5. INTEGRATED IMPACTS ON COASTAL AREAS AND RIVER FLOODING

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Summary

Climate change threatens increased levels of flooding in the coastal and riverine flood plain, as well as the degradation of nationally and internationally important coastal ecosystems such as saltmarsh and coastal grazing marsh. These changes interact, as the incidence of flooding has implications for the types of ecosystem that will be found and *vice versa*. In addition, these changes will have important consequences for the other sectors considered within RegIS, such as agriculture and biodiversity.

This chapter focuses on the impacts of increased flooding due to sea-level rise and increased flood flows on rivers and possible changes in the distribution of coastal ecosystems for the 2050s, and emphasizes those aspects that link with other components of RegIS. Other climate factors are assumed to remain constant, including storminess. The analysis includes evaluating the relative importance of climate versus socio-economic changes. In each case, standard impact models are used to evaluate the impacts of a Low and a High climate change scenario. These include spontaneous responses to climate change (such as saltmarsh accretion, or changing farmer behaviour), but exclude planned adaptation such as upgrading flood defences against climate change. This is designed to determine the worst-case impacts and to be consistent with the assumptions of the other RegIS components. The potential for adaptation to counter the identified impacts is also evaluated in a more qualitative manner, including a consideration of future needs.

The UKCIP98 Low scenario of sea-level rise is similar to the continuation of observed trends, while the UKCIP98 High scenario of relative sea-level rise represents a four-fold and seven-fold acceleration in East Anglia and the North West, respectively. Changes in river flooding are considered via assumed *uniform* increases in the 100-year flood flows of 5 % and 20 % for the Low and High scenario, respectively. These assumed values are derived from model studies of the impact of climate change on peak flows in the Severn and Thames in the absence of better data. The catchment modelling conducted within RegIS is consistent with an increase in flood risk along rivers, particularly in the North West (see Chapter 7). The changing risk of flooding in coastal areas is determined directly using the flood curves, the relative sea-level rise scenarios and the standard of service of the flood defences. Data sets for the analysis of river flooding are not as well developed and a number of assumptions were necessary for the flood analysis. These include estimating indicative standards of service based on the existing land use. Due to these limitations, the analysis of river flooding is less precise than the analysis of coastal flooding.

As well as considering a constant baseline (*i.e.* 1990s) socio-economic situation, two distinct evolving socio-economic storylines for the 2050s are also evaluated: Regional Enterprise (RE) together with the High climate change scenario, and Global Sustainability (GS) together with the Low climate change scenario. The Regional Enterprise storyline includes increased development in coastal and flood plain developments as well as a focus on "hold the line" in shoreline management. Therefore, there is little interest in policies, such as managed realignment, which would allow declining saltmarshes to migrate landward. The Global Sustainability storyline also sees increased development in both regions, but with careful land use planning steering these developments away from flood-prone areas. There is also significant habitat recreation to maintain and enhance natural and semi-natural habitats within areas such as the Fens, and widespread managed realignment along the coast.

Flooding in the 2050s is enhanced by all the climate change scenarios, but the impacts are much greater under the High climate change scenario. Sea defences, which presently provide protection to a 1 in 100 year standard, would be reduced to the range of a 2- to 8-year standard by the 2050s under this scenario. (By the 2080s, many of these defences would be at or below a 1-year standard under this scenario). In the Fens, the interaction of sea-level rise, increased river flows and ongoing subsidence/peat oxidation, could lead to severe flood impacts over a geographically large and important agricultural area. Significant flood impacts would also occur in the Norfolk Broads and the Lancashire coastal plain. Under the 2050s High scenario, our analysis suggests that arable agriculture would be precluded by the high frequency of flooding over 86 % of the Fens, 10 % of the remainder of East Anglia, and 7 % of the North West. Most of this land is expected to revert to grazing marsh, while in the Fens it is expected to revert to a mixture of grazing marsh and fenland, although this will also depend on the land management regime (*e.g.* amount of grazing).

Order-of-magnitude calculations of average annual flood damage to properties at the region-scale show that all climate change scenarios increase damages. However, raising all flood defences to the present indicative standard would more than counter the impacts of the Low scenario. In contrast, the High scenario significantly increases average annual flood damages, with coastal damages increasing 20-fold in East Anglia! Collectively, the total losses in the Anglian (*i.e.* a bigger region than assessed in RegIS) and North West regions of the Environment Agency could exceed £700 million and £400 million/year, respectively. The Regional Enterprise storyline will enhance these impacts due to increased exposure to flooding. The annual damages would increase by an additional 35 to 42 %, so that the main factor increasing flood damage is the more frequent flooding of areas which have already been developed. Therefore, flood impacts could be significantly enhanced by climate change, while socio-economic changes could produce important additional impacts.

The area of saltmarsh and coastal grazing marsh will change in response to climate and non-climate change, with both losses and gains being possible. However, much coastal grazing marsh is a man-made habitat which depends on artificial flood defence as it occupies former intertidal areas. There are limited coastal areas for grazing marsh creation, so losses are likely to predominate. Sea-level rise may produce losses of saltmarsh, while planned and unplanned coastal realignment will produce gains of saltmarsh and associated intertidal habitats. Thus, gains of saltmarsh will often produce losses of coastal grazing marsh. A balance may need to be struck to sustain coastal grazing marsh as a habitat, or alternatively grazing marsh will need to be created in more sustainable, non-coastal locations.

Under the 2050s Low climate change scenario, saltmarsh losses are confined to the Suffolk coast, while under the High climate change scenario, saltmarsh losses occur around the entire East Anglian coast. These losses are further exacerbated under the Regional Enterprise storyline due to reduced sediment availability. These losses may be compensated by unplanned retreat and coastal abandonment in areas subject to frequent flooding. The saltmarshes in the North West are predicted to remain stable under all the climate change scenarios, which is a function of the high tidal range in this region. Unplanned retreat and coastal abandonment in response to sea-level rise could even lead to net saltmarsh gains. However, additional saltmarsh losses could occur in both regions due to processes other than sea-level rise: increased wave action due to increased storminess is one possible driver. Under the Global Sustainability storyline and Low climate change scenario there is significant saltmarsh and intertidal habitat gain in both regions and a consequent coastal grazing marsh decline. Compensating habitat creation in non-coastal locations could occur in river valleys and coastal lowlands such as the Fens. In conclusion, for coastal ecosystems, climate change has important impacts, but human management of the coast also has an important control on the evolution of habitat.

As already noted, all these results explicitly assumed no planned adaptation to climate change, to identify worst-case impacts. Strategic adaptation to the flood impacts include raising flood defences, avoiding development on flood plains and managed realignment, implemented within a coastal management framework. Important efforts towards such approaches are already in evidence, including MAFF’s Shoreline Management Plans and English Nature’s Estuary Management Plans. These efforts need to be maintained and strengthened. In addition, MAFF already recommends an allowance for accelerated sea-level rise in the design of new tidal flood defences of 6 mm/yr in East Anglia and 4 mm/yr in the North West. This is more than sufficient to counter the Low climate change scenario, but under the High climate change scenario there might still be a seven-fold increase in average annual flood damages by the 2050s. Therefore, in addition to the MAFF allowance, it is important to monitor actual changes in sea level around the British Isles so that the timing and magnitude of any accelerated rise is observed and factored into flood defence policy in a timely manner. Similarly, the possibility of increased storminess under climate change needs further investigation. Many of the impacts described above could result from the combination of a smaller sea-level rise and more frequent and larger storm surges, as well as the High global sea-level rise scenario alone. (The potential impact of changes in storminess is being investigated by HR Wallingford and POL in the MAFF-funded ‘Coastal Vulnerability 2075’ project).

Coastal lowlands, such as the Fens, present particular problems in terms of responding to the flood problems identified, as there is the interaction of higher peak river flows, higher sea levels and (usually) localised subsidence. In the Fens, raising flood defences will be expensive due to soil conditions. Therefore, wider river channels might be more appropriate, although this will also be costly, possibly combined with storm surge barriers to keep surges at bay. At the same time, there is already significant interest in habitat recreation in the Fens, and it might be possible to combine flood management and habitat creation if there is more strategic planning. This should also consider land use planning so that the necessary corridors for flood management are maintained. Therefore, while they have not been explored in detail, there are several adaptation options available. The Fens comprise the largest coastal lowland in Britain and a strategic flood management plan of the entire region, analogous to the open-coast shoreline management plans, would seem a prudent measure. Such a plan would necessarily extend beyond the RegIS area. These risks and opportunities should be addressed under the forthcoming Catchment Flood Management Planning initiative, and more broadly under the EU Water Framework Directive.

While saltmarsh is threatened by sea-level rise around much of the coast, there seems to be sufficient scope for habitat recreation via managed realignment to sustain or even increase the area of saltmarsh if that objective is agreed. There is also the likelihood for significant and essentially unplanned retreat if coastal flood defences are not upgraded. The management issue is more concerned with loss of coastal grazing marsh and related freshwater habitats such as Cley in Norfolk and Minsmere in Suffolk. Climate change and coastal management are moving in the same direction and a decline in coastal grazing marsh seems almost inevitable. This raises the question of the strategic replacement of these coastal habitats with non-coastal grazing marsh. Regional scale plans to accomplish this goal would seem to be prudent.

An integrated regional study might be expected to produce a wider range of results for coastal areas and river flooding than presented here. The lack of both resources and also accessible and consistent datasets for many factors such as river flooding precluded such a comprehensive analysis. Future regional assessments might consider flood and erosion impacts on the built environment in much more detail such as the MAFF-funded ‘National Appraisal of Assets at Risk from Flooding and Coastal Erosion’ and the forthcoming follow-up which considers climate change implications. This could be pursued both in sectoral studies such as the National Appraisal, and within an integrated assessment framework to examine linkages to other sectors and issues. In addition, further work is recommended to examine:

- Improved scenarios of relative sea-level rise, river floods and storminess (if possible) to be included in future UPCIP guidance;
- How flood management might respond to a rapid rise in sea level as exemplified by the 2050s High scenario, particularly if combined with an increase in storminess;
- The development of a long-term integrated flood management plan for the entire Fens;
- The future of coastal freshwater habitats under a scenario of rising sea level and application of significant managed realignment.

5.1 Introduction

The autumn 2000 river floods have reminded us of the large exposure of Britain to flooding and hence climate variability and change. Historic events such as the 1947 floods in the Fens, and the large loss of life during the 1953 East Coast floods from the Humber to North Kent indicate the scale of flooding that is possible (Figure 5.1). In the North West, significant coastal floods have occurred more recently during 1977, 1983 and 1990: this last event producing the Towyn flood in North Wales. In coastal areas, long-term morphological change is also apparent with a dominantly erosional trend, including extensive loss of saltmarsh in North Kent and Essex (the outer Thames Estuary), and around the Solent and the Severn estuary.

While these problems have a multitude of causes, it is clear that climate change due to the anthropogenic greenhouse effect will exacerbate them (Nicholls, 2000). Sea levels have already risen around most of the British coast during the 20th Century (Woodworth *et al.*, 1999), steadily raising flood levels. This trend is expected to accelerate in the 21st Century and by the 2080s, global sea levels could be between 18 and 99 cm above their 1961–1990 average value (Hulme and Jenkins, 1998). Increased storminess and bigger waves have been observed since the 1970s (Environment Agency, 1999; JERICHO Project, 1999), and this has also contributed to an increased risk of storm damage and flooding in coastal areas. However, storminess has fluctuated greatly in the northeast Atlantic over the last 100 years or so (WASA Group, 1998), and these observations may be a feature of climate variability rather than long-term change. Under conditions of global warming, the future trends for storms remain poorly understood. More intense precipitation may increase peak river flows and increase the potential for river flooding (Reynard *et al.*, 1999), especially in coastal lowlands where these changes will interact adversely with sea-level rise. Therefore, climate change will have profound implications for all coastal and river valley activities.

The aim of this study is to evaluate regional impacts of climate change for East Anglia and the North West. Given resource constraints, impacts that will interact with the other sectors considered within RegIS were selected and evaluated as follows (see Figure 5.2):

- increased coastal flooding due to sea-level rise and its interaction with agricultural land use;
- increased river flooding (based on assumed increases in peak river flows for sensitivity analysis) and its interaction with agricultural land use;
- potential changes to saltmarsh habitats, and its interaction with coastal biodiversity issues; and
- potential changes to coastal grazing marsh, and its interaction with coastal biodiversity issues.

These impacts are then used as inputs into the agricultural and biodiversity components (Chapters 6 and 8). As discussed in Chapters 3 and 4, both climate change scenarios and socio-economic scenarios are used in the modelling so that the relative importance of climate change versus socio-economic effects can be distinguished. The methods use established techniques for impact analysis implemented in a GIS environment. The results for each region are displayed on a 5 km x 5 km grid. Some broader regional-scale results (not using the 5 km x 5 km grid) such as average annual flood damages are also included.

5.2 Background

5.2.1 Coastal area impacts

Sea-level rise is already being experienced in England and Wales: tide-gauge records indicate an increase in mean sea level of between 1 to 3 mm/year over the 20th century (Woodworth, 1987; Woodworth *et al.*, 1999). This rise is expected to accelerate under global warming. It is important to distinguish between 'global' and 'relative' sea-level rise (or global-mean changes, versus local-net changes, respectively). 'Global' sea-level rise is the result of an increase in global ocean volume from the thermal expansion of water and the melting of land-based ice. Rising sea surface temperatures and the retreat of most small glaciers suggest that global sea-level rise has occurred through the 20th Century (Douglas *et al.*, 2000). In addition to global-mean changes, regional oceanic processes such as currents and winds influence regional sea levels and any climate-induced changes may produce regional sea-level change under global warming (*e.g.* Gregory, 1993). Lastly, vertical change in the elevation of the earth's surface produces a relative change in sea level. Tectonic movements, neotectonic processes such as postglacial rebound, and human activities such as groundwater abstraction, or oxidation and loss of organic deposits can produce such elevation changes. 'Relative' sea-level rise (or fall) comprises the cumulative effects of global sea-level rise, regional oceanic changes, and regional to local land elevation changes (Nicholls and Leatherman, 1996). Therefore, it is fundamental to transform global sea-level rise scenarios to relative sea-level rise scenarios for impact analysis.

Britain is still being influenced by significant postglacial rebound, which is the isostatic adjustment of the crust due to changes in glacial loading (Peltier, 2000). This produces upward movement in formerly glaciated areas (*e.g.* north west Scotland) and downward subsidence elsewhere (*e.g.* East Anglia) (Shennan, 1989). Because of these isostatic effects, relative sea-level rise will be greater in East Anglia than in the North West. Within coastal lowlands such as the Norfolk Broads, the Lancashire coastal plain, and most particularly the Fens, draining and consolidation, as well as oxidation and subsequent loss of peat has produced substantial declines in land elevation. This is illustrated by the 4 m decline in land levels at Holme Fen Post in the Fens since the 1851. Subsidence of the thick Holocene sequence is also occurring. Today, most of the Fens lie at elevations below high tide levels and some areas are below mean sea level (Figure 5.3). Most remaining peat will be lost by the 2050s, so land elevation in the Fens (and potentially other coastal lowlands) will continue to decline. Detailed scenarios of these changes are unavailable, but local land elevation declines of up to 70 cm in the Fens (Richardson and Smith, 1977) and significant changes in the Norfolk Broads (Environment Agency, 1997) are possible by the 2050s based on historic experience.

Physical impacts of sea-level rise include inundation and displacement of wetlands and lowlands, and increased flooding during coastal storms (Biljsma *et al.*, 1996). In this context, the term 'flooding' describes a temporary effect from which the coastal system will recover, while 'inundation' describes a permanent loss of land to the sea. As sea levels rise, without adaptation land is flooded more and more frequently and hence is usually degraded in terms of its current use, although this change may have benefits to other uses. Inundation is the ultimate endpoint of this process and will generally only occur when a coastal defence is abandoned as part of managed, or unmanaged, retreat.

The large estuarine and other intertidal areas in Britain support internationally-important wintering bird populations. Over the last few centuries, these areas have experienced significant changes due to a variety of natural and anthropogenic reasons which remain incompletely understood (Carpenter and Pye, 1996). Significant saltmarsh losses have been widely reported in parts of Britain over the last few decades, including North Kent and Essex: increasing wave energy since the 1970s is argued as a key controlling process (Carpenter and Pye, 1996). These losses are expected to be exacerbated under climate change. However, a range of factors will control saltmarsh evolution to the 2050s, making precise prediction very difficult. Of relevance here is coastal squeeze, which is a process whereby as intertidal habitats migrate onshore, due to sea-level rise, they are blocked by any hard defences resulting in a net loss (Environment Agency, 1999). The more landward habitats such as high marsh are often lost first, so the mix of habitats is also affected. Landward of the flood defences in many estuarine situations is coastal grazing marsh – this is usually an artificial habitat created by land claim of former estuarine areas. This habitat will be affected by climate change and, maybe more importantly, by proposals for managed realignment which will see large areas returned to intertidal habitat (Lee, 1998).

Other changes in climate may have important coastal implications (Nicholls, 2000). Of particular concern are potential changes in the frequency, intensity and paths of storms. Since the 1970s there has been an increase in storminess and wave heights around Britain (Environment Agency, 1999;

Grevemeyer *et al.*, 2000) and this has caused a re-evaluation of the design standards required for sea and coastal defence (and also contributed to saltmarsh decline). However, an examination of storm patterns over the last 100 years suggests that this increase is consistent with climate variability (WASA Group, 1998), and may not be a long-term trend as is widely assumed by coastal practitioners, including many of those in the two RegIS regions. It is worth noting that significant variability, but no long-term trend in storminess, has also been found for the US East Coast during the 20th Century (Zhang *et al.*, 2000). Therefore, the trend of the last 30 years may not continue, and a decline in storminess may even occur. However, the implications of climate change for the magnitude, frequency and paths of storms may be important (JERICHO Project, 1999). The available studies based on climate models have conflicting results with some suggesting an intensification of storm activity and others showing opposite trends. Hulme and Carter (2000) conclude that it is *possible* that gale frequencies will increase. Several studies suggest that the present pattern of storm surges in north west Europe might change due to climate change (von Storch and Reichardt, 1997; Flather *et al.*, 1998; Flather and Smith, 1998; Lowe and Gregory, 1998), but further investigation is required to produce definitive results due to the high variability of storminess.

5.2.2 Fluvial area impacts

The effects of any given climate change scenario are likely to vary considerably between catchments: size, shape, soil type, geology, and land use are all important characteristics that will affect catchment response to changes in precipitation and evapotranspiration (Arnell, 1996).

Watson *et al.* (1996) and Handmer *et al.* (1999) indicate four main reasons for the uncertainty associated with the effects of climate change on river flooding:

- It is difficult to define credible scenarios at the catchment scale for changes in precipitation that produce floods;
- It is difficult to model the processes that transform rainfall into floods;
- Available climatic and hydrological records have limited information about flooding;
- It is often hard to distinguish the effects of climate change from anthropogenic changes due to changing land use.

Additionally, climate change will affect river flows both directly, through changes in rainfall and evaporation, and indirectly, through changes in vegetation and soil structure (Arnell *et al.*, 1994).

Reynard *et al.* (1999) examined the impacts of climate change on the Thames and Severn river catchments assuming the HadCM2-ensemble mean climate change scenario, which equates to the UKCIP Medium High scenario. By the 2050s, they found that the 50-year peak flow increased by 20 to 21 % in the Severn, and 15 to 16 % in the Thames. This suggests that climate change will produce a significant increase in the risk of river flooding. Changes in land use will also influence the changes in flooding. Under the same climate scenarios combined with an increase to 15 % urban cover, 50-year peak flow increased by 21 and 17 % in Severn and Thames, respectively. In contrast, the same climate change scenarios combined with a 50 % increase in forested land cover show much smaller increases: the 50-year flow increased by only 6 and 2 %, respectively.

5.2.3 Climate change scenarios

The global sea-level rise scenarios given in Table 3.1 need to be converted to relative sea-level rise scenarios for the regional impact analyses. In doing so, the scenarios are referenced to the base year (1990) for the impact analysis. A rise in global sea level of about 3 cm from the 1961 to 1990 average to 1990 is assumed (based on Douglas, 2000). In the North West limited regional land movement occurs, while in East Anglia, regional subsidence is expected (Shennan, 1989; Hulme and Jenkins, 1998). The resulting relative sea-level rise scenarios are shown in Tables 5.1a and 5.1b. The Low scenario is similar to a continuation of observed trends during the 20th Century, while the High scenario represents, in rough terms, a four-fold and seven-fold acceleration of recent sea-level rise to the 2050s in East Anglia and the North West, respectively.

Table 5.1a: Relative sea-level rise scenarios used for the North West Region (cm) referenced to the base year of 1990 (adapted from Hulme and Jenkins, 1998).

Scenario	2020s	2050s	2080s
Low	04	09	15
Medium Low	05	15	26
Medium High	09	22	38
High	35	64	96

Table 5.1b: Relative sea-level rise scenarios used for the East Anglian Region (cm) referenced to the base year of 1990 (adapted from Hulme and Jenkins, 1998).

Scenario	2020s	2050s	2080s
Low	07	16	26
Medium Low	08	22	37
Medium High	12	29	49
High	38	71	107

Hulme and Jenkins (1998) also suggest that sea levels will rise 10 % more than the global-mean rise on the UK coast due to climate change-induced regional oceanic changes within the Atlantic. However, the changes in these regional components of sea-level rise are less certain than the global components. Following discussion with Jason Lowe at the Hadley Centre, it was concluded that this factor is too uncertain to develop scenarios and it was not included in the analysis.

Local subsidence, such as occurs in the Fens and Broads, could more than double the rates of relative sea-level rise to more than 1.5 m by the 2050s. This is not explicitly considered in our analysis as there is significant spatial variation in this factor, there is limited data available on subsidence, and the impact methodology and assumptions employed do not require this input. However, the implications of declining land elevation is considered in the interpretation of the results.

Given the uncertainties about future storm surge characteristics in a globally warmed world (see Section 5.2.1), this factor is assumed to remain constant in time. However, it is worth remembering that the large inter-annual and inter-decadal variability will continue. The implications of increased storminess are considered in the interpretation of results.

As already discussed in Section 5.2.2, there are difficulties in identifying credible scenarios for the change in fluvial flood risk under climate change. To be precise, each catchment requires its own evaluation using the scenarios of Hulme and Jenkins (1998) together with catchment-specific data on the soils and geology. Although this has been done for both regions as part of RegIS (Chapter 7), the weekly time step of the SWANCATCH model used is too long to directly estimate change in flood risk. However, the results shown in Chapter 7, Section 4.3 are consistent with an increase in fluvial flood risk, most particularly in the North West. Following discussions with David Richardson (MAFF) for the purposes of sensitivity analysis, it was decided to assume that uniform increases in peak river flows of 20 % in the 2050s High scenario, and 5 % in the 2050s Low scenario. These are consistent with recent research on peak flows in the Thames and Severn rivers (Reynard *et al.*, 1999) and the relevant MAFF project appraisal guidance (MAFF, 2000).

5.2.4 Implications of the socio-economic storylines for coastal and river areas

In the following sections, the key issues within the Regional Enterprise and Global Sustainability scenarios for assessing the impacts of climate change on coastal areas and river flooding are explored. Future socio-economic change has a major effect upon vulnerability to climate change. Two regional socio-economic scenarios for the North West and East Anglia were developed within RegIS in addition to a constant (*i.e.* 1990s) baseline socio-economic situation (see Chapter 4). These storylines deliberately depart from the present path of socio-economic development to explore different possible futures for the 2050s.

5.2.4.1 Regional Enterprise

Under this storyline, there is an increase in population, households, urban areas, and second homes in both regions. Planning controls are relaxed, allowing more building and more people to live in river and coastal flood plains. Coastal areas will continue to be protected to present indicative standards, allowing for local and regional subsidence, but with no consideration of climate change. Recommendations for managed realignment will not be implemented and the existing shoreline configuration will be maintained. This encourages coastal squeeze under scenarios of rising sea level. In addition, there will be more coastal development, including cliff-top locations. This will lead to continued growth of the length of cliff protection, thereby reducing sediment supply for beaches and estuarine areas, including saltmarshes. (Much of the protection causing impacts in East Anglia may be external to the region, such as coastal development along the Holderness coast, Yorkshire.) These measures will further reduce the capacity of coastal systems to adapt to the climate change parameters of rising sea levels and increased precipitation (see Nicholls *et al.*, 2000). Given the greater length of soft eroding cliffs along the North Sea coast, and their importance to the regional sediment budget (Hanson, 1999) this will be a much more important factor for East Anglia. In the North West, cliff protection is not an important factor.

In terms of the analysis that follows, under this storyline, development increases exposure to flooding. Also, there is no planned managed realignment, and sediment availability declines, amplifying the impacts of sea-level rise on intertidal habitats.

5.2.4.2 Global Sustainability

This storyline proposes only small or minimal increases in population and households in both regions, but these will mostly be confined to existing urban areas. Strict planning controls will apply, including managing hazards – no new flood plain or coastal developments will be permitted. This sustains supplies of sediment from coastal erosion, maintaining the existing capacity of coastal ecosystems to adjust to sea-level rise. In addition, large-scale natural-system approaches that integrate habitat creation and hazard management are widely adopted in response to a desire to promote nature rather than as a response to climate change. Options include managed realignment in relatively undeveloped coastal areas and freshwater wetland creation in lowland areas such as the Fens. These measures could enhance the resilience of natural systems, allowing ‘room’ for natural adjustment to climate change and climate variability, including saltmarsh and estuary roll-back as a response to sea-level rise.

In terms of the analysis that follows, under this storyline, development occurs without any increase in exposure to flooding. Also, large-scale managed realignment increases the stock of intertidal habitats independent of climate change effects.

5.3 Methodology

The methodology combines a series of impact algorithms based on strategic impact assessment methods for coastal and river flooding and ecosystem response to climate change. For the flood analysis, the risk of episodic events is considered, and hence the manner in which climate and other possible changes will influence the *risk* of flood occurrence is evaluated. For coastal ecosystems, the impact of climate and other possible changes on their distribution, including potential losses and gains, is evaluated. Ecosystem change is strongly coupled to morphological change (Capobianco *et al.*, 1999). There are important interactions between coastal flooding and coastal ecosystems, as flood defences are the major barrier to ecosystem migration, while saltmarshes are an important buffer to waves attacking flood defences during storms (Allen and Pye, 1992).

In the impact analyses, spontaneous adaptation such as increased saltmarsh accretion and the individual farmer response to changing flood frequency are considered. (Such adjustments are often termed autonomous adjustments (Carter *et al.*, 1994; Parry and Carter, 1998)). However, explicit proactive adaptation to climate change, which is controlled by policy, is *not* considered so that the worst-case impacts of the change can be evaluated. This is also a consistent assumption made for all the impact analyses in RegIS. It should be noted that MAFF have recommended an allowance for relative sea-level rise (including both projections of global sea-level rise and long-term regional land movement) in project design of 6 mm/yr in East Anglia and 4 mm/yr in the North West since 1989 (MAFF, 1999), and they now provide guidance for climate change and river flooding (MAFF, 2000). The implications of this guidance on the results of these impact assessments are considered in Section 5.4.1.4.

Firstly, the key data sets that were used are summarised. Then the methods for the flood analysis and ecosystem analysis are considered. The limitations of the methods are considered in each section.

5.3.1 Key data sets and data issues

Given that the RegIS project involves integrating data at a range of levels, all analysis was based on existing data sets. Therefore, as an initial part of the research process, the availability, quality and suitability of existing data sets in the two study regions were evaluated. Some data sets were provided by UKCIP, others were independently obtained from the Environment Agency and MAFF. The main data sets utilised in this study are listed in Table 5.2, and described further in Appendix 2.

In many cases, there was a lack of suitable data, or they were scattered and / or available in different formats and quality in the two regions. In some cases, suitable data were unavailable- such as flood defence standards along rivers, or the distribution of coastal grazing marsh. Therefore, data handling and processing took considerably more time than expected, and the methodology employed had to be adjusted accordingly. Ongoing efforts to develop and better integrate data sets on coastal areas and rivers needs to be continued, particularly in the North West Region, as they will facilitate and extend the scope of strategic policy analyses such as RegIS.

An important problem was the lack of detailed information on the location of flood compartments (*i.e.* discrete flood-prone areas) and associated standards of protection (*i.e.* the risk of flooding) in the North West, particularly around the Solway Firth. There is a lot of missing data in the Sea Defence Survey, while the Indicative Flood Plain Map defines flood-prone polygons which are also mapped as saltmarsh. These issues were discussed at length with flood engineers in the North West, and they kindly provided their expert judgements, which are included in the analysis. However, this increases the uncertainty concerning flood impacts and related issues in the North West. This problem is not encountered in East Anglia, where there is a wealth of coastal data in both paper-based and digital forms. The differing availability of data seems to partly reflect the long history of flooding and perceived flood risk in East Anglia. In the North West, despite important recent flood events in areas such as Morecambe, water quality is the primary issue of concern for coastal areas (Environment Agency, 1998).

Lastly, the data used in the GIS analysis was captured at a range of scales and resolutions. This will affect the accuracy of the results, although the inaccuracy cannot be quantified.

Table 5.2: Important data sets utilised in the RegIS study. (D – digital format; P – paper format).

Data Set (and source)	Description	Use	Format
1999 Indicative Flood Plain Maps (Environment Agency)	Boundaries of fluvial and tidal flood plains	Establish extent of land at risk of flooding	D
Flood Risk Area Mapping Project (Environment Agency)	Additional detail on boundaries of individual flood compartments (East Anglia only)	Supplement indicative flood plain maps	D
Sea Defence Survey (MAFF)	Location and standard of service of coastal flood defences	Flood risk classification of coastal flood plains	D
Digital Elevation Data (Ordnance Survey)	Topographical data from OS Land-Form Panorama Digital Terrain Model (50 metre resolution)	Analysis of flood plain morphology	D
Land Cover Map (GB) (ITE)	Land cover classes for the UK (25 metre resolution)	Land use in flood risk zones; location of coastal ecosystems	D
Coastal Database (JNCC)	Location and extent of coastal habitats	Identification of existing habitat stock	D
Managed realignment in Anglian Region (Environment Agency)	Coverage of existing and proposed sites of managed realignment	Calibrate methodology for selecting sites for potential habitat creation	D
Shoreline Management Plans (MAFF)	Recommendations of future coastal management strategies.	Future coastal defence policy	P
Tidal Surge Data (Dixon and Tawn, 1997)	Quantitative study on present-day tidal surge levels around the UK coast	Use in conjunction with sea-level rise scenarios to estimate future return periods of present-day events	P

5.3.2 Flood analysis

5.3.2.1 Coastal flooding

The methodological framework adopted for the coastal flooding analysis is based on risk analysis and is shown in Figure 5.4. It follows the methods of the recent ‘National Appraisal of Assets at Risk of Flooding and Coastal Erosion’ (Halcrow Maritime *et al.*, 2000), and also draws on previous flood impact analyses (Bateman *et al.*, 1991; Turner *et al.* 1995), and a series of global assessments of sea-level rise impacts (Hoozemans *et al.*, 1993; Nicholls *et al.*, 1999; Nicholls and Hoozemans, 2001).

As sea-level rise occurs, so the existing flood plain is flooded more frequently, and the area that is flooded will also expand. Previous analyses demonstrate that the first effect dominates flood impacts (*e.g.* Nicholls *et al.*, 1999). Therefore, a fundamental assumption is that the 1999 Indicative Flood

Plain defines the flood hazard zone and sea-level rise only increases the risk of flooding within that zone.

The effect of the relative sea-level rise scenarios on coastal flooding was estimated by raising the surge heights as determined by Dixon and Tawn (1997) by the magnitude of sea-level rise. Examples demonstrating this technique for the North Norfolk coast and Liverpool are shown in Figure 5.5. In Liverpool the present-day 100-year event is reduced to a return period of between 7 and 8 years by the 2050s High scenario. At the North Norfolk coast, the reduction in the return period for the 100-year event, caused by the 2050 High scenario, is even greater to between 4 and 5 years. The biggest reduction in return periods within the two study regions occurs near Felixstowe, Suffolk and near Workington, Cumbria.

Regional summaries of how sea-level rise may affect the 100-year event are shown in Table 5.3. They illustrate that the increases in sea level given in Tables 5.1a and 5.1b, will significantly increase the frequency of flooding, unless the flood defences are raised.

The present standard of protection for the coastal flood plains was determined from the Sea Defence Survey, and the defence standard after sea-level rise was then determined as previously explained. Where defences of different standards were associated with the same flood compartment, the lowest standard of defence was selected as determining the safety of the flood compartment. If a flood event equal to the defence standard occurs, it is assumed that the entire flood compartment is compromised. The details of flood extent for different flood events, as well as the failure mechanisms of the defences (*e.g.* breaching, overtopping, etc.) are not considered. The resulting levels of protection under different scenarios were added to the flood plain attribute table in the GIS. ArcView queries could then identify flood plain compartments where the future standard of defence will be at, or below, any specified risk level.

Table 5.3: Regional averages of return periods calculated for the present 100-year event under a realistic range of sea-level rise scenarios (see Table 5.1).

Global sea-level rise (cm)	Future return period (years) for the present day 100 year event			
	East Anglia		North West	
	Average	Range	Average	Range
09 (2050s Low)	72	64 - 78	68	63 - 71
35 (2020s High)	21	13 - 26	21	15 - 25
50	10	5 - 14	11	6 - 13
64 (2050s High)	5	2 - 8	6	3 - 8
96 (2080s High)	1	<1 - 2	1	<1 – 2

This method of evaluating the impact of sea-level rise is an established approach that has been used in a number of previous studies at a range of spatial scales (*e.g.* Bateman *et al.*, 1991; Nicholls *et al.*, 1999). However, it does have a number of limitations. Firstly, the results are only as good as the input data on the size of the flood plain and standard of defence. This is of variable quality between the two regions. Secondly, the indicative flood plain only delineates one flood event. Therefore, it is impossible to delineate different magnitudes of flood events, while flood depth is not considered, except qualitatively in the Fens. Flood defences may fail in a number of ways, depending on a range of circumstances. These different failure mechanisms are poorly understood and it is assumed that they are fully addressed by the estimated standard of protection. While this method might overstate the impacts if the defences are able to survive a flood event, it correctly identifies the areas where the risk of flooding is most high. Better representations of the response of flood defences to climate change would require more detailed characteristics of the defences, including the range of failure mechanisms from short-lived overtopping to a complete breach. The storm surge data for the North West coast are less reliable than for East Anglia because of the more complex coastline shape, which leads to rapid change in tidal regime (Dixon and Tawn, 1997). Unfortunately, this uncertainty cannot be quantified. Lastly, like previous studies such as Bateman *et al.* (1991), the method assumes that present-day surge magnitudes and tide-surge interactions will remain constant in the future. Based on the assumption of constant surge-forcing and the magnitude of the sea-level rise scenarios considered, this assumption is reasonable.

5.3.2.2 Fluvial Flooding

A similar approach to that used in the coastal flood risk was employed in the fluvial flood risk assessment. However, no comparable data set to Dixon and Tawn (1997) exists for flood return periods in rivers, as many more site-specific factors control flood characteristics within rivers, and the characteristics evolve with changing land use. Further, there is no simple way to translate an increase in peak flows, such as considered here, to a change in the risk of flooding; again detailed, site-specific modelling studies are required. Such modelling studies for a few locations in East Anglia for a 20 % increase in flow suggest a five- or six-fold increase in flood risk (Heald, *pers. comm.*). Therefore, it was assumed in this study that a present-day 1 in 100-year event has a 1 in 20-year return period under the 2050s High scenarios. Another important difference in comparison to the coastal flood plains is that there was no suitable dataset comparable to the Sea Defence Survey to describe either the location or the standard of fluvial flood defences.

In response to these data limitations, a much simpler approach was adopted. The present risk of flooding was estimated based on land use within the 1999 Indicative Flood Plain. The actual land use was derived from the Institute of Terrestrial Ecology (ITE) land cover map (GB) (Table 5.2) and the associated indicative standards of protection determined in conjunction with MAFF (1999) (Table 5.4). There were some gaps in the 25-metre coverage in the upland areas of the North West, so the 25 metre data set was supplemented by the lower resolution (1 km) ITE land cover map.

The limitations are much greater than those for coastal flooding, with the additional uncertainties in the method of assessing the changes in flood return period and the standard of protection. While the method is appropriate for a regional-scale study (cf. Halcrow Maritime *et al.*, 2000), local scale results of the method (at the 5 km grid scale) need to be treated with caution.

Table 5.4: Indicative standards of protection for fluvial flood defences (MAFF, 1999)

Land use description	Indicative standard of protection (return period in years)
High density urban	1:100
Low density urban or rural communities with high productivity agricultural land	1:25
Arable farming with isolated properties Medium productivity agricultural land	1:10
Extensive pasture with few properties at risk. Low productivity agricultural land	1:1

5.3.3 Flooding-agriculture interactions and land use change

In terms of the response to flooding, as flood frequency increases so agricultural land use is expected to change towards less intensive activities. Observations of farmers' behaviour suggests that there are specific thresholds of flooding frequency at which different types of farming activity are abandoned (Morris, *pers. comm.*). Some commonly accepted minimum intervals between flood events, related to various crops, are shown in Table 5.5. These were simplified to a single arable threshold to link flood impacts with the agricultural analysis in Chapter 6. Based on these observations, flood plains with a future defence standard of ≤ 1 in 10 years were assumed to be unsuitable for arable farming. Flood plains with a future defence standard of ≤ 1 in 1 year were assumed to be unsuitable for any intensive farming. Under the scenarios considered, this situation can only occur in coastal areas or in low-lying areas requiring artificial drainage, including grassland areas. In these cases, the land use is assumed to become grazing marsh, although this will also depend on the land management regime (*e.g.* amount of grazing). In low-lying areas such as the Fens, conversion to standing water (*i..e.* mere or lake development) is possible.

As already discussed, for fluvial flooding, the risk of flooding is more poorly defined than for coastal areas. Therefore, it was assumed that under the 2050s High scenario, the 20 % increase in peak flows would preclude arable agriculture in the entire flood plain. Under the 2050s Low scenario, the impact was estimated using linear interpolation (*i.e.* 25 % of the difference between the baseline and 2050 High scenarios). This assumption is consistent with the National Flood Appraisal Methodology (Halcrow Maritime *et al.*, 2000).

Table 5.5: Acceptable Agricultural Flood Risk Standards (from Morris, not dated)

	Acceptable Minimum Intervals Between Floods (in years)	
Crop	Whole Year	April – October (inclusive)
Horticulture	20	100
Arable and roots	10	25
Arable cereals	5	10
Intensive grass	2	5
Extensive grass	<1	3

The approach used is binary – an agricultural activity is either possible or not possible. Under baseline conditions, a pastoral land use was presumed possible on all land types within both fluvial and tidal flood plains. The data outputs consist of two elements:

1) The percentage of each cell where, because of the frequency of flooding, arable agriculture will not be possible, although a change of landuse from arable to pasture will be possible; and
2) The component of the above percentage where the flood frequency is such that intensive pastoral agriculture will not be possible.

The consideration of the spontaneous adaptation of the farmers to increased flooding is consistent with the methodology for adaptation already outlined.

5.3.4 Coast-biodiversity interactions and habitat change

Sedimentary coastal habitats such as saltmarsh are sensitive to a range of factors, including sediment supply, climate variability, climate change and changes in human management such as managed realignment. The focus here is to predict the effects of climate change, and other possible long-term changes up to the 2050s. Additional variation is to be expected due to factors such as varying storminess, or the initial expansion and present decline of saltmarsh species such as *Spartina*. There is no attempt to predict this shorter-term variability in saltmarsh area. In addition, while saltmarshes may decline due to sea-level rise, they may gain due to managed realignment.

Coastal grazing marshes are often an artificial habitat occurring where intertidal habitats, including saltmarsh, would be the natural habitat. They are threatened *without* sea-level rise, as it seems likely they will be abandoned quite widely around the British coast, as the associated flood defences are now recognised as uneconomic to maintain, although maintenance of internationally-designated habitats are given a high priority under current funding arrangements. The responses of saltmarshes and coastal grazing marsh to climate change and the socio-economic storylines, which include quite different human priorities in terms of managing the coast, are evaluated. The methodological framework for evaluating coastal habitat change is shown in Figure 5.6.

5.3.4.1 Saltmarsh losses

Saltmarshes respond to sea-level rise by increased vertical accretion as they are submerged for longer periods, and inland migration if there is available space (Stevenson *et al*., 1986; Cahoon *et al*., 1995; Cahoon *et al.*, 2000). Therefore, saltmarshes are only 'drowned' if the rate of sea-level rise exceeds their accretional potential. In Britain, inland migration is nearly always prevented by flood defences, so it can only occur where these defences are abandoned.

To evaluate these changes, a method similar to that of Nicholls *et al. (*1999) is used which compares the vertical accretion potential to sea-level rise. Saltmarshes in coastal areas that have a small tidal range are more susceptible to sea-level rise than those in similar areas with a large tidal range. The capacity for saltmarshes to respond to sea-level rise is therefore parameterised as a function of the *rate of sea-level rise* divided by *tidal range*, thus giving a *normalised rate of sea-level rise*. This is used in conjunction with a critical value of sea-level rise derived from the literature to determine saltmarsh response to rising sea levels (see Nicholls *et al.*, 1999). Above the critical rate, losses of saltmarsh are assumed to occur linearly. The appropriate threshold values are outlined below, but there is considerable uncertainty about the values. In addition, the method is not specific about which part of the saltmarsh is lost – only a proportional loss is determined.

There is a pronounced difference in tidal range between East Anglia and the North West: the average mean spring tidal range is about 3.3 m and 7.5 m, respectively. This suggests that the saltmarshes in the North West are much less susceptible to sea-level rise than those in East Anglia. It is also important to note that some of the saltmarshes in Suffolk are already eroding, while those in North Norfolk and the Wash, and the North West are broadly stable with localised erosion, or accreting (Pye and French, 1993a; Environment Agency, 1999). This different behaviour is interpreted as reflecting a positive sediment budget in Norfolk, and less sediment availability in Suffolk. Therefore, the Suffolk marshes are more vulnerable to sea-level rise, and the critical rate of normalised sea-level rise that produces losses is lower than in Norfolk. The critical threshold value of sea-level rise was therefore scaled to reflect these differences in present-day conditions. For most of East Anglia, a critical value of 0.18 was used, but a value of 0.09 was applied at Lowestoft, decreasing linearly to 0.05 at Felixstowe. This yielded a baseline result that is consistent with observations of saltmarsh behaviour in East Anglia (Pye and French, 1993a & b). Under the Regional Enterprise storyline, critical values are reduced to 0.05 for all of East Anglia to reflect the decrease in sediment availability caused by increased cliff protection. The critical value applied in the North West is constant for all scenarios (*i.e*. 0.18), as cliff protection in the North West has limited consequences for sediment supply.

There are important limitations to the methods described here (see also Lee, 1998). Firstly, the loss method is difficult to validate or verify. Secondly, the response of a complex bio-sedimentary system to climate change is being modelled, to which a number of responses may occur. Only some of the processes associated with sea-level rise and human modifications to sediment supply are considered here. We consider the processes that we have modelled to be the most important determinants of long-term saltmarsh change, but other processes (*e.g*. carbon dioxide fertilisation) may be significant and there may be important interactions between processes. Thirdly, the role of other change mechanisms has not been considered. Therefore, the results which are presented are best interpreted as indicative results.

5.3.4.2 Saltmarsh Gains

Saltmarsh gains will occur due to planned or unplanned coastal abandonment. For planned coastal realignment, it was initially anticipated that areas of potential saltmarsh gain would be identified from the Shoreline Management Plans (SMPs), but the analysis revealed significant differences between the two regions. In East Anglia, the SMPs recommend extensive managed realignment, while the North West SMPs hardly recommend any managed realignment. Subsequent communications with the Environment Agency revealed that the North West SMPs had been compiled without consideration of the EU Habitats Directive, which mandates preservations of designated areas. Therefore, future revisions of the SMPs may recommend more managed realignment in areas where losses of designated habitat are expected.

A consistent approach for determining sites of potential saltmarsh gain could not be accomplished using the SMPs because of this inter-regional disparity. Instead, an alternative methodology was developed which identified all the sites potentially suitable for managed realignment in each region. The Anglian region of the Environment Agency provided maps of proposed sites of managed realignment in East Anglia. Although these maps were not of direct use (there being no equivalent data for the North West), they were used to validate the methodology described below. This method combined the indicative flood plains, elevation data and land use data to identify areas adjacent to existing saltmarsh which are suitable for managed realignment. For instance, the Norfolk Broads were assumed to be managed to sustain freshwater ecosystems, and therefore managed realignment is not an option. Most of the sites thus identified appear to be former intertidal areas that have been ‘reclaimed’. The procedure is not appropriate for identifying specific realignment sites, but is considered to provide appropriate estimates of the potential for managed realignment for a regional scale analysis such as RegIS.

Using the 1999 Indicative Coastal Flood Plain Map, all the flood plain areas that appeared appropriate for managed realignment were selected. Urban and suburban landuse classes from the ITE 25-metre data set (LCMGB land cover types 20 and 21) within each compartment were tabulated and expressed as a percentage of each flood plain compartment. Those flood plain areas with low levels of development were considered as potential sites for habitat creation. Low development was defined as $\leq$2.5 % urban and suburban per flood compartment, based upon results that were consistent with the proposed sites of managed realignment, as provided by the Anglian Region of the Environment Agency. Where there was a geographically distinct difference in the levels of development within a flood plain, it was divided into two or more compartments. This would necessitate building a new flood defence. Any resulting flood compartment with low development was considered suitable for realignment. Wherever possible, infrastructural constraints such as major roads were used as an inland limit of realignment. No digital data is held on the location of railway lines or secondary defences, both of which would also provide logical inland boundaries to realignment.

Under the Global Sustainability storyline, all the areas defined as suitable for managed realignment are assumed to have this policy implemented, irrespective of existing habitat designations. The types of initial habitat gain will depend on the initial land elevation: many areas are below mean high water neap tides, which is too low for immediate saltmarsh colonisation, and so unvegetated mudflat (and sandflat) habitats will be produced (Lee, 1998; Sharpe, 2000). Equally, some areas may be above regular tidal levels, precluding saltmarsh development. In accreting situations, a succession to saltmarsh may be possible for low-lying areas, although the timescale of this change will depend on a number of factors. Lee (1998) assumed that managed realignment would result in an average of 50 % non-vegetated mudflat(/sandflat) and 50 % saltmarsh, reflecting existing experience, but acknowledged that the saltmarsh/mudflat proportions would differ from site-to-site. In this study, the digital elevation model was used to analyse the areas that are suitable for managed realignment and to compare these with the elevation at which saltmarshes are found. Thus, if managed realignment is implemented, those areas that immediately turn to bare sediment, saltmarsh, high marsh and terrestrial habitats (by definition above regular tidal inundation, but within the coastal flood plain) can be determined. No attempt was made to model the changes from this initial state. The accuracy of this technique will depend on the quality of the indicative flood plain data, and the digital elevation model that was used.

In addition to these planned changes, unplanned realignment of the coast may occur under the 2050s High scenarios. As already noted, the areas with a flood risk of $\leq$ 1 in 1 years are considered to revert to grazing marsh (Section 5.3.3). If flooding is much more frequent than annual, then this grazing marsh will become increasingly saline, and would be transformed into saltmarsh and associated intertidal habitats if the seawalls are abandoned. However, the habitat type will depend critically on human agency; therefore these zones are distinguished as potential saltmarsh gains. These issues are discussed in more detail in the results (Section 5.4.2.1).

5.3.4.3 Coastal Grazing Marsh Change

While coastal grazing marsh is widely recognised as a distinct habitat type of conservation value, it is as much a land use and landscape type as a habitat set (Dargie, 1992). No data set on the distribution of coastal grazing marsh was available to RegIS. Therefore, LCMGB land cover types 6, 7, and 8 (which are mown/grazed turf, meadow/verge/semi-natural and rough/marsh grass, respectively) that occur within the 1999 Indicative Coastal Flood Plain, were considered as coastal grazing marsh for the purposes of the RegIS analysis. A key uncertainty in this approach is that the habitat 'quality' of these areas is not defined.

Possible changes in the area of coastal grazing marsh (see Figure 5.6) have been calculated based on:

- planned losses due to managed realignment;
- unplanned losses due to increased saltwater flooding and succession to saltmarsh; and
- potential gains of grazing marsh due to abandonment of intensive agriculture.

Managed realignment only occurs under the Global Sustainability storyline. Coastal flood plains, where the future standard of defence will be $\leq$1 in 1 years, are potential coastal grazing marsh gains, since they will be flooded too often to be used for arable or intensive pasture farming. As already noted in Section 5.3.4.2, a competing pressure which may cause a decline in these habitats, or components of them, is increasing saltwater flooding and thus a succession towards more salt-tolerant vegetation. The endpoint of this process is saltmarsh, but the intermediate stages might still be considered coastal grazing marsh. Given the limited empirical data on such changes, a detailed interpretation is difficult and the resulting uncertainties are discussed in the results.

There is scope for coastal grazing marsh gains in the Fens due to increased flooding and, under the Global Sustainability storyline, habitat recreation may allow this to occur. River valleys may also see an increase in grazing marsh as arable farming is abandoned, but this will depend on how intensively these areas are grazed.

In all cases, these areas were delineated in the RegIS GIS and are presented in the results.

5.4 Results and their interpretation

The results are presented and discussed in terms of possible flood impacts and possible changes in coastal habitats.

5.4.1 Flood Impacts

The general standard of service of the coastal defences in both study regions is the 100-year event. Therefore, under the baseline scenario, it is not surprising to find that tidal flooding is not a major constraint on the location of arable farming: 387 and 421 km^2 of land are unavailable to arable agriculture in East Anglia and the North West, respectively. This includes some of the Norfolk Broads where the present standard of protection is often considerably lower than the open coast. In some flood compartments, the level of protection is as low as a 1 in 5 year event, with several totally undefended areas. With respect to fluvial flooding, under baseline conditions, the pasture land use classes identified within the fluvial flood plain were assumed to be flooded too frequently for arable agriculture (Section 5.3.3).

Under all climate change scenarios, it is important to remember that there is a presumption of no adaptation to climate change. Therefore, no allowance is made for sea-level rise or increased peak flows when considering future flood defence standards. With respect to coastal defences, an allowance is made for both local and regional subsidence since this is not driven by climate change. Therefore, because an allowance is made for subsidence, the sea-level rise scenarios used in East Anglia are the same as that for the North West, *i.e*. the global scenarios of a 9 cm and a 64 cm rise from 1990 to the 2050s, respectively.

5.4.1.1 Agricultural Impacts

Changes in agriculture land use in coastal areas were evaluated by identifying the coastal flood compartments where the standard of protection will be $\leq$ 1 in 10 years and $\leq$ 1 in 1 year (corresponding to the arable and pastoral land use thresholds, respectively (Section 5.3.3)). These areas were identified for the Low and High sea-level rise scenarios and are shown in Figures 5.7 and 5.8. Under the 2050s High scenario, the flood plains with a standard of protection $\leq$ 1 in 10 years are very similar to the 1999 indicative flood plain (Figure 5.9), especially in East Anglia. This is because the general standard of protection around the coast is the 100-year event. As shown in Table 5.3, what is currently the 100-year event would have a future return period of between two and eight years under the 2050s High sea-level rise scenario of 64 cm. In the North West, some densely-populated coastal areas in or near the flood plain, such as Blackpool, have sea defences with a design standard for the 200-year event or better. This provides >1 in 10-year protection to flood plain areas even under the 2050s High scenario (although by the 2080s it would fall below a 1 in 10-year standard under the High scenario). As shown in Table 5.6 (below), larger areas of land are found in these high flood risk coastal areas in East Anglia than the North West in both absolute and relative terms.

The effects of flooding on agricultural land use, including the baseline, are shown in Figures 5.10 to 5.13. The loss of the Norfolk Broads and the Cambridgeshire (and by implication Lincolnshire) Fens to both arable and pastoral agriculture is the most striking impact of the 2050s High scenarios. Given the importance of this area to UK arable agriculture, this is a noteworthy impact that is considered more in Section 5.4.1.2 and in Chapter 6. Outside the Fens, the flood impacts under the High scenarios are more diffuse as shown in Table 5.6. The individual 5 km x 5 km cells that show the largest impacts are in the Norfolk Broads and in the Lancashire coastal lowlands near Stockport and the Fylde Peninsula, where up to 98 % of individual RegIS cells might be unavailable to agriculture.

Under the 2050s Low scenarios, flooding has no impact on agricultural land use in the Fens because the present standard of service for the Fens is the 100-year event. Hence, under this scenario the increase in flood risk is not sufficient to trigger significant changes in potential agricultural land use. In East Anglia and the North West, the area unavailable to arable agriculture increases by 80 % and 42 % relative to baseline conditions, respectively. The 2050s Low GS results are similar to the 2050s Low, but include additional losses in some coastal areas due to widespread adoption of managed realignment, as calculated for coastal-biodiversity and habitat changes (see Section 5.4.2). In regional terms, the amount of additional land that is unavailable to arable agriculture is quite small, being 18 %

and 16 % above the 2050s Low scenario in East Anglia and the North West, respectively. This corresponds to 127 km^2 and 97 km^2, respectively.

Table 5.6: Impacts of flooding on agricultural activity (by per cent cell).

Scenario	Area	Arable Agriculture Excluded				Pastoral Agriculture Excluded			
		Mean	Std. Dev.	Max.	Min.	Mean	Std. Dev.	Max.	Min.
Baseline	The Fens	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	East Anglia (excluding the Fens	3.3	7.1	56.2	0.0	0.0	0.0	0.0	0.0
	North West	2.6	4.7	40.2	0.0	0.0	0.0	0.0	0.0
2050s Low	The Fens	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	East Anglia (excluding the Fens	6.0	10.4	83.9	0.0	0.1	1.4	24.6	0.0
	North West	3.7	6.2	58.4	0.0	0.6	3.4	58.2	0.0
2050s Low GS	The Fens	0.7	3.4	22.3	0.0	0.7	3.4	22.3	0.0
	East Anglia (excluding the Fens	6.8	11.5	83.9	0.0	0.9	4.1	48.9	0.0
	North West	4.3	7.9	100	0.0	1.2	6.2	100	0.0
2050s High	The Fens	84.8	21.6	100	14.8	80.9	28.5	100	0.0
	East Anglia (excluding the Fens	9.6	13.0	83.9	0.0	3.1	10.5	84.1	0.0
	North West	6.8	12.1	98.4	0.0	0.7	3.9	58.3	0.0
2050 High RE	The Fens	86.4	19.7	100	19.3	86.4	19.7	100	19.3
	East Anglia (excluding the Fens	10.3	14.6	98.8	0.0	3.1	10.5	84.1	0.00
	North West	6.8	12.1	98.4	0.0	0.7	3.9	58.3	0.0

5.4.1.2 Impacts on coastal lowlands

Coastal lowlands may be particularly vulnerable to climate change if they are subject to both increased peak river flows and higher sea levels, especially as these areas are nearly always prone to localised subsidence. These issues are apparent for significant flood impacts in the Fens under the 2050s High scenario (Figures 5.10 and 5.12), which are now considered. It is worth noting that the analysis in Chapter 7 using SWANCATCH noted that the assumed 20% increase in peak flows used in the Fens analysis is not excessive for East Anglia.

Under the 2050s High scenario, each flood-causing agent in the Fens would increase the flood risk, but individually they would not produce severe impacts. The severe flood impacts on agricultural use (and all other present land use) are due to the *combined* effect of higher sea levels and the assumed increased river flow, as well as consideration of the drainage implications for this low-lying area, including the ongoing subsidence (see also Section 7.4.3). While it is unlikely that coastal surges and river floods will coincide, higher mean sea levels will raise the base level and hence exacerbate the impacts of river flooding across the Fens as compared to non-coastal locations. Hence, the boundary between the tidal and fluvial flooding is less defined in the Fens than the 1999 Indicative Flood Plain suggests and a large area is threatened by both types of flood (see tidal limits in Figure 5.3). As already noted, most land in the Fens is already below spring high tide (presently 3.5m O.D.), with the lowest areas below mean sea level occurring well inland, where the land surface is (or was) composed of peat (see Figure 5.3). Consequently, many of the Fenland rivers are perched (*i.e.* the river bed is above the surrounding land level). Collectively, this means that any flood event could be catastrophic, potentially drawing seawater into the inland Fens and flooding large areas to significant depths. For much of the Fens, pumping would be required to remove the water after the flood abates and the flood embankments had been repaired. Given the rise in sea level, as well as the continuing decline in land levels due to peat oxidation, increased pumping capacity would be required. Another effect of peat oxidation is soil degradation; the peat content of the Fenlands enhances its fertility considerably (Morris *et al.*, 2000). Thus, it will become increasingly expensive to drain agricultural land, which may anyway be decreasing in productivity. Collectively, these changes would make the Fens unsuitable for any type of intensive agriculture, unless there is substantial adaptation to these changes.

In the course of the RegIS project, there were discussions on the effective standard of protection for the Fens. Our analysis was based on an existing 1 in 100-year standard of defence, as described in the Sea Defence Survey and confirmed in discussions with Gordon Heald of the Environment Agency. In contrast, it was suggested that the effective standard might be nearer 1 in 500 year protection. If this is the case, the implications for the results previously presented are shown in Table 5.7. Using the UKCIP98 High sea-level rise scenarios, the 1 in 100-year defences fall to below a 1 in 10-year standard before the 2050s, while the 1 in 500 year defences fall below a 1 in 10 year standard before the 2080s. Therefore, while it would influence the timing of the impacts described above, it would only delay them at most for about 30 years. Similar results are evident when considering the interaction of sea-level rise with the assumed uniform increase in river floods, while subsidence is exacerbating drainage requirements. This demonstrates that, without any adaptation, the UKCIP98 High scenario would significantly increase the risk of major floods in coastal lowlands in both study regions.

Table 5.7: An analysis of the effect of the UKCIP98 High sea-level rise scenarios (Hulme and Jenkins, 1998) on the standard of protection on the open coast of the Fens.

	2020s (35 cm rise)		2050s (64 cm rise)		2080s (96 cm rise)	
1990s Standard of Protection	100 yr	500 yr	100 yr	500 yr	100 yr	500 yr
Gibraltar Point (Stn. 24)	17.9 yr	78.0 yr	3.9 yr	16.9 yr	0.7 yr	3.1 yr
North Norfolk (Stn. 25)	21.8 yr	90.6 yr	5.4 yr	22.8 yr	1.2 yr	5.0 yr

The Norfolk Broads experience similar impacts to the Fens, but an important difference is the lower standard of defence in The Broads. Therefore, unlike the Fens, significant flood impacts can be realised by the sea-level rise scenarios or the uniform increased river flow scenarios, in either isolation or together.

5.4.1.3 Average annual flood damage

The change in flood risk suggests significant impacts on the built environment. This was not explicitly addressed in RegIS due to resource constraints. However, the "National Appraisal of Assets at Risk from Flooding and Coastal Erosion" (Halcrow Maritime *et al.*, 2000) provides useful estimates of the present level of damages. Given that the average change in flood risk associated with the climate change scenarios is known, a region-wide estimate of the order-of-magnitude effect of climate change on flood damages can be developed. In addition, the influence of increased flood plain development in the Regional Enterprise storyline can also be considered. This analysis is constrained to the scale of the regions reported in this study, and hence refers to the entire Anglian Region of the Environment Agency, rather than just Norfolk, Suffolk and Cambridgeshire. If it is assumed that the increase in flood risk due to climate change simply results in more of the same floods, rather than more extreme events, the results of this study can be easily translated into annual damages. Under the Regional Enterprise storyline, it is assumed that similar flood plain development occurs across the Anglian Region, and that this new development has the same unit damage characteristics as existing development. The limitations of these calculations are that:

- No allowance is made for the increased depth and extent of flooding under climate change, which will increase the losses;

- Some properties that presently sustain flood damage might be abandoned under climate change scenarios, which might reduce the losses due to flooding;
- Uniform changes are being assumed across both regions, and the more severe impacts described for coastal lowlands such as the Fens are not resolved;
- The basic results are based on different assumptions in different regions and should be treated with caution (Halcrow Maritime *et al.*, 2000).

The results are given in Table 5.8 for two protection scenarios defined by Halcrow Maritime *et al.* (2000):

1. Maintaining present levels of protection (consistent with the RegIS assumptions); and
2. Meeting indicative standards (upgrading some substandard defences to the indicative standard, and then maintaining these defence elevations).

All climate change scenarios increased the annual damages. However, the 2050s Low scenario combined with meeting indicative standards suggests annual damages *below* those experienced today. In contrast, given the 2050s High scenario, annual damage would be two to ten times above today's levels, independently of the two protection scenarios considered, and coastal damages would increase more than fluvial damages. The increased exposure of the Regional Enterprise storyline enhances the average annual flood damages by 35 % in East Anglia and 42 % in the North West. Therefore, climate change is the biggest factor in increasing damages, but the increased flood plain development under Regional Enterprise causes a significant increase in flood damages.

Table 5.8: Order of magnitude effects of the scenarios on average annual damages to properties in the North West and Anglian Regions of the Environment Agency (based on Halcrow Maritime *et al.*, 2000).

Protection Scenario	Region	Flood Type	Average Annual Damages to Properties (£millions/yr)				
			1990s	2050s Low	2050s Low GS	2050s High	2050s High RE
Maintaining present levels of protection	Anglian	Fluvial	55	69	69	275	380
		Sea/Tidal	22	30	30	430	574
		Total	77	99	99	705	954
	North West	Fluvial	19	24	24	96	145
		Sea/Tidal	19	28	28	313	438
		Total	38	52	52	409	583
Meeting indicative standards	Anglian	Fluvial	31	39	39	155	214
		Sea/Tidal	8	11	11	162	216
		Total	39	50	50	317	430
	North West	Fluvial	7	9	9	35	53
		Sea/Tidal	3	4	4	45	63
		Total	10	13	13	80	116

5.4.1.4 Adaptation to flood impacts

All the results presented above are based on an assumption of no adaptation to the increasing flood risk caused by climate change. However, adaptation for coastal areas has already begun: it has already been noted that guidance has been provided for the inclusion of relative sea-level rise in the design of new sea defences since 1989 (MAFF, 1999). The allowance for relative sea-level rise is 6 mm/yr in East Anglia, and 4 mm/yr in the North West, taking account of regional subsidence and median estimates of global sea-level rise. This allowance can be included by designing a flood defence structure including the additional height, or designing a structure that can easily be raised. If this existing guidance is implemented over the next 50 years with a 50-year design life, we could conservatively assume that all the coastal flood defences in East Anglia and the North West would be raised at least 30 cm and 20 cm, respectively, compared to the baseline. (This would include subsidence, so it needs to be compared with the relative sea-level rise scenarios given in Table 5.1). This is more than the 2050s Low relative sea-level rise scenario, and in this case the risk of coastal flooding would be reduced by the 2050s compared to the 1990s. However, this allowance is still 41 cm and 44 cm smaller than the 2050s High relative sea-level rise scenario in the two regions. This magnitude of rise would reduce most 100-year standard defences to a 15-year standard by the 2050s, equivalent to a seven-fold increase in average annual damages relative to today! Therefore, while flood impacts are reduced compared to the case of no adaptation, significant flood impacts would still occur under the 2050s High scenario. This shows the importance of a combined response startegy including proactive upgrade of new flood defences (*cf*. MAFF, 1999) and monitoring efforts to detect the occurrence and magnitude of accelerated sea-level rise (cf. Woodworth, 1990; Woodworth *et al.*, 1999; Douglas *et al.*, 2000) in time to allow the implementation of appropriate responses, if the High scenario is realised.

While not quantitatively evaluated here, the net effects on flood risk presented for the 2050s High scenario could also be realised by some combination of increased storm surge frequency and magnitude, and regional sea-level rise in the north east Atlantic, combined with a smaller rise in sea level. Therefore, continued assessment of regional sea levels and the possibility and implications of changes in storminess would be prudent.

It has recently been suggested that the design of fluvial flood defences should consider the implications of a 20 % increase in peak river flows (MAFF, 2000) (which is equivalent to the assumed High change scenario used in this study). While there is much less experience of this policy compared to coastal defences, it would clearly have important flood alleviation benefits, if fully implemented.

It is noteworthy that there is no guidance on considering climate change in flood protection in coastal lowland areas where increased river flows and sea-level rise might interact adversely. For example, the Fens present particular problems when considering a response to the increased flood risks presented by climate change. Clearly there is considerable experience of managing floods in this area and the absence of significant flooding since 1947 might be taken as an indication of the success of existing policies. However, it will be difficult to raise many of the existing flood banks due to soil conditions (Heald, *pers. comm.*). This suggests that following the existing MAFF (2000) guidelines on responding to climate change might be difficult. Therefore, more radical (and more expensive) approaches might be necessary. The issues of responding to climate change in the Fens are discussed further in Section 5.5.

5.4.2 Changes in coastal habitats

The present stock of saltmarsh habitats in the two regions is about 3,200 ha in East Anglia and 7,700 ha in the North West (Figure 5.14). In East Anglia, this is divided into about 1,100 ha of saltmarsh in Suffolk, and about 2,100 ha of saltmarsh in north Norfolk and The Wash. It is important to note that some of the small areas of saltmarsh identified in the LCMGB land cover map are erroneous, such as the saltmarsh identified between Great Yarmouth and Cromer, where the coast is either cliff or artificially-maintained sand dunes. Such errors are to be expected with satellite-derived maps of land cover with quoted accuracy of 70 to 80 % (Wyatt *et al.*, 1994). The areas involved are small and the data set is used in an unmodified form for the analysis.

The present stock of coastal grazing marsh is estimated to be about 23,500 ha in East Anglia and 25,600 ha in the North West, respectively (Figure 5.17). Based on the definition used here, coastal grazing marsh extends significant distances inland, particularly in the Fens and The Broads. In the Fens, nearly 3,000 ha of coastal grazing marsh occurs along tidal rivers.

5.4.2.1 Saltmarsh change

The method utilised here reproduces present-day patterns of saltmarsh loss assuming a global sea-level rise of 1.8 mm/yr over the course of the 20th Century (taken from Douglas, 1991). In East Anglia, losses are predicted between Lowestoft and Felixstowe (and continuing into Essex), with no losses in North Norfolk or the Wash (Figure 5.15). The North West is predicted to experience no losses. These are broadly consistent with observations of saltmarsh trends over the last few decades by Pye and French (1993a & b), who observed some losses on the Suffolk coast, accretion in North Norfolk and the Wash and a mixture of accretion and erosion in the North West, with no overall regional trend.

The qualitative direction of possible changes in saltmarsh area for the different combinations of climate change scenarios and socio-economic storylines is given in Table 5.9. When they occur, saltmarsh losses are always the result of sea-level rise. Saltmarsh gains can be the product of both sea-level rise leading to coastal abandonment (an unplanned retreat), or a deliberate policy of managed realignment.

Table 5.9: Likely trends of saltmarsh change given the different scenario combinations used in RegIS.

Socio-economic storyline	2050s climate change scenario	
	Low	High
Baseline	no change/losses	losses/gains
GS	losses/gains	not evaluated
RE	not evaluated	losses/gains

Figure 5.15 shows the percentage loss of existing saltmarsh stock for three future scenarios in East Anglia: 2050s Low, 2050s High and 2050s High RE. For the 2050s Low scenario, the results are similar to the present losses, with 7 % of the Suffolk’s saltmarshes being lost. For the 2050s High scenario, losses from Lowestoft to Felixstowe increase, and losses begin to occur in North Norfolk and the Wash: in East Anglia losses total about 505 ha, or 14.5 % of the regional stock, while in Suffolk about 50 % of existing saltmarshes are lost. The largest saltmarsh losses occur under the 2050s High RE scenario, where the impact of sea-level rise is enhanced by reduced sediment availability due to cliff protection (Sections 5.2.4 and 5.3.4): total losses are 776 ha, or 22 % of the regional stock. Again, the largest losses occur between Lowestoft and Felixstowe, but significant losses are also predicted for the North Norfolk coast and The Wash.

The difference in tidal range between the two regions had a pronounced effect on the predicted impacts; in the North West losses due to vertical saltmarsh response are negligible for all relative sea-level rise scenarios due to the large tidal range. It is worth noting that Lee (1998) forecast saltmarsh accretion in the North West under a relative sea-level rise scenario of 4 mm/yr, which is consistent with the results presented in RegIS. The marshes in the North West are not dependent on cliff erosion for their sediment supply, so cliff protection under the Regional Enterprise storyline will not influence the results.

To put these losses due to sea-level rise into context, it is useful to compare them with the implications of a region-wide 10 m saltmarsh edge retreat. A rough estimate of the length of the seaward saltmarsh edge is about 417 km and 950 km in East Anglia and the North West, respectively. Therefore, a 10 m retreat of the marsh edge would lead to the loss of about 400 and 900 ha of saltmarsh in the same regions, respectively. This is more than 10 % of the existing saltmarsh stock in both regions. Such a retreat is well within present experience (*e.g.* Carpenter and Pye, 1996) and might be realised by increased wave activity due to climate variability and/or change. This indicates that the existing saltmarshes may be more vulnerable to loss, due to a combination of factors, than the results due to sea-level rise alone might suggest.

In addition to these saltmarsh losses, saltmarsh gains may occur due to both managed and unplanned realignment of the coast. The analysis of land elevation within the areas of potential managed realignment are given in Table 5.10. Suffolk and Norfolk are distinguished due to the significant difference in tidal conditions. Managed realignment produces between 32 and 68 % saltmarsh/high marsh depending on the region (Table 5.10). Areas of high marsh may be of particular value as this habitat has often declined more than the lower marsh. The large amount of terrestrial habitat distinguished for Suffolk, and to a lesser extent in the North West, seems anomalous given that these areas are all- by definition- within the 1 in 200-year flood plain. This illustrates that the areas delineated by the Indicative Flood Plain may change significantly as it is improved.

Table 5.10: Regional conversion factors for managed realignment.

	% mud	% saltmarsh	% high marsh	% terrestrial habitat
Suffolk	15	20	12	53
Norfolk	23.5	55	12.5	9
North West	24	33	13	30

Under the 2050s Low GS scenario, climate change produces the same losses in East Anglia as for the 2050s Low scenario, but there are net gains of 5294 ha of saltmarsh due to managed realignment (Figure 5.16). Similarly, in the North West there are also substantial gains of more than 5,000 ha in saltmarsh due to managed realignment. In both regions, these potential gains exceed likely losses by a factor of five or more, and are even larger than the existing saltmarsh stock in both regions. When compared with other studies of managed realignment, the saltmarsh gains under the 2050s Low GS scenario are significantly larger than other estimates (Table 5.11). This reflects the fact that the RegIS analysis was conducted without many of the constraints on other assessments. Therefore, it must be recognised that the saltmarsh gains described here are unlikely to be realised in full. However, these results do indicate that there are sufficient sites available for managed realignment to be able to counter any likely losses of saltmarsh (and other intertidal habitats) over the next 50 years. The main constraint is releasing the sites for this purpose. The main cost of these gains in saltmarsh is the loss of coastal grazing marsh in many cases (see Section 5.4.2.2 below).

Unplanned saltmarsh gains are more difficult to predict. Strictly speaking, under all the scenarios considered here, flood defences are maintained at their existing level, excluding global sea-level rise. This means that they would be rebuilt after every flood and this would prevent full saltmarsh colonisation, although increasingly salt-tolerant vegetation might be expected landward of the flood defence. Under the 2050s Low sea-level rise scenario, this seems a plausible assumption, but under the 2050s High sea-level rise scenario, some coastal areas would be flooded so often (much greater than once per year) that coastal abandonment after a major storm seems more likely. Of the area defined in Section 5.3.4.2 as suitable for managed realignment, in East Anglia 68 % are in flood compartments which would be flooded more than once per year under the 2050s High sea-level rise scenario, while in the North West it is 38 %. This translates into potential gains of about 2,900 ha and 1,000 ha of saltmarsh, respectively. Under the 2050s Low scenario in the North West, the area of managed realignment in flood compartments flooded more than once a year is very similar, at 37 %, to the High scenario. This reflects the low standard of protection (according to the Sea Defence Survey) of many of the flood compartments in this region. Under the 2050s Low scenario, the figure for East Anglia is reduced to 10.5 %, translating into potential gains of around 451 ha of saltmarsh. While these are only indicative, these results suggest a possible net gain of saltmarsh due to unplanned retreat given the 2050s High scenario. Again, these gains in saltmarsh come partly at the expense of loss of coastal grazing marsh (see Section 5.4.2.2 below).

Table 5.11: Potential saltmarsh gains and coastal grazing marsh losses due to managed realignment (see also Table 5.10). Saltmarsh gains for the Environment Agency and Sharpe (2000) assume 50 % conversion (after Lee, 1998). For Lee (1998), the loss of coastal grazing marsh is equated to their wet grassland losses.

Source	Geographic Area	Area of Managed Realignment (ha)	Saltmarsh Gain (ha)	Coastal Grazing Marsh Loss (ha)
This study	Suffolk	6,410	2,051	2,748
	Norfolk	3,335	2,251	872
	North West	5,557	2,556	3,466
Environment Agency (internal database)	Anglian region (Suffolk and Norfolk only)	2,647	1,324	2,152
Sharpe (2000)	Humber to Thames	6,664	3,332	Not available
Lee (1998)	Cell 3, Wash to Thames	5,322	2,661	1834
	Cell 11, Great Orme to Solway Firth	1,662	781	170

In conclusion, saltmarshes in East Anglia appear more threatened than those in the North West, with those marshes on the Suffolk coast appearing to be most threatened. In all regions saltmarsh decline might compromise existing flood defences as larger waves will be able to reach the defences. This effect will be most marked in Suffolk and adoption of managed realignment would seem a prudent response, as is recommended extensively in the relevant shoreline management plan. While saltmarsh habitats may decline under scenarios of rising sea level and maintenance of the existing defence line, there is likely to be a net expansion in the area of saltmarsh, and related intertidal habitats, under scenarios of planned and unplanned realignment. Based on present trends in coastal management, the latter possibility appears more likely.

5.4.2.2 Coastal Grazing Marsh Change

Coastal grazing marsh is largely an artificial habitat formed by land claim over the last few hundred years (see French, 1997). In the last few decades, it is a habitat type that has declined due to conversion to arable agriculture (Chapter 8). Looking to the future, there are widespread proposals to allow much of this land to return to intertidal habitat, including saltmarsh, via a policy of managed realignment as already discussed in Section 5.3.4.

The present distribution of coastal grazing marsh as defined in this study is shown in Figure 5.17. The qualitative direction of possible changes in these areas of coastal grazing marsh for the different combinations of climate change scenarios and socio-economic storylines are given in Table 5.12. These trends can be related to the saltmarsh changes already discussed in Section 5.4.2.1: saltmarsh gain is often coastal grazing marsh loss (see Table 5.11). Coastal grazing marsh gains are possible if arable agriculture is abandoned in the coastal flood plain. Therefore, any coastal grazing marsh gains are always the result of sea-level rise. Coastal grazing marsh losses can be the product of both sea-level rise leading to coastal abandonment (an unplanned retreat), or a deliberate management policy of managed realignment. It is worth noting that under a scenario of rising sea levels, any gains in coastal grazing marsh are likely to be temporary, as sea levels will continue to rise beyond the 2050s and planned or unplanned abandonment of these areas to intertidal habitat seems the ultimate response in many cases.

Under the 2050s Low scenario, there is no change because the increase in flood frequency is insufficient to trigger agricultural land use changes, or unplanned coastal abandonment. Under the 2050s Low GS scenario, there are significant losses of coastal grazing marsh due to managed realignment (Figure 5.18). Unplanned coastal grazing marsh losses are more difficult to predict (see Section 5.4.2.1 on unplanned saltmarsh gains). Of the area defined in Section 5.3.4.2 as suitable for managed realignment, 3090 ha (29 %) in East Anglia, and 1927 ha (19 %) in the North West, are coastal grazing marsh in flood compartments that would be flooded more than once per year under the 2050s High sea-level rise scenario. Hence, these areas give some indication of the potential unplanned coastal grazing marsh losses under this scenario.

Table 5.12: Likely trends of coastal grazing marsh change given the different scenario combinations used in RegIS

Socio-economic storyline	2050s climate change scenario	
	Low	High
Baseline	no change	losses/gains
GS	losses	not evaluated
RE	not evaluated	losses/gains

Coastal grazing marsh gains will occur in areas where arable agriculture is abandoned, although some of these areas may be converted directly to intertidal habitat by managed realignment. Under the Global Sustainability storyline, it is expected that grazing marsh and associated freshwater habitats will be created in the Fens or similar areas to help substitute for coastal losses. Grazing marsh may also expand along many river valleys due to increased flooding.

Any losses of coastal grazing marsh are hard to replace given the profile of the coastal zone – managed realignment is usually allowing former intertidal areas to return to their natural state. Figure 5.19 shows the distribution of land elevations in both regions within the coastal zone (below 10 m O.D.). These might be interpreted as average coastal cross-sections. The distributions are quite different, with East Anglia having a high proportion of land below the present high water mark. In contrast, the North West has a more uniform distribution with elevation. This suggests that it will be easier to create coastal grazing marsh in the North West than East Anglia.

In conclusion, coastal grazing marsh appears threatened in both regions, and while sea-level rise could be a problem if the High scenario is experienced, changes in coastal management towards a policy of managed realignment are equally important. To continue to preserve these artificial habitats in coastal locations seems economically and ecologically unsustainable. The challenge will be the strategic planning of these changes so that as coastal grazing marsh progressively declines, replacement habitat is provided in more sustainable (and hence non-coastal) locations.

5.5 Further Work

This research has identified a number of issues that require further investigation. Problems with the availability and resolution of suitable data sets have been a major constraint on the analysis that could be attempted in RegIS. Continued efforts to develop and improve consistent databases on coastal and river flood defence infrastructure and related factors should be given a high priority, as their widespread availability would greatly facilitate strategic policy analysis, such as RegIS, or updating the National Appraisal. In addition, methods to better assess the failure of defences under climate change scenarios are required which include the maintenance regime of the defences, and the full range of hydrodynamic impact factors from mean and extreme water levels to wave conditions. This will be particularly important if scenarios of changes in storminess are analysed. More generally, appropriate scenarios of change could be better developed and possibly included in future UKCIP guidance. This could include:

- A synthesis to develop more detailed scenarios on future rates of land subsidence, with a focus on the vulnerable coastal lowlands, where this factor is most important;

- Extending the catchment modelling on the Thames and Severn (Reynard *et al.*, 1998) to a representative range of catchments of different sizes and hydrological response, ideally including catchments in each Environment Agency Region. This will provide more regionally-focussed guidance on likely changes to flooding;
- Other climate change factors relevant to coasts, particularly consideration of changes and variation in storminess. For the purposes of sensitivity analysis, development of appropriate uniform scenarios of increase and decrease could be explored to guide future policy analysis.

The analysis of flood risk shows that although climate change could be the major factor increasing the risk of flooding, increased flood plain development could further exacerbate such problems. Based on the existing allowance for sea-level rise in project guidance, the High scenario will significantly increase flood impacts, unless there is an additional adaptation response. This raises the question of what would be necessary to manage the 2050s High scenario, particularly if it was combined with an increase in storminess? While this worst-case scenario may be considered unlikely, it would be prudent to simulate the evolution of flood risk through time under this scenario and identify the critical barriers to implementing an appropriate adaptation response. Issues might include the difficulty of detecting an acceleration of sea-level rise (see Woodworth, 1990; Douglas, 2000), which would delay recognition of the problem, the time required to upgrade defences once the problem is recognised, etc.

The Fens are the most vulnerable area to increased flooding in the two regions. An integrated study of the Fens that examined the management of increasing flood risk in more detail is recommended. This is consistent with the forthcoming Catchment Flood Management Planning initiative and more broadly with the EU Water Framework Directive. Such a plan would provide the basis for a long-term flood management plan for the entire Fens. It would need to take account of subsidence and peat wastage, global sea-level rise and changes in peak river flows, as well as changing storminess. Other issues that should be considered are emergency planning, land use planning and the potential for habitat recreation. Climate change and the recognition that the risk of flooding is likely to increase with time suggest that emergency planning for flood events within the Fens needs to be improved. For long-term planning, it is important that sufficient corridors are left undeveloped and available for flood management purposes. Given the high flood risk within the Fens, new developments might be concentrated in areas where they can be most easily defended, including providing new flood defences, if appropriate. There is also considerable interest in habitat recreation in the Fens (*e.g.* the Fens Floodplain Project of English Nature is proposing creating at least four large wetlands in the Fens by 2050 (www.floodplains.org)) and this could sensibly be combined with improved flood management in a win-win collaboration. Lastly, the Fens are only one of a number of coastal lowlands in Britain. These other vulnerable areas should be similarly evaluated.

Changes in coastal habitats will be influenced both by climate change and changes in coastal management, which increasingly favour managed realignment. Based on the analysis described here, there is sufficient land available in East Anglia and the North West to sustain or even enhance the existing stock of intertidal habitat. However, maintenance of the intertidal habitat stock produces significant losses of coastal grazing marsh and other freshwater habitats (*cf.* Lee, 1998). Given that there is limited information on the ‘quality’ of the areas lost, it is difficult to be more precise about the implications. Further analysis of the likely stock of coastal habitats over time, including coastal grazing marsh and other freshwater habitats would be prudent. This might define the coast more broadly to include habitat creation within coastal lowlands such as the Fens.

Lastly, an integrated regional study might have been expected to address a wider range of the issues for coastal areas and river flooding than presented here. As already discussed, the lack of both resources and also accessible and consistent datasets for many factors precluded such a comprehensive analysis. Given the importance of flood impacts on the built environment, future regional assessments should consider these impacts in more detail. Such a research effort might be pursued both in a sectoral manner as in the National Appraisal, and within an integrated assessment framework to examine the linkages to other sectors and issues.

5.6 Conclusions

This study has shown that climate change could have profound implications for coastal areas and river valleys. While the Low climate change scenario causes relatively minor impacts to the 2050s, the High climate change scenario raises the risk of flooding significantly. Without any adaptation, increased flooding would have important implications for land use and the magnitude of flood damage. Existing project guidance would reduce but not avoid these impacts, and it would be prudent to evaluate how the High climate change scenario could be effectively managed. In coastal areas, a worst-case scenario would include sea-level rise, combined with an increase in storminess. When compared to the effect of climate change, the increased exposure under the Regional Enterprise socio-economic storyline only has a secondary influence on the magnitude of impacts. However, it would still be prudent to steer new developments away from floodplain areas to the maximum degree possible. In the Fens, as in many other coastal lowlands, the interaction of sea-level rise, increased river floods and subsidence could lead to severe flood impacts and in the worst-case, the large-scale abandonment of this prime agricultural area. It is recommended that these issues are explored in a detailed study which should lead to a strategic Fens flood strategy, consistent with the Catchment Flood Management Planning initiative.

Coastal ecosystems, such as saltmarshes and coastal grazing marshes, will also respond to climate change. However, the uncertainties about this natural-system response is much greater than for flooding as these ecosystems are already changing rapidly for reasons that are not always clear, and the effects of climate change are numerous and often difficult to quantify. Sea-level rise appears to threaten saltmarshes in East Anglia more than those in the North West. In Suffolk, over half the existing saltmarsh could be lost and this would further degrade the protective function of sea defences situated landward of the saltmarsh. Elsewhere, the losses are not sufficient to cause widespread degradation of flood defence, but localised weakening is still likely, particularly in North Norfolk and the Wash. This will favour a policy of managed realignment for low-lying coastal areas with limited human development. This policy is already widely advocated in East Anglia and the RegIS analysis suggests that there are sufficient areas available to more than counter all saltmarsh and other intertidal losses to the 2050s, if that is the agreed policy goal. Managed realignment under the Global Sustainability storyline lead to substantial saltmarsh and intertidal habitat gains and coastal grazing marsh losses. A decline in coastal freshwater habitats seems likely irrespective of the magnitude of sea-level rise, due to the increasing application of managed realignment. The implications and possible management responses to these trends require more assessment.

Thus, climate change is a critical issue for understanding future flood risk. For coastal ecosystems, climate change is an important factor, but present trends in coastal management are also likely to have profound effects on the stock of different habitats that will be found in the 2050s. Therefore, more assessment of impacts and adaptation to increased flood risk under climate change scenarios would be prudent. Impacts on the built environment and coastal lowlands, and adaptation issues in general would seem to be the most pressing needs.

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Figure 5.1: Flooded areas on the east coast due to storm surge of 31 January 1953 (from Steers, 1964).

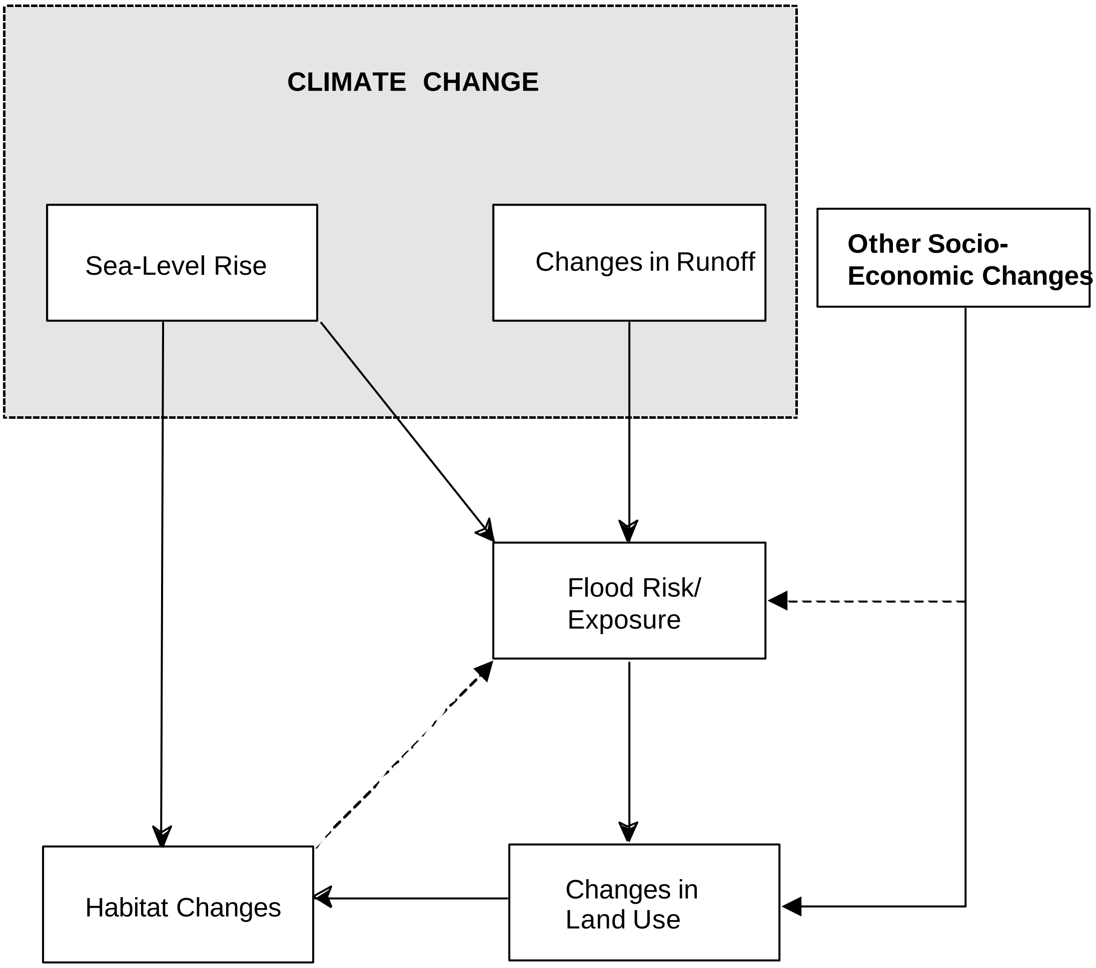


Figure 5.2: Overview of integrated assessment of impacts of climate change on coastal area and river flooding. Broken lines are only considered qualitatively, or at the regional scale.

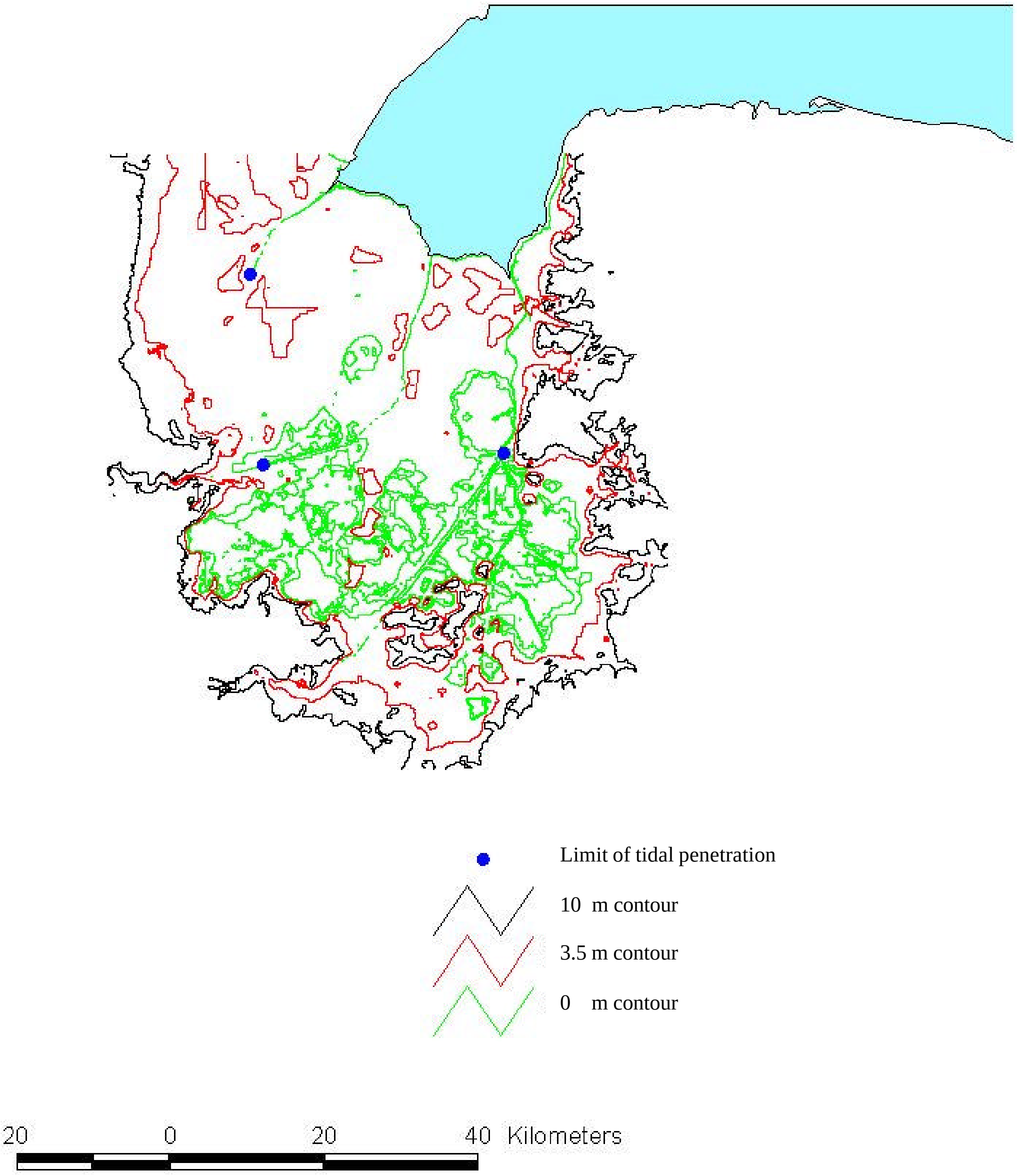


Figure 5.3: Land elevations and tidal limits in the Fens. The 3.5 m contour is the height of normal high water spring tides and the zero contour approximates mean sea level.

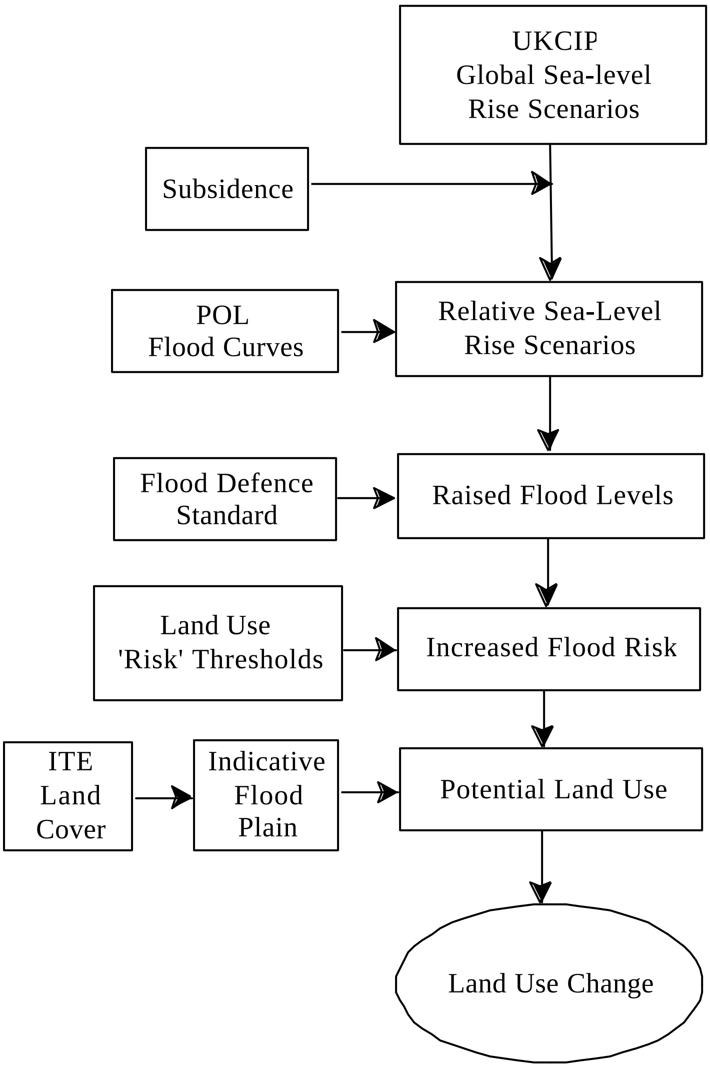


Figure 5.4: Methodological framework for flood risk evaluation in coastal areas.

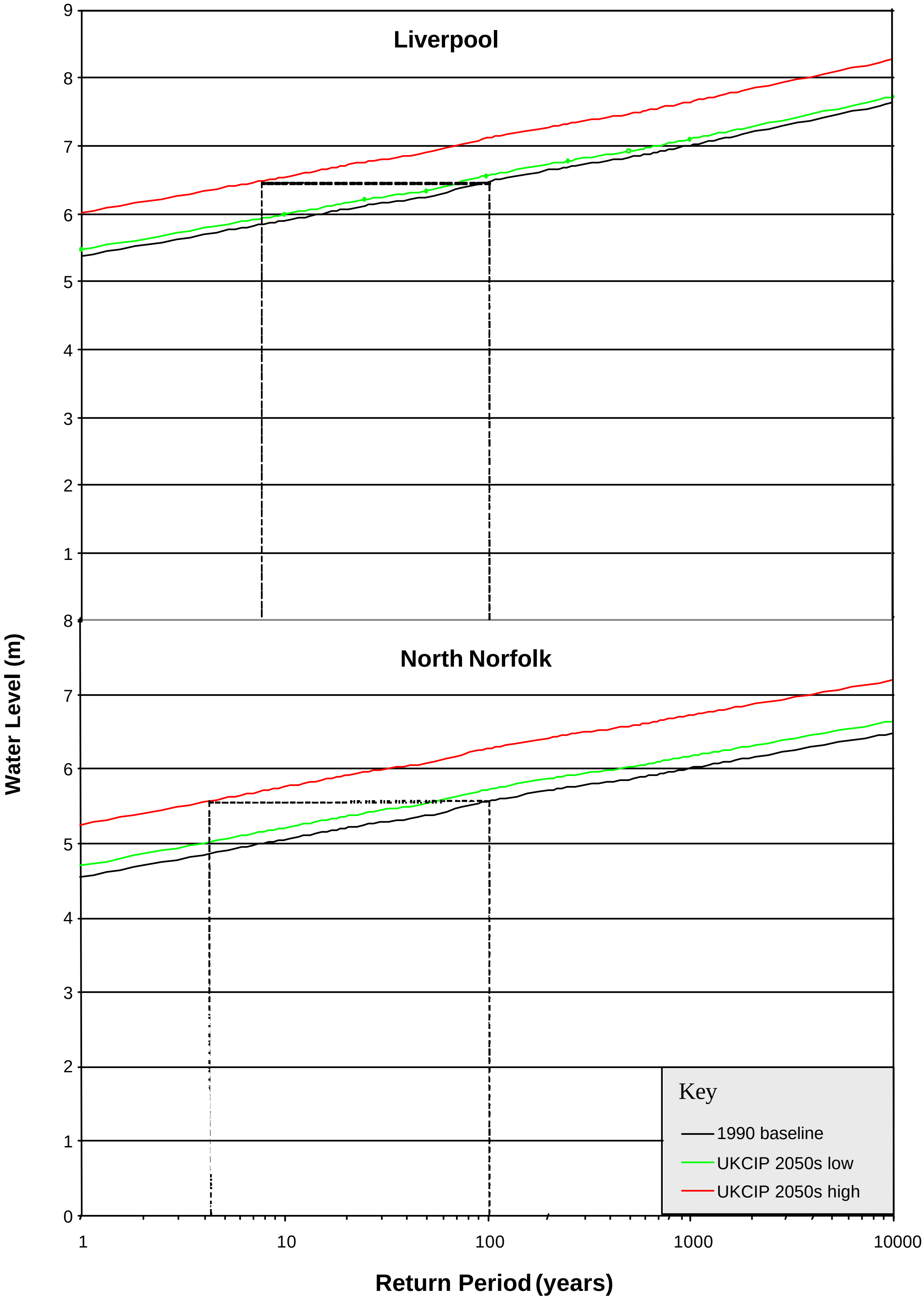


Figure 5.5: Flood probability curves for Liverpool and North Norfolk, showing the 1990 baseline and the effect of the 2050s Low and High relative sea-level rise scenarios.

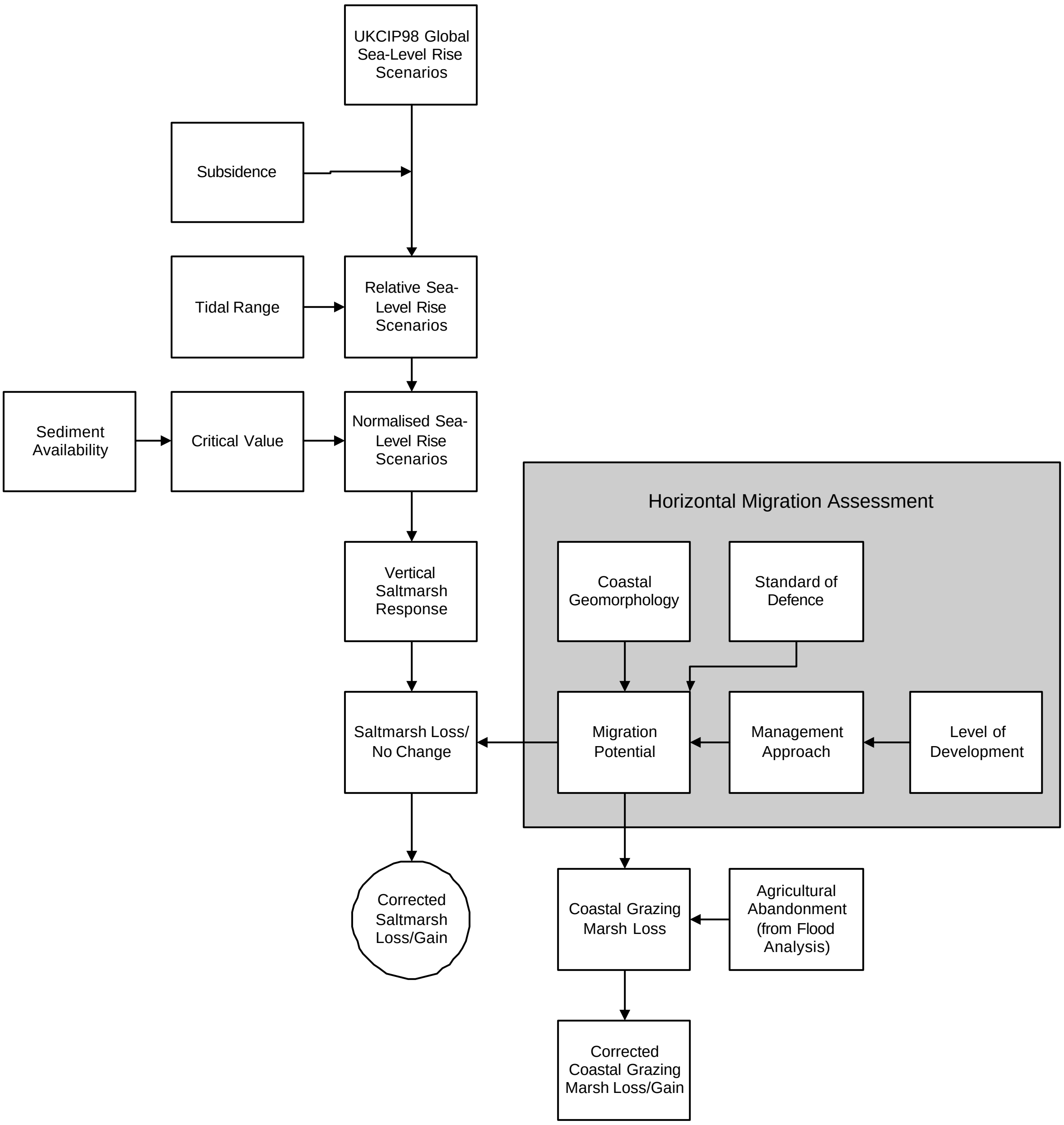


Figure 5.6: Methodological framework for coastal habitat analysis: changes to saltmarsh and coastal grazing marsh.

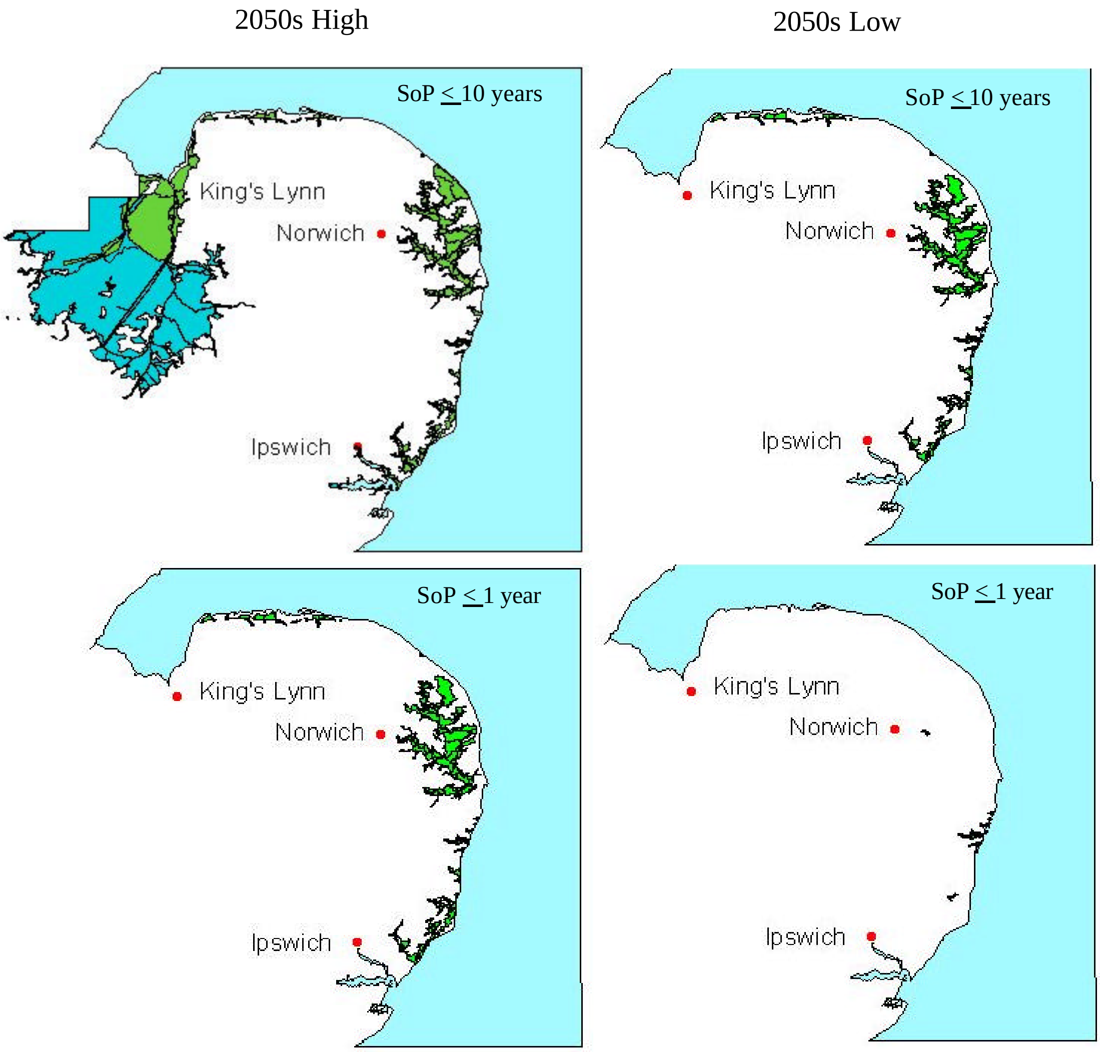


Figure 5.7: Flood compartments in East Anglia with a future standard of protection (risk of flooding) of ≤1 in 10 years and ≤1 in 1 year under the 2050s Low and High scenarios (including the Fens).

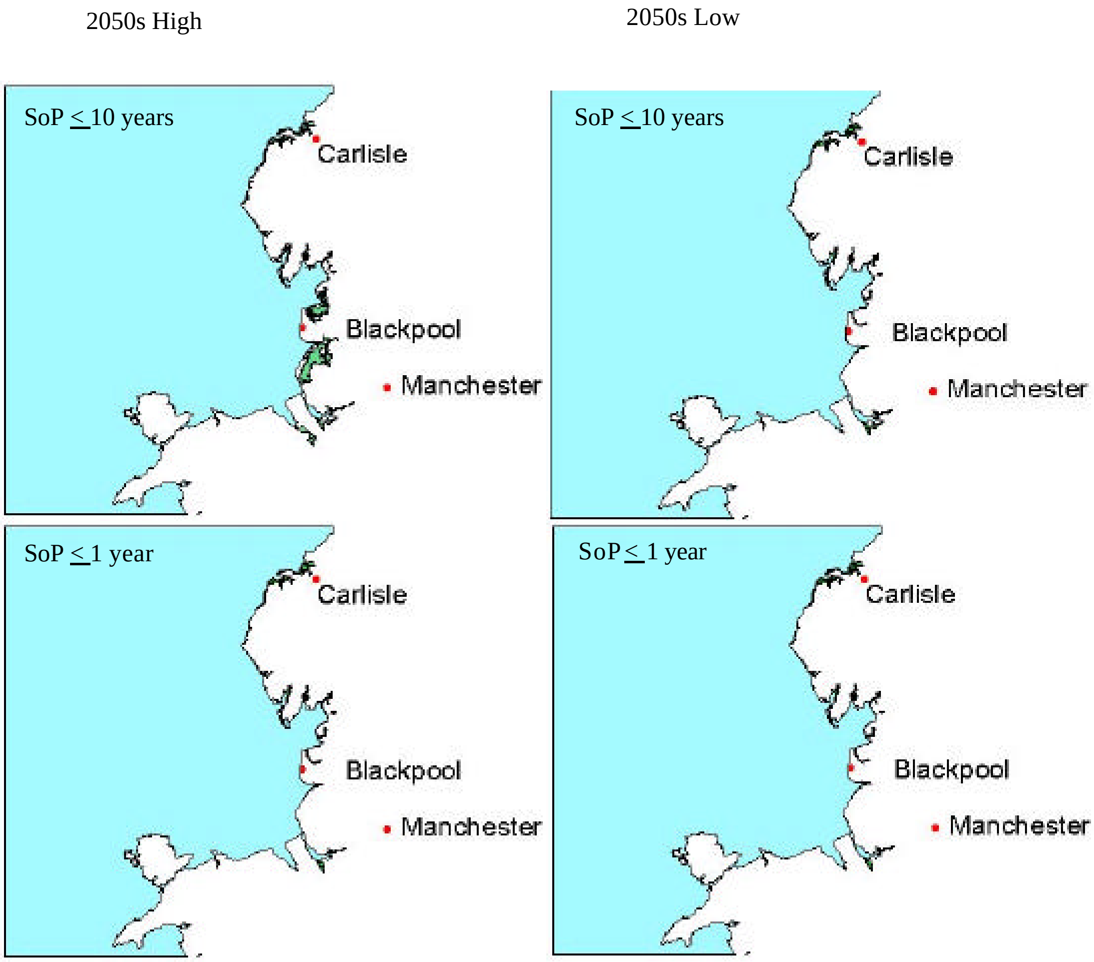


Figure 5.8: Flood compartments in the North West with a future standard of protection (risk of flooding) of ≤1 in 10 years and ≤1 in 1 year under the 2050s Low and High scenarios.

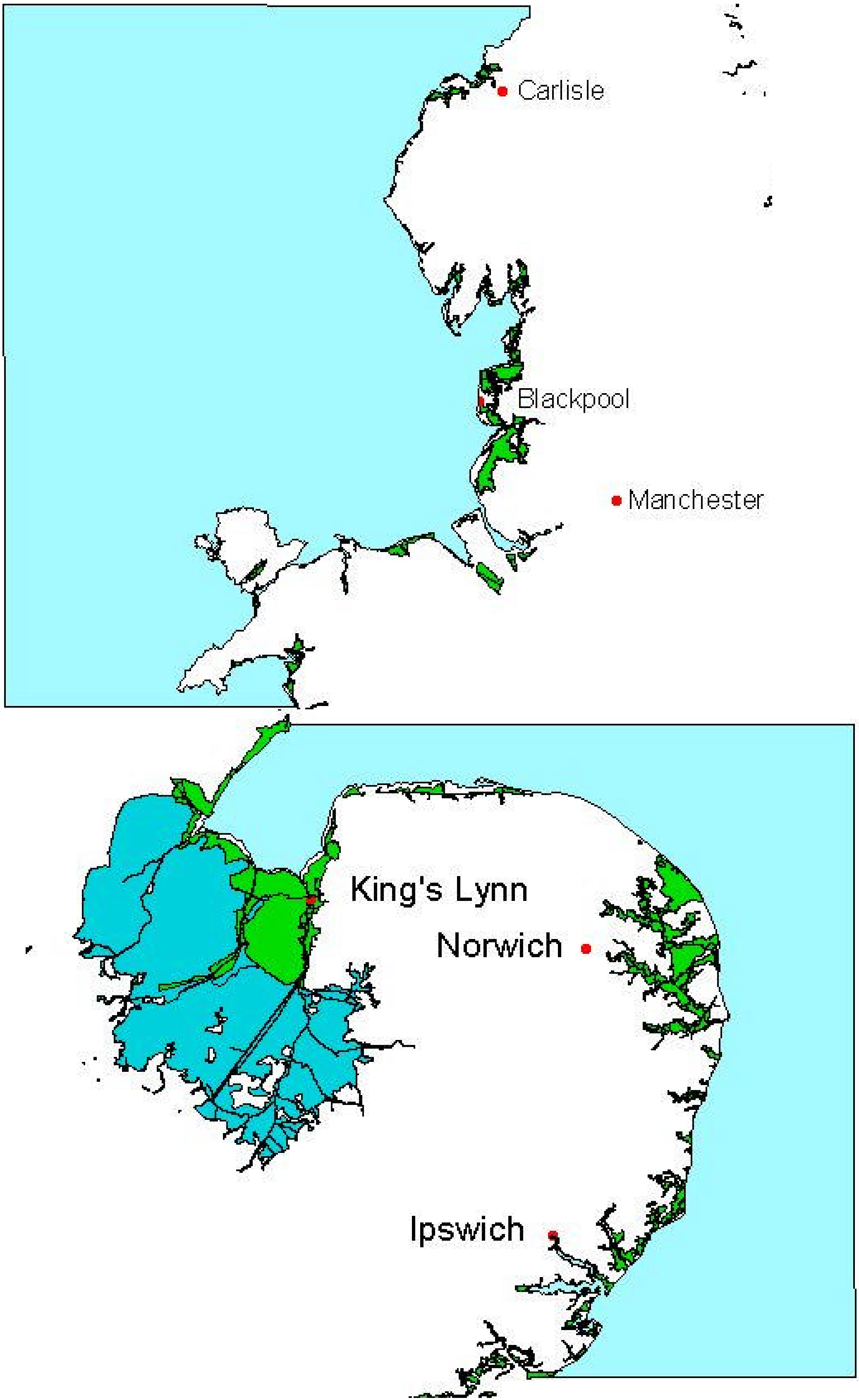


Figure 5.9: The 1999 indicative coastal flood plain for the North West and East Anglia, plus the Fens (which is mapped as part of the fluvial flood plain).

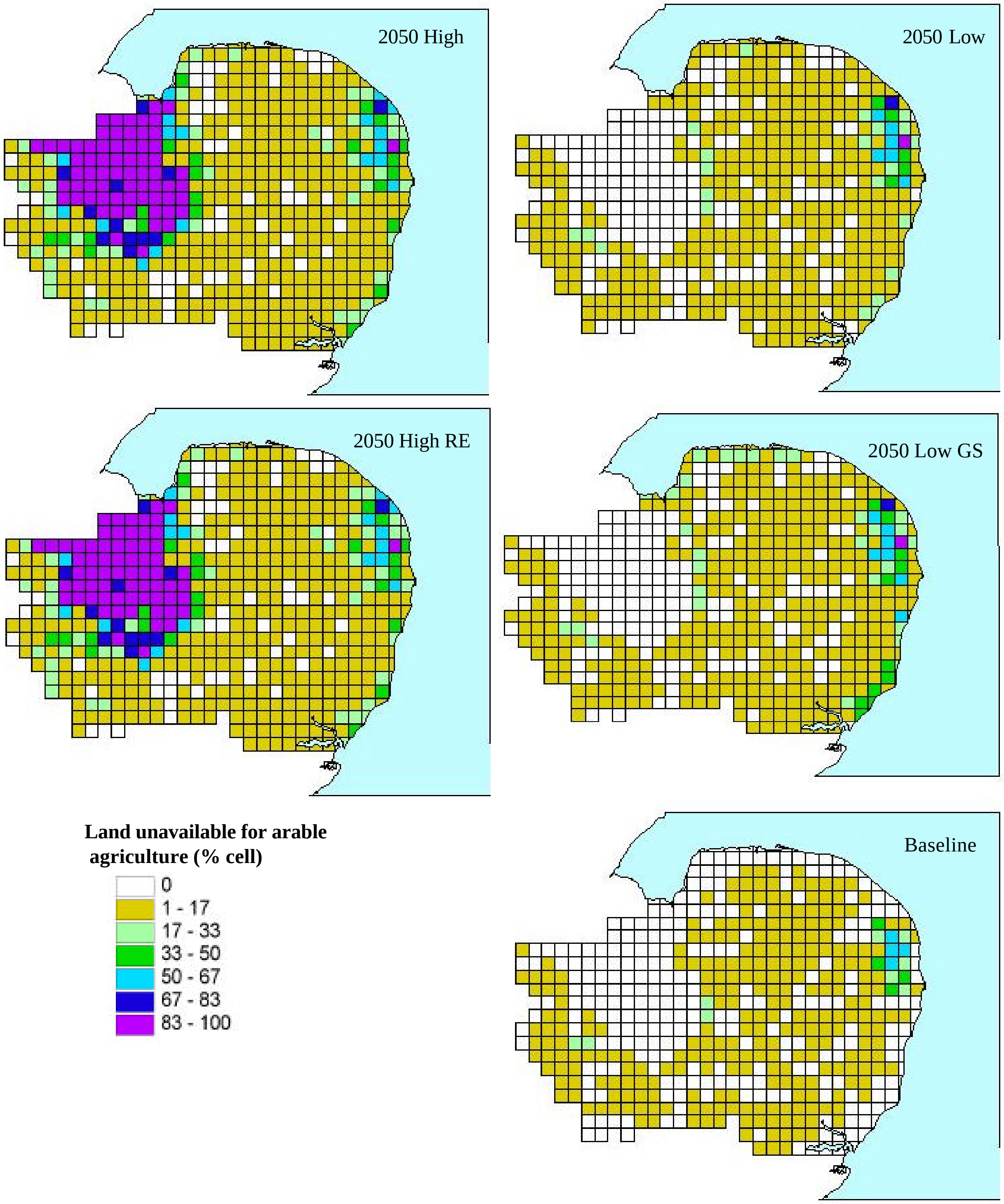


Figure 5.10: Land that would be unavailable to arable agriculture due to high flood frequency in East Anglia. Under the Global Sustainability storyline, small additional areas of land are unavailable to arable agriculture due to managed realignment.

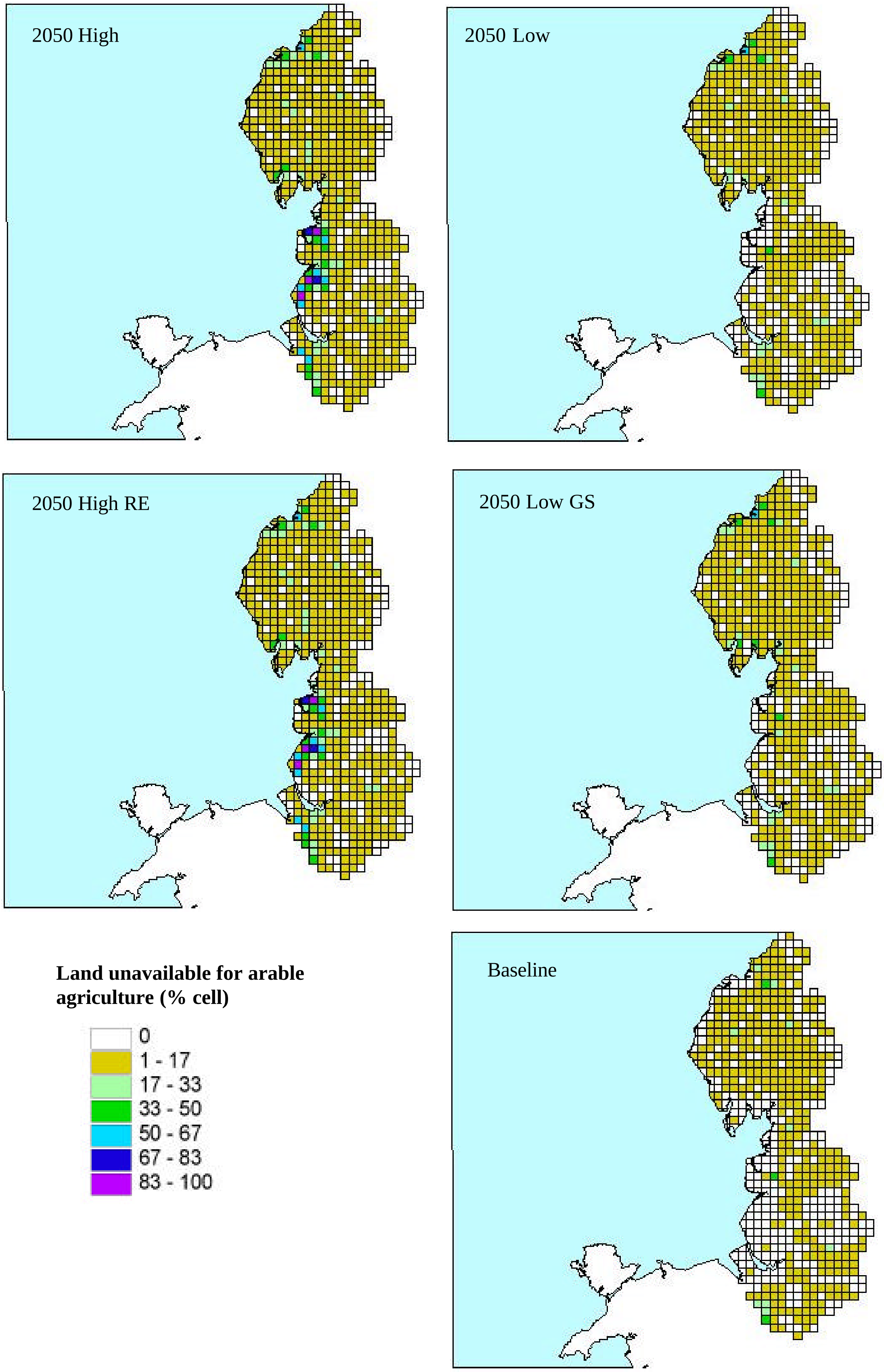


Figure 5.11: Land that would be unavailable to arable agriculture due to high flood frequency in the North West. Under the Global Sustainability storyline, small additional areas of land are unavailable to arable agriculture due to managed realignment.

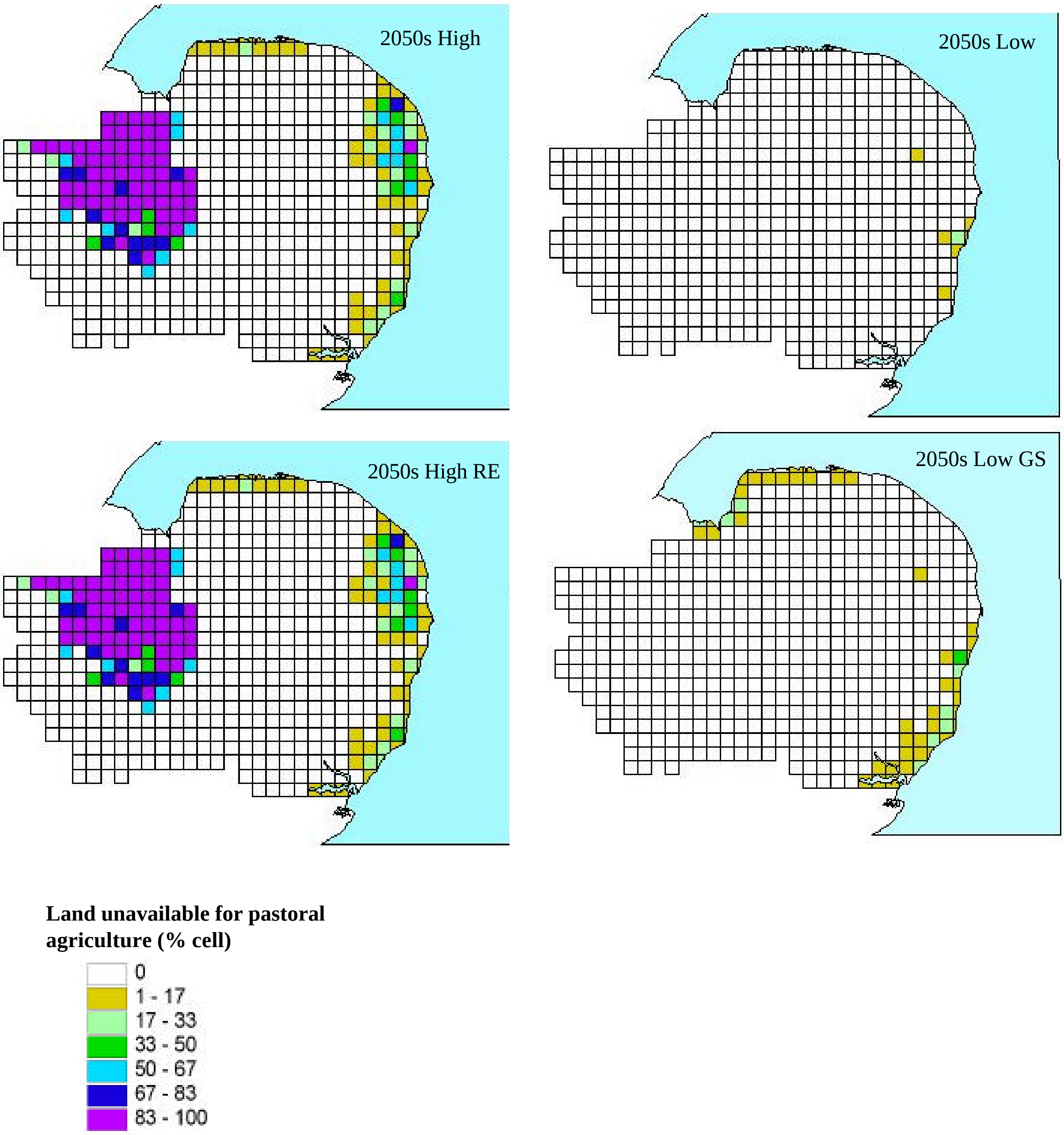


Figure 5.12: Land that would be unavailable to pastoral agriculture due to high flood frequency in East Anglia. Under the Global Sustainability storyline, small additional areas of land are unavailable to pastoral agriculture due to managed realignment.

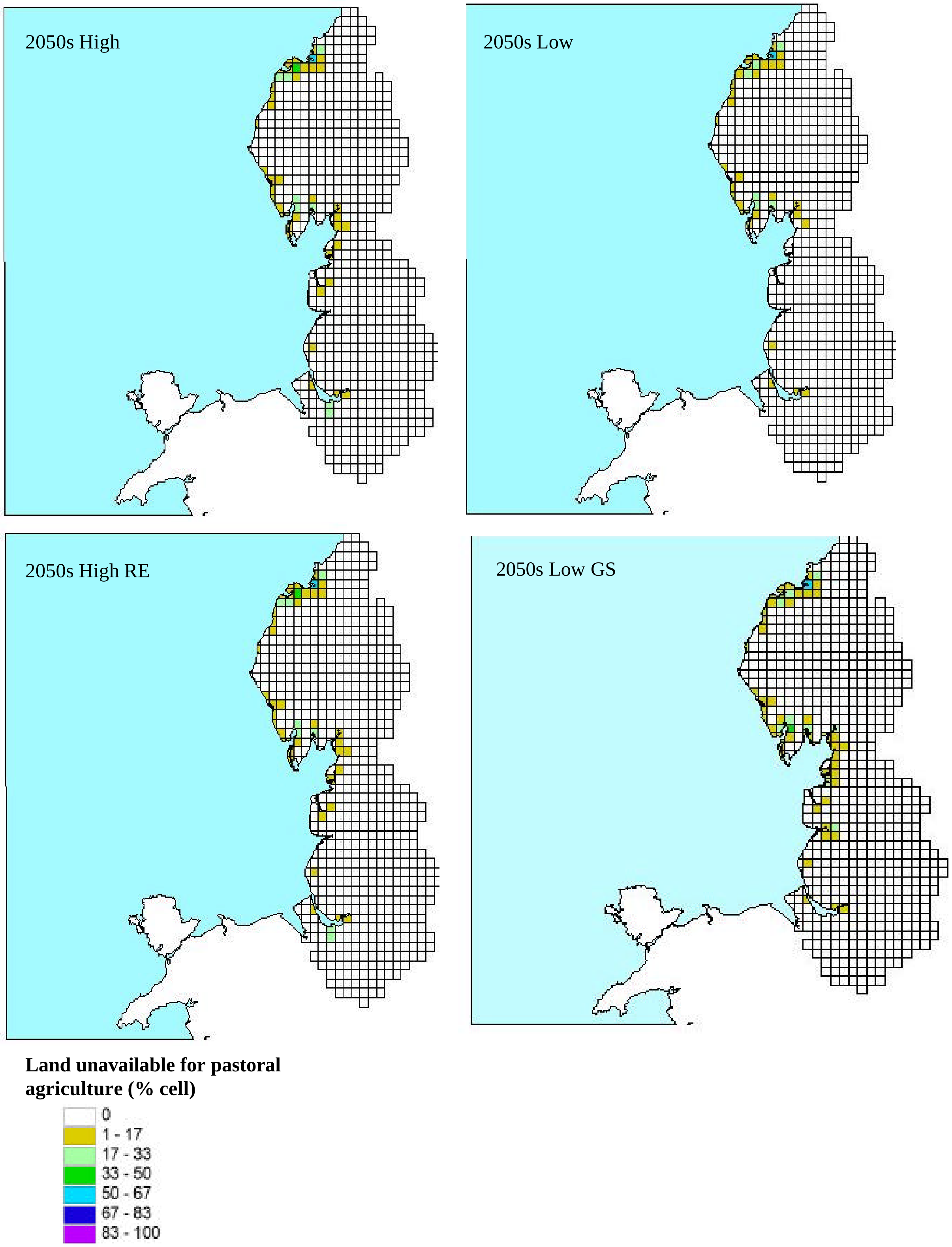


Figure 5.13: Land that would be unavailable to pastoral agriculture due to high flood frequency in the North West. Under the Global Sustainability storyline, small additional areas of land are unavailable to pastoral agriculture due to managed realignment.

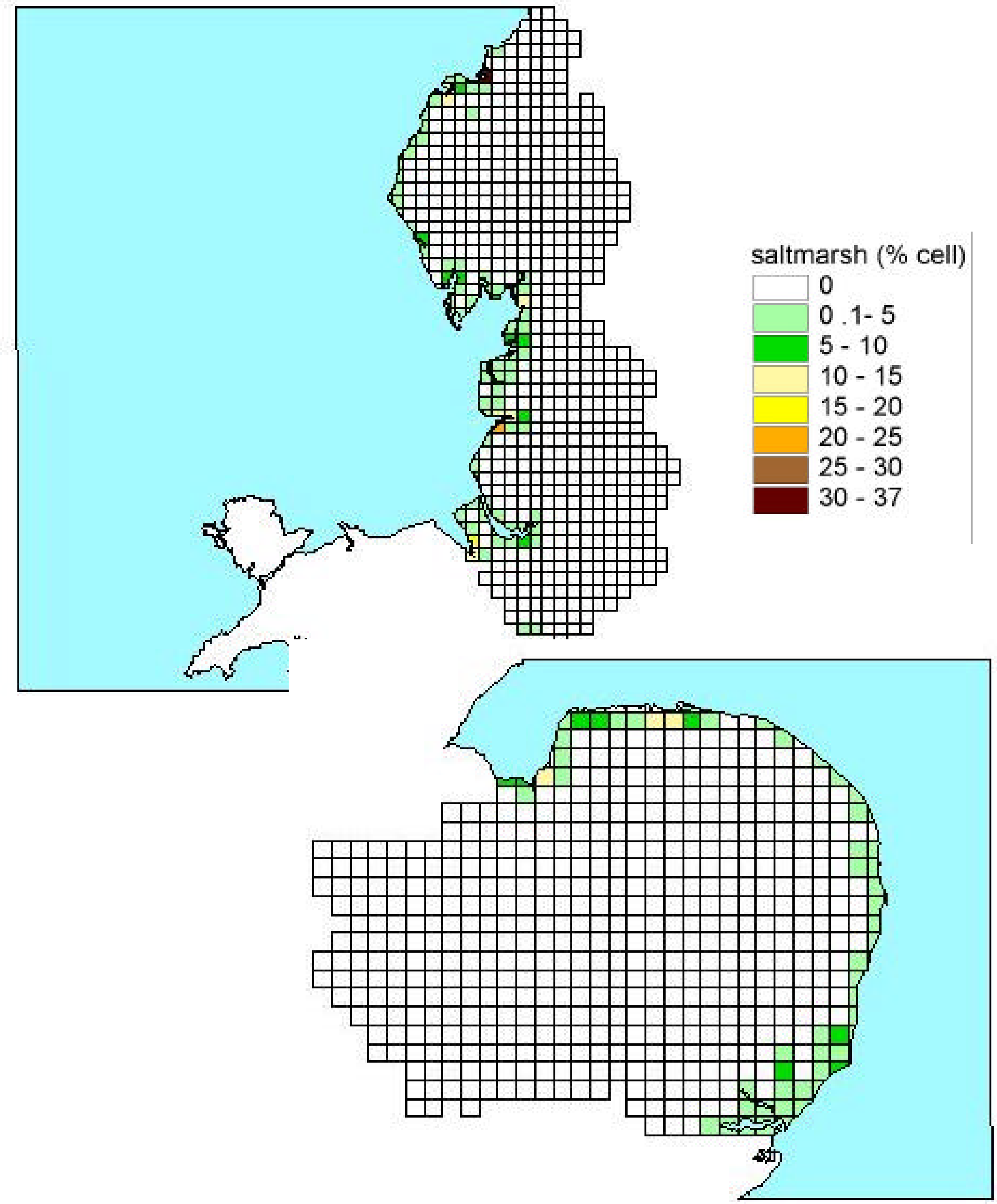
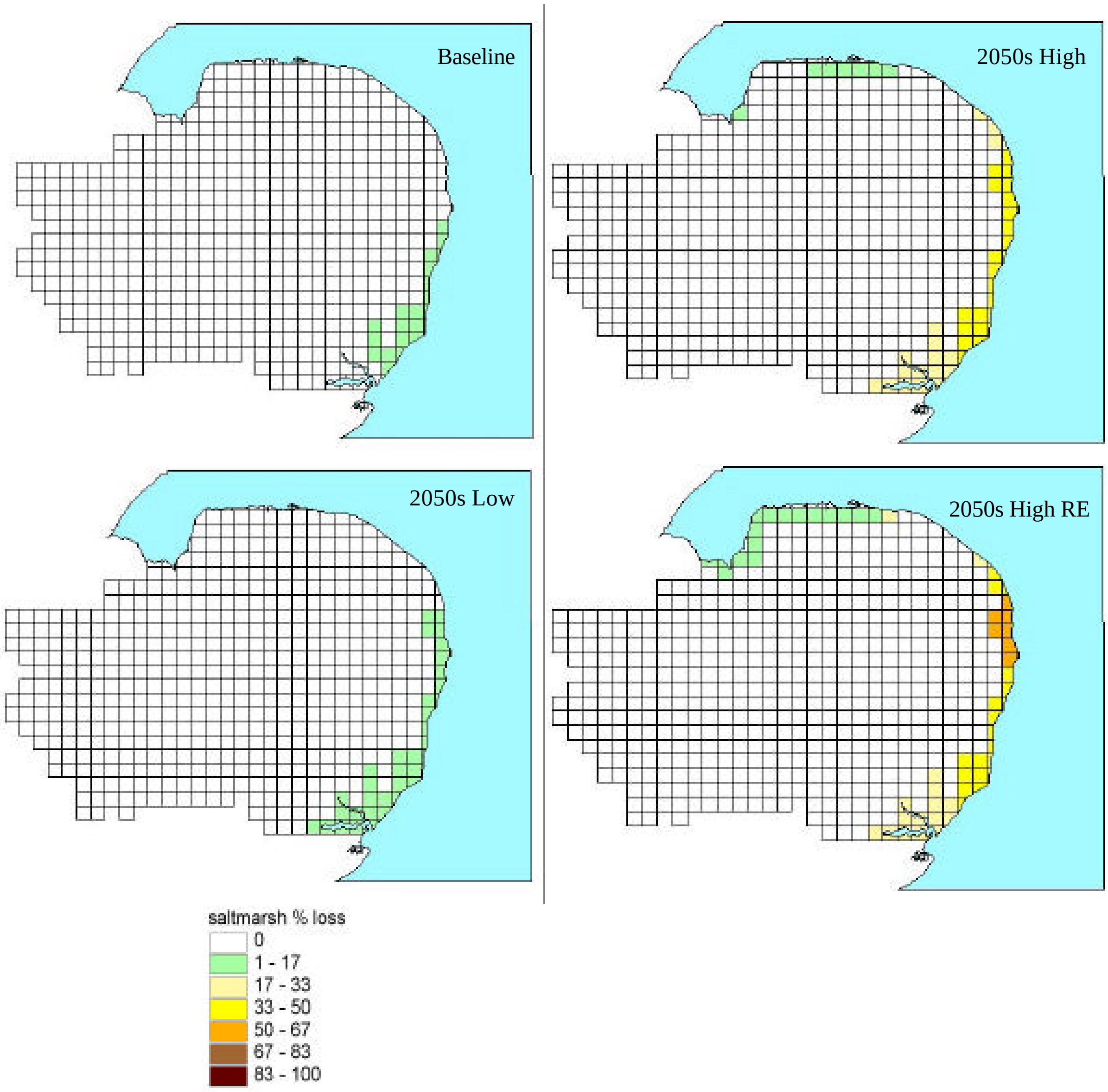


Figure 5.14: Present saltmarsh distribution based on the ITE land cover map (GB).



Baseline

2050s High

2050s Low

2050s High RE

Figure 5.15: Saltmarsh losses in East Anglia due to sea-level rise by the 2050s.

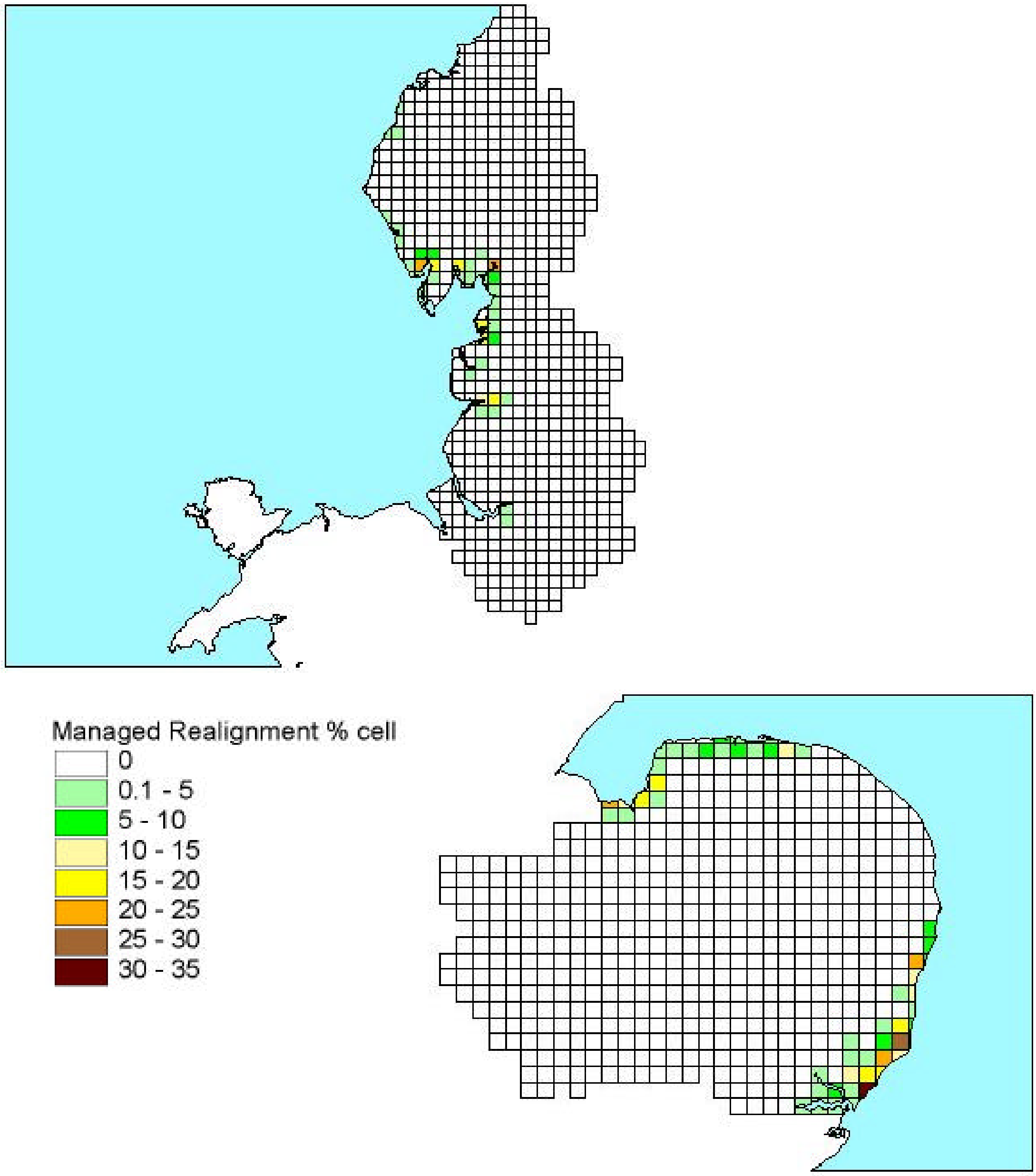


Figure 5.16: Areas of potential managed realignment based on elevation and present land use. Managed realignment is fully implemented under the Global Sustainability socio-economic storyline.

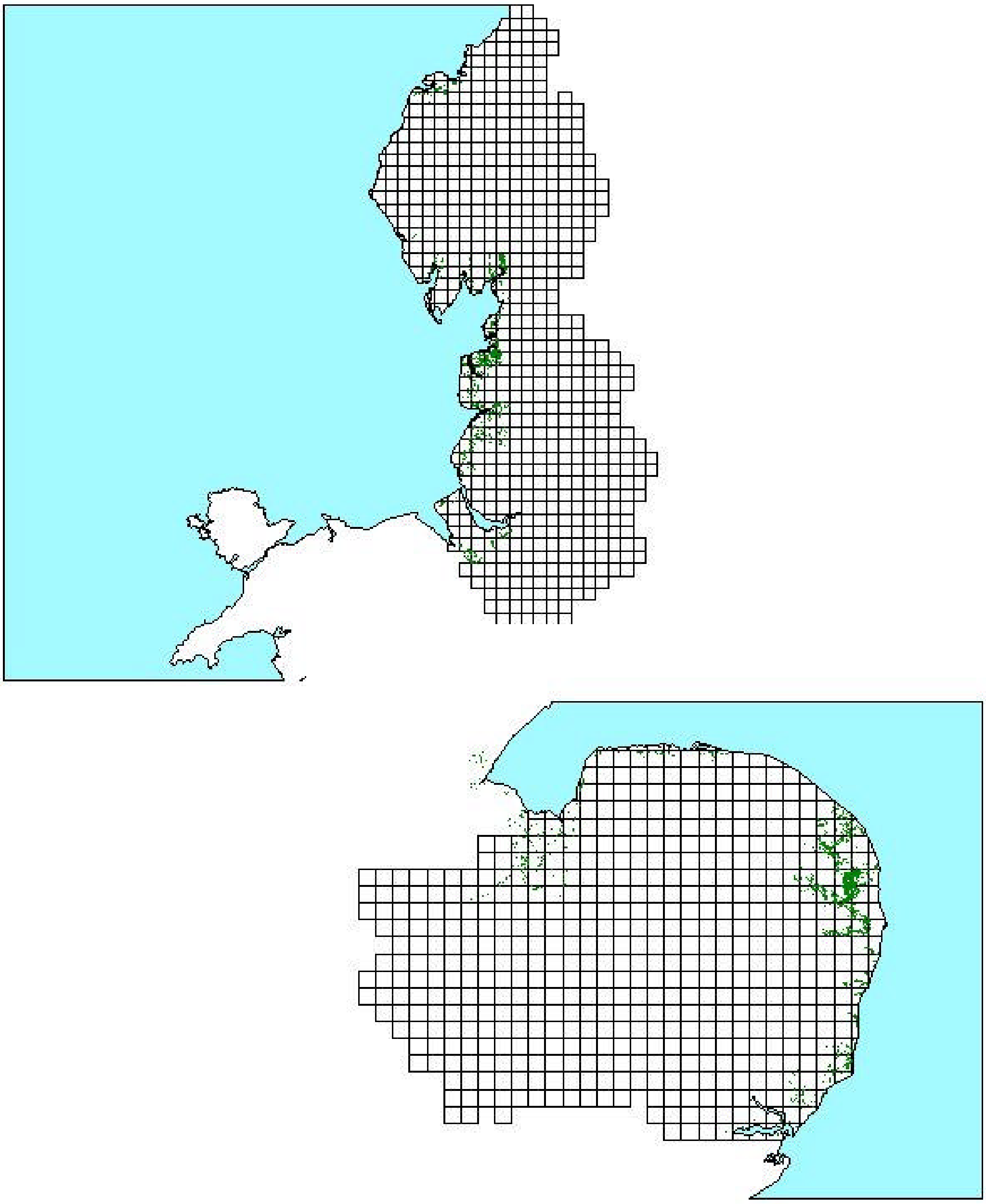


Figure 5.17: Present distribution of coastal grazing marsh based LCMGB land cover types 6, 7, and 8 (mown/grazed turf, meadow/verge/semi-natural and rough/marsh grass, respectively) that occur within the 1999 Indicative Coastal Flood Plain

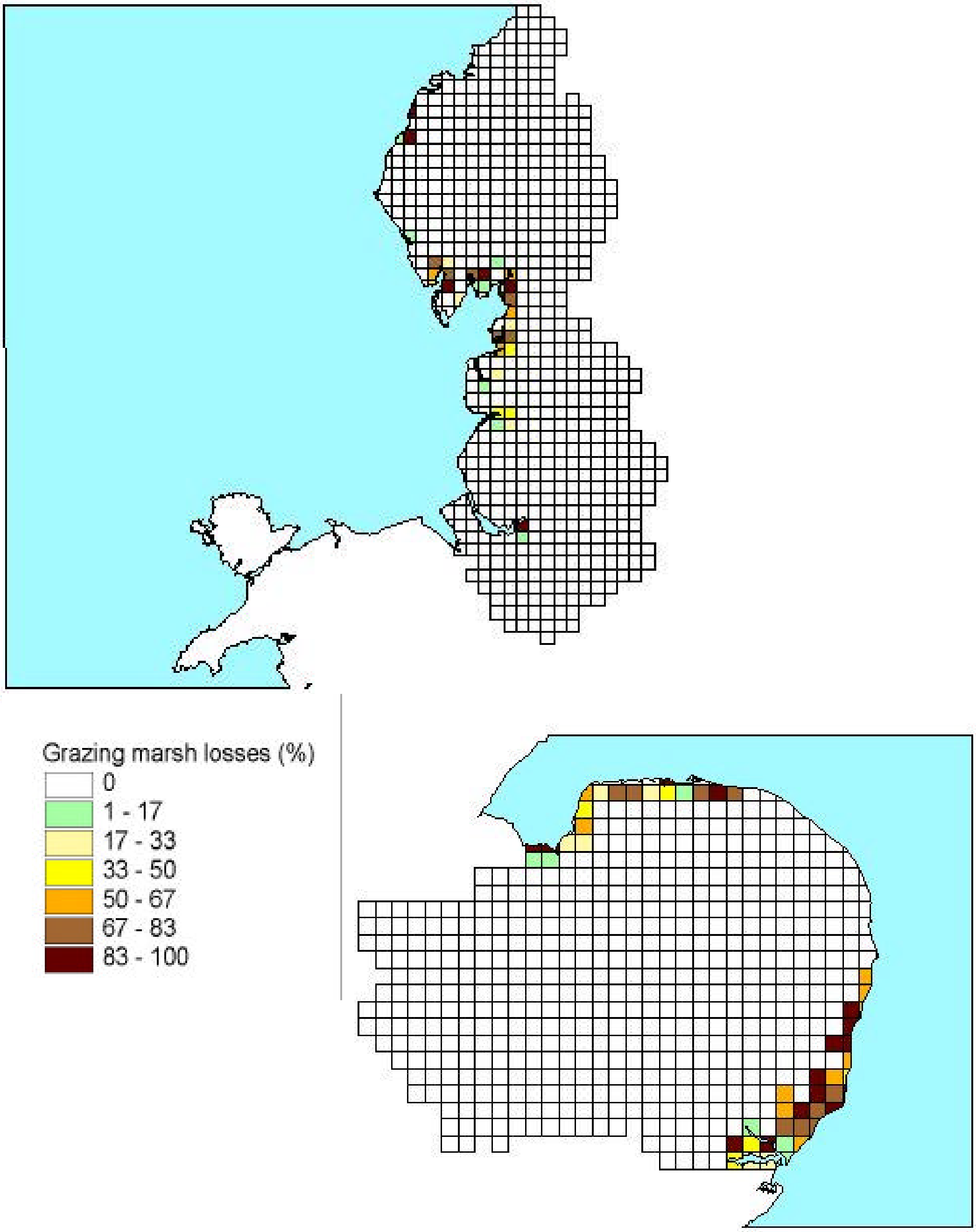


Figure 5.18: Losses of coastal grazing marsh under the Global Sustainability socio-economic storyline.

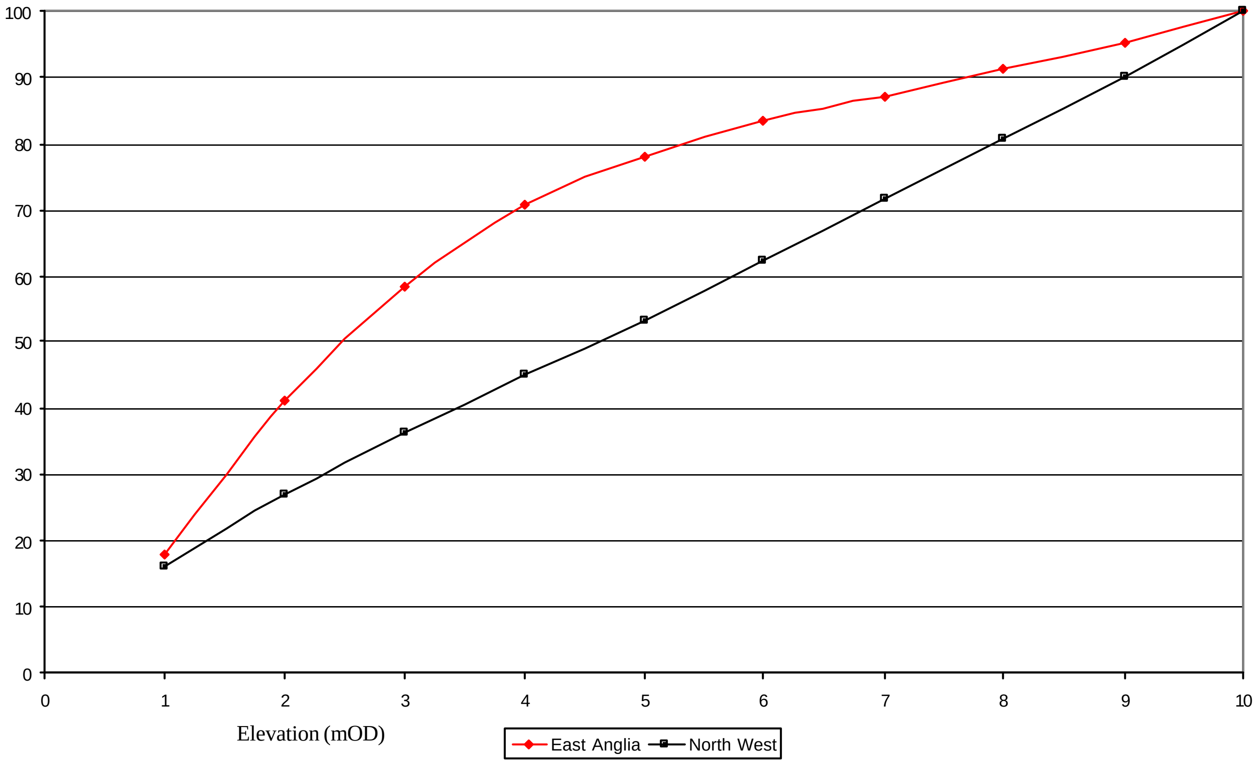


Figure 5.19: Cumulative percentage of land elevations within the coastal zone (below 10 m O.D.) of East Anglia and the North West.