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**Scenarios of future built environment for coastal risk assessment of climate change
using a GIS-based multi-criteria analysis**

M. Mokrech⁽¹⁾, R.J. Nicholls⁽²⁾, R. Dawson⁽³⁾

⁽¹⁾ Environmental Institute of Houston, University of Houston-Clear Lake, 2700 Bay
area Blvd, Houston, Texas 77058, USA.

Email: mokrech@uhcl.edu

⁽²⁾ School of Civil Engineering and the Environment and Tyndall Centre for Climate
Change Research, University of Southampton, Highfield, Southampton SO17 1BJ, UK.

Email: R.J.Nicholls@soton.ac.uk

⁽³⁾ School of Civil Engineering and Geosciences and Tyndall Centre for Climate Change
Research, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK.

Email: richard.dawson@newcastle.ac.uk

Corresponding author: M. Mokrech

Environmental Institute of Houston,

University of Houston-Clear Lake,

2700 Bay area Blvd,

Houston, Texas 77058,

USA

Tel. +1-281-283-3950

Email: mokrech@uhcl.edu

Abstract

Assessment of changing risks in the future often focus on climate change alone, and ignore other relevant drivers, such as socio-economic changes. If they are considered at all, expert judgment is often used to create scenarios and the underlying logic is not always apparent. This paper describes an algorithm-based method for developing quantitative future scenarios of the built environment in East Anglia within a main study area in Norfolk and Suffolk and a focus on coastal management unit sub-cell 3b. The four UK Foresight socio-economic storylines were inputs to the study: World Markets, Local Stewardship, Global Sustainability and National Enterprise. Based on estimated regional demand, the distributions of new residential and non-residential properties were calculated under all scenarios using a GIS-based multi-criteria analysis. The buildings are distributed across a large swath of East Anglia based on four attraction factors with different weightings to reflect the storylines. The factors are the existing settlements, transport networks, coastline and floodplain. The results show increases in the number of residential and non-residential properties within the coastal floodplain of sub-cell 3b under all socio-economic scenarios, especially under World Markets and National Enterprise. These increases may lead to a significant increase in flood risk and to a less extent in the erosion risk in the study site. More importantly, the multi-criteria method presented here demonstrates an algorithm-based approach that provides feasible and flexible tools for socio-economic scenarios development in the context of impact and risk assessment. Hence, the scenario assumptions are explicit, reproducible and easily adjustable, as required.

Keywords: built environment, socio-economic scenarios, multi-criteria analysis, flood risk, climate change, GIS

1. Introduction

Planning decisions will have implications for long term climate risks: buildings and infrastructure constructed today is likely to have a design life of 50+ years. On this timescale, projected changes in climate are expected to aggravate a range of risks, such as flooding and cliff erosion. Here, our interest is in the long term processes of change, motivated by the extended legacy of spatial planning policies and demand for new development and how they alter risk. It is these major decisions that we seek to inform through provision of risk information so as to avoid decisions with consequences that are undesirable in terms of future flood and erosion risks or ‘lock in’ development to undesirable patterns in the future.

Assessing future risks in the context of climate change requires information on how social and economic as well as climate conditions will develop in the future including the growth and distribution of population and the built environment. Because risk is a function of both hazard and impact it is necessary to investigate climate risks in the context of plausible scenarios of the future, and characterising trends in economic and environmental emphasis from global to national and sub-national domains. The development of diverse socio-economic scenarios is needed to expressing the uncertainty that might rise from attempting to predict a single future or using a static baseline, which is most often incorrect and could lead to costly mistakes and bad decisions (Nicholls *et al.* 2008; Shackley and Deanwood 2003). Such scenarios tend to be developed at the global or national scale and so a further step is to “downscale” them to the relevant spatial domain (Gaffin *et al.*, 2004). The IPCC Special Report on Emission Scenarios (SRES 2000) provided storylines of social, economic and

technological development that can be downscaled to project population and economic product at the national/sub-national scale. In this context, there is now a considerable literature on scenarios for impact assessment of climate change including environmental and socio-economic impact assessments (Berkhout *et al.* 2002; Carter *et al.* 2007; DTI 1999, DTI 2002; Shackley and Deanwood 2003; UK Climate Impacts Programme 2001).

Various urban growth theories and models have been developed over time carrying conflicting views in regards to the levels of complexity, order and dynamic they contain (Andersson *et al.* 2002; Allen and Lu 2003; Barredo *et al.* 2003; Zellner *et al.* 2008). However, few studies have investigated how the built environment might evolve in the future in the context of risk assessment of climate change. Some studies have applied socio-economic scenarios based on expert judgment (e.g. Holman *et al.* 2005), while others have produced scenarios of the built environment using intricate algorithm-based approaches such as the Regional Urban Growth (RUG) model (Fontaine and Rounsevell 2006) and the innovative method of Agent-Based Modelling (ABM), (Fontaine and Rounsevell 2009). A detailed review of the range of urban models is not the objective of this paper, but this has recently been covered by Haase and Schwarz (2009).

While the expert judgment method over simplifies the planning process, more sophisticated approaches such as ABM can be difficult to interpret because of the multiple algorithms that simulate interacting agents at the local, regional and national levels (Fontaine and Rounsevell 2009). This requires extensive investigation to identify and characterise the agents and their behaviour rules, but also requires substantial effort

to explore multiple planning scenarios. Whilst we recognise the value of more detailed approaches to support specific and detailed planning decisions, to facilitate broad scale flood and erosion risk analysis, a method to interpret global or national socio-economic scenarios is required that is:

- Quick to operationalise;
- Flexible enough to explore many planning scenarios;
- Accessible and easily interpreted by non-technical policy makers;
- Based on readily available and standard datasets;
- Provides spatial outputs at a broad scale; and
- Auditable and transparent.

This paper describes such an accessible/flexible algorithm-based model for predicting scenarios of future built environment using a GIS-based multi-criteria analysis to interpret and downscale global/national socio-economic scenarios to a regional scale. The influence of different socio-economic and climate scenarios on flood and erosion risk is quantified. Following this introduction, this paper introduces the study area and the climate and socio-economic drives in the region. The GIS-based method is described before presenting and discussing results and key findings.

2 Introduction to the case study site

The case study site is focused around a 72km length of coastline and its hinterland between Weybourne and Lowestoft on the east coast of England (Figure 1) covering an area of almost 2000 km². It constitutes a ‘coastal sub-cell’ (number 3b) in UK shoreline management planning (Leafe *et al.* 1998; DEFRA 2006). In the north are continuous soft and erodible cliffs along approximately 30 km between Weybourne and

Happisburgh in northeast Norfolk. Over the last century, this cliff was protected with groynes and seawalls encouraging more developments near the cliff, including in towns such as Cromer and Mundesley (Dickson *et al.* 2007): there are almost 500 properties within 100m of the cliff edge. However, the most recent Shoreline Management Plan (SMPs) proposes a significant reduction in protection and consequently greater cliff erosion (e.g., Dawson *et al.* 2009). The southern part of the site between Happisburgh and Great Yarmouth and Lowestoft includes extensive floodplains and an increasing risk of coastal flooding under climate change. The majority of the floodplain in this area is reclaimed marshland that has a low density of built environment. It is protected along the open coast by a system of dunes, groynes and seawalls, combined with periodic beach nourishment (Dawson *et al.* 2009). Currently almost 20,000 properties (over 3,000 of these are non-residential properties) are at risk of flooding in the study area. The floodplain covers a total area of 340 km² and much of this is premium agricultural land, whilst 35% of this area is currently registered as being environmentally sensitive (with SSSI, Ramsar, saltmarsh, national nature reserve designations).

The geographical extent of the study site was selected to explore possible spatial attractions at the sub-regional scale under future socio-economic scenarios and their implications for future erosion and flood risks (see Figure 4). It includes the entire sub-cell and its interior, including the major city of Norwich.

Figure 1. Map of the case study area, showing the sub-cell 3b boundaries, major settlements and the topography of the land.

2.1 Climate change

Climate change projections are a driver relating to the probability of flooding and coastal erosion through its influence on sea-level rise, storminess and precipitation changes. Rise in global mean sea level is a consequence of global warming. This rise will not be uniform but interacts with regional oceanic and meteorological processes and gravitation effects of land and ice masses to generate patterns of regional sea-level change (see Lowe *et al.* 2009). This will be compounded by isostatic subsidence in the south and east of Great Britain and result in East Anglia experiencing faster relative sea

rise which, coupled with storm surges, will heighten the risk of flooding during storms in the Norfolk coastal floodplain and increase the rate of cliff erosion. A ‘mid-range’ climate scenario based on UKCIP02 is followed in this paper, which is a 0.45-m rise in sea level by 2100. This includes a regional subsidence rate based on long-term geological observations of 0.7 mm yr⁻¹ (Shennan and Horton 2002). This scenario is consistent with the latest UK Climate Projections (Lowe *et al.* 2009), which estimate a range of 0.23-0.91 m for relative sea-level rise for this region by 2100.

2.2 Socio-economic change

Future socio-economic change has a major effect upon the vulnerability to climate change as it directly influences the distribution of population and associated resources at risk, and influences the costs and feasibility of possible responses to adverse impacts (Klein and Nicholls 1998). Built environment that is at risk of flooding or permanent loss due to coastal erosion is a significant contributor to climate risks. However, the number and distribution of new properties is subject to both demand and social preferences, which are mainly influenced by the socio-economic context.

For example, demand for new developments is strongly linked to economic growth, reflecting regional and national, and to some extent global trends. A successful regional economy will cause inward migration and consequently an increase in the demand for new development, placing pressure on the property market and local/regional authorities to ease planning controls in some areas that are at high risk such as floodplains or cliff tops. Moreover, prosperity is related to property occupancy (Mokrech *et al.* 2008) with greater financial comfort, property occupancy will drop consequently increasing

demand for space for new properties, and vice versa. Climate risks can be reduced through a number of measures (c.f. Evans *et al.* 2004b); however, society's capacity to fund and implement management options such as managed realignment and beach nourishment is mediated by socio-economic conditions.

The scenarios framework developed for the Office of Science and Technology (OST) Foresight Programme has been used as a basis to produce four socio-economic scenarios of the Anglian region for flood and erosion analysis of Sub-cell 3b. The OST Foresight Futures scenarios (Figure 2) examine alternative, but internally consistent, directions in which social, economic and technological changes may evolve over the coming decades in the UK (DTI 2002). The OST Foresight scenarios have been widely used in a range of studies to assess future changes, including climate change impacts and national scale assessment of flooding and coastal defence (Evans *et al.* 2004a; 2004b; Thorne *et al.* 2007). The scenarios allow the exploration of a set of partially viewable alternative futures that describe "possibility space" and hence the ultimate aim is to explore future trends and potential discontinuities to inform decision-making (Berkhout and Hertin 2002).

Figure 2. The four Foresight worlds, defined using axes of autonomy-interdependence and consumerism-community (DTI 2002).

A scenario corresponding to the regional spatial strategy was not the purpose of this work as we are interested here in exploring much longer term changes in risk. Therefore, we focused on four well established and internally consistent UK government scenarios. However, existing trends have a strong inertia that needs to be considered. According to the East of England Regional Housing Strategy (RHS) the population of East of England is expected to grow by 11.5% by 2021, with a corresponding increase in number of households by 18.5% by 2021 from the 2002 baseline (as household size is falling). These 2021 forecasts have been adopted and then diverged linearly to the 2080s for each socio-economic future scenario. Hence, all four futures see a growth in the number of properties on the baseline. However, a review of the (then current, but now superseded) plan suggests that a scenario in

between the Local Stewardship and Global Sustainability may have been most representative.

In brief, the Global Sustainability scenario proposes increases in population and household numbers and the new developments will be mostly confined to existing urban areas. Less new development on coasts and floodplains arises partly through more planning and also through smaller growth in the number of households. Floodplain occupancy is discouraged under this scenario.

In the Local Stewardship scenario, a conservationist ethic and lower demand for new development contributes to the continuing dominance of traditional housing (DTI 2002). Floodplain occupancy is kept stable in this scenario. The urbanisation of the countryside comes to a halt as planning controls are tightened (DTI 2002) and strong land-use control avoids flood prone areas.

The National Enterprise scenario has a large increase in population, households, urban areas, and second homes in the area. However, the increase will not be as high as that of the World Markets Scenario since there are lower levels of investment in housing (DTI 2002). As well as the issue of urban spread, the increase in the number of households may be exacerbated by a coastal attraction and people relocating in coastal regions from large urban areas like London. Under this scenario planning controls are relaxed and this will allow more buildings and more people to live in floodplains.

In the World Markets scenario, there will be a continued pressure to build more houses and these are attracted to coastal and floodplain locations. Consequently, significant developments would occur in all areas including the floodplain and cliff areas.

3. Quantifying change in the built environment

The main steps in the method are shown in Figure 3 and described in more detail in the following sections. It starts with the quantification of the numbers of new residential and non-residential properties over the 21st century in East Anglia. These proportional estimates are then applied to a smaller geographical domain (i.e. East Norfolk and parts of Suffolk) in order to reduce the computation demand to an acceptable level, but large enough to maintain the influence of attraction factors that affect the planning process as described in the storylines of the socio-economic scenarios. The influences of the attraction factors are quantified in the forms of weights, which are combined to calculate how the new properties are distributed spatially into postcode polygon areas. The distribution of properties will then be used to conduct flood and erosion risk assessments. The methodology has been implemented in a GIS.

Figure 3. The main steps in the methodology

(RPs: Residential Properties, NRPs: Non-Residential Properties)

3.1 Projections of regional growth

The first step towards the implementation of this methodology is to quantify the total number of new properties in the East Anglian region, both residential properties (RP) and non-residential properties (NRP), under each socio-economic scenario. Current trends and the storylines of socio-economic scenarios provided the basis to estimate most change rates in RP and NRP from the present baseline as described in detail in Nicholls *et al.* (2005), (Table 1). The change in the number of NRP is obtained by applying a correction factor to the change of RP based on expert judgement. This reduces relative growth of NRPs under Local Stewardship and increases growth under World Markets, which follows the storylines. The correction factor is a decrease and increase of 10% from the RP rate, which translates into an increase in NRP of +18%

and + 87%, respectively. NRPs under Global Sustainability and National Enterprise are assumed to follow RP trends.

Table 1. The percentage growth of RP and NRP, and the total numbers of new properties created under each socio-economic scenario in the study area by 2080s (Nicholls *et al.* 2005).

	Change in RP	NRP Correction	Change in NRP	Total no. of new RP	Total no. of new NRP
Local Stewardship	+28%	-10%	+18%	62607	4069
Global Sustainability	+44%	0%	+44%	98158	9939
National Enterprise	+61%	0%	+61%	136053	13785
World Markets	+77%	+10%	+87%	171790	19662

3.2 Attractors of new development

The distribution of new development is influenced by a number of factors. Our interest here was in the planning implications on climate risk, and so we selected two attraction factors relevant to the spatial strategy and general process of urbanisation: (1) existing settlements, (2) transport networks that are major drivers of new development. The other two attractors (3) the coastline and (4) floodplain were specifically chosen to explore the planning policies of interest here. The spatial properties of these attractors were extracted from nationally available mapping data as shown in Table 2. There is no limit to the number of factors that could be included, for example previously developed, or brownfield, land. However, in this example we have kept attraction factors to a minimum to facilitate the interpretation of results.

Table 2. Summary of spatial datasets - OS: Ordnance Survey.

Data	Source
Indicative Floodplain Map 2003: tidal and fluvial	Environment Agency
National Property Database (NPD)	Environment Agency
Transport data: A Roads	OS Meridian data
Coastline	Extracted from OS Meridian data
Inland water layer	OS Meridian data
Major settlement layer	Digitized from OS Meridian data
Postcode polygon layer	OS address-point data

Figure 4 shows the distribution of the four attraction factors in the case study area. In line with current planning policy, the Indicative Floodplain Map is used to represent the flood hazard zones, and includes the outlines for the 1:100 year fluvial floodplain and the 1:200 year tidal floodplain. The National Property Database is used to identify the location of existing RPs and NRPs. This database also provides information on the business type of the NRP and enables the corresponding depth-damage relationship to be extracted from the Multi-Coloured Manual (MCM) (Penning-Rowsell *et al.* 2005) which is used in the flood risk analysis described in Section 4.

Figure 4. The location of the four attraction factors in the study area and the postcode base map.

3.3 Define weights for attraction factors

Some key variables, such as changes in employment, population, housing density are quantified in the scenario documentation. However, not all the necessary variables for a climate risk analysis have been quantified – particularly those related to locational preferences. Therefore, a quantified estimate was made by interpreting the qualitative scenario description, of the strength of each attraction factor in each scenario and the effect it would have on the distribution of people and employment in the future. This parameterisation was achieved based on expert judgment and a consensus between

modellers over the interpretation of the socio-economic storylines. While not done here, a more consultative process with a range of stakeholders is possible.

The first stage, summarised in Table 3, shows the relative importance of the four attraction factors in each socio-economic scenario. The relative importance is represented by a categorical scale of --, -, 0, +, and ++. The negative side of the scale indicates less importance, while the positive side indicates more importance of the attraction factor.

Table 3. Summary of the attraction factors under the socio-economic scenarios.

	Existing Settlements	Transport Networks	Coast	Floodplains
Local Stewardship	--	-	-	--
Global Sustainability	+	0	+	-
National Enterprise	0	0	+	+
World Markets	0	+	++	++

The category assigned to each factor in each scenario is inferred directly from statements in the socio-economic scenario description (DTI 2002; Evans *et al.* 2004a).

For example “*Demand for development in flood prone areas remains, with development often driven by higher income groups*” from the World Markets scenario are quite different to the Local Sustainability scenario: “*Strong regulation and enforcement prevents new development in floodplains*”. The pattern of urbanisation under the Local Stewardship scenario therefore tends to avoid both floodplains and existing settlements and move away from the coast and transport networks. This contrasts to many aspects of the World Markets scenario, where urban developments will expand across much of the countryside, floodplain and the coastal zone, with a corresponding desire to be close

to transport networks for easy commuting. Meanwhile, the Global Sustainability governance structure lends itself to stronger planning regulation which is parameterised in the model in terms of a reduction in permitted developments in the floodplain. Conversely, the utility of land use planning in the World Markets scenario is reduced by a more laissez-faire attitude to governance.

3.4 Spatial allocation of new development

It has been assumed that there is no spatial correlation between the new RP and NRP, which could influence the spatial distribution of the properties. Therefore, the single objective multi-criteria decision making technique (Eastman *et al.* 1993) is implemented in order to determine the locations of both RP and NRP. This technique is based on combining the criteria in order to produce a single quota map, which is used to extract the number of new properties in each postcode polygon. The criteria are split into two types, constraints and factors, which are defined as follows:

- *Constraints*: used to exclude some areas from the allocation of new properties by applying constraint mapping using Boolean algebra. For example, inland water bodies and developed land are excluded by giving them a zero code (0) and areas open for consideration are coded with one (1). This binary coded map is intersected with the postcode polygon map to leave only developable land.
- *Attraction factors*: enhance or detract from the suitability of postcode polygons to accommodate new properties. The four factors defined in Table 3 are used to influence the distribution of RP and NRP.

The decision rule is structured to quantify the single quota score (S) of new properties (*i.e.* RP or NRP) for each postcode polygon. This is achieved by using the weighted linear combination standardised by the area of postcode polygons and multiplied by the product of the constraints:

$$S = ((\sum W_i X_i) A_{ii} / \sum A_{ii}) \times \prod c_j \quad (1)$$

where W_i is the weight of factor i , X_i the criterion score of factor i , A_{ii} is the area of postcode polygon ii , and c_j is the criterion score (0/1) of constraint j and $\prod$ is product.

A weighted combination has been used to evaluate the attractiveness of each postcode polygon for new development based upon multiple criteria (Malczewski 2006) rather than use a spatial interaction, or more complex, predictive model.

The criterion scores are quantified using the proximity of the postcode polygons to the factors. Standardisation of the criteria is needed before combination in Equation 1 as they represent different entities (Carver 1991; Voogd 1983). The centre of each postcode polygon was used to calculate the proximity to major settlements, roads and coastline and then equation 2 is applied in order to standardise the outputs, using the minimum and maximum values as scaling points of the factor scores, and to rescale the final scores. Thus, the closer the polygon to an attraction factor (*e.g.* coastline), the higher the criterion score will be.

$$X_i = 1 - [(D_i - D_{min}) / (D_{max} - D_{min})] \quad (2)$$

where D_i is the proximity of a factor i , D_{min} the minimum value of proximity of a factor i and D_{max} the maximum value of proximity of a factor i . In the case of the Floodplain Attraction Factor, any postcode polygon or portion of a postcode polygon not within the floodplain is assigned a value of $W_i=1$. Six general distance-attraction functions have been identified by Hagoort *et al.* (2008). However, the process of selecting and parameterising the most appropriate function for each attraction factor under each socio-economic scenario would require expert elicitation of many more variables. Mindful of the modelling requirements set out in Section 1 we used only a linear distance-attraction function across all scenarios, which also facilitates interpretation of the results.

It is clear that the standardisation process has an important role in quantifying the criterion score and the scaling points deserve closer attention (Harker and Vargas 1987; Saaty 2000). The qualitative scores in Table 3 are quantified (Table 4) based on expert judgment and understanding of the storylines of socio-economic scenarios. Consensus values for weightings were achieved iteratively through reviewing the spatial outputs of the model until the results were spatially consistent with the socio-economic scenario storyline and the geography of the region.

Table 4. The quantification of criterion weights based on the level of importance.

--	-	0	+	++
Less important		equally important		More important
1/16	1/8	1	8	16

As postcode polygons have different sizes, the area of each postcode polygon is used as an additional factor in the decision rule in order to allocate the new properties proportionally by area. Once the weights and the factor scores are linearly combined, they are rescaled to 1 in order to produce the quota scores that reflect the number of the

new properties in each postcode polygon – as represented in equation 1. As the attractors here are applied at the postcode scale, it worth noting that at smaller scales different features can start to dominate, for example proximity to a railway station is desirable, but at very close distances they can have a negative attraction (Hagoort *et al.* 2008) – this type of complexity has not been considered in our modelling. On the other hand, the possibility of properties being abandoned on any substantial scale is not considered because of the underlying population growth and demand for development under all scenarios so only new properties are created (and properties remain occupied regardless of erosion and flood risk). The numbers of new NRP for each particular business type are scaled according to changes in the economy associated with each scenario (*e.g.* a greater proportion of the new NRP are financial services under the World Markets scenario). NRP are subsequently allocated to polygons with similar attributes leading to natural expansion trends in business types.

4. Flood risk analysis under different socio-economic scenarios

These socio-economic scenarios were used in a combined analysis of erosion and coastal flooding in Sub-cell 3b (Dawson *et al.* 2009). Here we focus on flood risk to illustrate the utility of the scenarios. The occurrence of a damaging flood on the coast is determined by highly variable marine processes (surge tides, extreme waves) and the (uncertain) responses of the coastal system. It is therefore impossible to predict coastal flooding and erosion in deterministic terms. Instead, a risk-based approach is adopted in which coastal behaviour is predicted, through time, in probabilistic terms and combined with assessment of impacts in order to quantify the ‘expected annual damage’. The primary metric for comparison of scenarios and management options here is economic

risk, but this can be supplemented by indicators of potential social or environmental impact if available. Flood risk is a combination of probability and consequences. For a system of m basic variables $\mathbf{x} := (x_1, \dots, x_m)$, which describe the loading and resistance of the system, the flood risk is (Dawson and Hall 2005):

$$R = \int f(\mathbf{x})D(\mathbf{x})d\mathbf{x} \quad (3)$$

where $f(\mathbf{x})$ is a joint probability density function, which describes how $\mathbf{x}$ may vary, and D may be expressed in terms of economic loss or some other quantified measurement of harm. In general, however, the amount of loss will depend upon the values of $\mathbf{x}$ when failure takes place, which also determines the mode of failure in systems with multiple failure modes.

The behaviour of beaches is a key determinant of coastal flood risk (Dawson *et al.* 2009). Beach morphology has a critical role in dissipating incident wave energy. Moreover, on natural coasts, the beach is the ‘defence’, while on artificially managed coasts the reliability of structures usually depends on beach volume as the level of the adjacent beach influences the likelihood of toe scour, the most critical failure mechanism for coastal structures (Thomas and Hall 1992). Sediments released from erosion may serve to increase beach volume and reduce the probability of structural failure on neighbouring coasts. Conversely, the existence of structures that disrupt sediment movement may starve down-drift beaches of much needed beach protection. Therefore, a precursor to the flood risk calculation was the simulation of the evolution of the foreshore and the soft cliffs, updrift of the Norfolk Broads floodplain, that supply significant quantities of sediment into the coastal system. In summary, the coastal flood risk analysis requires estimation of:

- (i) extreme loads, including a joint probability distribution function of water levels and wave heights;
- (ii) coastal dike system reliability as a function of the extreme loading conditions, properties of the coastal dikes, and shoreline position;
- (iii) dike breach characteristics;
- (iv) inundation depth and extent, due to wave overtopping or breaching of the dikes; and
- (v) damage to individual properties resulting from inundation to a given depth, calculated using standard depth-damage functions for different property types.

The results are influenced by three drivers: climate, shoreline management, and alteration of the built environment from socio-economic change (as considered here) (Dawson *et al.* 2009). Defence upgrade and beach nourishment are not considered in the analysis.

5. Results and Discussion

While Table 1 shows the total numbers of new properties created under each socio-economic scenario in the entire study area, Table 5 shows the numbers of both residential and non-residential properties located in the 2003 floodplain and the number of new properties within 400m of the cliff top.

The spatial distributions of new properties show consistency with the urbanisation policies and the attraction factors described in the storylines of socio-economic scenarios. For example, Figure 5 compares the spatial distributions of residential properties under the World Markets and the Local Stewardship scenarios. Under the World Markets scenario there is significant urban development across the entire region

including floodplain, coastal areas and countryside, while under the Local Stewardship scenario there are a limited number of developments in the floodplain, in the coastal areas and inside the existing major settlements. The same pattern can be observed for non-residential properties under these two scenarios (Figure 6).

Table 5. Summary of the new properties in the floodplain and within 400 m of the cliff top under the four socio-economic scenarios till the 2080s: *N*: number of properties, %: percentage increase of properties in floodplain or cliff top.

Scenario	Type of property	Local Stewardship		Global Sustainability		National Enterprise		World Markets	
		<i>N</i>	%	<i>N</i>	%	<i>N</i>	%	<i>N</i>	%
New properties in the coastal floodplain	RP	1,343	8	10,882	64	19,550	114	19,719	116
	NRP	80	2.5	1,082	34	1,908	60	2,127	66
New properties within 400 m of cliff top	RP	330	7	511	11	654	14	787	17
	NRP	17	2	44	5	52	6	85	9

Figure 5. The spatial distribution of total residential properties under the World Markets and the Local Stewardship scenarios in the Norfolk Broads over the 21st century. L – Lowestoft, GY – Great Yarmouth, H – Happisburgh.

Figure 6. The spatial distribution of the total non-residential properties under the World Markets and the Local Stewardship scenarios in the Norfolk Broads over the 21st century. L – Lowestoft, GY – Great Yarmouth, H – Happisburgh.

All the scenarios show new properties in the floodplain: the highest percentage increase is under the World Markets scenario, while the lowest is under the Local Stewardship scenario. The highest percentages of new properties inside the floodplain under the World Markets are due to the combination of all attractions - under this scenario, there is a desire to live within the floodplain as properties could be cheaper than elsewhere, other factors also act as attractants, including the coast and transport networks, whereas under the National Enterprise scenario, by comparison, the only other attraction is the coast (see Table 3). This increases the proportion of new properties within the tidal floodplain.

The scenarios were used to conduct a risk assessment of climate change as described briefly in section 4. Figure 7 summarises the expected economic damages discounted over the 21st century for the ‘mid-range’ sea-level rise scenario of 0.45m, the four socio-economic scenarios and the baseline (no change), and a range of different management options for the cliff from Weybourne to Happisburgh ranging from no protection to 100% protection.

Figure 7. Flood risk in the low-lying land (sub-cell 3b) under 45 cm of sea-level rise and 7% increase in wave height in 2080s for various levels of protection along the cliffed coast.

In a wider analysis of climate scenarios and cliff management options Dawson *et al.* (2009) demonstrated that the economic risks from erosion are substantially lower than the flood risk. This is because (i) the area at risk of erosion is concentrated in a narrow band near the cliff top while the flood risk zone extends far inland, (ii) fewer properties are located along the cliffed coast than within the floodplain and (iii) properties can be flooded on multiple occasions, whereas a property is only lost to erosion once. Furthermore, the accelerated cliff recession associated with reducing the cliff protection generates additional sediment which can reduce recession rates elsewhere along the coastline and reduce flood risk.

As expected, socio-economic growth in the study area leads to increases in flood risk as expressed in terms of changes to the built environment. In all scenarios the damages are

increased, with average increases in direct damages (at 2003 property prices) of 6%, 9%, 16% and 19% under the Local Stewardship, Global Sustainability, National Enterprise and World Markets futures, respectively. The effect of this growth on flood risk is mainly influenced by the assumptions made in this study especially the scale used to quantify the weights of attraction factors and the interpretation of the storylines of scenarios to quantify the weights associated with these factors. When comparing scenarios it is important to be careful and consistent with the interpretation of the qualitative storylines. However, any changes to the values of the weights will still produce a similar pattern and ranking of damages across scenarios, albeit of different magnitudes.

It is crucial to recognise that this model does not attempt to predict urban growth. Moreover, we recognise that these four scenarios imply some substantial reorientation of the built environment and planning policies which in some cases may seem unlikely. However, planning policy has changed much over the last century and it would be naïve to explore only one possible socio-economic future when considering long term climate risks. As described in Section 3.3 the current regional plan implies a future between the Local Stewardship and Global Sustainability scenarios. However, current development in the UK has for some time been between the National Enterprise and World Markets scenarios (DTI 2002), highlighting the need for this type of analysis. Thus, whilst the model does not predict future urban growth, or address local design issues, it provides an important tool for analysing long term changes to climate risks over a broad scale. This information can be used to inform and set the context for the local planning

process and explore the wider and longer term impacts of development plans on climate risks.

Overall, while the traditional method of expert judgment tends to increase urban patterns uniformly leading to a constant pattern of exposure, the multi-criteria analysis links the spatial pattern of exposure to the storyline interpretation of various futures allowing a wider range of evolution pathways and hence changing risks. The developed method is an algorithm-based approach capable of providing feasible and flexible tools for developing and exploring plausible future socio-economic scenarios for impact and risk assessment. It has the advantage that the scenario assumptions are explicit, reproducible, and can be easily changed. This allows for an in depth investigation of stakeholder views concerning possible futures and their implications in terms of climate risk. Although the model has proven itself fit for the purposes of this study, there are a number of improvements that could be made. These include, capturing both horizontal and vertical urban growth (e.g. converting single properties into multi-story buildings). Likewise other attraction factors such as brownfield sites would enable additional planning tensions to be explored. Furthermore, the use of a linear distance-attraction and linear multi-criteria summation of total attraction could be improved through development of logit or other value functions, or even application of a spatial interaction model. However, this either requires additional information in the scenarios or a further elicitation process to parameterise functions.

6. Conclusions

Scenarios of future built environment were developed using a GIS-based multi-criteria analysis for application in broad scale climate risk assessment. We applied and demonstrated the method in East Anglia with a focus on flood risk from sea-level rise.

Socio-economic storylines for East Anglia were the basis for quantifying and predicting future property distribution. The current baseline property distribution is augmented with new properties based on the four downscaled Foresight socio-economic scenarios. We identified and quantified the relative importance of four attraction factors of (1) existing settlements, (2) transport networks, (3) coastline and (4) floodplain to produce a spatial rule for distributing new residential and non-residential properties across the investigated region. These attraction factors reflect important aspects of the urbanisation process and the levels of attraction that areas and infrastructures are likely to generate under the different socio-economic scenarios.

The multi-criteria analysis is capable of rapidly generating development patterns reflecting the storylines of the socio-economic scenarios, which are appropriate for conducting impact assessment of climate change at the regional scale. This algorithm-based method, as implemented, provides transparency of the assumptions made and flexibility in tuning the influence of attractors, which makes it an attractive method for interactively exploring stakeholders' views on future scenarios of built environment in the context of risk assessment of climate change.

The results produced in this study were influenced by the assumptions, especially the number of attraction factors and the scaling scores of these factors. Different weight scales are expected to generate similar generic urban patterns but they may vary at the local scale. More factors could be included in the model such as the land available for development including brown fields and possible changes in the density of built environment. However, including more details will make the model more complex to implement. Thus, a balance between the level of detail incorporated in these broad scale analyses and appropriate outputs is a key to maintain the flexibility associated with this approach.

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