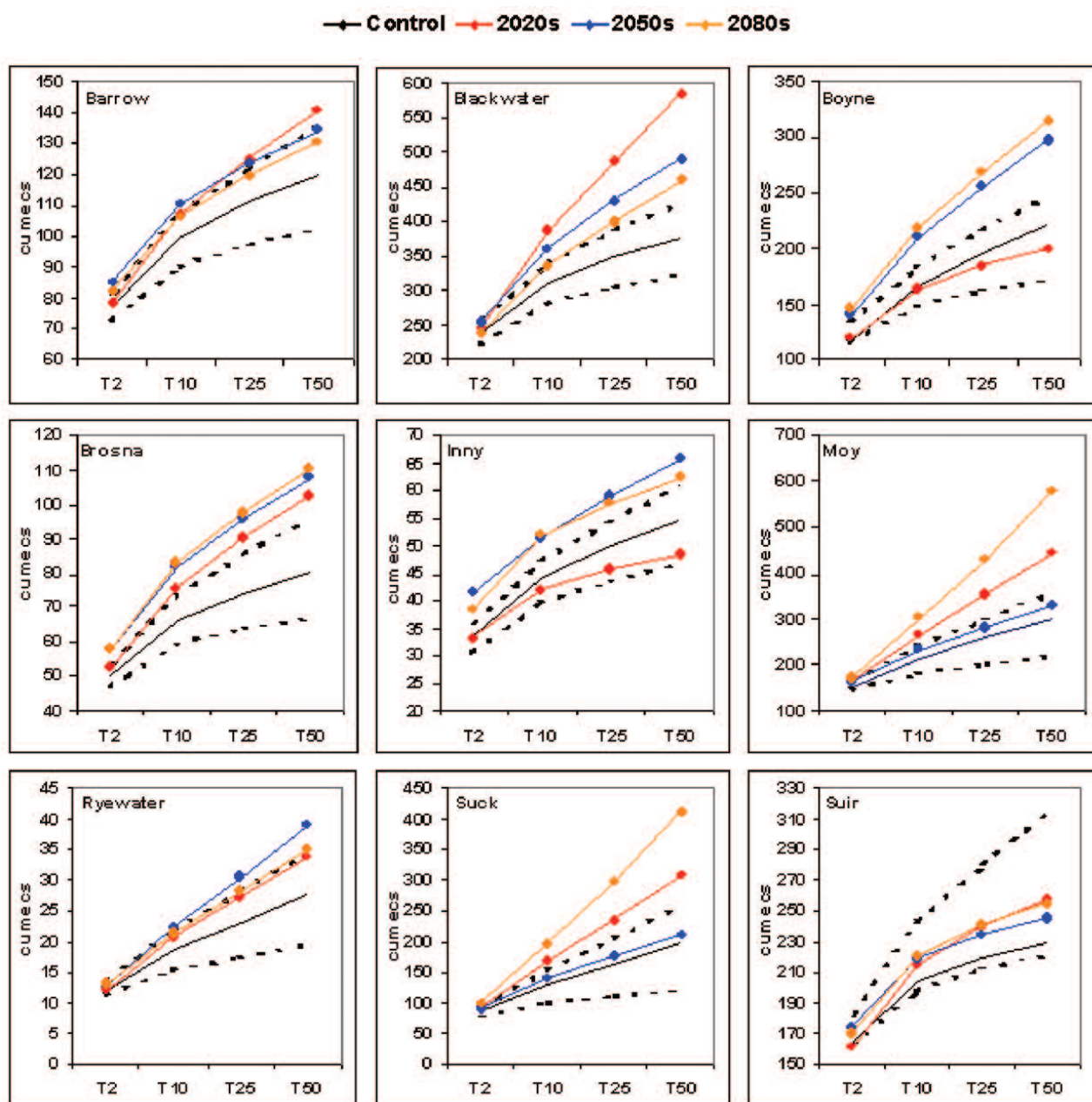
4.2.3 Indirect impacts

The simulations conducted by Murphy and Charlton indicate that all catchments will experience decreases in streamflow, most especially in late summer and autumn. The most notable reductions in surface water are simulated for the Ryewater and Boyne. Unfortunately, these catchments are located in the vicinity of the most heavily populated in the analysis. Furthermore, population growth and changing lifestyles will effect new water demands. In studying the impact of climate change on water consumption in the UK, Herrington (1996) suggests that, if unconstrained, a rise in temperature of 1°C would lead to an increase in average domestic per capita demands of approximately 5%. Simulations suggest that demand will be greatest in the summer and autumn when the greatest reduction in surface water resources is also likely. Furthermore, increases in evaporation are likely to result in increased losses from storage reservoirs. Agricultural demand will also be particularly sensitive to climate change.

Navigation on unregulated watercourses is likely to be affected by both high and low flow situations. Floating marinas may have to increase their range of operation to allow for greater seasonal fluctuations in water levels. Low flows during the summer months are likely to pose a hazard for navigation, a situation that is likely to be further exacerbated during prolonged dry periods when an increased abstraction, for potable supplies and irrigation use, is likely.

Water quality is threatened from both the direct and indirect effects of climate change. Direct effects include increasing water temperatures and changes in precipitation intensity together with associated reduction in the dissolved oxygen concentration. Indirect effects include the greater pressure exerted on the hydrological system from increased abstractions and discharges into watercourses. In the Irish context, the greatest effects on water quality are associated with the drier summer and autumn months when reduced water levels are less effective at diluting effluent. Morphological changes will also occur due to changes in erosion, sediment transport and deposition.

4.2.4 Issues for water management

Effective management of our water courses will help to provide defence from extreme events and will be critical to the continued growth in tourism and recreation. However, meeting the challenges posed by climate change is a challenging issue for a number of reasons. Firstly, modern approaches to water management have been founded on historically reactive measures triggered by past or current events, rather than measures based on an assessment of future conditions (Adger *et al.,* 2005). Traditionally such anticipatory measures have been built on the premise that the past is the key to the future. Climate change will mean that past events can no longer be relied on for future decision-making.

Secondly, uncertainty in modelling climate change has major implications for deciding on successful management options (note uncertainty ranges for monthly streamflow in Figure 4.2). In light of these uncertainties, it would not be good practice to base decision making on a single GCM. In such cases, there is a significant risk of over or underestimating impacts. Rather, we will need to use multi-model ensembles that provide representative uncertainty ranges for impacts. There will also be a requirement for industry standard climate scenarios, continually updated, which can be used in advising policy implementation throughout the water sector.

Historically, water management has been largely concentrated on the physical control of water. The recent shift, internationally, towards an integrated assessment of water resources has resulted in a less disjointed approach to management and a move away from site specific hard engineering approaches, to dealing with water management issues holistically at the catchment scale. This shift partly reflects developments at European level through the Water Framework Directive.

The capacity to adapt to greater extremes in hydrological conditions depends on the ability to apply integrated decision making together with technology and systems that are appropriate and sustainable. With this in mind, adaptation should be focused on reducing sensitivity, increasing resilience and altering exposure, through greater preparedness.

4.3 The likely impact of climate change on the coastal environment

The present day morphology of the Irish coastline is comprised of a number of different landform types. The west coast is a high wave energy 'crenellate' coastline of high relief and low-lying bays. In contrast, the east and southeast coasts are low-lying and composed of poorly consolidated sediments and glacial tills. Of the total coastline length of 6,500km, approximately 3,100km is comprised of hard coastline with 850km comprised of sandy shoreline (ECOPRO, 1996). The remainder of the coast is generally comprised of cliffs, gravel beaches and barriers, lagoons, saltmarshes, wetlands and mudflats, in addition to manmade structures, such as sea walls.

The west coast of Ireland experiences wave heights of between 2.5 to 3.5m due to the longer fetch of open water over which the wind can act. By comparison, the Irish Sea experiences lower wave heights, of between 0.5 to 2.0m. As wave energy is proportional to wave heights, there is greater energy available for erosion on the west coast, although the rocky headlands act to absorb much of this energy and so provide protection for the adjacent soft coasts (ECOPRO, 1996).

Table 4.3 *Long term (>50 year) erosion rates for various lithologies (ECOPRO, 1996)*

Lithology	Rate of recession (m/year)
Glacial till	1.0-10.0
Sandstone	0.1-1.0
Shales	0.01-0.1
Limestone	0.001-0.01
Granite	0.001

Erosion rates vary greatly depending on the structure of landform types and wave energy. Table 4.4 shows the indicative long-term (>50 year) erosion rates associated with various lithologies found around the coast. In a European-wide study undertaken to provide quantified evidence of coastal erosion, Lenôtre *et al.* (2004) found that extensive areas of soft coastline around the Irish coast, particularly in the east, are currently undergoing rapid erosion.

Current erosion trends around the Irish coast may be associated with the significant increase in wave heights reported for the Atlantic between the 1960s and the 1990s. This trend has been linked with an increase in the North Atlantic Oscillation, an index of increased or diminished westerliness, over the same period. Even without a change in wave heights, coastal defences are at risk of being breached or over topped due to changes in relative sea level.

4.3.1 Sea level rise

Any fluctuation in relative sea level, i.e. the height of the sea relative to the land, ultimately determines coastal morphology. Globally, sea level has been rising over the twentieth century at a rate of 1-2mm yr^{-1}, resulting in a total rise of 0.17m. Over the period 1961-2003, sea level rose at an average rate of 1. mm yr^{-1}. However, an accelerated increase to 3.1 mm yr^{-1}, was observed over the 1993-2003 period. Warming of the oceans has occurred to depths of at least 3000m. and this, in turn, has resulted in thermal expansion which is estimated to have contributed 13.5% of the rise between 1993-2003.

Continuing thermal expansion together with the gradual melting of the large ice sheets of Greenland and Antarctica, are likely to result in a sea level rise of at least 0.28 to 0.43m by the end of the present century relative to 1980-1999 (IPCC, 2007a). However, these ranges may be significant underestimates as they do not include important uncertainties in the carbon-cycle feedback. Some researchers, for example Hansen (2007), argue that sea level rise could be much greater, possibly of the order of several metres, due to the non-linear response of ice sheets to warming.

4.3.2 Projected changes in regional sea level around the Irish coast

Determining future changes in sea level around the Irish coast is complex due to isostatic rebound, i.e. post-glacial changes in the elevation of the land relative to the sea. During the last glaciation, a large ice dome was centred on the north of the island depressing the Earth's crust. The melting of this large ice mass during the early Holocene caused the land surface to uplift or rebound. Rebound is continuing with the highest rates in those locations where the greatest mass of ice originally lay, approximately north of a line from north Wexford to south Donegal (Edwards & O'Sullivan, 2007). South of this line rebound rates are slight or negative (Figure 4.4).

Figure 4.4 Simulated long-term rates of crustal movement (mm/yr) over the last 4000 years. Positive values indicate uplift, whilst negative values indicate subsidence (submergence). (Edwards & O'Sullivan, 2007)
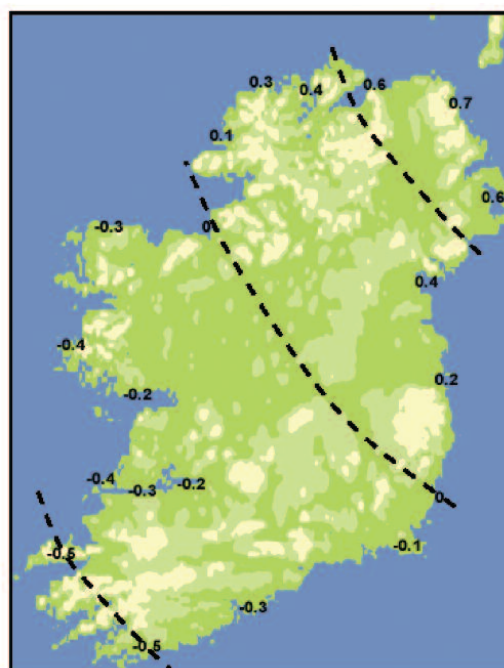
Eustatic, or global, changes in sea level occur when the volume of water is increased or decreased, such as during periods of glaciation. Global sea level has varied considerably over the last 20,000 years; during the last glaciation it was almost 120m lower than present. The interaction between both eustatic and isostatic changes have resulted in considerable variability in relative sea level around the Irish coast, particularly in the north west of the country where sea level was higher than present between 6,000 to 5,000 years BP. Evidence for these past fluctuations in sea level can be seen in the raised beaches in Counties Antrim and Donegal, the drowned forests found at low tide along the south and west coasts, and peat found along present day shorelines.

Regional projections of sea level rise for the present century are subject to a high degree of uncertainty as warming of the surface layers of the oceans is not likely to be uniformly distributed across the ocean surface. Regional changes in atmospheric pressure and ocean circulation will also affect the distribution of sea level rise (Hulme *et al.*, 2002). As these predictions are based on global projections, under or over estimates of regional sea level rise up to 50% are possible (Hulme *et al.*, 2002).

Projections from a range of climate models suggest that globally averaged sea level will rise annually by 2.8 to 4.3mm yr^{-1} over the course of the century assuming a linear trend without positive feedback. If a wider range of emissions scenarios is included, a range of between 0.18 to 0.59m is considered more likely. Higher rates of sea level rise cannot be excluded, but our understanding of key processes (such as the response of the Greenland and Antarctica Ice Sheets) means that our ability to quantify an upper value is limited (IPCC, 2007a).

Combining these sea level projections with isostatic rebound rates for Ireland (after Edwards & O'Sullivan, 2007), means that projected rates of relative sea level vary substantially around the Irish coast. For example, locations in the extreme southwest, from the Dingle Peninsula to Cape Clear are likely to experience the largest increases in relative sea level, at a rate of between 3.3 to 4.8mm yr^{-1}, while on the north east coast, from Malin Head to north of Dundalk, a rate of between 2.2 to 3.7mm yr^{-1} is likely (again assuming a linear increase).

Based on previous estimates of sea level rise (IPCC, 2001), Fealy (2003) calculated the potential area of land likely to be inundated due to a sea level rise of 0.48m, and found that over 380km^2 of the land area of Ireland had a greater than 10% risk of inundation due to sea level rise over the present century (Figure 4.5). While this figure represents a lowering of previous estimates, locations especially vulnerable to inundation include areas with significant land values, such as Dublin, Cork, and Wexford and the Shannon Estuary.

The projected increase in relative sea level is also likely to result in an increase in wave energy being transmitted to the shoreline (Hulme *et al.*, 2002). In addition, coastal locations are likely to be impacted due to changes in rates of erosion and deposition.

*Figure 4.5 Probability of inundation associated with a sea level rise of 0.48 m (Fealy, 2003)*
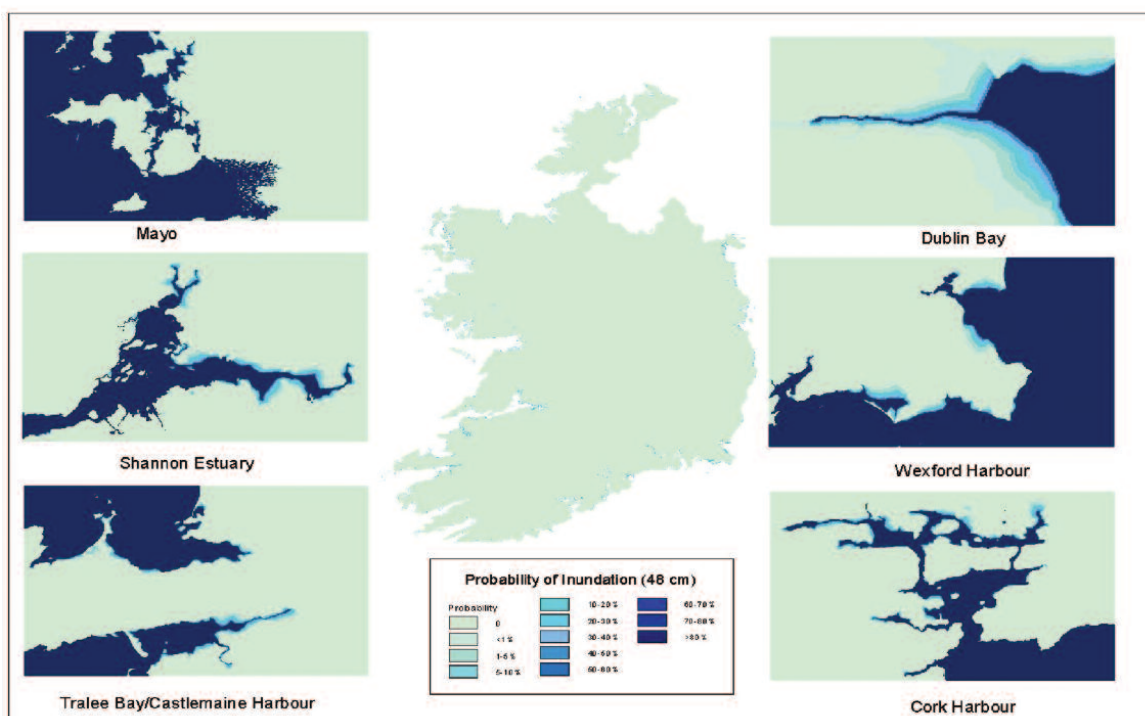
4.3.3 Storm surge

An increase in relative sea level over the present century will mean that low-lying coastal areas will be increasingly susceptible to permanent inundation with subsequent changes in erosion and deposition. Temporary changes in extreme water levels resulting from storm surge events (Figure 4.6), particularly if coupled with high tides, are likely to present additional potential for damage through overtopping of coastal defences. Storm surge events can also have a significant and lasting impact on the coastal morphology through the processes of erosion, transportation and deposition.

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Storm surge 1 February 2002

Significant damage was caused to parts of the east coast of Ireland as a consequence of a severe storm surge event that occurred on the 1 February 2002. The storm surge, which resulted from a combination of several meteorological factors coupled with a high tide, resulted in an extreme water level of 5.46m. being recorded at the North Wall gauge in Dublin, the highest level recorded since records began in 1923. While a high tide had been forecast to occur, the previous days high water level of 4.46m. had passed off without incident. The following extreme water levels resulted from a deepening area of low pressure in the North Eastern Atlantic, which produced gale force south-westerly winds (inset 1). On the Isle of Man, wind speeds reached 50mph, with gusts of up to 70mph being recorded. The sustained winds and long fetch over the ocean, resulted in increased water levels being forced up the Irish Sea (inset 2). These increased water levels or surge coupled with a forecasted high tide, produced extreme water levels over 1m. above expected levels based on astronomical calculations of tidal motion.

Figure 4.6 Skew surge for the afternoon tide on 1 February 2002
(Proudman Oceanographic). The water height, in centimetres, that exceeded the predicted level.
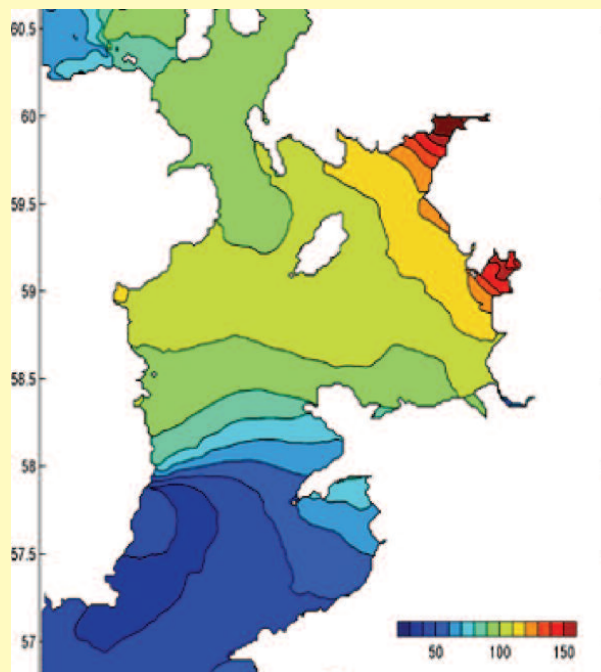
Overtopping of the coastal defences lasted approximately two and a half hours, resulting in severe flooding in Clontarf, Sandmount and Ringsend (inset 3). It is estimated that over 300 people were directly affected and required re-housing as a consequence of the flood damage.

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Global climate models indicate that it is very likely that tropical cyclones will become more intense, with higher wind speeds and more intense precipitation (IPCC, 2007a). While Ireland is not directly affected by hurricane activity, the remnants of Atlantic hurricanes can be rejuvenated as they pass over the warmer sea surface temperatures associated with the Gulf Stream. If model projections of storm intensity are realised, a significant enhancement of wave heights is likely to occur in the Atlantic. For countries along the eastern Atlantic seaboard, such as Ireland, a rise in surge elevation is likely to increase vulnerability to flooding and storm

damage. An increase in relative sea level will further exacerbate the surge events associated with more intense tropical storm activity.

In an analysis of extreme water levels and sea level rise, Fealy (2003) estimates that 680km^2 of land is at risk of inundation (>10% probability) based on an increase in sea level of 0.48m. together with an extreme water level of 2.6m. representing a 1-in-100 year event on the east coast and 1-in-12 year event on the west coast (Carter, 1991). The return period associated with such an event is likely to shorten as a consequence of sea level rise. For example, the current 1-in-100 year event is likely to become a 1-in-10 year (or less) event.

4.3.4 Likely impacts on the coastal zone

Coastal morphology
The morphology of the coast is undergoing continual modification in response to the varying forces acting upon it (ECOPRO, 1996). Short-term changes, such as the tidal cycle and wave energy, combine with longer term coastal processes associated with changes in the wave climate, sediment supply and sea level (Charlton & Orford, 2002).

Human activities, such as the removal of beach material or the building of coastal infrastructure, can also have a significant and long lasting effect on the morphology of the coast. For example, Orford (1988) suggests that the twentieth century erosion and shoreline adjustment evident in Rosslare Bay could be attributed to nineteenth century land reclamation activities undertaken in Wexford Harbour. These activities are likely to have resulted in the erosion of Rosslare Spit, shortening its length by approximately 2km.

Discussions of 'hard' and 'soft' coastlines can be misleading. While localised cliff failure due to the erosion of 'hard' coastlines can be dramatic, recent research suggests that the sensitivity of these coastlines, particularly to the impact of high magnitude, low frequency events, such as extreme wave heights, may be greater than previously thought (Hansom, 2001). For 'soft' coastlines, the coastal response to sea level may be self-regulating over short time scales (Carter, 1991). Sediment, such as that stored in dune systems, acts as a reservoir in the exchange between near-shore, beach and dune. Erosion and subsequent removal of this material to sand bars or shoals, may act to diminish incoming wave energy and therefore reduce erosion (Carter, 1991).

In spite of these complexities, a rise in sea level will have an impact on much of the extensive low-lying areas of 'soft' coastline. Figure 4.7 illustrates the variety and type of coastal landforms found around the Irish coastline. These coastal landforms, comprised of silt, mud, sand, peat, gravel or unconsolidated glacial tills, represent fast responding and mobile systems that are highly sensitive to environmental change (Hansom, 2001).

The availability and transport of sediment is central to morphological changes that occur around the coastline (Pethick, 1984; Carlton & Orford, 2002). The sedimentology of the inshore zone is largely determined by the amount of available energy (wave, tidal) and the type of sediment supply. On exposed parts of the coast, where sediments are derived from eroding boulder clay cliffs or from off shore gravel deposits, fringing gravel beaches and shingle banks or storm beaches are formed (ECOPRO, 1996). In more sheltered areas, fine sediments such as muds and fine-grained sands, are common, reflecting the tidal range and lower energy regime (ECOPRO, 1996; Charlton & Orford, 2002).

An alteration in the amount of energy entering the coastal zone, resulting from an increase in sea level, is likely to destabilise existing equilibriums resulting in changes to the coastal morphology, particularly on exposed locations along the coast. Exactly how these will respond depends on sediment supply (Figure 4.8) and the ability of the landform types to migrate landwards. The presence of natural barriers, such as gradient of slope, or man-made infrastructure, is likely to impede landward migration, resulting in 'coastal squeeze'. An increase in sea level will also affect the morphology of landforms which are sheltered from the effects of wind driven waves.

Figure 4.7 Location of coastal systems in Ireland compiled from various sources (after Fealy, 2003)
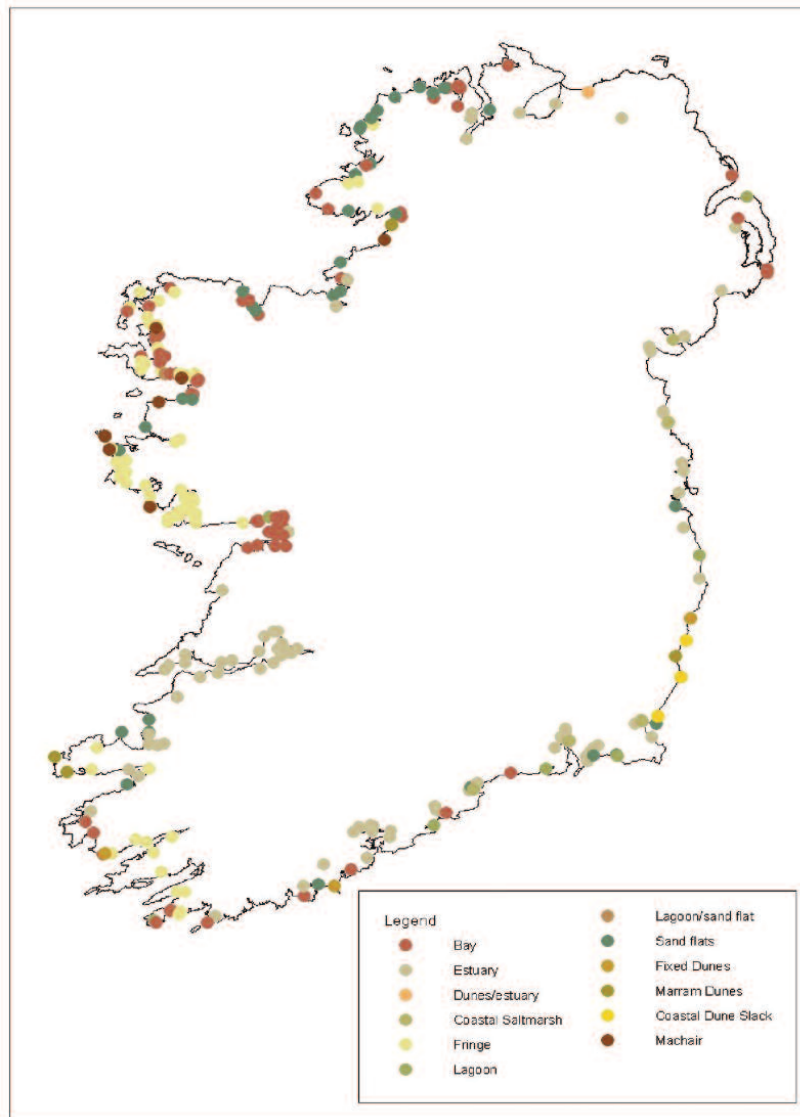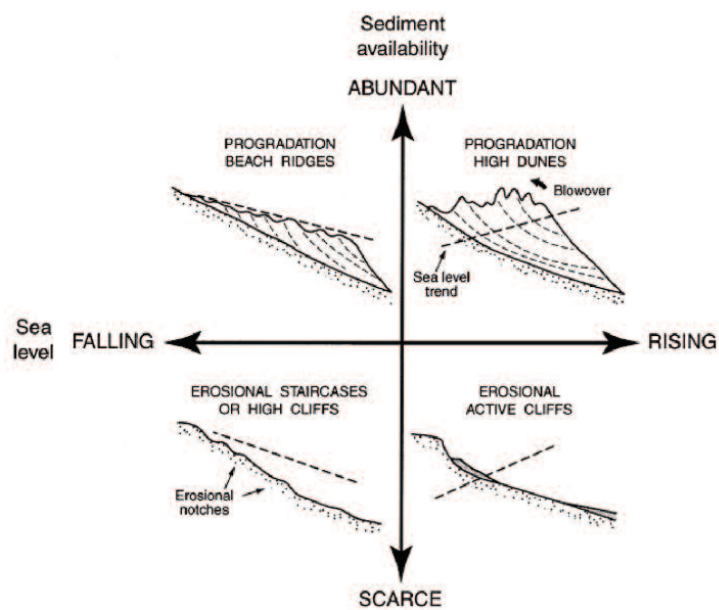

Figure 4.8 Coastal response to sea level rise and sediment availability (Hansom, 2001; after Carter, 1988)

In order to assess the impact of the projected increases in sea level on the morphology of the coast, a selection of landform types is examined in the following section. These range from gravel beaches, associated with exposed, high energy locations, to salt marshes, associated with sheltered, low energy locations and formed of fine grained silts and clays. However, impacts are not likely to be uniform around the coast. Differences in wave energy, sediment supply and other local factors are likely to result in a variety of impacts depending on local conditions (IPCC, 2001).

Gravel Beaches
Gravel or storm beaches are highly mobile geomorphic systems (Carter, 1991) which respond to both seasonal and long term changes in wave energy and sediment supply. During high-energy storm events, material is transferred upslope from the base and seaward face resulting in an over-steepened seaward profile (Charlton & Orford, 2002). Material may also be pushed on to the back slope due to wave overtopping of the barrier crest, resulting in the landward transgression of the beach ridge. Sea level rise is likely to increase the occurrence of wave overtopping, leading to an increased vulnerability of backshore flooding, while increased re-working of the beach material up slope is likely to result in 'roll-over' of the gravel ridge onshore.

Coastal defences designed to prevent over-topping, flooding or to slow the landward transgression, are likely to result in an artificially over-steepened profile increasing the probability of catastrophic failure or break down of the gravel ridge during a subsequent storm event (Charlton & Orford, 2002). Where gravel beaches are impeded from migrating landwards, sediment is likely to be lost through reworking of the sediments along shore (Devoy, 2000).

Back beach lagoons are often formed in the lee of gravel or shingle ridges (ECOPRO, 1996). Lagoons, such as that found on Lady's Island in Wexford (see case study), are designated as a high priority for conversation in the EU Habitats Directive, reflecting their importance as a coastal habitat type that is under threat. Lagoons are likely to be negatively impacted by changes in sea level and storm surges which may result in the penetration of the lagoon barrier, due to reworking of material and overtopping of the barrier (Healy, 1997).

Sand Beaches
Similar to gravel beaches, sand beaches can adjust their shape rapidly to changes in wave energy (Pethick, 1984). During low, flat swell waves, experienced during the summer months, sediment is mobilised on shore, resulting in the beach prograding to form a steep profile. Storm waves experienced during the winter months act to erode the previous season's beach face resulting in a widening of the profile and reduced slope gradient (Pethick, 1984). As a consequence, a beach can maintain a dynamic equilibrium with its environment through changes in its profile that dissipate wave energy.

On much of the south, west and north coasts of Ireland, beaches tend to occupy distinct compartments, or sediment cells, separated by headlands (ECOPRO, 1996; Bird, 2000). Within each coastal cell, the total amount of sediment remains relatively constant but highly mobile. The beach system maintains dynamic equilibrium with the energy gradient through sediment being transported alongshore or exchanged between off shore, beach and backshore storage.

In the absence of an adequate supply of sediment, an increase in sea level will result in a deepening of nearshore waters which will enhance wave energy and accelerate beach erosion (Bird, 1993). Human activities, such as the removal of beach material are likely to exacerbate existing erosion rates. On the other hand, if sufficient material can be supplied through longshore transport, beaches may be maintained or prograded during sea level rise (Bird, 1993).

Where possible, beaches are likely to migrate landwards in response to a higher coastal energy gradient. Sand spits will be increasingly vulnerable to wave over topping and to the flooding of the backshore, although the breakdown of these landforms would provide scavenged sediment to supply downstream locations.

Sand Dunes
Sand dunes, in addition to being features of much ecological interest, protect the surrounding hinterland through the dissipation of wave energy and also help to protect against saline intrusion into the water-table. Sand dunes have an important function in maintaining beach stability through the exchange of material between the dune-beach system (Carter, 1991b). Unlike gravel and sand beaches, they are formed by air or aeolian sand transport.

An increase in sea level is likely to result in the cliffing or scarping of the seaward margins of coastal dunes (Bird, 2000) as is already evident on parts of the Wexford coastline. Where this occurs, strong onshore wind action can initiate blowouts (Ford, 1998).

Landward sediment transfer is likely to facilitate dune migration and the development of transgressive dune fields.

Ultimately, dune response to an increase in sea level will be determined by the amount of sediment transferred to the off shore zone or transferred landward as new dunes.

Over grazing and recreational activities can also significantly damage dune vegetation, reducing the natural resilience of the dune and beach system, resulting in an increased exposure to wind erosion (ECOPRO, 1996). These activities are likely to further expose the coastal zone already made vulnerable by ongoing changes in climate.

Salt Marshes

Salt marshes provide an important ecosystem service through the regulation of nutrients and flood attenuation as well as providing an important habitat for wildlife and fish. They are also sensitive indicators of changing sea levels as they accrete vertically to just below the high water mark (Carter, 1991a). If the rate of vertical accretion can keep pace with increasing sea level, then salt marshes will maintain their position within the tidal range.

Accretion rates of 4-8mm/yr have been found to be occurring on sites along the south and west coasts, linked to increased sediments transfers associated with storm action (Devoy, 2000). These accretion rates may provide some resistance to an increase in sea level, assuming an adequate supply of sediment. Where salt marshes are prograding, vegetation is likely to invade the surrounding hinterland, assuming no barriers exit. Along sections of the coastline where erosion is the dominant process, salt marshes may initially respond positively to an increase in sea level due to increased sedimentation associated with a reworking of material into the inner estuary (Carter, 1991a). However, where low accretion rates occur due to a diminished sediment supply, salt marshes are likely to be submerged and replaced with erosion on their seaward margins.

Salt marshes that occur in areas with a low tidal range are likely to be more vulnerable than those in areas with a larger tidal range. Continued human activities, such as drainage or the building of coastal infrastructure, are likely to further reduce the resilience of salt marshes to the impact of increasing sea levels.

4.3.5 Coastal management issues

The coastal zone is a dynamic system that is sensitive to environmental change. Consequently, a rise in relative sea level is likely to result in modification and spatial reorganisation of the coastal zone. Coastal landforms, which may currently be in equilibrium are likely to exhibit marked changes in response to climate change. Where an adequate supply of sediment is available, coastal landforms may either prograde or migrate landwards in response to a higher energy gradient assuming no barriers exist. If there are barriers, or where sediment supply is limited, erosion of the seaward margins is likely to increase, resulting in 'coastal squeeze'.

In addition to changes in coastal morphology arising from climate change, human activities along the coast can have a significant impact on the coastal morphology. Land reclamation, the building of coastal infrastructure, such as marinas and piers, or coastal defence structures, all act to modify the 'natural' transfer of sediments within the coastal zone requiring shoreline adjustment before a new stable shoreline is achieved. This process of readjustment may take several decades (Pethick and Crooks, 2000).

This displacement of the coastal response, in both space and time, to both climate and human induced changes in morphology presents significant management issues. Implementing effective coastal management is further complicated by the uncertainties associated with the response of the coast to predicted increases in sea level. In order to reduce some of these uncertainties, an understanding of sediment dynamics will be necessary (UK-CHM, 1999).

A number of management strategies exist, which generally involve 'soft' or 'hard' engineering options, retreat/abandonment or a mixture of these. In cases where the retreat of the shoreline is estimated to incur high economic losses, costly reinforcement of existing defences or 'hard' engineering options is normally considered. 'Soft' options such as beach nourishment or dune restoration are usually considered for vulnerable locations with lower associated economic losses. Where the costs of coastal protection exceed a manageable scale or complexity, the 'do nothing' approach often becomes a default management option (Charlton & Orford, 2002).

'Local' actions taken to reduce vulnerability or halt erosion/retreat of the shoreline ignore the larger spatial and temporal context of the coastal sediment budget. They reflect a fragmented view of the coastal system. Such localised interventions may act to ini-

tiate or enhance erosion occurring further alongshore.

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Coastal management in the UK

In the UK, the Environment Agency has responsibility for fluvial flood management. From 2008, its responsibilities will extend to coastal management too. The Agency will have a statutory input to all shoreline management plans, and will assume responsibility for flood risk assessment, coastal protection and coastal habitat.

The responsibilities are huge. DEFRA has estimated that at least €130 billion worth of property is at risk, including industries and infrastructure such as ports, oil refineries, power stations (including nuclear) and power lines. At least 100,000 properties are threatened. This number rises to over 400,000 along the east coast alone should a coastal surge comparable to the 1953 flood disaster coincide with a 0.4m rise in sea levels (Donovan, 2007). Coastal schemes and spatial planning have been required to incorporate potential climate change impacts since 2006. UK planning now requires local authorities to be mindful of a sea level rise of up to one metre by 2100.

Adaptation plans include forward planning and new warning systems, but also higher coastal defence ratings. Hard engineering is anticipated for some locations where infrastructure or towns are at risk. However, the cost of maintaining hard coastal defences will increase due to the combined effect of sea level rise and wave scouring of the beach ahead of defences. On this basis, it is has been predicted that the cost of maintaining any one structure in response to a 30cm rise in sea level will multiply by over 180%. Based on a survey of 400 locations, the costs of maintaining coastal defences are predicted to rise by between 28% and 125% depending on whether a low or high emission scenario is assumed (Burgess & Townend, 2007). As a result, the Environment Agency strategy is having to give serious consideration to greater 'coastal naturalisation' and managed re-alignment, the latter to include some level of abandonment.

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4.3.6 Adaptation

The NDP 2007-2013 has allocated €23 million to protect the coastline from the impact of flooding and erosion. It is intended that these resources will finance structural works for the construction of Flood Relief Schemes, which "will be implemented in an environmentally friendly fashion, as far as possible".

However, approaches which seek to preserve or protect the present day shoreline are unlikely to represent an optimum long term management strategy for the coastal zone. A more effective management option is one that seeks to manage change in the coastal system so that it is allowed to adjust to environmental or human changes. This requires a high level of understanding of the coastal system supported by effective monitoring of vulnerable locations to identify where and when remedial action is necessary.

Implementing an approach of shoreline realignment, or 'managed retreat', is likely to be contentious where economic losses are possible or where coastal archaeology or tourist sites exist. Nevertheless, the extreme of abandonment may represent the most economic strategy where the cost of implementing coastal defences exceed the value of the structure(s) being protected (Bird, 1993).

Local authorities involved in the planning and development of the coastal zone may need to adopt set back lines, seaward of which no development should be allowed. A precautionary approach should be used to determine these buffer zones taking account of future sea levels, erosion and landward migration of coastal landforms.

There is an urgent need to implement an island wide and integrated coastal zone management (ICZM) policy, the objective of which should be to establish sustainable levels of social and economic activities while still protecting the coastal environment. Cummins *at al.* (2004), in their comprehensive review of ICZM, have made a number of important recommendations in this respect.

The coastal zone provides important economic and recreational benefits to society as well as providing important habitats for plant, animal and fish species. Large parts of the coast are protected under the EU Birds Directive, EU Habitats Directive or the Wildlife Act reflecting the international importance of the coastal zone and the ecosystem services it provides. However, the coastal zone is becoming increasingly vulnerable to socio-economic pressures, particularly from development and over utilisation of resources. Its ability to withstand these pressures is likely to be further compromised by climate change.

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