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Assessing the effectiveness of non-structural flood management measures in the Thames Estuary under conditions of socio-economic and environmental change

Abstract
Risk analysis and appraisal of the benefits of structural flood risk management measures such as embankments is well established. Here, a method to quantify, over extended timescales, the effectiveness of non-structural measures such as land use spatial planning, insurance and flood resilient construction is presented. The integrated approach couples socio-economic and climate change scenarios with long term land use modelling and flood risk analysis to generate maps and timeseries of expected annual damages. The analysis has been applied on a case study in the Thames Estuary in the UK. Stakeholders helped develop a number of scenarios that might lead to substantial changes in existing planning and insurance policies in the UK. The effectiveness of these changes was analysed and showed the substantial benefits in terms of reduction of future flood risks that are achievable with changes in planning policy, financial incentives and resilient property construction in the floodplain. Moreover, the reward can be increased through earlier action. Subsequently, the benefits of a range of policies are explored under the UK Foresight socio-economic scenarios. Different structural and non structural flood management interventions are tested and the results demonstrate that despite the potential for large increases in flood risk in the Thames Estuary, in all scenarios substantial flood risk reductions are possible. The effectiveness of non-structural measures is however sensitive to socio-economic changes and governance arrangements. The analysis described here will help to identify portfolios of non-structural and structural options that are robust to uncertainties.

Keywords
Flooding; Risk analysis; Insurance; Planning; Non-structural measures;
1 Introduction

Contemporary flood risk management seeks to reduce the consequences of flooding as well as its probability by considering a mix of management options which extend beyond traditional engineering measures such as flood defences (so-called structural measures) and incorporate a wide range of mechanisms which are referred to as being “non-structural”.

For a number of years quantitative flood risk analysis has provided decision makers with a powerful tool to support appraisal and investment in structural measures (c.f. USACE, 2000; Hall et al., 2003a; Dawson and Hall, 2006; Jonkman et al., 2008 etc.). However, analyzing the risks and benefits of non-structural measures has hitherto been limited to a scalar estimate of their influence on parameters such as damage, in part due to the complexity of analysing the human system responsible for their construction, maintenance and successful operation on which their success is often dependent. Moreover, the longer term ‘risk signals’ given through non-structural (and structural) measures such as development policy, insurance premiums etc., as well as actual flood events influence longer term trends of development in the floodplain because the human system adapts its behaviour accordingly (i.e. it is a reflexive system).

This paper describes a method for appraising the benefits of non-structural measures, in terms of reduction to economic flood risk over the extended timescales that they operate. In doing so we seek to demonstrate explicitly the processes by which risk evolves through time and how human settlements respond to the communications of that risk. The approach is based upon simulation modelling of flood risk and changes in land use and buildings, but is grounded in analysis of policy, planning and insurance arrangements in the UK. After this introduction, non structural flood risk management measure are introduced with a particular focus on the UK planning and insurance market. Subsequently, a methodology for broad scale risk analysis of non-structural measures is described, that is then applied to a case study in the Thames Estuary. The risk analysis is demonstrated in two ways (i) exploring the impact of changes to existing planning and insurance systems, and, (ii) analysing long term socio-economic and climate influences using the Foresight socio-economic scenarios. Finally, the results and their implications are considered.

2 Non-structural flood risk management measures

A number of substantial reviews of flood risk management measures already exist (c.f. Kundzewicz, and Takeuchi, 1999; Hall et al., 2003b; Evans et al., 2004a) so only a limited review is provided here. Typically non structural measures are those not involving physical construction but use knowledge, practice or agreement to reduce risks and impacts, in particular through policies and laws, public awareness raising, training and education (UNISDR, 2009). A range of flood risk management measures, and their effect on flood risk, is summarized in Table 1. Land use planning and insurance, which are the two key foci of this paper are discussed at greater length in the following sections in the context of the UK planning system and insurance market.
<table>
<thead>
<tr>
<th>Intervention</th>
<th>Effect of action</th>
<th>Potential modification of risk calculation (Equation 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate change mitigation</td>
<td>Mitigation of greenhouse gases will lead to less significant changes in the climate</td>
<td>Different climate change mitigation strategies are considered through alteration of the probability of a given loading through time</td>
</tr>
<tr>
<td>River and Coastal engineering measures</td>
<td>Hard engineering measures (e.g. river conveyance, defences, engineered storage) reduce the probability of flooding by providing more efficient mechanisms of removing water from the system, or increasing the capacity to withhold greater quantities of water. ‘Soft’ engineering measures (e.g. beach nourishment, vegetation management) reduce the vulnerability of defences through dissipation of energy.</td>
<td>The effectiveness of flood defences may be considered through appropriate alteration of the probability of flooding at the time they are implemented.</td>
</tr>
<tr>
<td>Rural runoff reduction and storage</td>
<td>Reduce flood severity from altered runoff properties through changing the infiltration, storage and conveyancing properties of catchments and floodplains.</td>
<td>Alters the probability of flooding.</td>
</tr>
<tr>
<td>Urban runoff reduction and storage</td>
<td>Reduce the probability of flooding using a combination of storage, infiltration, conveyancing and drainage capacity management.</td>
<td>Alters the probability of flooding.</td>
</tr>
<tr>
<td>Flood incident management</td>
<td>Flood-forecasting and warning systems provide information to flood risk managers, local authorities and emergency services which is subsequently disseminated to the public in order to sufficient time that they can take effective mitigative actions before the flood arrives. Proactive pre-incident activities ensure that the public, emergency services and other key stakeholders are well prepared and able to act sensibly, and understand information on flood warnings, during and just before the flood to</td>
<td>Most flood incident measures act to change the depth-damage relationship of floods (if followed by appropriate action by the public) and increase public safety and reduced health impacts of flooding. However, some flood-fighting actions (e.g. reinforcing failing defences) can reduce the probability of flooding and their success is tied to timely responses to specific flood events.</td>
</tr>
<tr>
<td>Flood-proofing</td>
<td>Reduce flood damage</td>
<td>Flood-proofing measures change the depth-damage relationship for the properties in which they are implemented. These could be retrofitted to old properties or designed into new builds.</td>
</tr>
<tr>
<td>Land-use planning</td>
<td>Limit construction of buildings and infrastructure in the flood plain, hence controlled increase in vulnerability.</td>
<td>Land-use planning measures change the overall damage function through time by altering the rate of floodplain development.</td>
</tr>
<tr>
<td>Building codes</td>
<td>Reduced flood damage. In new buildings it is possible to implement flood proofing measures that are more reliable than retrofitted properties. For example, raising buildings on stilts.</td>
<td>Flood-proofing measures change the depth-damage relationship for newly built properties in which they are implemented.</td>
</tr>
<tr>
<td>Risk spreading (e.g. insurance)</td>
<td>Redistribution of the cost of damage across the population and through time</td>
<td>As well as redistributing risk, insurance is a potent means of communicating flood risk through an economic signal so it can change the overall damage function through time by providing a mechanism for discouraging development in high risk areas.</td>
</tr>
<tr>
<td>Health and social measures</td>
<td>Reduced social, health and associated economic impacts of flooding</td>
<td>Health, social measures could be incorporated if an appropriate health/social, or secondary economic impacts damage function were available.</td>
</tr>
</tbody>
</table>
2.1 Planning policy in England and Wales

A number of Planning and Policy Statements (PPS) set out the UK Government’s policy in England (Scotland and Wales have devolved responsibilities for planning policy and separate statements on planning and flooding) and reflect the changes to the planning system brought in by the Planning and Compulsory Purchase Act 2004 and Planning Act 2008. PPS25: Development and flood risk (CLG, 2006) is the most relevant document with regards to flooding, although local (PPS12) and regional (PPS11) strategies and sustainable development objectives (PPS1) should also be considered.

PPS25 is a risk-based approach that can be applied at regional, strategic and site specific scales in the planning process. The first stage in the assessment is to identify three zones based on their inundation probability:

- **Zone 1 - Low Probability**: land assessed as having a less than 1 in 1,000 annual probability of fluvial or coastal flooding (<0.1%).
- **Zone 2 - Medium Probability**: land assessed as having between a 1 in 100 and 1 in 1,000 annual probability of river flooding (1% - 0.1%), or between a 1 in 200 and 1 in 1,000 annual probability of sea flooding (0.5% - 0.1%).
- **Zone 3a - High Probability**: land assessed as having a 1 in 100 or greater annual probability of flooding (>1%) or a 1 in 200 or greater annual probability of flooding from the sea (>0.5%).
- **Zone 3b - The Functional Floodplain**: land where water has to flow or be stored in times of flood.

The type of development being proposed is classified as either essential infrastructure (e.g. evacuation routes, strategic utility infrastructure); water compatible (e.g. docks, flood control, water transmission); highly vulnerable (e.g. emergency services; caravans; hazardous materials); more vulnerable (e.g. hospitals, care homes, hotels) or less vulnerable (e.g. shops, offices, water treatment). According to the vulnerability of development and the inundation probability, the proposed development is classified as ‘appropriate’, ‘subject to an exception test’ or ‘inappropriate’ (Table 2). The outcome of the exception test is to reclassify the development as appropriate or inappropriate. To be reclassified as appropriate, the exception test must demonstrate that development (i) provides wider sustainability benefits that outweigh flood risk, (ii) is on previously developed land and no reasonable alternatives on previously developed land are available, and (iii) a detailed flood risk assessment must show that the development will not increase flood risk elsewhere and where possible reduce flood risk overall.

### Table 2 Flood risk vulnerability and Flood Zone ‘Compatibility’ (CLG, 2006)

<table>
<thead>
<tr>
<th>Vulnerability</th>
<th>Essential Infrastructure</th>
<th>Water compatible</th>
<th>Highly Vulnerable</th>
<th>More Vulnerable</th>
<th>Less Vulnerable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Zone 2</td>
<td>✓</td>
<td>✓</td>
<td>Exception</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Zone 3a</td>
<td>Exception</td>
<td>✓</td>
<td>x</td>
<td>Exception</td>
<td>✓</td>
</tr>
<tr>
<td>Zone 3b</td>
<td>Exception</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>
2.2 Insurance

Insurance is the transfer of the risk of a loss, from one entity to another, in exchange for a premium—a guaranteed and known small loss to larger, possibly devastating losses. By spreading risk across policy-holders, insurance enables property owners and businesses to minimise the financial cost of damage from flooding. In a competitive market, premiums tend to reflect the risks customers face. However, the spreading of risk creates the possibility of ‘moral hazard’ in higher risk areas. Awareness of this possibility has been argued as one reason why insurance is not available in some low probability but high risk locations that have had devastating floods, such as the Netherlands (Jongejan and Barrieu, 2008).

Under-insurance in flood risk areas has a number of explanations. People may ignore, knowingly or not, low probability but high consequence events. Others may be aware but are priced out of the insurance market by high premiums or deductibles (Kunreuther et al. 1978; Smith, 1986; Slovic, 1987; Kunreuther, 1996). In many cases the risk is underestimated because of overconfidence in ‘hard’ measures such as dikes (Burby et al. 1988; Pynn and Ljung, 1999). This underestimation may apply equally to insurers, who are aware of the risk on the basis on information on flood risk thresholds, and the general public, who may simply be unaware of any residual risk. However, a recent flood experience appears to be an important criterion in the purchase of flood insurance (Brown & Hoyt, 2000). Householders will not be able to obtain cover if an insurance market does not exist or they are refused insurance from all potential providers.

2.2.1 The UK insurance market

The Association of British Insurers (ABI) is the national trade association for insurance companies, representing over 400 members who collectively account for 95% of the UK market. The UK market differs from many others in its comprehensive cover of risks – including: fire, theft, storm, flood, and subsidence – is bundled together as a standard package for domestic properties and small businesses and is available on a near universal basis.

Following large scale floods in 2000 that led to claims in excess of £1billion, the ABI set out the principles by which their members would continue to offer flood insurance. In return for providing Government investment to reduce flood risk the ABI committed itself to continue to provide flood insurance (ABI, 2002) until 2013 for any existing property subject to annual inundation probability no greater than 1.3%. Where the protection was currently less than this, but defence improvements were planned, cover would remain available for five years. Where no defences were planned, the insurers would not guarantee to maintain cover, and any cover offered may be priced to reflect a property’s exposure. However, the agreement states that insurers would work with owners to see what action could be taken (by the owner, local authority or Environment Agency) to improve the insurability of the property. After the 2007 flood, the ABI restated their commitment to the 2002 statement (ABI, 2008), but a 0.5% annual probability would be the minimum level of flood protection required to enable insurers to make cover readily available for residential properties built from 2009.
2.2.2 The Reinsurance market

Insurance companies acquire reinsurance to offset their exposure to risk. For example, a company may seek reinsurance for storm and flood cover from losses of about £100-200 million to their calculated maximum potential loss, allowing them to remain trading and comply with UK and EU solvency regulations.

Britain is unique in Europe in not having the State as the insurer of last resort. UK flood risk is therefore a somewhat unusual product for the reinsurance market to trade. Thus far, it has proven to be an attractive market for investors; however, the levels of reinsurance that have been paid out have been relatively small. The summer floods of 2007 cost the UK insurance sector approximately £3 billion overall, but because of the relatively high retention levels (the excess for the insurance company over which repayment is made), the even spread of claims against all of the major companies, and the fact that flooding occurred in two separate events (Hull/South Yorkshire in June, and Gloucestershire/Upper Thames in July), only one company triggered a reinsurance payment.

If losses had been more substantial the market would probably have reacted by increasing the price of reinsurance cover. The market for reinsurance is global, diverse and increasing in value and sophistication. If UK storm and flood cover was deemed to offer a poor return relative to other markets the price would rise. Insurance companies could only tolerate a certain increase in costs before having to pass on that increase to their customers. Indeed in their recent negotiations with the Government the ABI (2008) emphasised that current arrangements are entirely dependent upon the continued availability of flood reinsurance.

2.2.3 Other insurance models

The UK approach is by no means typical and other countries have developed their own approaches to flood insurance. These approaches can be considered along two axis: the degree of bundling and the level of state support (Figure 1).
Figure 1 Different countries have different home insurance markets where insurance can come bundled with all cover (including flooding), or unbundled (where each component is sold separately) whilst the market may be entirely private, or a state monopoly.

**Unbundling**

Unbundling is common in insurance markets; some companies may specialise in offering specific insurance for risks considered too high by others. Within a single company, the pricing of policies and setting of excess/deductible values may vary. In relation to excesses, such a change appears to already be taking place in home insurance for flood risk areas in the UK, with premiums and excesses offered by some companies tending to vary according to historical flood risk. Although actual figures are hard to come by since they tend to be negotiated on an individual basis, this effect has been documented in Scotland by Werritty et al. (2007) with increases in excesses of £5k-£10k.

**State funding**

National systems of flood insurance also vary considerably in respect of the type and degree of Government intervention. In the U.S.A. the Federal Emergency Management Agency (FEMA) allows property owners in participating communities to purchase flood insurance as a protection against flood losses as long as the state and local community implement floodplain management regulations (Brown and Hoyt, 2000). In many European countries the Government is the insurer of last resort, but there is a great variety of approaches from no insurance at all (as in the Netherlands; Jongejan and Barrieu, 2008), through state-sponsored and mediated insurance systems with varying degrees of private sector involvement: for example, France, Germany (Schwarze and Wagner, 2004) and Spain (Von Ungern Sternberg, 2003), to the fully private UK model.

**3 Broad scale flood risk analysis**

Flood risk analysis provides a rational basis for the appraisal of policy options, allocation of resources and monitoring performance of substantial government investment in flood management (Hall et al., 2003b). Here, our interest is in the long term processes of change, motivated by the
extended legacy of flood management policies such as changes to planning policies, building design codes or insurance provision. It is these major decisions that we are seeking to inform through provision of risk information so as to avoid decisions with consequence that are undesirable in terms of flood risk or lock out the opportunity for alternative actions in future.

The risk analysis framework is shown in Figure 2 and comprises several components. At the top of the figure are the socio-economic drivers of change that influence population growth at a regional scale. A spatial interaction module provides high resolution spatial scenarios of population and land use that form the basis for flood risk analysis. The influence of different socio-economic scenarios, climate scenarios and flood risk management policies can be explored by adjusting the appropriate component of the integrated assessment.

![Figure 2 Overview of risk analysis framework, highlighting how the drivers of change and non-structural flood risk management measures interact with the risk calculation](image)

**3.1 Introduction to the Thames Estuary**

The Thames Estuary is in the Southeast of Great Britain (Figure 3). The study area includes the entire Greater London Authority and other local or unitary authorities that border the Thames Estuary. The tidal limit of the river Thames extends to Teddington Weir in west London. A large part of London lies within the Thames tidal floodplain and without the protection afforded by the flood defences, this area would flood regularly. The current Thames tidal defence system, comprises the Thames Barrier, 185 miles of floodwalls, 35 major gates and over 400 minor gates which protect London from tidal surges.

Currently there is an area of approximately 345km² at risk of flooding which contains 1.25 million people; nearly 500 schools and hospitals, 5,540ha of nationally and internationally designated sites
of nature conservation importance (representing 16% of all land at risk of flooding), the 2012 Olympic park site, 2,450km of transport links (Motorway, A-Road and Rail, including the Channel Tunnel rail link) and 481,180 properties in the floodplain of which 76,000 are residential (GLA, 2007). The Thames Tidal floodplain has been sub-divided into so-called “embayments” (London Resilience Partnership, 2007) which are topographically defined flooding areas (Figure 3). For all but the most severe floods these areas are hydraulically self-contained.

Figure 3 Domain of modelling extent for flood risk analysis showing all 801 wards in the Greater London Authority boundary and the Thames Gateway, the 40 Thames Tidal Embayments, the Thames Barrier, location of upstream inflow and estuary tidal surge boundaries

3.1.1 Climate change

Rise in global mean sea level is a consequence of global warming. This rise will not be uniform but interacts with gravitation effects of land and ice masses to generate patterns of regional tide level change. This will be compounded by isostatic subsidence in the south of Great Britain and result in London experiencing faster relative sea rise which, coupled with storm surges, will heighten the risk of surge flooding in the tidal Thames.

The problem could be further aggravated by extreme river flows. The median flow and 100 year return period flow are ~350m$^3$/s and ~550m$^3$/s respectively but over the next century, increased amounts of rainfall are predicted over the Thames river catchment which could lead to changes in extreme river flows (Reynard, 2003).

Table 3 Summary of the influence of different climate change scenarios on the 50 year return period river flow in the 2080s and mean sea level at 2100. Although not available for this analysis, the recently published UKCP09 results are of similar magnitude and the 95% percentile ranges for the low, medium and high
scenarios are approximately 19-83cm relative sea level rise for London.

<table>
<thead>
<tr>
<th>UKCIP02 climate change scenario</th>
<th>Low</th>
<th>Medium Low</th>
<th>Medium High</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in extreme river flow in 2080s (%)</td>
<td>-1.4</td>
<td>-1.4</td>
<td>+0.6</td>
<td>+4.2</td>
</tr>
<tr>
<td>Relative sea level in 2100 (m)</td>
<td>+0.26</td>
<td>+0.40</td>
<td>+0.58</td>
<td>+ 0.86</td>
</tr>
</tbody>
</table>

3.1.2 Development plans in the Estuary

The London Plan is the spatial development strategy for London developed by the Greater London Authority setting out an integrated social, economic and environmental framework for the future development of London for the next 15-20 years. The Plan highlights areas that are targeted for development, with an emphasis upon development of previously developed land and upon certain areas that are targeted for regeneration. The Thames Gateway is a 40 mile tract of land that stretches from the Isle of Dogs (Figure 3) to the Thames Estuary. The Gateway has been targeted for significant development over the coming decades and will host the Olympics in 2012. By 2016, 120,000 new households and related infrastructure will be developed in the Thames Gateway area (ODPM, 2003; 2005).

3.2 Flood risk calculation

Flood risk is conventionally defined as the product of the probability of flooding and the consequential damage and is often quoted in terms of an expected annual damage, sometimes referred to as the ‘annual average damage’. More formally, risk can be expressed as the mathematical expectation of damage as described by Dawson and Hall (2006):

\[
R = \int \rho(x)D(x) \, dx
\]

where \(x\) is a vector of variables that describe the properties of the system such as the strength of flood defences or the loading to which they are exposed. \(\rho(x)\) is a joint probability density function of \(x\), whilst \(D(x)\) is a quantified measurement of impact (often expressed in economic terms), which is a function of \(x\).

This risk calculation provides a snapshot of risk at any instance in time. In general, risks will be changing through time due to a host of natural and socio-economic processes as well as due to deterioration, upgrade or replacement of components of the flood defence structures. Benefits from many non structural flood risk management measures are only realized over time: for example changes to building codes are only applied to future development, conversely a flood defence provides instantaneous protection to existing development as soon as it is constructed.

Equation 1 is therefore extended to consider changes to the system over time, \(t\):

\[
R(t) = \int \rho(x,t)D(x,t) \, dx
\]

To compare the benefits net of all costs for each year of different adaptation strategies discounted back to the present date the present value of the risk, \(PVR\), over an \(n\) year time period with discount rate \(d\), is calculated using:

- 10 -
\[ PVR = \sum_{i=1}^{n} \frac{R(t)}{(1 + d)^i} \] (3)

### 3.3 Application of flood risk analysis to the Thames Estuary

Equations 1 and 2 provide a general framework for quantifying risk. This section describes how risk is calculated in the Thames Estuary. Figure 4 shows an idealised cross section of an embayment.

The main steps for calculating flood risk in each embayment are:

(i) estimation of the joint probability, \( \rho(q,w) \), of on extreme river flows, \( q \), at the tidal extent in Teddington and storm surge levels, \( w \), at Southend at the estuary extent;

(ii) use a hydraulic model (Halcrow, 2005) to establish a structure function, \( l_e(q,w) \), that describes the water level at an embayment, \( l_e \), in terms of the boundary conditions;

(iii) subsequently integrate \( l_e \) over \( \rho(q,w) \) to establish the probability of water levels, \( \rho(l_e) \) at each embayment;

(iv) estimation of defences breach characteristics and performance using fragility curves (Dawson and Hall, 2002) to describe the probability of defence failure, individually or in concert with other defences, conditional on the water level at the embayment, \( P(B_i|l_e) \);

(v) employment of a volume filling algorithm to estimate inundation depth and extent due to overtopping or breaching of the defences;

(vi) evaluation of inundation depth and spatial extent, \( h \), for each loading condition;

(vii) use information on property location and type from the National Property Database, and depth-damage relationships, established by Penning-Rowsell et al. (2005), to construct a function describing damage in the floodplain conditional on flood depth, \( D(h) \);

The final stage is to integrate over the probability of extreme loadings, the probability of defence failure, the inundation depths and extents and damages to evaluate flood risk. For 40 embayments, each comprising \( n \) defences, the risk as a function through time, \( t \), can be calculated as:

\[ R(t) = \sum_{c=1}^{40} \int \rho(l_c, t) \sum_{i=1}^{2^n} P(B_i|l_c, t)D(h_i|l_c, t)dl_c \] (4)
To estimate risk under future conditions, the three components of Equation 5 are adjusted as appropriate. For example, changes in landuse (which is described in the following section) are captured by altering $D(h \mid l, t)$ to reflect the outputs of the landuse model such as increased development, or adaptations designed to reduce damage associated with flooding. Climate change manifests itself in terms of sea level rise and changes to extreme flows, altering the probability of extreme events, $\rho(q, w)$ and subsequently $\rho(l)$. The range of climate change scenarios considered in this study are summarised in Table 3. In this study we do not deal with the deterioration of flood defences which influences $P$.

Expected annual damages for 2005 are calculated to be £29million, which is of similar order to other modelling studies in the area (HR Wallingford, 2006; Environment Agency, 2009). As in these other studies, the largest risks tend to be nearer the coast (Figure 5) reflecting the importance of the Thames Barrier at protecting central London and the lower standard of protection in these areas.

![Map of flood risk, in terms of expected annual damage, by ward in the year 2005](image)

**Legend**
- GLA Border
- Expected annual damages (£k)
  - 0
  - <0.25
  - 0.25-0.5
  - 1-5
  - 5-10
  - >10

3.4 **Land use change**

To explore the impact of different land use planning and insurance policies a spatial interaction model is used to allocate future population and employment growth into administrative units. The model is built upon the principles outlined in Lowry’s (1966) original model, but has been extended to explore alternative scenarios of:

- densities of new residential and employment developments,
• drivers of employment activity,
• drivers of residential development,
• development constraints for residential and employment land uses,
• planning and insurance policies.

The model operates at the scale of UK census wards.

First exogenously generated projections of five employment sectors (Primary industries; Retail; Construction; Finance; Other services (e.g. public sector)) are allocated to census wards according to its attractiveness to a particular employment sector, where attractiveness is a weight, $W$, reflecting a series of attraction factors obtained from user derived development scenarios. For $k$ employment sectors, the total employment, $E^k_T$, is disaggregated according to:

$$E^k_T = W_i E^k_i$$

(5)

The population, $P$, is subsequently allocated to wards according to their relative accessibility to different types of employment, planning policy and desirability:

$$P^k_j = \sum_i \frac{E^k_i}{T_{ij}}$$

(6)

where $T_{ij}$ is the number of journeys between the household ward, $i$, and the employment ward, $j$. $O_i$ is the number of journeys starting in ward $i$ and $D_j$ is the number of journeys finishing in ward $j$ and is a function of preference and accessibility:

$$T_{ij} = W_i p O_i D_j f(C_{ij})$$

(7)

where $\sum_{i=1}^N T_{ij} = O_i$ and $\sum_{i=1}^N T_{ij} = D_j$. $W_i$ represents the attractiveness of a census ward for population. In a situation with $R$ attractors, the attractiveness of a ward is a normalized function of the mass, $m_i$, of each attractor, which is weighted according to its relative importance, $w_j$:

$$W_i = \sum_{i=1}^R w_j \frac{m_i}{N}$$

(8)

The mass generally corresponds to the area of a particular attractor (e.g. area of available previously developed land). The function $f(C_{ij})$ describes the generalized cost of travel between wards takes into account network length, travel speed, financial costs (e.g. petrol or ticket fare), travel mode and waiting times (DfT, 2008). The generalized cost between each ward for the four travel modes of car, underground and tram, bus and heavy rail has been calculated by Ford and Barr (in review). The aggregate cost of travel for four modes is then calculated using the method recommended by Ortuzar and Willumsen (2001).

Constraints are imposed on the solution of $P$ and $E$ to ensure that the total available area of development in each ward is not exceeded. The total available area for development includes land that is already physically developed and land that, as a result of planning policy, is unavailable for development. The model was calibrated against observed data of population and employment in each census ward by adjusting $W$ and variables describing modal preference in $f(C_{ij})$. The model is not dynamic, but equilibrium projections can be generated for times in the future. At each timestep the increments in population and employment activity are added to existing development patterns according to the drivers of development, constraints, planning policies and travel cost at that timestep. Household numbers are calculated from 2005 occupancy rates. The influence of different occupancy rates and population densities can be explored by adjusting this baseline. The model is described in full by Barr et al. (in prep.) but Figure 6 shows how the location of new development is
influenced according to two very different planning policies which evidently have different implications in terms of the number of people living in the floodplain.

Figure 6 Population change between 2005-2100 under two planning policies where development is (a) not allowed on greenfield sites and (b) new development is targeted almost exclusively at previously developed land.

4 The benefits of non-structural measures

The integrated assessment described previously has been used to test the effectiveness of non-structural measures through two approaches: (i) exploring the impact of major changes to insurance and planning policy using stakeholder informed scenarios and (ii) analysing the effectiveness of non-structural measures under wider socio-economic and climate scenarios. Consequently, a number of combinations of climate and socio-economic scenarios are analysed, as shown in Table 5.

Table 4 Summary of the climate and socio-economic scenario combinations analysed

<table>
<thead>
<tr>
<th>UKCIP02 Climate scenarios</th>
<th>Stakeholder insurance scenarios</th>
<th>Foresight scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Business as usual</td>
<td>National Enterprise</td>
</tr>
<tr>
<td></td>
<td>Catastrophic event</td>
<td>Local stewardship</td>
</tr>
<tr>
<td></td>
<td>Extreme surge</td>
<td>World Markets</td>
</tr>
<tr>
<td>Low</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Medium Low</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Medium High</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>High</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

4.1 Planning and insurance scenarios

Three planning and insurance scenarios were developed through stakeholder consultation to analyse the effectiveness of different planning and insurance measures at managing flood risk as well as understand the conditions that might bring about substantial change to the planning and insurance policy. Stakeholders consulted included representatives from the Environment Agency for England
and Wales (who manage the Thames tidal defences), DEFRA, the Association for British Insurance, local authority planners and engineering consultants and academics with expertise in the insurance sector and flood risk. Semi structured interviews were carried out using as a question framework divided into two parts: current policy by government and influences on organisational behaviour; likely circumstances in which policy could change; the most likely changes to in organisational behaviour that would result.

All stakeholders agreed that an extreme future scenario of absolutely no flood insurance provision of any kind was unlikely but certain events might lead to a radical shift in planning and insurance policy. Although a consensus did not emerge on the exact scale of event necessary to effect a change, there was agreement that a severe event could deliver a severe shock to international markets.

Stakeholders felt that the two changes most likely from a severe shock involved either the existing system holding, or establishment of a new state supported system. Were a new system to emerge it was deemed unlikely that a new state monopoly system would be allowed to form within the EU. Thus, a modified version of the French insurance arrangement was identified as the most likely candidate to replace the existing system and this consensus view was chosen as the basis of our analysis. In both scenarios, changes in the cost of insurance would reflect development location (and hence risk) rather than be imposed generally across all locations. A new system might be viewed as a model of ‘state support, but with no solidarity element’; those in the risk areas from which withdrawal has occurred are left to bear the increased costs of insurance from the Government although to reduce their own exposure, there is therefore a strong incentive to tighten planning controls.

Here we make no attempt to value the cost of land use planning constraints. Whilst the direct cost of making plans is minimal, substantial benefits of development may be foregone because of land use planning constraints. Floodplains have historically been developed because they offer comparative advantage, in particular in terms of transport connectivity, flat land and agglomeration at existing floodplain towns and cities. Constraining development foregoes the opportunity to further exploit these benefits. However, it is difficult to establish whether or not benefits forgone because of land use planning constraints are transferred to locations where those constraints do not apply, so have no net effect. No other drivers of socio-economic change (e.g. changing value of buildings and contents) are considered in these scenarios which are now described:

(a) Business as usual
The Statement of Principles (ABI, 2008) continues to act as the settlement between the insurance industry and Government.

(b) Catastrophic event(s) leading to a change in the reinsurance market
A major event, or series of large sequential events outside the UK, leads to substantial claims on the global reinsurance market. For instance, this might involve an enormous flood across central Europe occurring not long after a Category 5 hurricane wrecks havoc along the Eastern seaboard of the USA affecting numerous insurance companies. This large scale global ‘shock’ would most likely lead to UK insurers reassessing their entire risk portfolios and could result in an unbundling of flood cover from general buildings insurance. Niche companies specialising in flood risk cover
increase their market share to provide a form of cover for such properties. However, this is at a much higher price than general buildings insurance as cover is being sought on an individual actuarial basis. Significant increases in the cost of flood insurance results in property blight for buildings in the highest risk areas and planning policy is tightened to restrict future development.

(c) Extreme storm surge devastating the UK

A major storm surge event, spread over a wide area, leads to devastating losses in the UK leading to a major withdrawal of insurers from the flood risk market. This is driven in part by a collapse of smaller firms and substantially increased reinsurance premiums for those UK insurers that survive. In response, the government tightens planning policy to the extent that almost no floodplain development can take place. In the most extreme case, the Government might step in to provide insurance along the lines of the U.S.A. model, but at the price of higher premiums and excesses to individuals and communities living in areas at risk.

In developing and subsequently quantifying these scenarios, flood risk areas have been divided in to three zones, \( z \), based upon their Standard of Protection:

- Low: \(<1 \text{ in } 75\);
- Moderate: \(1 \text{ in } 75 – 1 \text{ in } 200\);
- High: \(>1 \text{ in } 200\)

To reflect the influence in insurance premium costs on preferences for new development, the costs are translated into a mass for each floodplain zone, \( m_f \), which can be inserted into Equation 9.

\[
m_f = C_I/[C_I S_I + C_R + C_E S_E \times P]
\]

where \( C_I \) represents the average cost, £339, of annual insurance premiums in the UK (Cabinet Office, 2008) which is incurred whether inside or outside the floodplain. \( C_R \) is the additional cost (annualized over 50 years at present value as per DEFRA (2008)) of installing resilience measures in a new property which is approximately £333, \( C_E \) is the flooding excess which is assumed to be £100 but is only incurred after a flood exceeding probability \( P \). The scalars \( S_I \) and \( S_E \) are the multipliers of the annual insurance premiums and excess respectively given in Table 5. \( W_f \) varies from 0.24-1.0 for the scenarios considered here, where a lower value of \( W_f \) is more likely to discourage floodplain development. The values of these scalars for each scenario, and floodplain zone, were agreed in consultation with the stakeholder group over several iterations. Initial values proposed by the authors were revised by the stakeholders, before the scenario results were fed back to the stakeholders who were subsequently invited to amend the values. Each stakeholder was interviewed separately, so mean values have been used in the results presented here. Resilient flood buildings alter the depth-damage relationship for a building as shown in Figure 8.

The results presented in Table 6 should be interpreted with care. The lower total net present risk values associated with the more extreme scenarios represent the benefits of avoiding future floodplain development through the use of regulation and financial mechanisms. This should not be interpreted as such extremes being desirable – they represent the stimuli considered necessary by a wide group of stakeholders to drive substantial changes to the existing insurance and planning systems that might subsequently lead to long term reductions in flood risk. Moreover, it is important to note that the calculation does not include the present value damages associated with such a disaster. Indeed whilst the property at risk in the Thames Estuary is valued at £80billion (Lavery and Donovan, 2005), the long term impacts of an extreme event in London would defy
calculation (c.f. Dawson et al. 2005; Lonsdale et al., 2009) and may alter people’s perceptions of risk and their preferences for locating development. A crucial insight though is the substantial benefits of implementing any form of incentives to reduce floodplain vulnerability – either through use of resilience measures or planning and financial incentives to steer development away from the floodplain. Earlier implementation of these policies delivers increased risk reduction.
Table 5 Changes to insurance and planning policy under the three scenarios

<table>
<thead>
<tr>
<th></th>
<th>Business as usual</th>
<th>Reinsurance market change</th>
<th>Major event</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>&lt;1 in 75 years</strong></td>
<td>Insurance</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Premium: ×2</td>
<td>Premium: ×3</td>
<td>Premium: ×3</td>
</tr>
<tr>
<td></td>
<td>Excess: ×25</td>
<td>Excess: ×50</td>
<td>Excess: ×100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cover unavailable for new build</td>
</tr>
<tr>
<td></td>
<td>Flood resilient</td>
<td>New development will be</td>
<td>New development will be rejected in all circumstances. Small developments</td>
</tr>
<tr>
<td>Planning</td>
<td>construction mandatory</td>
<td>rejected in all circumstances. New development will be rejected in all</td>
<td></td>
</tr>
<tr>
<td></td>
<td>for new properties</td>
<td>all circumstances. Small developments and critical infrastructure relocated.</td>
<td></td>
</tr>
<tr>
<td><strong>1 in 75 – 1 in 200 years</strong></td>
<td>Insurance</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Premium: ×1 (×2 for new build)</td>
<td>Premium: ×3</td>
<td>Premium: ×3</td>
</tr>
<tr>
<td></td>
<td>Excess: ×1</td>
<td>Excess: ×50</td>
<td>Excess: ×50</td>
</tr>
<tr>
<td></td>
<td>Flood resilient</td>
<td>Rejection rates for planning</td>
<td>New development will be rejected in all circumstances. Small developments</td>
</tr>
<tr>
<td>Planning</td>
<td>construction mandatory</td>
<td>applications are 25%.</td>
<td>all circumstances. Small developments and critical infrastructure relocated.</td>
</tr>
<tr>
<td></td>
<td>for new properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>&gt;1 in 200 years</strong></td>
<td>Insurance</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Premium: ×1</td>
<td>Premium: ×1.5</td>
<td>Premium: ×3</td>
</tr>
<tr>
<td></td>
<td>Excess: ×1</td>
<td>Excess: ×25</td>
<td>Excess: ×50</td>
</tr>
<tr>
<td></td>
<td>Rejection rates for</td>
<td>Rejection rates for planning</td>
<td>Rejection rates for planning applications are 90% and require resilient</td>
</tr>
<tr>
<td>Planning</td>
<td>planning applications</td>
<td>applications are 15%.</td>
<td>applications are 50%.</td>
</tr>
<tr>
<td></td>
<td>are 15%.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6 Net present risk for future planning and insurance scenarios. All scenarios are assumed to occur in either 2020 or 2050 under the UKCP02 medium-low relative sea level rise scenario. The no floodplain policy scenario is where planning and insurance policy is the same inside or outside the floodplain.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Present Value Risk (£m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Year scenario materialises</td>
</tr>
<tr>
<td></td>
<td>2020s</td>
</tr>
<tr>
<td>No floodplain policy</td>
<td>585</td>
</tr>
<tr>
<td>Business as usual</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Shock to the system</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Major storm surge</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.2 Effectiveness under scenarios of climatic and socio-economic change

Whilst the planning and insurance scenarios are useful to explore the effectiveness of these types of policies, in the longer term it is useful to consider the impact of flood risk management responses in the context of broader changes. Over the lifetime of non-structural measures, a number of drivers will alter flood risk.

4.2.1 Drivers of change

Climate change projections are a driver relating to the probability of flooding through its influence on sea level rise and precipitation changes. Climate change scenarios are taken from UKCIP02 (Table 3). Sea level rise, and changes to extreme river flows are the only variables used in this study: potential changes to the height of extreme surges and other processes have not been incorporated into the analysis. The variables listed in Table 3 are used to modify the probability of extreme events in the flood risk calculation. The UKCP09 scenarios were not available for this work, however, are compatible with this analysis.

Evans et al. (2004b) noted the potential magnifying effect of socio-economic change on flood risk. Socio-economic scenarios provide the context within which flood management policies will be enacted and the extent to which society is affected by flooding, consequently socio-economic factors largely relate to the impact of flooding.Whilst higher population and employment growth has greater potential to place more people and assets in locations vulnerable to flooding, a larger economy has more resources to manage flood risk. Stronger local government may stimulate greater community empowerment in protecting their local environment, but can reduce the capacity to deliver major infrastructure that requires substantial resources and strategic planning.

To understand the context in which flood risk management policy and practice will be enacted and influence the vulnerability of the Thames Estuary four possible long term futures, exploring alternative directions in which social, economic and technological changes may evolve over coming decades are considered (SPRU, 1999; OST, 2002). These scenarios, often known as the Foresight Futures, are represented on a two-dimensional grid in Figure 7. On the vertical dimension is the system of governance, ranging from autonomy where power remains at the national level, to interdependence where power increasingly moves to other institutions e.g. up to the EU or down to regional government. On the horizontal dimension are social values, ranging from individualistic values to more community oriented values. A summary of the underlying philosophy of each scenario is given in Table 7.
Figure 7 The Foresight scenario axis and the four scenarios used in this analysis (SPRU, 1999; OST, 2002).
Table 7 Summary of the Foresight socio-economic scenarios (OST, 2002). Quantified parameters shown are for London only (values also available for other UK regions) from Evans et al. (2004a) and Dahlström and Salmonds (2005).

| Social values | Nationalist, individualist | Localist, co-operative | Internationalist, libertarian |
| Governance structures | Weak, national, closed | Strong, local, participative | Weak, dispersed, consultative |
| Role of policy | State-centred, market regulation to protect key sectors | Interventionist, social and environmental | Minimal, enabling markets |
| Economic development | Medium-low growth, Low innovation, Maintenance economy | Low growth, low innovation, modular and sustainable | High growth, high innovation, capital productivity |
| Structural change | More stable economic structure | Moderate, towards regional systems | Rapid, towards services |
| Fast-growing sectors | Private health and education, Domestic and personal services, Tourism, Retailing, Defence | Small-scale manufacturing, Food and organic farming, Local services | Health & leisure, media & information, financial services, biotechnology, nanotechnology |
| Declining sectors | Public services, civil engineering | Retailing, tourism, financial services | Manufacturing, agriculture |
| Income | Medium-low | Low | High |
| Equity | GDP Growth (% per year) | decline | improvement | decline |
| | 2020s | 2050s | 2020s | 2050s | 2020s | 2050s | 2020s | 2050s |
| | 2 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 |
| | 592 | 997 | 953 | 1862 | -5.7 | -7.0 | -5.7 | -7.0 |
| | 372 | 355 | 652 | 1048 | 0.9 | 14.5 | -7.9 | -15.9 |
| | 851 | 1601 | 1378 | 3029 | 3.5 | 2.75 | -6.6 | -6.6 |
| | 631 | 1099 | 1080 | 2473 | 2.75 | 2.75 | -6.6 | -6.6 |
| | ×3.2 | ×4.5 | ×4.5 | ×4.5 | ×0.9 | ×0.9 | ×4.0 | ×4.0 |
| | ×0.9 | ×6.4 | ×0.9 | ×6.4 | ×0.9 | ×6.4 | ×0.9 | ×6.4 |

For the National Enterprise scenario, people aspire to personal independence and material wealth within a nationally-based cultural identity. Liberalised markets together with a commitment to build capabilities and resources to secure a high degree of national self-reliance and security are believed to best deliver these goals. Political and cultural institutions are strengthened to buttress national autonomy.

For the Local Stewardship scenario, people aspire to sustainable levels of welfare in federal and networked communities. Markets are subject to social regulation to ensure more equally distributed opportunities and a high quality local environment. Active public policy aims to promote economic activities that are small-scale and regional in scope, and acts to constrain large-scale markets and technologies. Local communities are strengthened to ensure participative and transparent governance.

For the World Markets scenario, people aspire to personal independence, material wealth and mobility to the exclusion of wider social goals. Integrated global markets are seen as the best way to deliver this. Internationally coordinated policy sets framework conditions for the efficient functioning of markets. Wherever possible, the provision of goods and services is privatised, under the principle of minimal government. Rights of individuals to personal freedoms are enshrined in law.

For the Global Sustainability scenario, people aspire to high levels of welfare within communities with shared values, more equally distributed opportunities and a sound environment. These objectives are thought to be best achieved through active public policy and international cooperation within the EU and at the global level. Social objectives are met through public provision, increasingly at an international level. Markets are regulated to encourage competition amongst national players. Personal and social behaviour is shaped by commonly-held beliefs and customs.
4.2.2 Adaptation to flood risk

In the previous section the current flood defence system and levels of investment in maintenance and renewal were kept the same across all scenarios. In other words it was assumed that there would be no adaptation to climate or socio-economic change or in response to increasing flood frequency. In fact, these practices and standards will be modified in response to changing risks and society’s expectations for risk reduction. In other words, flood risk management policies and practices are scenario-dependent. In order to analyse the amount by which the risk estimates presented above may be reduced, a set of flood risk management policies and practices were identified for each scenario from the summary in Table 1 to manage the probability and consequences of flood risk. These packages of flood risk management measures are not policy prescriptions; they are merely intended to illustrate in an internally consistent way alternative plausible futures in order to inform long-term decision making.

Table 9 describes in qualitative terms the approach to flood risk management under the four scenarios, and subsequently how these have been translated into model parameters for the quantified risk analysis. Where possible, existing quantified values for UK Government Office regions (of which London is one) for the 2020s, 2050s and 2080s from Dahlström and Salmonds (2005) and Evans et al. (2004b) were used, and extrapolated to 2100. Key variables such as changes in employment, population, housing density that can be used as direct inputs into the flood risk calculation are listed in Table 7. Those areas of the Thames Gateway that fall outside the Greater London Authority boundary were parameterised using the Southeastern and Eastern Government Office regions also from the same studies. However, not all the necessary variables for a flood risk analysis have been quantified. Therefore, a quantified estimate was made by interpreting the qualitative scenario description, of the effect in each scenario of different landuse drivers would have on the distribution of people and employment in the future (Table 9). For example, the global responsibility governance structure lends itself to stronger planning regulation which is parameterised in the model in terms of increased flood resilient construction and a reduction in permitted developments in the floodplain. The utility of land use planning in the world markets scenario is reduced by a more laissez-faire attitude to governance. However, in this scenario the markets may still driver an increase in flood proofing of buildings. A full analysis of the cost of different interventions was not performed, but is reflected in a qualitative manner in the extent and type of interventions implemented. For example, in the World Markets future the largest defence crest level raise is made, whilst lower growth scenarios of Global Responsibility and National Enterprise cannot afford such large crest raising interventions. The portfolios chosen here are of course indicative – a wide range of different option portfolios could be developed and tested that would be considered consistent with each future.

The flood risk analysis outlined previously was used to calculate the effects of climate and socio-economic change by making appropriate modifications to the model parameters to reflect the time and scenario under consideration.

- Buildings & contents multipliers shown in Table 9 are used to scale changes to the depth-damage relationship to reflect changes to the value of buildings and contents under different futures.
- Population projections from the landuse model are converted into estimates of households based on changes in occupancy rates using the percentage adjustments shown in Table 9.
The defence crest levels used in the flood risk model are raised according to the values in Table 9 to test the effectiveness of structural measures within the different portfolio responses.

Land use planning policy is reflected by adjustments to the variables describing attractors and constraints of development in Equation 8-9 using the weightings in Table 9.

Floodproofing adaptations are tested by modifying the depth-damage relationships according to the changes shown in Table 8 and Figure 8.

Climate change scenarios are tested by adjusting storm surge levels and extreme river flows using the UKCIP02 scenarios listed in Table 3. The function, $\rho(l_e)$ describing the probability of extreme water levels at each embayment is recalculated.

Removal of developed property from the floodplain was implemented by reducing the number of houses by the given proportion, in equal decadal increments, over the analysis period.

The cumulative effect of each of the changes in the given scenario and its portfolio of adaptation measures was then calculated. The results are given in the following section.

### Table 8 Description of different floodproofing measures

<table>
<thead>
<tr>
<th>Floodproof measures</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temporary resistance</strong></td>
<td>Manually installed door guards and air brick covers, sump/pump and remedial works to seal water entry points.</td>
</tr>
<tr>
<td><strong>Permanent resistance</strong></td>
<td>Permanent floodproof external doors, automatic air bricks and external wall render / facing, sump/ pump and remedial works to seal water entry points.</td>
</tr>
<tr>
<td><strong>Resilience without flooring</strong></td>
<td>Resilient plaster (up-to 1m), lightweight internal doors, resilient windows and frames, resilient kitchen, raised electrics and appliances.</td>
</tr>
<tr>
<td><strong>Resilience with flooring</strong></td>
<td>Concrete/sealed floors, resilient plaster (up-to 1m), lightweight internal doors, resilient windows and frames, resilient kitchen, raised electrics and appliances.</td>
</tr>
</tbody>
</table>

![Figure 8 Depth damage functions for different floodproofing measures (after DEFRA, 2008)](image-url)
<table>
<thead>
<tr>
<th>Scenario</th>
<th>Implications for flood risk management</th>
<th>Model parameterisation</th>
<th>Further adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>National Enterprise</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low regulation and limited emphasis on the environment. Flood risk management is centrally managed with limited local capacity. Piecemeal 'traditional' engineering approaches dominate response.</td>
<td><strong>Flood defence</strong> Despite a focus on structural measures to reduce flood risk, the medium-low economic growth constrains deployment of expensive defence structures to areas at greatest risk.</td>
<td><strong>Development drivers and land use planning</strong></td>
<td><em>Medium low growth and funds available limits scale of infrastructure deployed</em></td>
</tr>
</tbody>
</table>
| | **Land use drivers** Development is driven by economic development zones designated to stimulate growth. There is a presumption towards new housing developments and a liberalised market and lower density living encourage people away from existing built up areas. Lower environmental emphasis reduces the attractiveness of investing in remediating previously developed land for new development. | **Development attractors**  
- Previously developed land: x0.75  
- Existing employment and population areas: x0.75  
- Thames Gateway development areas: x2  
- Less deprived areas: x2  
- Education and amenity: x2 | *Defence crest raising: +0.5m by 2030 and +1m total in 2060* |
| | **Vulnerability** Development controls remain similar to the present but a lack of coordination leads to some relaxation of regulation and enforcement. Weak building regulations means slow progress is made in flood-proofing new and existing buildings, with most provision from the private market. Insurance is widely (but not universally) available, with high premiums in vulnerable areas resulting in scattered and uneven uptake. | **Planning adaptation**  
- 20% of Greenbelt freed for development by 2020  
- Floodplain development policy remains the same | *Flood storage: reduces extreme flows by 10% in 2020* |
| | | | *Flood proofing of new build: 30% temporary resistance measures in 2030* |
| | | | *Insurance in 1 in 200 year floodplain: +20%* |
| | | | *Insurance in 1 in 75 year floodplain: +50%* |
| **Local Stewardship** | | | |
| A variety of approaches to flood risk management are envisaged across different areas, with little co-ordinated strategy. Low growth, low technology scenario means wealth does not keep pace with flood risk growth. Coupled with a greater focus on the environment, measures to reduce exposure and vulnerability to flooding are favoured over structural measures. | **Flood defence** Construction of new defences is limited by a preference for flood-management measures that have minimal environmental impact and low economic growth. Indirect and diffuse measures such as flood storage and managed retreat become preferred options. | | *Low growth and funds available precludes significant infrastructure and limits investment to maintenance of existing system* |
| | **Land use drivers** A community oriented approach to living encourages densification of existing development. A focus on environmental values encourages new development to prioritise previously developed land. More egalitarian markets and high quality local environments do not increase the attractiveness of high amenity or low deprivation areas. Strong regulation and enforcement prevents new development in floodplains. | **Development attractors**  
- Previously developed land: x5  
- Existing employment and population: x10  
- Thames Gateway development areas: -  
- Less deprived areas: -  
- Education and amenity: - | *Flood storage: reduces extreme flows by 20%* |
| | **Vulnerability** Rigid application of land use planning laws not only prevents new development, but leads to relocation of existing development away from the floodplain. Risks are shared through insurance, government payments, and community-based mechanisms. Access to these schemes is fairly even. Damage is reduced through changes in location and economic activity and acceptance of loss accelerates the uptake of floodproofing measures. | **Planning adaptation**  
- Development in greenbelt and floodplain constrained  
- Floodplain planning policy effectiveness: 100% by 2020  
- 25% existing floodplain development relocated by 2100 | *Flood proofing of new build: temporary resistance with resilience measures* |
| | | | *Government and community support do not lead to increased costs of floodplain insurance* |
World Markets
The wealthiest of the scenarios: by the 2080s GDP could be ten times (in real terms) its present value and is thus able to protect against the risks to which it is exposed. Free market provision of measures to reduce impacts of flooding, and few incentives for environmentally sensitive flood management leads to major engineering measures to keep pace with increasing flood risk.

Flood defence
Flood defences protect almost all developed areas to a very high standard making use of advanced technology, but at significant cost. Although there is little need for consideration of environmental issues, some coastal grazing marshes would be abandoned due to increasing flood risk and resources only able to cover more developed areas.

Land use drivers
Demand for development in flood prone areas remains, with development often driven by higher income groups. A free market reduces the effectiveness of Land-Use Planning and Management and prevents effective implementation of diffuse run-off reduction measures etc. Development plans are transformed into much less detailed development zones, and development controls as well as government policy in several areas are substantially relaxed, or even reversed, as with green belt policy.

Vulnerability
Insurance is generally widely available but the markets reflect higher flood risk in slightly increased premiums. New construction techniques reduce the damage from flooding events. Responses aimed at reducing flood losses reflect the individualistic attitudes of the scenario, with property owners taking responsibility for marked risk reductions through Flood-Proofing Buildings and Individual Damage Avoidance.

Global Responsibility
Government plays a leading role in providing a range of structural and non-structural measures and society is more willing to share risks. Increased environmental awareness, strategic regulation of development and management of impacts places flood management within broader environmental management of, for example, land use, water supply.

Flood defence
Developed areas and high value assets are typically protected by engineering structures, but will be designed to have minimal environmental impact and include, for example, managed realignment of the coast, and inland measures to maintain and enhance connections between rivers and floodplains, and to minimise the effect of activities in the catchment on flood runoff. Where budgets are too low to maintain defences, there would be active, managed realignment or planned abandonment with recreation of habitat where appropriate.

Land use drivers
Strong planning controls prevent development in the green belt, and restrict further developments in areas most vulnerable to flooding. Development zones remain similar, but opportunities are more equally distributed due to less deprivation.

Vulnerability
Building standards changes lead to expansion of the planning departments remit and enforcement of flood resilient construction and floodproofing of existing properties. Land use planning is generally preferred over physical measures to reduce exposure to flooding and supported by strengthened development controls. Governments prioritise access to insurance, and provide assistance to those who are without protection. Uptake of insurance is fairly even, although some limitations and restrictions remain.

Development attractors
- Previously developed land: x0.5 (reflects additional costs of developing used land)
- Existing employment and population: x0.5
- Thames Gateway development areas: x4
- Less deprived areas: x2
- Education and amenity: x2

Planning adaptation
- Development driven by markets
- Greenbelt development constrained
- Floodplain planning policy effectiveness: 70% by 2020

- High growth allows significant infrastructure construction
- Defence crest raising: +1m by 2020 and +2m total by 2050
- Flood resilience in new build: temporary resistance by 2020 and permanent resistance with resilience measures by 2040
- Flood proofing in existing stock: temporary resilience measures retrofitted by owners to 40% of floodplain houses by 2100
- Insurance in 1 in 200 year floodplain: +10%
- Insurance in 1 in 75 year floodplain: +30%
4.3 Results

Results of the flood risk scenarios analysis are summarised in Table 10. Net present risk has been calculated under stationery (i.e. considering only socio-economic change) and non-stationery climatic conditions. In all cases, risk is discounted according to HM Treasury (2009) guidelines (i.e. 3.5% for years 0-30, 3% for years 31-75 and 2.5% thereafter). Figure 9 shows the spatial distribution of increases in flood risk in different census wards at the end of the 21st Century for the four scenarios, relative to the estimated risk in 2005.

All four scenarios show an increase in flood risk resulting from socio-economic change alone. By the end of the 21st century, the risk analysis shows (in today's prices) that, in the worst case scenario considered here, risk may be 19 times greater in the Thames Estuary assuming no adaptation. However, the magnitude of this increase is highly socio-economic scenario dependent and greatest in the World Markets scenario. Increased floodplain occupancy is a key driver of this and is most prevalent in the World Markets and National Enterprise scenarios, but marked growth in household building and contents values also drives this rise. Only the Local Stewardship scenario does not see a sharp rise in flood risk as a result of socio-economic change.

Factoring in climate change amplifies risk yet further. Future flood risk in the Thames Estuary is most sensitive to changes to sea level rather than extreme river flows at Teddington. There is no direct correspondence between the climate and socio-economic scenarios, not least because the socio-economics are defined at the London and UK scales, whereas the climate scenarios are based on global emissions. However, an approximate correspondence might be expected, but this is not the only conceivable relationship and the results for other combinations are shown in Table 10. Based on the most likely correspondence, the greatest increase in flood probability is to be expected with the coupled World Markets - High UKCIP02 climate scenario.

Table 10 also summarises results for implementation of the adaptation portfolios described previously. In the first instance, only the land use planning adaptation strategies were implemented to explore the relative effectiveness of this particular non-structural management measure at reducing flood risk. The second adaptation uses the same land use planning policies, but also includes engineering measures as well as further non-structural measures such as flood resilient building and insurance. This influence of this full adaptation portfolio on flood risk is mapped spatially in Figure 9. These maps show how flood risk management measures, whether resulting from restricting floodplain development or raising defences temper the rise in flood risk in the highest growth scenarios, and can even reduce risk in some census wards under the Local Stewardship scenario. However, it is clear from the non-discounted risk in 2100 in Table 10 that the risk is substantially reduced across all scenarios as a result of the adaptation measures.

Societal and individual expectations for risk management are likely to be higher in the more consumer oriented scenarios of National Enterprise and World Markets. However, the cost of engineering protection is sensitive to the total amount of sea level rise (Burgess and Townsend, 2004). In relative terms the cost of providing the same level of protection under the World Markets scenario as the National Enterprise scenario is 30% higher, but National Enterprise is hindered by from substantially lower GDP growth (2% as opposed to 3.5%) which will constrain the resources
available for structural measures relative to World Markets. Moreover, these engineering works will be focused on protecting strategic industries. Although the Local Stewardship scenario has the lowest growth, it has to manage a smaller potential growth in flood risk and adaptations portfolios place a greater emphasis on non-structural measures that tend to have lower costs (Evans et al., 2004b). The emphasis on landuse planning and non-structural measures in the Global Responsibility scenario also demonstrate their potential to substantially reduce flood risk. Even within the World Markets economy, the cost of relying only on structural measures to achieve comparable risk reductions to those in Table 10 is likely to be prohibitive. More generally the effectiveness of non-structural measures, and their lower capital cost, suggests that under any future a portfolio of measures will realistically be required to manage flood risk.

Agricultural land is currently focused in the East of the estuary. Under the World Markets scenario only land that provides sufficient financial return is protected, with lower grade land being abandoned. Whilst, abandonment also occurs under the Global Responsibility scenario, the wider sustainability ambitions of this scenario produce an emphasis upon restoring habitat and enhancing the environment. In the Global Responsibility scenario, and particularly the Local Stewardship scenario, flood risk is projected to increase at a slower rate so there is likely to be less of an expectation for risk reduction which will be reinforced by their less individualistic, more equitable societies. Whereas governance in the Global Responsibility scenario is characterised by strategic and pre-emptive management of risks, the Local Stewardship response will be more spatially heterogeneous.
Figure 9 Maps of changes to flood risk from baseline, expressed in terms of expected annual damage, for the four Foresight scenarios with and without flood risk management measures. The baseline risk is shown in Figure 5.
Table 10 Results of scenario analysis showing net present risk values for a ‘basic’ permutation where development is not allowed on greenfield sites, but is otherwise uninfluenced by policy. The ‘planning adaptation’ calculates the risk after only the planning strategies in Table 9 have been implemented. The ‘other adaptation’ calculation includes all other responses to manage flood risk, also listed in Table 9. There is no direct correspondence between the socio-economic scenarios and the climate scenarios, but approximate matches are highlighted. For these cases, the undiscounted risk in 2100 is also given. For comparison the baseline risk in 2005 is £29m and the baseline net present risk, with no change in climate or socio-economics, would be £933m.

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<th>Socio-economic scenario</th>
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<tr>
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4.4 Discussion

An important observation is the balance between new development and climate in mediating future flood risk. In many scenario combinations, new development is responsible for over 50% of the increase in risk. This does not only highlight the important role spatial planning and broad scale development strategies in managing future risks, but also the importance of a much wider range of socio-economic variables (e.g. changed buildings and contents). This is in broad agreement with the observation of Maaskant et al., (2009) that population growth contributed more than sea level rise to an increase in flood related fatalities.

The systems approach seeks to represent the interactions between different functions and objectives. Here we have focused on flood risk, climate and socio-economic change and land use planning policy. In addition to policy insights, a key methodological development has been to deal with these processes from an integrated systems perspective in order to provide internally consistent quantified...
scenarios of long term change in to inform flood risk management and planning decisions. Given the complexity of interactions and the large range of possible futures and decision options, system-scale policy analysis of long term change would be challenging without the support of such an integrated assessment. The number of processes and interaction that could be included are potentially overwhelming and so inevitably, the analysis has made a number of simplifying assumptions. In developing future integrated assessments, the following steps are recommended:

- Define the policy questions that the assessment is seeking to address. This paper presented an approach for assessing the effectiveness of non-structural flood risk management measures.
- Identify the drivers of long term change and the processes of interaction that therefore need to be incorporated in the assessment. This study predominantly focused on climatic and socio-economic change.
- Define the policy options that are intended to be analysed and the metrics of assessment. The main options of interest have been insurance and planning policies.
- Develop a representative set of scenarios that spans the range of possible futures. The scenarios considered here included climate scenarios (based on UKCIP02) and socio-economic scenarios (based on UK Foresight).
- Quantify the performance of policy options in the context of a range of different scenarios. Performance has been described here in terms of a common currency of risk, expressed in terms of expected annual damages. Other performance metrics (e.g. expected fatalities as used by Maaskant et al. (2009)) could be used.

Although described linearly, in practise these should be implemented iteratively through regular interaction with stakeholders.

Long term projections of climate and socio-economic changes are fraught with uncertainty. We have made use of the full range of UKCIP02 climate scenarios (Hulme et al., 2002) and Foresight socio-economic scenarios (OST, 2002) to capture a representative range of uncertainty. As with other scenario studies these are plausible and internally consistent projections, conditional upon a clearly specified set of assumptions. However, to suppose that these processes could be forecast on a timescale of decades is quite unrealistic. Yet the scenarios enable reasonably plausible bounds on risk to be identified and policies can be tested in the context of these plausible bounds. These uncertainties may be large, but by exploring a range of possible futures we can identify options that are as far as possible robust to uncertainties. Recently published climate scenarios (UKCP09) could address uncertainties in climate models by sampling from the probability distribution of variables such as rainfall and sea level rise. In this case study sea level rise is the dominant driver of climate risk. Consideration of the central probability estimates from UKCP09 scenarios (Lowe et al., 2009) gives a sea level rise range of 0.40-0.56m, but expanding the sample to include the 5th and 95th percentiles the range broadens to 21-0.89m which is very similar to the range considered in the four scenarios here. The headline results presented here would therefore not be expected to change much, however, the UKCP09 scenarios would provide a much greater understanding of the sensitivity of risk analysis to climate uncertainties. UKCP09 also includes a H++ scenario (0.9-1.9m) which includes possible additional contributions to sea level rise from accelerated ice sheet dynamics is thought to provide a plausible but highly uncertain and very unlikely scenario for sea level rise. A risk analysis under such a large sea level rise scenario poses additional challenges (c.f. Dawson et al., 2005; Lonsdale et al., 2008).
5 Conclusions

To analyse the effectiveness of many non structural flood risk management measures requires a generic long term analysis framework to analyse long term changes to the flooding system. A new method which quantifies at a high spatial resolution the benefits in terms of risk reduction from non structural flood risk management measures has been presented. The integrated approach described here couples socio-economic and climate change scenarios with long term land use modelling and flood risk analysis.

The utility of the method for the appraisal of the effectiveness of non-structural measures has been demonstrated in the context of stakeholder generated scenarios of changes to insurance and planning policies. The analysis showed the potential efficacy of both regulatory and market incentives at managing future flood risk. These changes might be driven by many factors, but here stakeholder informed scenarios were used to highlighted how extreme events either in the UK or internationally might stimulate substantial shifts in UK planning controls and the insurance markets.

Packages of flood risk management measures were subsequently analysed under more complex and realistic scenarios of global environmental change. The method calculates the impact of local effects of local or national drivers of development and land use policies on flood risk which improves on the more usual approach of using scaling parameters to represent the effect on flood risk of such policies. These projections of flood risk allow the effectiveness of policies to be tested against different socio-economic futures in order to understand the implications of different drivers of future flood risk. The methodology is repeatable, transparent and auditable as the assumptions for each model parameterisation (i.e. reflecting the drivers of change) can be scrutinised in further studies.

Calculated in real terms, a major driver of increasing flood risk is the increasing value of domestic and commercial buildings and their contents. However, the extent to which society tolerates risk will determine willingness to pay to reduce risk through taxation or market measures such as insurance. In the absence of adaptation, flood risk in the Thames Estuary may increase by 19 times in present day costs by 2100 under UKCIP02 climate scenarios (although is unlikely to be greatly altered by UKCP09 scenarios). This also reflects the influence of climate change, particularly sea level rise. The risk analysis has considered only direct economic damages and not considered other risks, such as disruption to the economy or the loss of life which may be mitigated by other non-structural measures such as flood warning and evacuation. Under all four scenarios considered here, society is capable of adapting and significantly reducing flood risk using currently available measures. No single measure is likely to be capable of reducing, at least within a realistic budget and political constraints, flood risk by the amount achieved by the portfolio of measures used here. Landuse planning achieves flood risk reduction in all scenarios, but is most effective where stronger governance arrangements, whether driven by national strategy or local concerns about the environment, exist. Conversely, structural measures achieve the greatest reduction in more individualistic and less risk tolerant scenarios. More generally, and given our uncertain knowledge about longer term governance and growth rates, portfolios of flood risk management measures are most likely to deliver robust strategies under a wide range of possible futures.
Whilst the benefits of non-structural measures have, to date, been difficult to appraise it is clear that they can offer greater benefits in terms of reducing vulnerability if implemented within the right governance context. Moreover, the role of socio-economic change, which is more effectively curbed using non-structural measures, has potential to make a greater contribution towards changing flood risk than sea level rise. In appraising non structural flood risk management measures it is therefore crucial to take a long term view and understand the socio-economic and climatic drivers of change and attempt to address these drivers in an integrated manner. In doing so, flood risk managers will be better placed to construct portfolios of flood management measures that are robust against uncertainties surrounding future socio-economic and climatic changes – particularly those that are outside their control.

The integrated assessment presented in this paper is likely to be one of several sources of evidence that decision makers may employ when making difficult and often highly contested long term planning and flood risk management decisions. Yet it provides new insights and tools for policy analysis that were hitherto unavailable and, perhaps most significantly, proves a concept of evidence based system-scale analysis that shows enormous potential for improving decision making in future.

6 References


