Climatic Change (2008) 90:31–55
DOI 10.1007/s10584-008-9449-2

Regional impact assessment of flooding under future climate and socio-economic scenarios for East Anglia and North West England

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Received: 30 May 2006 / Accepted: 10 June 2008 / Published online: 29 July 2008

Abstract Interactive tools developed within the RegIS project for assessing the impacts of flooding provide information to support flood management policies and analyse the performance of possible adaptation activities to climate change. This paper describes the methodologies used in the development of these tools including tidal and fluvial flooding processes with different levels of climate pressures, represented by changes in sea level and peak river flows. Potential impacts of climate change for East Anglia and North West England are explored to the 2050s using four socio-economic scenarios to represent plausible futures. This includes changes in urban land use as well as adaptive responses to flooding comprising dike upgrade and realignment options. The results indicate that future climate will increase flood risk in both regions. East Anglia is more vulnerable to climate change than North West England at the present level of protection, especially in the extensive coastal lowlands of the Fens and Broads because of the combined effects of sea-level rise and increased fluvial flows. Although the present adaptive policy of upgrading defences in East Anglia will reduce the impacts of flooding, this policy is not effective in the case of the more extreme climate change scenarios by 2050s. In this case, more extensive adaptation would be required.

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1 Introduction

Since 1945, significant flood events have occurred in Britain such as the coastal flood in 1953, the river floods of 1947, 1998, 2000, 2001 and most recently the extreme 2004 flash flood at Boscastle leading to substantial economic damages. Under climate change scenarios, the risk of flooding will increase significantly (Thorne et al. 2006). Sea levels have risen around the British coast during the twentieth century and this rise is expected to accelerate during the twenty-first century increasing the risk of flooding (Hulme et al. 2002)—other marine drivers of flooding may also intensify during the twenty-first century (Lowe and Gregory 2005). Peak river flows may also increase as a result of intensified winter precipitation and consequently cause river flooding (Hulme et al. 2002; Reynard et al. 2001). These changes may be most adverse in coastal lowlands where peak river flows interact adversely with rising sea levels (Nicholls and Wilson 2001). A regional impact assessment of the costs of climate change will support the adaptation process at these scales, concerning issues such as raising defences versus land use planning, and the interaction of these responses with other regional issues, such as fluvial and coastal habitats (Richards et al. 2008).

The Foresight flood and coastal defence project developed an integrated analysis of drivers, including climate and socio-economic changes, and impacts of flood risk in the UK (Evans et al. 2004a, b). The project showed that the future flood risks under the existing approaches and expenditure on flood and coastal management will increase to an unacceptable level. This implies that there is a need for significant additional adaptive measures in order to face the challenges caused by future climate. The Foresight study of future flooding and coastal defence suggested that a portfolio of adaptation approaches would be most effective in managing this challenge (Evans et al. 2004b). However, identification, selection and implementation of such portfolios is another challenge.

Phase 1 of the Regional Impact Study (RegIS; Nicholls and Wilson 2001) explored the regional flood risk and associated impacts within the GIS environment. It was developed through an integrated methodology including agriculture, hydrology, biodiversity and coastal sectors but it was not possible to fully integrate with the cross-sectoral impacts (Holman et al. 2005a, b). Phase 2 of the RegIS project builds on this to develop a Regional Impact Simulator that is designed for use by non-scientists such as planners and other stakeholders (Holman et al. 2008).

This paper aims to describe the flood metamodel developed within the RegIS interface to evaluate regional impacts of flooding by focusing on the flood risk drivers, flood risk analysis, economic impact of flooding and the role of adaptation. The paper also explores the results associated with some future scenario combinations to demonstrate what the RegIS interface is able to offer to the user. The flood metamodel is developed to provide computationally simpler modelling techniques compared with most existing models for allowing rapid simulation and interactive engagement within the RegIS interface. The flood metamodel explores flooding due to sea-level rise and increased peak flows in rivers for the 2020s and 2050s time slices in conjunction with future socio-economic scenarios. It estimates the areas at risk of flooding, the economic damages and the number of people affected by flooding in East Anglia and North West England across these scenarios. It also explores the impacts of the adaptive measures of upgrading flood defences and managed realignments.

The regional impact assessment of flooding used in this study is developed around the 'Drivers-Pressure-State-Impact-Response' (DPSIR) framework to build consistent structure of linked assessments (Holman et al. 2005a, b). This framework was first proposed by Rapport and Friend (1979) and then developed further by the Organization for Economic Co-operation and Development (1993). The DPSIR framework identifies the causes of environmental change such as greenhouse gas emission and socio-economic change. Then, it quantifies the pressure variables, e.g. sea level, standard of protection, population, etc. The state variables represent the sensitivity of the system to pressure variables, such as river flows and landuse; the impacts of the state variables on society and environment determine the adaptive responses that aim to minimise negative impacts and/or maximise positive impacts.

2 Study areas

East Anglia and the North West of England (Fig. 1) were selected for investigation because they have contrasting characteristics in terms of climate, topography, economic activities and urbanisation, which allows diverse explorations of the regional impact assessment for future climate and socio-economic scenarios (Holman et al. 2005a).

East Anglia has a relatively dry climate with average annual rainfall 550–750 mm. It is mainly low-lying with low relief with many areas near or even below sea level. There are low levels of urbanisation and significant agricultural land use especially for arable farming. In contrast, the North West region of England has a wetter climate with average annual rainfall of 650–3,200 mm. High lands dominate most of the region with some low areas in the east and the south of the region. The North West region has various types of agricultural farming and has a high level of urbanisation especially in the south.

3 Overview of methodologies

A series of impact/adaptation models are integrated within the RegIS interface under the name of the flood metamodel to allow assessment of changes to coastal and river flooding and the related flood plain ecosystems due to climate change, as well as the possible influence of future socio-economic change. The frequency of flooding is used in the flood analysis to evaluate the impacts of flooding. The framework of the flood metamodel in Fig. 2 illustrates the pressure variables that represent future climate and socio-economic scenarios and also indicates the relationship with the high river flow metamodel which provides an estimate of the change in peak flow. The framework shows various outputs that are communicated either directly to the end user or to the biodiversity and the agriculture metamodels. More details on all these elements and methodologies as implemented are described in the following sections.

3.1 Socio-economic scenarios

Future socio-economic changes are expected to have a major effect upon the vulnerability to climate change (Holman et al. 2005b). The RegIS socio-economic

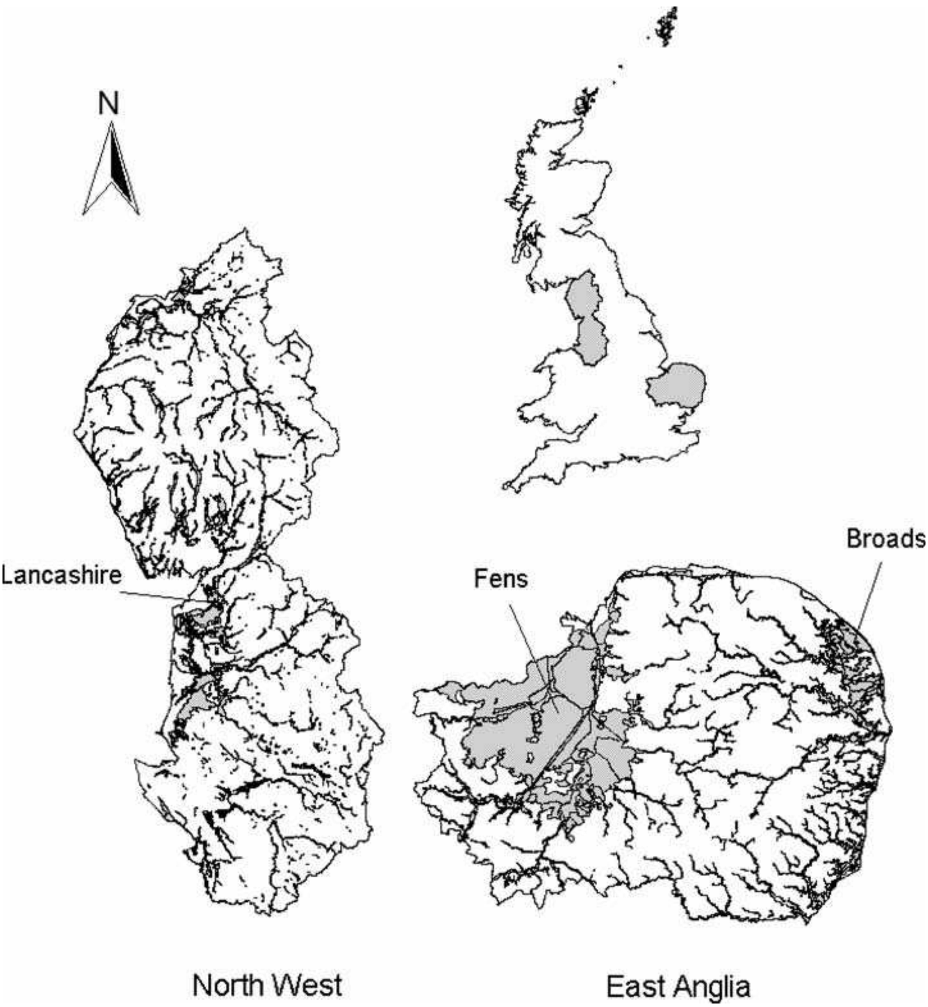


Fig. 1 East Anglia and North West: general location and indicative floodplains

scenarios are regionalized versions of the four UK Climate Impacts Programme (UKCIP) socio-economic scenarios (UKCIP 2001). The UKCIP socio-economic scenarios were derived from the A1, A2, B1 and B2 scenarios developed by the Intergovernmental Panel on Climate Change (IPCC 2000). The four RegIS socio-economic scenarios are: Regional Stewardship (RS), Global Market (GM), Regional Enterprise (RE) and Global Sustainability (GS; Shackley and Wood 2001; Shackley and Deanwood 2003). The storylines of these scenarios in respect to environment, economy and society, informed by regional trends and government projections, are used to develop a number of quantitative parameters (Table 1), which are used in the flood metamodel to estimate the economic impact of flooding on future urban patterns across both regions.

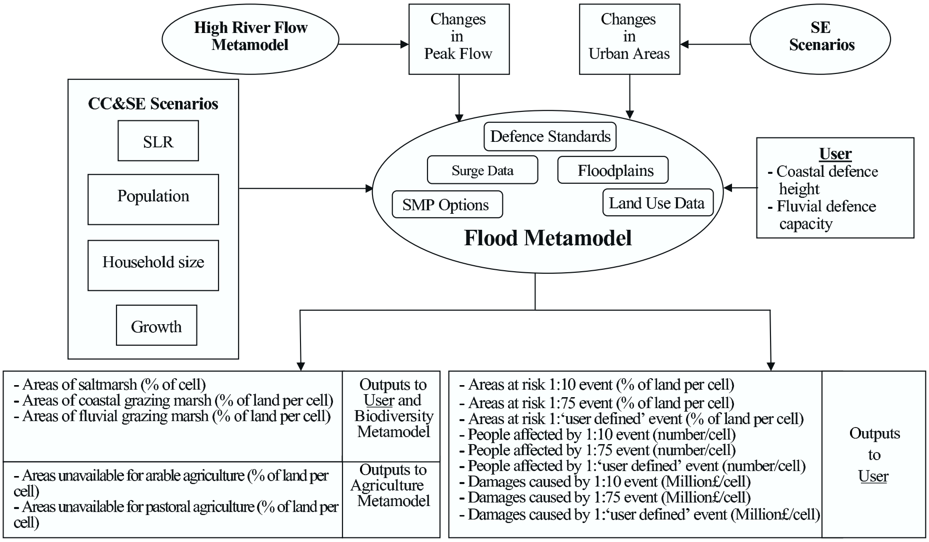


Fig. 2 Flood metamodel framework (*CC* climate change, *SE* socio-economic, *SLR* sea-level rise)

The Regional Stewardship scenario in both regions indicates that the lower level of economic growth limits the resources available for expensive measures in defending the coast and consequently managed realignment based on the concept of 'work with nature' will be preferred. The most vulnerable settlements in the floodplain are abandoned and their residents are relocated. The population will increase to 2.5 m in 2020s and then will decrease to 2.2 m by 2050s in East Anglia, while it will decrease to 6.5 m by 2050s in the North West. The household occupancy will increase in both regions reducing pressures on urban developments.

Table 1 Summary of the parameters developed for the socio-economic scenarios

Region	Parameter	Time periods	GM	RE	GS	RS
East Anglia	Population	2001	2,189,900	2,189,900	2,189,900	2,189,900
		2020s	2,513,600	2,513,600	2,513,600	2,513,600
		2050s	3,068,320	2,805,850	2,513,600	2,237,780
	Persons per household	2001	2.4	2.4	2.4	2.4
		2020s	2.0	1.7	2.2	3.0
		2050s	2.0	1.7	2.2	3.0
	Annual growth rate (%)		2.50	3.50	0.88	0.00
North West	Population	2001	6,767,000	6,767,000	6,767,000	6,767,000
		2020s	6,767,000	6,767,000	6,767,000	6,767,000
		2050s	7,338,570	7,067,630	6,767,000	6,459,940
	Persons per household	2001	2.4	2.4	2.4	2.4
		2020s	2.0	1.7	2.2	3.0
		2050s	2.0	1.7	2.2	3.0
	Annual growth rate (%)		1.50	2.50	0.88	0.0

The Global Sustainability scenario reflects a focus on sustainable technologies associated with low economic growth in both regions. The population will increase and stabilise at the 2020s projection in East Anglia, while it will stabilise at the current level in the North West. The household occupancy will stabilise at the 2020s projection in both regions leading to low pressures on developments especially in the North West. Strict planning controls will apply in coastal and floodplain areas, and a managed realignment policy is implemented as part of national/supranational strategy.

The Global Market scenario will lead to sustained growth within a global context. The population will increase and the household occupancy will fall in both regions, where intense development pressures will result in significant exploitation of environmental resources. The intense competition in a deregulated economy will encourage migration to seek work and disrupt community links to places and people. In East Anglia, the existing centers of economic activity such as Cambridge, Peterborough and Norwich will be the centers of urban expansion. In the North West, the north south axis will be the focus of much of the development centered on existing settlements, particularly linking the towns and cities spanning the M6 motorway.

The Regional Enterprise scenario suggests an increase in population and a decrease in household occupancy, which will lead to an increase in urban development in both regions. Planning controls will relax allowing the spread of properties throughout the regions including the coastal and floodplain areas. The economic growth in East Anglia will be higher than the UK average due to the proximity to South East and London (3.5% pa.), while it will be just below the UK average in the North West region (2.5% pa.).

3.2 Flood risk drivers

3.2.1 Sea-level rise and future climate scenarios

The UKCIP (2002) sea-level rise scenarios for 2020s and 2050s are used to determine the regional sea-level rise scenarios (Hulme et al. 2002). The UKCIP02 scenarios use the HadCM3 model results and additionally take into account the full range of scenarios of the IPCC TAR (Third Assessment Report), which considers most uncertainties across the range of climate models (Church et al. 2001). The values of relative sea-level rise that reflect sea-level rise in the North-West Atlantic are incorporated within the RegIS interface using a slider as shown in Table 2. The default value in the interface is taken directly from the HadCM3 results, which is not necessarily the mid-point of the range. The credible limits are defined by the IPCC TAR range and the extreme limits are given by the range over which the model will give meaningful results irrespective of the plausibility of such changes over the selected timescale. The uplift/subsidence of land is considered in the regional sea-level rise scenarios using results published by Shennan and Horton (2002). In East Anglia the subsidence rate ranges from −0.6 to −0.9 mm/year, while in the North West the uplift rate is +0.9 mm/year at the Scottish border, decreasing to subsidence at −0.2 mm/year in Merseyside.

3.2.2 Extreme river flows

The Catchment Descriptors method (Robson and Reed 1999) of the Flood Estimation Handbook is the centre of the High River Flows metamodel (HRF) that has

Table 2 Sea-level rise default, credible range and extreme limit values, for each of the climate change scenarios

Climate change scenario	Default value (cm)	Credible lower limit (cm)	Credible upper limit (cm)	Extreme lower limit (cm)	Extreme upper limit (cm)
Baseline	0	Not applicable	Not applicable	0	+100
2020s Low	+6	+2	+21	0	+100
2020s High	+7	+2	+21	0	+100
2050s Low	+14	+4	+45	0	+100
2050s High	+18	+5	+54	0	+100

been developed to estimate a flood index to be used by the Flood metamodel to investigate flood frequency. This method allows preliminary estimates of the median annual flood (QMED), which is the flood exceeded on average "every other year" (Robson and Reed 1999). QMED was simulated for the baseline, 2020s and 2050s time slices for all sub-catchments and catchments in East Anglia and North West England, using a national catchment boundary dataset, from the physical (e.g. area and soil types according to the Hydrology of Soil Types classification of Boorman et al. 1995) and climatological properties as defined in Bayliss (1999).

The Catchment Descriptors method uses Standard Average Annual Rainfall (SAAR) as the climatological descriptor. Climate change is expected to lead to seasonal changes in precipitation (Hulme et al. 2002) and an overall reduction in Average Annual Rainfall. If Average Annual Rainfall were used, according to Robson and Reed (1999), a reduction in future QMED would be predicted, which is contrary to most studies (e.g. Holman et al. 2005b; Arnell and Reynard 1996; Reynard et al. 2001; Prudhomme et al. 2003) which simulate an increase in high flows and flood quantiles. Because of the relatively uniform current seasonal distribution of rainfall in the UK, it has therefore been assumed that SAAR is a surrogate for the average winter half-year precipitation (October to March). Analysis of the dominant flooding period using Annual Maxima data showed 82% and 75% of floods occurring in the winter half-year in the North West and East Anglia regions, respectively. Assuming that floods are sensitive to the winter half-year precipitation is further supported by Bayliss and Jones (1993), Hess and Morris (1988) and Cunderlik and Burn (2002). Therefore, to estimate future QMED, SAAR was multiplied by the winter half-year change in precipitation for the scenario in question.

Urbanisation typically has its strongest effect on floods of short return period, such as the QMED (Robson and Reed 1999). Therefore, an adjustment accounting for the change in infiltration characteristics from rural to urbanised conditions according to the soil permeability was applied (Bayliss 1999; Robson and Reed 1999) for catchments with more than 2.5% of sealed surfaces derived from the urbanisation patterns within RegIS socio-economic scenarios. This adjustment describes the net effect of urbanisation if a typical degree of flood alleviation has taken place (Robson and Reed 1999) thereby assuming that similar flood amelioration continues in the future.

Although the Catchment Descriptors method is a recognised and nationally validated approach (Robson and Reed 1999), additional regional validation of the HRF was carried out for baseline conditions comparing the simulated with the 'measured' QMED. The latter was obtained according to the method of Robson and Reed (1999) from measured peak-over-threshold and Annual Maxima series. The geometric mean regression (Ricker 1973; Draper 1992) was used as both regression variables are subject to error inherent to the sampling and methods used. For 15 catchments in East Anglia and 39 catchments in the North West, the HRF results are generally within the 95% confidence intervals presented for the method, although QMED tends to be overestimated in East Anglia. The Catchment Descriptors method is a highly generalised model with very wide confidence intervals (Robson and Reed 1999); however, it is suitable for an integrated regional application for describing broad variations in QMED.

In order to validate the modified climatological descriptor analysing if future estimated changes in QMED are credible and realistic, estimated QMED was compared with the changes of the equivalent one in 2-year flood event of Prudhomme et al. (2003), although this study used several global climate models and did not consider future urbanisation changes. The validation was applied to four catchments in the North East, Midlands, Southeast, and Wales for the 2050s using the classic two-sample student t statistics. The estimates of QMED by the HRF are within the range of uncertainty of estimates using other climate scenarios and conceptual hydrological models. Additionally, Prudhomme et al. (2003) observed that catchments with greater increases in winter-half year precipitation show greater increases in the flood magnitude and a regional pattern showing upward trends over time of the median of changes of flood magnitude, which are both consistent with the HRF. Collectively these comparisons suggest that the HRF can be used for regional impact studies.

3.3 Flooding

The flood risk analysis is the core of the flood metamodel. It is based on analyzing the effect of climate change on the standard of protection for tidal and fluvial defences. As relative sea-level rises and river flow increases, the frequency of flooding will increase in the tidal and the fluvial floodplains respectively.

The flood metamodel uses the 2003 Indicative Floodplain Map (from the Environment Agency) to represent the maximum extent of flood hazard zones in both regions. The floodplain map includes the outlines for the 1:100 year fluvial floodplain and the 1:200 year tidal floodplain. Both floodplains are subdivided into 1×1 km impact zones. Consequently, one or more flood compartments might be located within each impact zone. If the flood compartment is defended it will be associated with the system of flood defences that protect the compartment. A flood defence can fail either by breaching or overtopping. The breaching mechanism is not considered in this study because it requires too much information about the hydraulic loads and the response of a flood defence. The overtopping mechanism is considered in the flood risk analysis through the use of standard of protection for each defence. The standard of protection is defined as an assessment of the return period at which the defence will be significantly overtopped (Hall et al. 2003). In reality, each flood impact zone may be protected by one or more defences and if one of these were to be overtopped, the impact zone would be partially or completely flooded. Within the flood metamodel, the defence with the lowest standard of protection is used to characterise the whole of the impact zone and if the flood frequency is greater than the standard of protection of that defence the whole of the impact zone is assumed to be flooded.

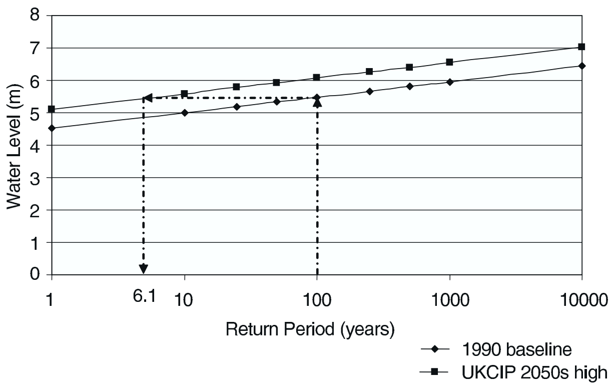
Table 3 Summary of datasets used within the flood metamodel

Data	Source
Floodplain	Indicative Floodplain Map 2003, Environment Agency
Flood defences	National Flood and Coastal Defence Database (NFCDD)
	National Flood Risk Assessment (NaFRA—East Anglia only)
Land use	CEH Land Cover Map 2000
Digital Terrain Model	Landform Panorama Digital Terrain Model (DTM)
Property locations	Address Layer-Ordnance Survey MasterMap
Habitat	English Nature GIS Digital Boundary Datasets (grazing marsh)
	CEH LandCover Map 2000 (saltmarsh)

The standard of protection values associated with the 1 km impact zones are extracted from the National Flood and Coastal Defence Database (NFCDD) and the National Flood Risk Assessment (NaFRA; see Table 3). However there are gaps in these databases, observed in both regions, where defences are not associated with standard of protection values. In such cases standard of protection values are assigned according to the dominant land use within the impact zone and the indicative standard of protection given in project appraisal guidance (FCDPAG3 1999).

The impact of sea-level rise on the standard of protection of tidal defences is estimated by increasing surge heights by the magnitude of the relative sea-level rise without the consideration of potential changes in surge frequency (Dixon and Tawn 1997; Lowe et al. 2001). Figure 3 is an example of this technique that shows the 1990 baseline and the effect of the extreme 2050s high sea-level rise scenario (i.e. 54 cm) in North Norforlk. As a consequence, the one in 100 year event (in 1990) becomes a one in 6.1 year event (in the 2050s). The effect of changing the fluvial flows on the standard of protection is determined by establishing a relationship between the change in flow, the defence standard and the change in defence standard using relevant UKCIP02 data. Figure 4a shows an example that illustrates the effect of an increase of 10% peak flow on the frequency of fluvial flooding, where the one in 100 year event becomes a one in 64 year event. In coastal lowlands, such as the Fens, the flood risk may potentially be exacerbated by the combined effects of sea-level rise and increased fluvial flows to create extreme impacts of climate change.

Fig. 3 An example of the flood probability curves in North Norfolk showing the 1990 baseline and the effect of the 2050s high sea-level rise scenario (i.e. 54 cm). The one in 100 year event is degraded to one in 6.1 year event



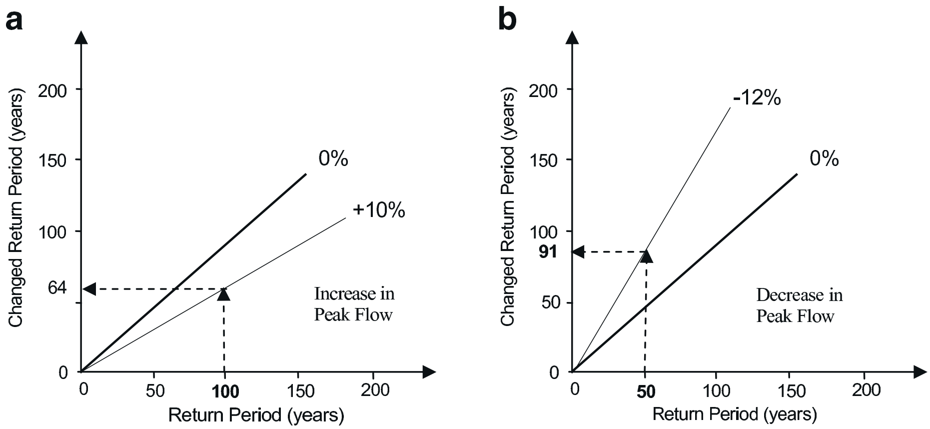


Fig. 4 Examples of how the fluvial model works: **a** The effect of an increase of 10% peak flow on the frequency of fluvial flooding. The one in 100 year event became a one in 64 year event. **b** How the model works in reverse in order to allow more flow capacity within the river channel by raising the height of river defences. The one in 50 standard of protection became one in 91

To analyse these combined effects, the effect of the peak flow is transformed into as effective water depth for a flood compartment; and then is added to the sea-level rise as shown in Fig. 3 resulting in a higher flood frequency.

3.4 Impacts of flooding

3.4.1 Economic impact

Rather than focus on average annual damages, which are computationally too slow to calculate in an interactive tool like RegIS, the economic assessment is developed to estimate the damages arising from a specific return-period flood event. The principle of damage assessment requires the identification of impact zones, flood depth, flood duration and properties affected by flooding. The flooding methodology described above is used to identify the probabilities of flooding within the impact zones. The flood depth at each 1 km grid between a defence and a floodplain boundary is estimated using the methodology described in Hall et al. (2003), which uses a statistical representation of typical flood depths experienced under a range of flood scenarios. For example, the flood depth for a 1 km grid that is located midway between a defence and a floodplain boundary and subject to flood event of one in 30 years is approximately 0.7 m, as shown in Fig. 5.

Flood duration has a major impact on the scale of flood damages (Penning-Rowsell et al. 2003); the longer the flood duration the greater the damages that can be expected. Two categories of flood duration are considered: less than and more than 12 h. Topography, as the major factor affecting water flow during a flood event, is used to determine which of the flood duration categories is applicable (steeper topography should result in a shorter flood duration). The Landform Panorama Digital Terrain Model (DTM) is used to classify the topography of both regions into two classes; a shallow class where flood duration is assumed to be more than 12 h and a steep class where flood duration is assumed to be less than 12 h.

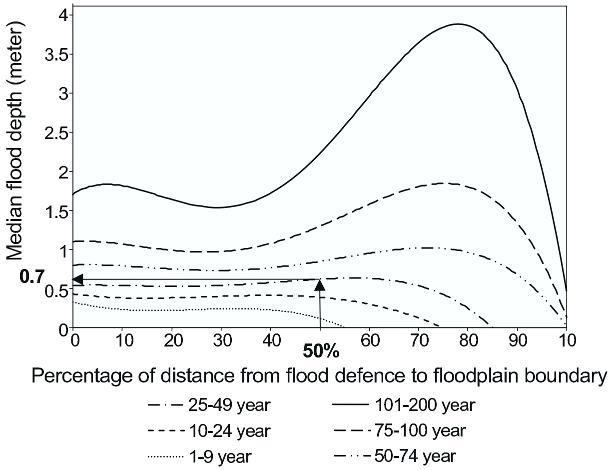


Fig. 5 Statistical data on flood depths across the floodplain for flood of varying return period (adapted from Hall et al. 2003)

The address layer of the Ordnance Survey MasterMap (Table 3) is used to identify the number of residential properties that are located within the flood impact zones. The number of properties at the same location is used to distinguish the ground-level properties from above ground-level properties as indicated in Table 4 (Entec UK Ltd. 2005) and the relative risk is rescaled to reflect the importance of vertical flat/apartment developments; the ground-level properties are considered to be at 100% risk, while the above ground-level properties are at 10% risk. The flood damage to the contents of all residential buildings is estimated using the May 2002 prices as reported by Penning-Rowsell et al. (2003). In addition, the average occupancy of households in each socio-economic scenario and for a specific flood event is used to calculate the number of people affected within the flood impact zones.

3.4.2 Impact on habitats

Climate change may cause a decline of valuable ecosystems. Saltmarshes may decline due to sea-level rise while they may gain due to managed realignment (Nicholls and Wilson 2001; Nicholls et al. 1999). Coastal grazing marsh is affected by tidal flooding

Table 4 Determining the number of properties at the ground-level based on the total number of properties at the same location (Entec UK Ltd. 2005)

Number of properties at location	Number of properties at 100% ground-level risk
1	1
2	1
3	1
4	1
5	2
6	2
7	2
8	2
9	3
10+	Total number of properties/4

and also threatened by the managed realignment of coastal defences. Fluvial grazing marsh can also be threatened by the increase in flood frequency and by the expansion of urban developments under some socio-economic scenarios. More details on the impacts of flooding on habitats can be found in Richards et al. (2008).

3.4.3 Impact on agriculture

The increase in flood frequency can affect the use of agricultural land. As the flood frequency increases the agricultural land use moves towards less intensive activities (Audsley et al. 2006; Berry et al. 2006). The impact of flooding on agriculture is analysed using thresholds of flood frequency. Floodplains with a future defence standard $\leq$1 in 10 years are assumed to be unsuitable for arable faming, while those with a future defence standard $\leq$1 in 1 year are assumed to be unsuitable for both arable and pastoral farming following Nicholls and Wilson (2001).

3.5 Adaptation responses for flooding

Adaptation refers to the responses to climate change that may be used to reduce negative impacts and also to maximise positive impacts that may arise as a result of climate change (Burton et al. 1998; Smit et al. 2001). In assessing the impacts of flooding, it is essential to examine the effectiveness of possible adaptation responses in order to demonstrate the seriousness of the damages that might happen as a result of increasing climate pressures and to inform public and policy makers about what can be done to reduce the risks of climate change. Two generic response strategies are selected for examination. First, upgrading flood defences by building and strengthening the structures of flood defences aiming to increase protection standards. Secondly, setting environmental objectives for managed realignment of flood defences, where land at risk of flooding will be given up to maintain and/or enhance the dynamic nature of ecosystems to meet preset environmental objectives (see Richards et al. 2008).

3.5.1 Upgrading flood defences

The adaptation response for the flood defences is represented within the flood metamodel at three distinct upgrade scenarios:

1) No upgrade: it is assumed that the flood defences are not upgraded from the baseline and the corresponding standard of protection will decrease over time as climate changes.
2) Existing upgrade: the current project appraisal guidance on the allowance for climate change is applied (FCDPAG3 1999): 6 mm/year for East Anglia and 4 mm/year for North West. This is implemented by increasing the height of the coastal flood defences by 300 mm in East Anglia and 200 mm in North West, and increasing the height of the fluvial flood defences to allow for a 20% increase in peak flows in both regions. These upgrades are all (reasonably) implemented progressively with 40% of defences upgraded by 2020s, targeting highly populated areas first, and 100% of defences upgraded by 2050s.

3) Enhanced upgrade: the current project appraisal guidance is enhanced over the 50 year timescale by raising the height of the coastal flood defences by 500 mm in East Anglia and by 400 mm in North West. The height of the fluvial flood defences is raised to allow a 30% increase in peak flows across both regions. Again, this is implemented progressively with 40% of defences upgraded by 2020s, by targeting highly populated areas first, up to 100% of defences upgraded by 2050s.

The 'Existing upgrade' scenario is the default option for flood defences under all socio-economic scenarios in the RegIS interface as it is the current practice. However, the options of 'No upgrade' and 'Enhanced upgrade' can be explored in the interface. The methodology used to calculate the decreased standard of protection values due to the effects of climate change in both tidal and fluvial floodplains is implemented in reverse to predict the increase in standard of protection values as a result of upgrading defences. For example, Fig. 4b demonstrates how the model works in reverse in the case of allowing more flow capacity within the river channel by raising the height of river defences.

3.5.2 Environmental objectives

The environmental objectives are directly linked to the future managed realignment policies. For example, in East Anglia and under the Regional Stewardship scenario there is an ambitious management realignment policy that aims to replace lost coastal habitats and to improve existing stocks. The implementation of such a policy reduces the estimated areas at risk of flooding as well as the economic damages.

Four distinct habitat creation options can be explored under the flood environmental objectives:

a) No Planned Creation: No attempt to create habitat. However, the likelihood of unplanned habitat creation is considered; for example, coastal grazing marsh is more likely to be converted into saltmarsh if tidal flooding becomes too frequent.
b) Maintain Existing Stocks: A systematic creation of habitat designed to maintain stocks
c) Double Existing Stocks: A systematic creation of habitat designed to double existing stocks (where possible):
d) Maximum Creation: A systematic creation of habitat designed to maximise possible stocks

The default setups of the four options are linked to the socio-economic scenarios as shown in Table 5. However, the other options can also be applied using the tools in the RegIS interface.

Table 5 The default setup of habitat creation options and socio-economic scenarios

	Socio-economic scenarios				
	Baseline	GM	RE	GS	RS
No planned creation		✓	✓		
Maintain existing stocks	✓				
Double existing stocks				✓	
Maximum creation					✓

3.6 RegIS interface

The flood metamodel within the Regional Impact Simulator allows impact assessment of flooding under any of the above described climate change and socio-economic scenarios for East Anglia and the North West regions (see Holman et al. 2008 for more details on the design of interface and the involvement of stakeholders). The methodologies developed in the flood metamodel are implemented at a 1 km × 1 km grid and the results are degraded to a 5 km × 5 km grid for visualisation purposes. The user can display the results as maps on the 5 km grid and as graphs where total estimates of the impacts for the region, counties and unitary authorities are provided. The interface, which is available for download from the UKCIP website, operates at three levels: (1) pre-defined scenario, (2) exploratory analysis and (3) influencing the impacts levels, see Fig. 6.

A) The predefined scenario level is designed to reflect future climate change and socio-economic scenarios using defaults and linkages that represent sea-level rise, river peak flow, habitat creation options and flood defence standards.
B) The exploratory analysis level allows the user to change the pressure variables through sliders in order to explore a wide range of scenario combinations. The 'sea-level rise' slider allows up to 1 m change. The 'flood event' slider allows the selection of any flood event up to the one in 1,000 year event. In addition, the

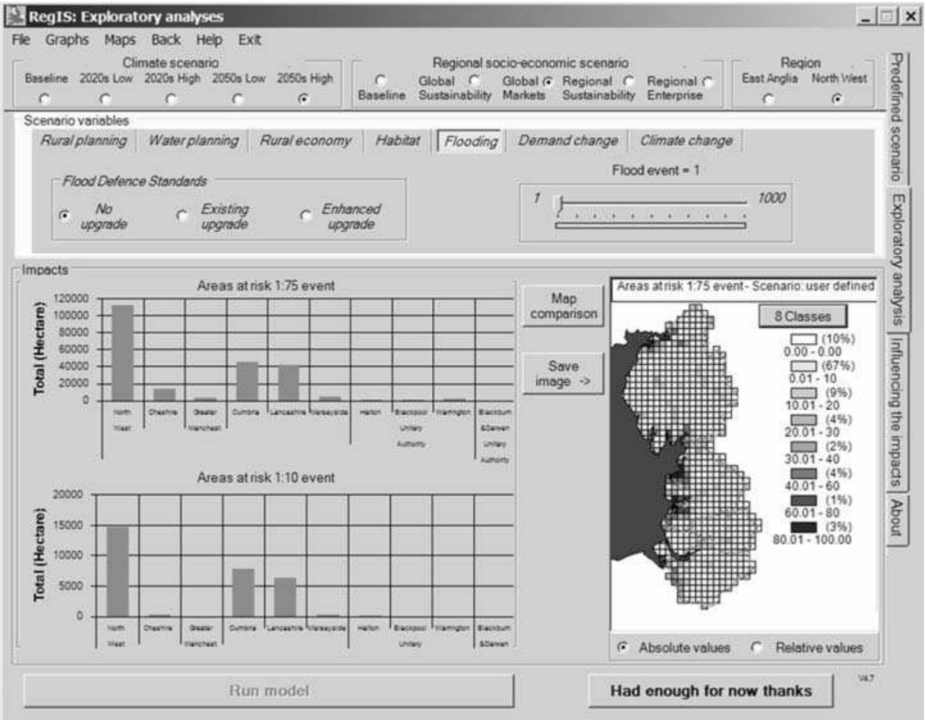


Fig. 6 Screenshot of the flood metamodel within the RegIS interface

impact of plausible adaptive responses such as upgrading defences and habitat creation options can be explored.

C) The ‘Influencing the impact’ level permits the user to interact further with the interface to assess the damages and people affected for a continuous range of adaptive responses related to upgrading defences. The ‘change in coastal defence height’ slider allows up to 1 m increase of defence height, while the ‘increase in flow capacity of fluvial defence’ slider allows up to 100% increase in flow. The ‘flood event’ slider provides the possibility to explore the impacts for any event up to one in 1,000 year event.

4 Results and discussion

As the tools in the RegIS interface allow the user to explore a large number of scenario combinations, only the results from selected scenario combinations are presented and discussed (Table 6). These examples demonstrate how the methodologies described in the previous sections can be used to assess possible flood impacts, including the adaptive responses of upgrading flood defences and managed realignment. The scenario combinations in Table 6 are selected at the 2050s time slice with various emission levels to reflect low, high and extreme levels of climate pressures by choosing various values of Sea-Level Rise (SLR), Temperature (T), Winter Precipitation (WP) and Summer Precipitation (SP). The Regional Stewardship and Global Market scenarios are examined because these two scenarios contain a range of contrasting aspects that characterise future socio-economic scenarios with respect to environment, economy and society. Building on Section 3.1, the Regional Stewardship storylines foresee a decrease in urban development, due to the increase in the household occupancy (Table 1), associated with strict planning controls in the floodplains and the coastal zones, and also a migration out of urban into rural areas in both East Anglia and North West. The storylines also suggest a large scale of managed realignment in East Anglia where low urbanised areas will be abandoned to allow significant habitat creation. This is not seen to happen at the same scale in the North West region due to the more limited suitable space available. On the contrary, the Global Market scenario pursues an intensive urban development throughout both regions including floodplains and coastal zones and there would be a little interest in managed realignment. Although the selected scenarios have

Table 6 Climate change and socio-economic scenario combinations presented in this study

Climate scenario	Socio-economic scenario	Region applied	SLR (cm)	*T* (°C)	WP (%)	SP (%)
2050s Low$^{(1)}$	GM&RS	EA	14	+1.5	+5	−11
2050s High$^{(2)}$	GM&RS	EA	18	+2.3	+8	−18
2050s High$^{(3)}$	GM&RS	EA	54	+2.3	+8	−18
2050s High$^{(4)}$	GM&RS	EA & NW	54	+3.5	+21	−20
2050s Low$^{(5)}$	GM&RS	NW	14	+1.3	+5	−10
2050s High$^{(6)}$	GM&RS	NW	18	+2.1	+8	−16
2050s High$^{(7)}$	GM&RS	NW	54	+2.1	+8	−16

EA East Anglia, *NW* north west, *GM* global market, *RS* regional stewardship, *SLR* sea-level rise, *T* temperature, *WP* winter precipitation, *SP* summer precipitation various contrasting aspects, the defences will continue to be upgraded in both cases over time as a result of current policies.

Although climate change is expected to increase the extent and the frequency of flooding causing significant damages from high flood risk events, the damage estimates are also influenced by the future urban patterns within floodplains. The results presented in this section aim to highlight the effect of implementing the adaptive measures described in Section 3.5. Tables 7 and 8 summarise the impacts of flooding for eight scenario combinations with and without the adaptation responses at three flood events: one in 1 year, one in 10 year and one in 75 year events.

The impacts of possible future climate change assuming no adaptation is apparent in Table 7 where consistent increases in the areas at risk of flooding are observed in East Anglia at the three events examined. For example, the area at risk of flooding for the one in 10 year flood event will increase to 32% of the floodplains (i.e. 95,605 ha) under the 2050s High$^{(2)}$ + GM scenario and to 97% of the floodplains (i.e. 288,611 ha) under extreme climate pressures in the 2050s High$^{(4)}$ + GM scenario combination (see Table 7 and Fig. 7). At the high risk one in 75 year flood event, there will be systematic increases in areas at risk as climate pressures increase till the whole floodplains become at risk (e.g. 297,356 ha will be at risk from the 2050s High$^{(3)}$ + GM scenario).

In North West a threshold pattern (e.g. 10,054 and 21,418 ha under the one in 10 year event) can be observed as climate pressures increase (Table 7). This indicates that the increases in climate pressures are not affecting the areas at risk of flooding because the existing level of protection is high enough to cope with the increasing climate pressures. In the case of one in 75 year event (Fig. 8), the areas at risk will increase dramatically but some flood compartments of 2,267 ha will be able to cope with extreme climate pressures.

Considering existing levels of protection, the impact of future climate on the areas at risk of flooding that was described in the previous paragraphs and the fact that there are large lowlands in northern Norfolk such as the Fens where the flood risk may potentially be exacerbated by the combined effects of sea-level rise and increased fluvial flows, East Anglia can be considered more vulnerable to flooding than North West England.

Overall, while the results show a clear correlation between the increases in area at risk of flooding and the future climate pressures, the indicators of damage and number of people affected by flooding have different patterns. The extent of damage caused by flood events will be influenced by future economic growth and it could be approaching the figure of £9 billion for the one in 75 flood event in East Anglia under the 2050s High$^{(4)}$ + GM scenario. The number of people affected by flooding is influenced by the household occupancy. The highest figures will occur under the Regional Stewardship scenario where the household occupancy rises to 3 by the 2050s (as opposed to 2 by the 2050s under the Global Market scenario). Thus, the future evolution of society and economy will influence the impacts of flooding.

The adaptive responses of upgrading defences to existing project appraisal guidance and creating habitats through management realignment are expected to reduce the negative impacts of flooding. Both responses are assumed to be implemented where possible under the Regional Stewardship scenario to allow maximum creation of habitats. The Global Market future has no plans to create habitats, which means that only the effect of upgrading flood defences is reflected under this scenario.

Table 7 Summary of results without the adaptation measures of upgrading defences and habitat creation scenarios

Region	Scenarios	1 in 1 year event			1 in 10 year event			1 in 75 year event		
		Area at risk of flooding (ha)	Damage (£ million)	People affected	Area at risk of flooding (ha)	Damage (£ million)	People affected	Area at risk of flooding (ha)	Damage (£ million)	People affected
EA	Baseline	10,467	32	2,705	76,938	527	48,034	140,845	1,087	77,866
	2050s Low$^{(1)}$ + GM	11,620	163	4,158	89,038	2,176	51,592	295,328	7,260	132,314
	2050s Low$^{(1)}$ + RS	10,748	37	4,551	88,678	496	56,163	295,191	1,690	147,372
	2050s High$^{(2)}$ + GM	12,874	249	5,808	95,605	2,304	54,090	297,215	8,606	160,008
	2050s High$^{(2)}$ + RS	12,624	55	6,138	92,674	511	57,819	297,215	2,034	181,251
	2050s High$^{(3)}$ + GM	54,200	919	28,456	276,949	4,547	102,144	297,356	8,856	164,452
	2050s High$^{(3)}$ + RS	53,950	215	31,863	274,018	1,057	113,586	297,356	2,094	186,306
	2050s High$^{(4)}$ + GM	59,642	1,115	32,186	288,611	4,926	117,724	297,356	8,856	164,452
	2050s High$^{(4)}$ + RS	55,030	237	33,819	287,819	1,160	133,305	297,356	2,094	186,306
NW	Baseline	9,338	25	2,064	10,054	53	4,291	81,633	1,735	122,633
	2050s Low$^{(5)}$ + GM	9,338	54	1,850	10,054	118	3,918	103,934	6,253	182,770
	2050s Low$^{(5)}$ + RS	9,338	22	2,262	10,054	47	4,680	103,934	2,332	205,311
	2050s High$^{(6)}$ + GM	9,338	54	1,850	10,054	118	3,918	109,649	6,600	192,408
	2050s High$^{(6)}$ + RS	9,338	22	2,262	10,054	47	4,680	109,649	2,461	216,060
	2050s High$^{(7)}$ + GM	9,439	54	1,850	21,418	614	22,164	112,291	7,727	224,588
	2050s High$^{(7)}$ + RS	9,439	22	2,262	21,418	230	24,951	112,291	2,901	253,992
	2050s High$^{(4)}$ + GM	9,439	54	1,850	21,418	614	22,164	112,291	7,727	224,588
	2050s High$^{(4)}$ + RS	9,439	22	2,262	21,418	230	24,951	112,291	2,901	253,992

GM Global market, *RS* regional stewardship, *SLR* sea-level rise, *T* temperature, *WP* winter precipitation, *SP* summer precipitation.

$^{(1)}$(SLR = 14 cm, T = +1.5°C, WP = +5%, SP = −11%), $^{(2)}$(SLR = 18 cm, T = +2.3°C, WP = +8%, SP = −18%), $^{(3)}$(SLR = 54 cm, T = +2.3°C, WP = +8%, SP = −18%), $^{(4)}$(SLR = 54 cm, T = +3.5°C, WP = +21%, SP = −20%), $^{(5)}$(SLR = 14 cm, T = +1.3°C, WP = +5%, SP = −10%), $^{(6)}$(SLR = 18 cm, T = +2.1°C, WP = +8%, SP = −16%), $^{(7)}$(SLR = 54 cm, T = +2.1°C, WP = +8%, SP = −16%)

Table 8 Summary of results including the adaptation measures of upgrading defences and habitat creation scenarios

Region	Scenarios	1 in 1 year event			1 in 10 year event			1 in 75 year event		
		Area at risk of flooding (ha)	Damage (£ million)	People affected	Area at risk of flooding (ha)	Damage (£ million)	People affected	Area at risk of flooding (ha)	Damage (£ million)	People affected
EA	Baseline	10,467	32	2,705	76,938	527	48,034	140,845	1,087	77,866
	2050s Low$^{(1)}$ + GM	2,137	2	46	38,852	1,198	25,336	135,702	4,062	75,580
	2050s Low$^{(1)}$ + RS	1,818	0	0	37,006	252	25,113	119,665	918	81,972
	2050s High$^{(2)}$ + GM	8,037	47	996	46,788	1,415	30,232	141,838	4,288	79,630
	2050s High$^{(2)}$ + RS	4,667	0	0	38,429	279	28,182	123,760	975	86,907
	2050s High$^{(3)}$ + GM	9,490	130	3,530	113,160	2,067	49,132	291,869	8,370	155,606
	2050s High$^{(3)}$ + RS	5,717	20	2,907	90,499	420	48,183	267,286	1,950	173,931
	2050s High$^{(4)}$ + GM	12,608	185	4,562	116,751	2,223	52,520	297,256	8,856	164,452
	2050s High$^{(4)}$ + RS	11,171	41	4,929	100,875	497	56,352	273,058	2,065	183,876
NW	Baseline	9,338	25	2,064	10,054	53	4,291	81,633	1,735	122,633
	2050s Low$^{(5)}$ + GM	9,338	54	1,850	9,363	55	1,888	21,252	687	19,110
	2050s Low$^{(5)}$ + RS	5,927	16	1,713	5,951	16	1,755	15,778	249	20,853
	2050s High$^{(6)}$ + GM	9,338	54	1,850	9,363	55	1,888	21,471	687	19,114
	2050s High$^{(6)}$ + RS	5,927	16	1,713	5,951	16	1,755	15,862	249	20,853
	2050s High$^{(7)}$ + GM	9,338	54	1,850	10,876	66	2,208	52,164	4,372	125,550
	2050s High$^{(7)}$ + RS	5,927	16	1,713	7,047	19	2,043	33,835	1,636	141,609
	2050s High$^{(4)}$ + GM	9,338	54	1,850	10,876	66	2,208	52,164	4,372	125,550
	2050s High$^{(4)}$ + RS	5,927	16	1,713	7,047	19	2,043	33,835	1,636	141,609

GM Global market, *RS* regional stewardship, *SLR* sea-level rise, *T* temperature, *WP* winter precipitation, *SP* summer precipitation.

$^{(1)}$(SLR = 14 cm, T = +1.5°C, WP = +5%, SP = −11%), $^{(2)}$(SLR = 18 cm, T = +2.3°C, WP = +8%, SP = −18%), $^{(3)}$(SLR = 54 cm, T = +2.3°C, WP = +8%, SP = −18%), $^{(4)}$(SLR = 54 cm, T = +3.5°C, WP = +21%, SP = −20%), $^{(5)}$(SLR = 14 cm, T = +1.3°C, WP = +5%, SP = −10%), $^{(6)}$(SLR = 18 cm, T = +2.1°C, WP = +8%, SP = −16%), $^{(7)}$(SLR = 54 cm, T = +2.1°C, WP = +8%, SP = −16%)

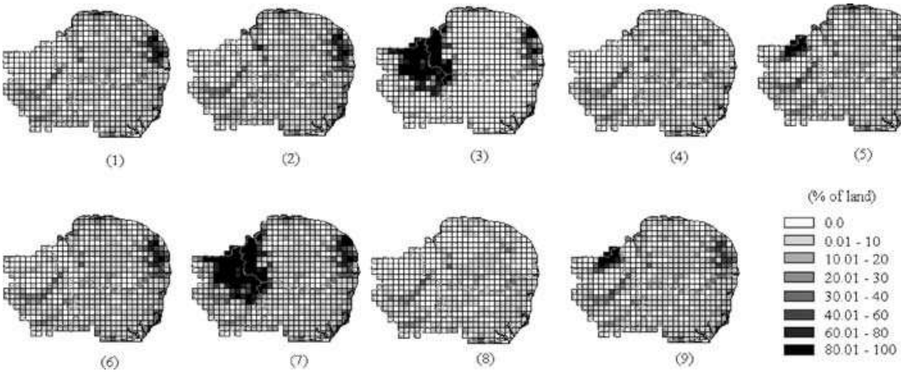


Fig. 7 Areas at risk of flooding one in 10 years in East Anglia under various scenarios: (*1*) Baseline, (*2*) 2050s High$^{(2)}$ + GM + No Adaptation, (*3*) 2050s High$^{(4)}$ + GM + No Adaptation, (*4*) 2050s High$^{(2)}$ + GM + Adaptation, (*5*) 2050s High$^{(4)}$ + GM + Adaptation, (*6*) 2050s High$^{(2)}$ + RS + No Adaptation, (*7*) 2050s High$^{(4)}$ + RS + No Adaptation, (*8*) 2050s High$^{(2)}$ + RS + Adaptation, (*9*) 2050s High$^{(4)}$ + RS + Adaptation

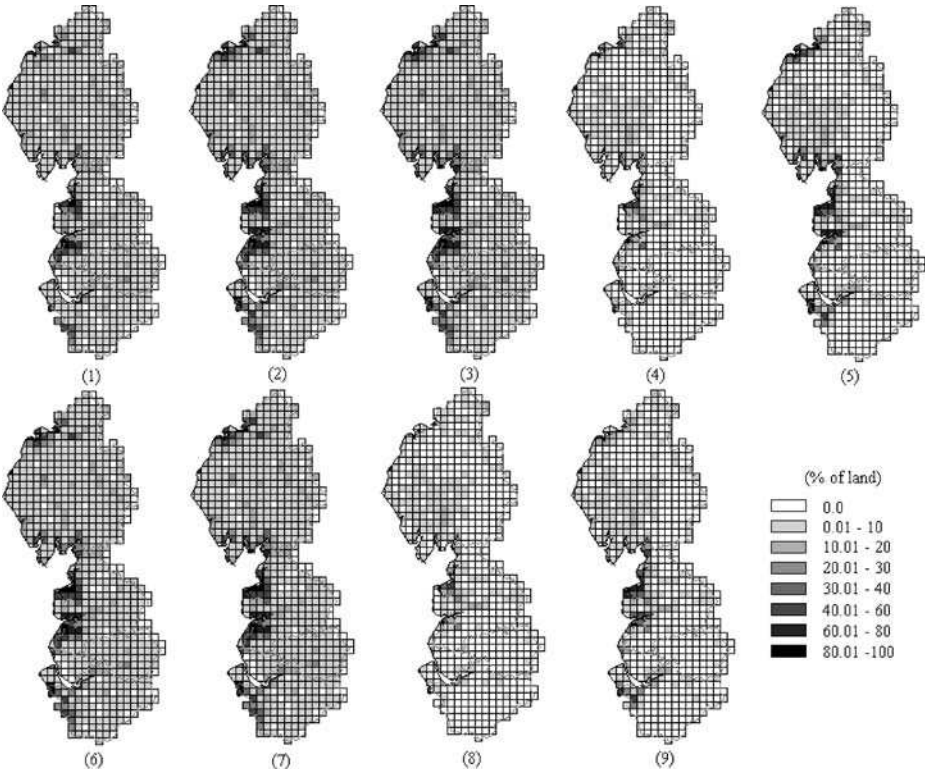


Fig. 8 Areas at risk of flooding one in 75 years in North West England under various scenarios: (*1*) baseline, (*2*) 2050s High$^{(6)}$ + GM + No Adaptation, (*3*) 2050s High$^{(4)}$ + GM + No Adaptation, (*4*) 2050s High$^{(6)}$ + GM + Adaptation, (*5*) 2050s High$^{(4)}$ + GM + Adaptation, (*6*) 2050s High$^{(6)}$ + RS + No Adaptation, (*7*) 2050s High$^{(4)}$ + RS + No Adaptation, (*8*) 2050s High$^{(6)}$ + RS + Adaptation, (*9*) 2050s High$^{(4)}$ + RS + Adaptation

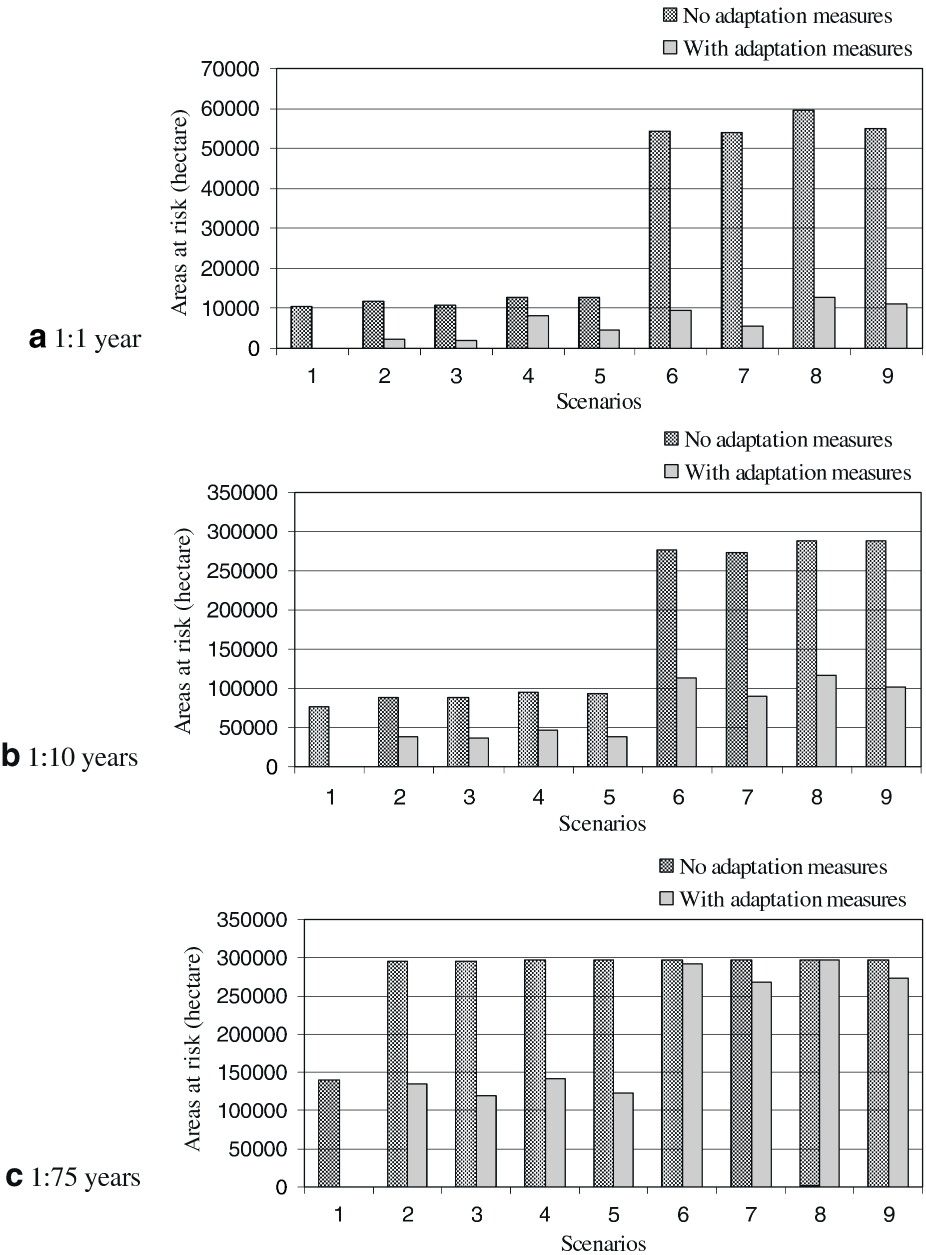


Fig. 9 Areas at risk of flooding in East Anglia under the following scenarios: (*1*) Baseline, (*2*) 2050s Low$^{(1)}$ + GM, (*3*) 2050s Low$^{(1)}$ + RS, (*4*) 2050s High$^{(2)}$ + GM, (*5*) 2050s High$^{(2)}$ + RS, (*6*) 2050s High$^{(3)}$ + GM, (*7*) 2050s High$^{(3)}$ + RS, (*8*) 2050s High$^{(4)}$ + GM, (*9*) 2050s High$^{(4)}$ + RS

Tables 7 and 8 allow the comparison between the impacts of climate change with and without the adaptive responses. The results show that adaptation in the North West is very effective for all the investigated flood events and under all scenarios.

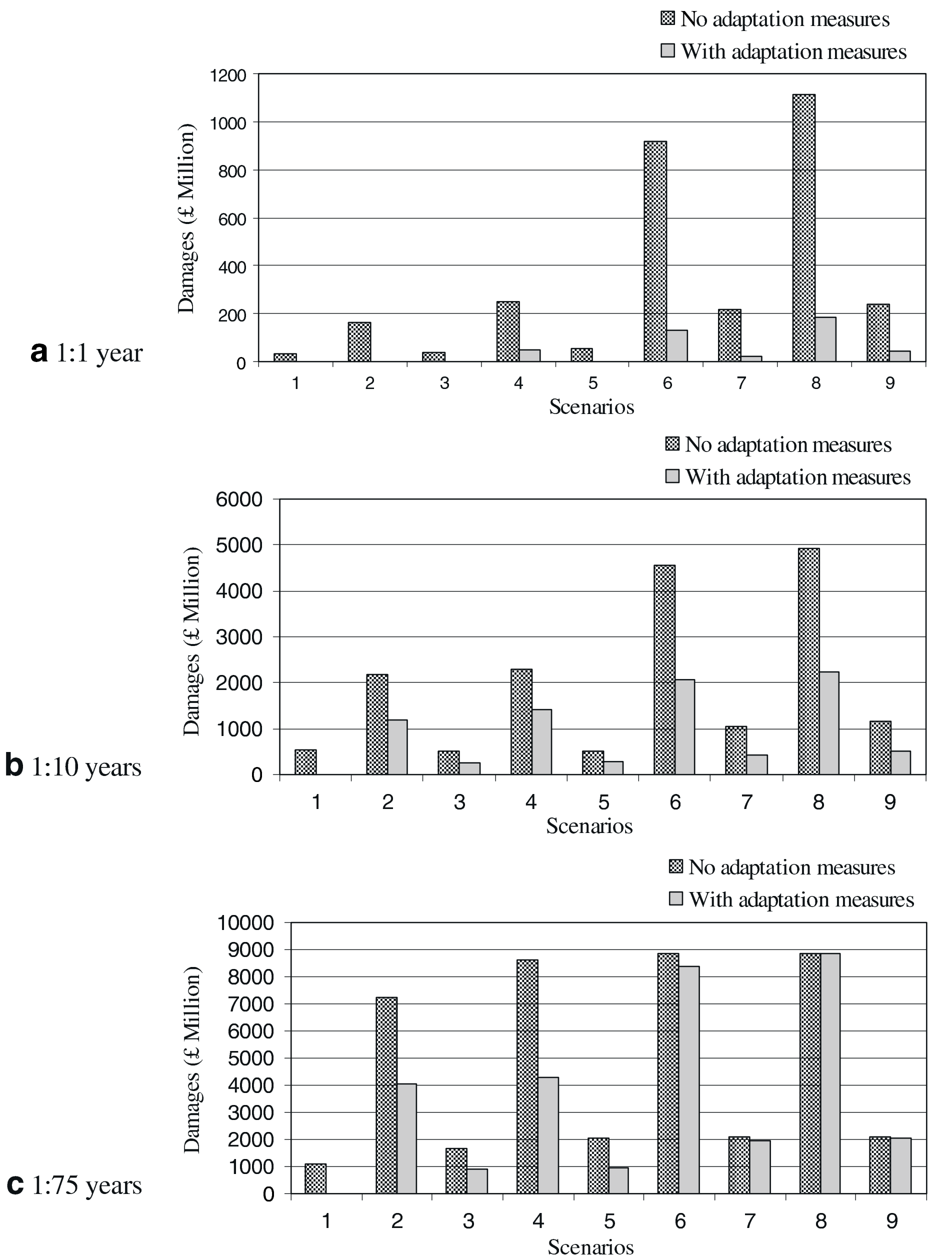


Fig. 10 Damages of flooding in East Anglia under the following scenarios: (*1*) Baseline, (*2*) 2050s Low$^{(1)}$ + GM, (*3*) 2050s Low$^{(1)}$ + RS, (*4*) 2050s High$^{(2)}$ + GM, (*5*) 2050s High$^{(2)}$ + RS, (*6*) 2050s High$^{(3)}$ + GM, (*7*) 2050s High$^{(3)}$ + RS, (*8*) 2050s High$^{(4)}$ + GM, (*9*) 2050s High$^{(4)}$ + RS

For example, the areas at risk of flooding and economic damages under the extreme 2050s High$^{(4)}$ + RS scenario will be less than those experienced at the baseline. The number of people affected by flooding will decrease too but it may remain above the baseline for the one in 75 year flood event because of the high figure of household occupancy under this scenario.

In East Anglia (Figs. 7, 9 and 10), the investigated adaptive measures are very effective under the default setup of the 2050s High climate for all investigated flood events. For example, for the one in 10 year event, the adaptation measures implemented under the 2050s High$^{(2)}$ + RS scenario will decrease the total areas at risk, economic damages and the number of people affected by flooding to become less than those experienced at the baseline. Equally, the total areas at risk and the number of people affected by flooding will decrease under the High$^{(2)}$ + GM scenario in similar way for the same event. The economic damages will also decline dramatically to £1.4 billion but it will stay above the baseline's figure because of the high economic growth foreseen under the Global Market scenario. As climate pressures increase towards the extreme credible levels under the 2050s High$^{(3)}$ and 2050s High$^{(4)}$ scenarios, the adaptive measures will stay effective for the one in 1 year and one in 10 year flood events, while this effect will start to diminish in the case of the high risk flood events such as one in 75 year event (Figs. 9 and 10). In this case, the current guidance for upgrading flood defences will not provide protection or reduce the impacts of such extreme future climates.

The impact of climate change on agriculture is evaluated by examining the areas at risk of flooding at ≤1 in 10 years and ≤1 in 1 year that correspond to the arable and pastoral land use respectively. The worst impact on agricultural sector will be in East Anglia, where 288,611 ha will not be available for arable farming and 59,642 ha will not be available for any agricultural activity under the 2050s High$^{(4)}$ + GM scenario. Much of these losses are concentrated in the Norfolk Broads. On the contrary, climate change has much less impact on agricultural activities in the North West. However, the existing plan for upgrading defences will benefit the agricultural sector significantly especially in East Anglia. For example, the area unsuitable for arable farming will decrease by 60% and the area unsuitable for any agricultural activity will decrease by 79% under the 2050s High$^{(4)}$ + GM scenario, see Table 8.

5 Conclusions and further work

The RegIS interface was developed to provide non-scientific users with interactive tools to extract information that support planning and policy development. These tools allow the examination of the impacts of flooding under future climate and socio-economic scenarios and the exploration of how the adaptive measures of upgrading defences and managed realignment could reduce these impacts. The climate scenarios representing increases in sea level and river peak flows at the 2020s and 2050s in conjunction with four socio-economic scenarios are available for exploring the impacts of flooding on three indicators: areas at risk, economic damages and number of people affected by flooding. This demonstrates how the RegIS interface brings together key interrelated factors relevant to flood risk analysis as well as the impacts of flooding. Moreover it can be used to explore the effectiveness of adaptive responses to flooding and to consider the development of environmental policies in relation to wider regional socio-economic changes.

Based on the discussion of some of the results, the key conclusions that have been drawn are:

- Simplified models could represent complex processes such as the impact assessment of flooding caused by future climate and socio-economic scenarios and consequently provide useful results for policy purposes.
- Future climate will increase flood risk in both regions if no adaptation measures are implemented. The East Anglian region is more vulnerable to climate change than North West England especially in the coastal lowlands such as the Fens, where the flood risk may potentially be exacerbated by the combined effects of sea-level rise and increased fluvial flows.
- The adaptation measures of upgrading defences and managed realignment have a significant capacity in reducing the flood risk and consequently the impacts of flooding, including economic damages and the effect on agriculture.
- Existing guidance for adaptation is sensible especially with the low to medium flood risk events. However, in the case of extreme climate conditions and the high risk one in 75 year flood event, the present plans for adaptation in East Anglia are insufficient to manage increasing risk and there would be a need for more ambitious measures to strengthen and raise defences and to sacrifice land in order to reduce the impacts of such events.
- Hence, adaptation requires long term dynamic planning alongside continuous monitoring of climate in order to make sure flood risks do not exceed allowances and social, economic and environmental balance is achieved.
- Socio-economic pressures and how the environment, economy and society will evolve in the future also have significant influence on the impact assessment of flooding.

During the development of the flood metamodel within the RegIS interface a number of issues were identified for future investigation and possible improvements. More efforts are required to improve the existing database on flood defences and to use better flood maps. In addition, as this study included the overtopping of flood defences only in the flood analysis, including the breaching mechanism would be a significant improvement in a future work. Although it is complex and computationally costly, economic damages caused by flooding can also be improved by including non-residential properties, including economic costs of displacing people, and estimating average annual damages instead of the damage associated with a specific flood event. Furthermore, the RegIS interface could be developed further by using a smaller grid with more sophisticated spatial tools to allow better visual interpretation of outputs. In this context, the GIS environment is seen to be the suitable platform for such future developments.

Acknowledgements This work was carried out as part of the RegIS2 project (CC0362) funded by the UK Department for Environment, Food and Rural Affairs. Catarina Henriques was partly subsidised by the Portuguese 'Fundação para a Ciência e a Tecnologia', funded by the European 'Fundo Social Europeu' and the National MCES.

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