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Quantified scenarios analysis of drivers and impacts of changing flood risk in England and Wales: 2030–2100

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Abstract

Flood risk to the economy, society and the environment reflects the cumulative effects of environmental and socio-economic change over decades. Long-term scenarios are therefore required in order to develop robust and sustainable flood risk management policies. Quantified national-scale flood risk analysis and expert appraisal of the mechanisms causing change in flood risk have been used to assess flood risk in England and Wales over the period 2030–2100. The assessment involved the use of socio-economic and climate change scenarios. The analysis predicts increasing flood risk unless current flood management policies, practices and investment levels are changed—up to 20-fold increase in economic risk by the 2080s in the scenario with highest economic growth. The increase is attributable to a combination of climate change (in particular increasing precipitation and relative sea level rise in parts of the UK) and increasing socio-economic vulnerability, particularly in terms of household/industrial contents and infrastructure vulnerability. The policy implications of these findings are discussed.

Keywords: Flood risk; Vulnerability; Climate change; Socio-economic scenarios

1. Introduction

Recent flooding in the UK has illustrated the potential impact of floods not only on the UK economy but also on the health and well-being of communities. This pattern of increasing flood damage is repeated worldwide.[1] Concerns persist about the potential for climate change to increase the frequency of flooding in the 21st Century (Doornkamp, 1998; Dorland, 1999; Smith, 1999; Schreider, 2000; Frei, 2000; Palmer and Räisänen, 2002; Milly et al., 2002).

The study described in this paper was a systematic attempt to understand and where possible quantify the extent and scale of risks from flooding in England and Wales over a time-scale of 30–100 years in the future. The purpose of analysis was to (i) establish the potential scale of the flooding problem (ii) identify the processes that are driving future flood risk and the approximate magnitude of their contribution to risk, and (iii) identify limitations to the current flood management policy and practice. By doing so, the analysis is intended to provide the basis for identification and analysis of policy responses to future risks, in particular those whose implementation may take several decades.

Previously, attempts have been made to quantify specific aspects of long-term change in flood risk, in particular the potential change in flood frequency in the UK due to climate change (Arnell and Reynard, 1996;

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[1] See for example Mileti (1999) for an account of increasing damage from natural hazards, including flooding, in the USA.

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Arnell, 1998; Reynard et al., 2001; Crooks and Reynard, 2002). However, integrated assessment of the type described in this article, which deals with climatic and socio-economic changes, has only to date been applied for selected regions of England (Nicholls, 2001; Nicholls and Wilson, 2001). Before the emergence of climate impact studies, analysis of change in flood risk on a time-scale of decades was practically unheard of. Progress in integrated assessment using scenarios of climate and socio-economic change (Bruce et al., 1996) has provided some methodological framework for the approach proposed here. Moreover, in recent years tools for quantified assessment of flood risk on a national scale have become available (Entec and JBA, 2000; Deakin et al., 2001; Hall et al., 2003a), although they have not until the current study been used for systematic scenarios analysis. These new flood risk assessment tools are severely limited by the availability of data, particularly relating to the reliability of flood defence systems. The quantified risk analysis methodology adopted was designed to make use of datasets held by the Environment Agency of England and Wales, so the study excludes the remainder of the United Kingdom where physical and socio-economic conditions and flood management practices are rather different.

The analysis described in this article has two strands: (1) a quantified analysis of future risks of fluvial, coastal and urban flooding England and Wales and potential impacts on the economy, people and the environment; and (2) expert analysis of drivers of future flood risk, ranking of their importance and analysis of interactions and uncertainties. These tasks were conducted by a multi-disciplinary team of experts, overseen by a panel of stakeholders and subject to peer review.

In order to adopt a consistent approach to this multi-disciplinary task a conceptual framework is introduced in the following section. The quantified flood risk assessment and driver analysis that are then discussed were set within this conceptual framework.

2. Analysis methodology

2.1. Conceptual framework

Integrated assessment of flood risk involves a broad definition of the flooding system. For the purposes of this study, the flooding system was viewed as encompassing all of those physical and organisational systems that influence or are influenced by flooding (Hall et al., 2003b), as follows:

- The physical attributes of the earth's surface involved in the water cycle, i.e., the processes of rainfall, snow melt, and marine storms that lead to fluvial and coastal flooding, runoff from the land, groundwater flows, and flood inundation in fluvial floodplains and coastal lowlands.
- The artificially created systems of drainage, storage, and flood defence that are intended to convey flood discharges and resist or control inundation of floodplains.
- The economic, social, and environmental assets that are located in floodplains and are impacted upon by flooding and/or have an impact on the flooding process.
- The organisations with a statutory responsibility for managing flood risk. These may be government organisations or other organisations with duties or powers to manage flood risk.
- Insurers, who provide cover for flood risks.
- Broader stakeholder groups who have an interest or role in the impacts (both positive and negative) of flooding and the actions that they may take to manage flooding.

Change in the flooding system can be conceptualised using the Pressure-State-Impact-Response (PSIR) model (Turner et al., 1998), based on Rapport and Friend's (1979) Pressure-State-Response model. In the PSIR model:

1. Socio-economic drivers lead to environmental pressures.
2. Environmental pressures lead to changes in environmental state.
3. Changes in environmental state are reflected in environmental and socio-economic impacts.
4. Stakeholder gains/losses from impacts lead to policy responses.

Whilst the PSIR framework deals with the changes in system state, further conceptual structure is required to evaluate instantaneous system state in terms of risk. A well-established framework in environmental risk assessment is the Source-Pathway-Receptor (SPR) model (DETR et al., 2000), which is based upon the causal linkage between the source of environmental hazard (for example a pollutant), the mechanism by which it is transmitted (for example in the groundwater) and the receptor, which suffers some harmful (in the case of pollution) impact. The same framework is useful in the context of flooding, as it reflects the physical processes by which flooding occurs. In the case of flooding:

- *Sources* are the weather events or sequences of events that may result in flooding (e.g. heavy or sustained rainfall, marine storms).
- *Pathways* are the mechanisms that convey flood waters that originate as extreme weather events to places where they may impact upon receptors. Pathways therefore include fluvial flows in or out of river channels, overland urban flows, coastal

processes, and failure of fluvial and sea defence structures or urban drainage systems.

- *Receptors* are the people, industries, and built and natural environments that may be impacted upon by flooding.

The division between sources, pathways, and receptors is not crisp and depends upon the context of the analysis, though this indeterminacy should not, in principle, be problematic.

The instantaneous flooding system state can be captured in terms of a set of state variables that characterise flooding sources, pathways, receptors, or a combination thereof. Typical state variables might be flood defence levels, numbers of properties in the floodplain, etc. Some state variables may be naturally fluctuating, for example rainfall intensity or tide level in an estuary, so will be characterised by probability distributions representing (stationary) time-averaged behaviour.

The changes in the flooding system captured in the PSIR model are reflected in changes in the state variables over a range of time scales. Any phenomenon that may change the time-averaged state of the flooding system is referred to as a *driver*. Some of these drivers will be under the control of flood managers, e.g. construction and operation of flood defence systems, or use of flood warning systems to reduce the consequences of flooding (i.e., reduce the number of human receptors). Many other drivers, e.g. rainfall severity, or increasing values of house contents, are outside the control of flood managers and even government in general. The distinction between these two types of drivers is not crisp and in terms of policy relates to the extent to which government has power to influence change and the level of government at which power is exercised (Fig. 1). For example, decisions regarding local flood defence improvements decisions are devolved to local decision-makers, whereas decisions to limit emissions of greenhouse gasses are taken at a national and international level.

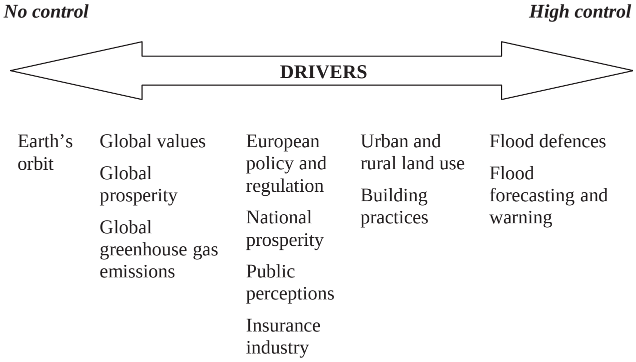

Fig. 1. Example drivers classified according to degree of control.

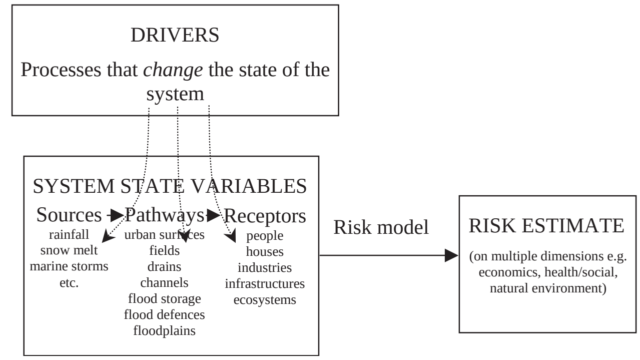

Fig. 2. Summary of conceptual framework.

The conceptual framework introduced above is summarised in Fig. 2. The flooding system is described in terms of a set of state variables that characterise flooding sources, pathways, receptors, or a combination thereof. A multi-attribute risk measure is used to characterise flood system behaviour with respect to stakeholder values. Future changes in risk (due to the influence of drivers) are estimated by making appropriate changes to state variables and estimating the consequent change in risk.

There may be feedback in the flooding system, particularly as the consequences of an impact on the environment may result in an alteration of the flooding pathways (and potentially sources) that then influence future SPR relationships. This is particularly important for climate change where long-term impacts are likely to result from interaction of earth surface and socio-economic processes perhaps leading to wholesale changes in land use, aquatic character, etc. It is conceivable that these interactions may represent some of the greatest threats and opportunities for flood management in the long term. It is argued that these complex interactions over timescales of decades do not succumb to conventional quantified risk analysis (IPCC, 2000) so a scenarios-based approach has been adopted.

2.2. Scenarios analysis

The use of scenarios for policy analysis far into the future has been stimulated by the long-term nature of climate change and the socio-economic uncertainties surrounding greenhouse gas emissions and projections of societal vulnerability. Flood defence is an interesting application of the scenarios-based approach because it involves integrated use of two different types of scenarios:

- Climate change projections are based on *emissions scenarios*. Climate change is the key driver relating to the flooding 'source' variables in the SPR model.
- *Socio-economic scenarios* provide the context in which flood management policy and practice will be

enacted and relate to the extent to which society may be impacted upon by flooding.

The UKCIP02 climate scenarios for the UK (Hulme et al., 2002) have been used. These scenarios are based on four emissions scenarios: Low emissions; Medium-Low emissions; Medium-High emissions; and High emissions, corresponding to the IPCC's SRES (IPCC, 2000) scenarios B1, B2, A2, and A1F1, respectively. The UKCIP02 scenarios predict that annual average precipitation across the UK may decrease slightly, by between 0% and 15% by the 2080s depending on scenario. The seasonal distribution of precipitation will change, with winters becoming wetter and summers becoming drier, the biggest relative changes being in the South and East. Under the High Emissions scenario winter precipitation in the South and East may increase by up to 30% by the 2080s. By the 2080s the daily precipitation intensities that are experienced once every 2 years on average may become up to 20% heavier. By the 2080s and depending on scenario relative sea level may be between 2 cm below and 58 cm above the current level in western Scotland and between 26 and 86 cm above the current level in South East England. For some coastal locations a water level that at present has a 2% annual probability of occurrence may have an annual occurrence probability of 33% by the 2080s for Medium-High emissions. The climate change scenarios included within UKCIP02 do not include allowance for model error and do not therefore represent the maximum potential range of climate change effects.

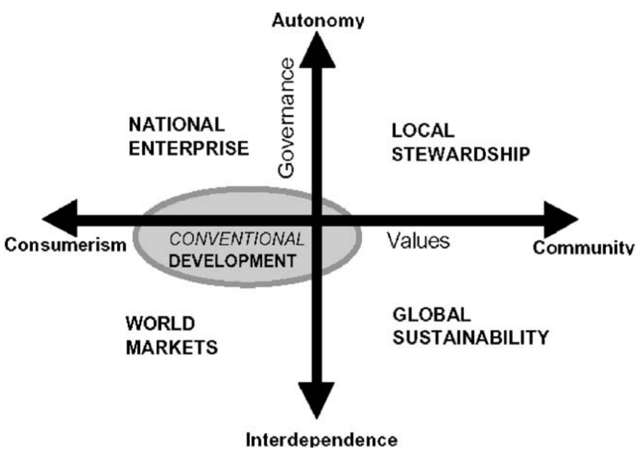

Fig. 3. Foresight Futures (SPRU et al., 1999; OST 2002).

The Foresight Futures socio-economic scenarios (SPRU et al., 1999; OST, 2002) are intended to suggest possible long-term futures, exploring alternative directions in which social, economic, and technological changes may evolve over coming decades. The scenarios are represented on a two-dimensional grid (Fig. 3). 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, for example the European Union or regional government. On the horizontal dimension are social values, ranging from individualistic values to community-oriented values. The four Foresight Futures that occupy this grid are summarised in Tables 1 and 2.

Table 1
Summary of Foresight Futures (OST 2002)

	World markets	National enterprise	Global sustainability	Local stewardship
Social values	Internationalist, libertarian	Nationalist, individualist	Internationalist, communitarian	Localist, co-operative
Governance structures	Weak, dispersed, consultative	Weak, national, closed	Strong, co-ordinated, consultative	Strong, local, participative
Role of policy	Minimal, enabling markets	State-centred, market regulation to protect key sectors	Corporatist, political, social and environmental goals	Interventionist, social and environmental
Economic development	High growth, high innovation, capital productivity	Medium-low growth, Low innovation, Maintenance economy	Medium-high growth, high innovation, resource productivity	Low growth, low innovation, modular and sustainable
Structural change	Rapid, towards services	More stable economic structure	Fast, towards services	Moderate, towards regional systems
Fast-growing sectors	Health & leisure, media & information, financial services, biotechnology, nanotechnology	Private health and education, Domestic and personal services, Tourism, Retailing, Defence	Education and training, Large systems engineering, New and renewable energy, Information services	Small-scale manufacturing, Food and organic farming, Local services
Declining sectors	Manufacturing, agriculture	Public services, civil engineering	Fossil fuel energy, Traditional manufacturing	Retailing, tourism, financial services
Unemployment	Medium-low	Medium-high	Low	Medium-low (large voluntary sector)
Income	High	Medium-low	Medium-high	Low
Equity	Strong decline	Decline	Improvement	Strong improvement

Table 2
Snap shot statistics for 2050s for Foresight Futures (UK Climate Impacts Programme 2000)

	Mid 1990s	World markets	National enterprise	Global sustainability	Local stewardship
Population (million)	58.5	59	57	57	55
GDP growth per year (%)	2	3	1.75	2.75	1.25
GDP (current prices)	£615 billion	£3600 billion	£1700 billion	£2300 billion	£1300 billion
GDP/capita	£10,500	£61,000	£31,000	£41,000	£24,000
Land use (%)					
Agricultural	75	60	70	70	75
Urban	15	22	19	15	14
Forest, woodland	10	18	11	15	11

Table 3
Correspondence between UKCIP02 scenarios and foresight futures

SRES	UKCIP02	Foresight futures 2020	Commentary
B1	Low emissions	Global Sustainability	Medium-high growth, but low primary energy consumption. High emphasis on international action for environmental goals (e.g. greenhouse gas emissions control). Innovation of new and renewable energy sources.
B2	Medium-low emissions	Local Stewardship	Low growth. Low consumption. However, less effective international action. Low innovation.
A2	Medium-high emissions	National Enterprise	Medium-low growth, but with no action to limit emissions. Increasing and unregulated emissions from newly industrialised countries.
A1F1	High emissions	World Markets	Highest national and global growth. No action to limit emissions. Price of fossil fuels may drive development of alternatives in the long term.

There is no direct correspondence between the UKCIP02 scenarios and the Foresight Futures 2020, not least because the Foresight Futures are specifically aimed at the UK whereas the emissions scenarios used in UKCIP02 are *global* emissions scenarios. However, an approximate correspondence can be expected, as shown in Table 3. This is not the only conceivable correspondence and several alternatives are explored by the UK Climate Impacts Programme (2000).

2.3. Quantified flood risk assessment

In recent years, it has become possible to do approximate national-scale analysis of the risks from river and coastal flooding in England and Wales. The same is true of the risks of urban flooding (due to sewer flooding and insufficient capacity in the urban drainage system), where urban drainage models can be up-scaled to generate national estimates of the risks of urban flooding. Inevitably, these approximate models contain a great deal of uncertainty and are not appropriate for detailed local analysis. However, they do provide a broad impression of the scale and distribution of flood risk, so provide a powerful tool for policy analysis.

Hall et al. (2003a) developed a quantified model for assessment of flood risk from rivers and the sea that takes explicit account of the reliability of flood defences and their modifying effect on flood risk. The methodology was developed to make use of the following GIS databases for all of England and Wales and no other site-specific data:

1. *Indicative floodplain maps*, which are outlines of the area that could potentially be flooded, in the absence of flood defences, in a 1:100 year return period flood for fluvial floodplains and a 1:200 year return period flood for coastal floodplains.
2. *1:50,000 maps with 5 m contours*, which were used to classify floodplain types. Flood depths were estimated from statistical data for given floodplain types and widths rather than being calculated on a site-specific basis.
3. *National centreline map of all watercourses*.
4. *National flood and coastal defence database*, which provides the location, type, and condition of all flood defences, together with an estimate of the return period of the flood for which they were designed.
5. *National databases of residential and business properties*.
6. *Population census data*.

The flood risk assessment method operates on a GIS, first identifying interconnected floodplain areas and the system of defences protecting them from flooding. Information on the flood defence design standard, type, and condition is used in an approximate reliability analysis of each system of flood defences. A parametric flood spreading routine is used to estimate flood depths in a large number of combinations of flood defence failure in flood events of different severity, and hence estimate a probability distribution of flood depth in each area, no greater than $1\,km \times 1\,km$, in the floodplain. These depth–probability relationships are combined with census data and commercial databases of property and population location, together with relationships between flood depth and economic damage that have been developed from empirical analysis of past flooding events (Penning–Rowsell et al., 2003). No discounting or inflation is applied to economic risks. Risk is estimated at time points in the future using today's prices. The results have been aggregated and are reported nationally, regionally and on a $10\,\text{km} \times 10\,\text{km}$ grid. An estimate of the risk to lives, health, and communities was obtained by analysing population density and census data indicating the potential vulnerability of difference sectors of the community to flooding (Tapsell et al., 2002).

The flood risk assessment model has been used for a national assessment of the risk from flooding in 2002 (HR Wallingford, 2003; Sayers et al., 2003), and this 2002 analysis was used as a basis for comparison with future changes. The 2002 analysis has been compared with recent flood events to assess the dependability and uncertainties in the methodology (HR Wallingford, 2003). The annual average flood damage estimate of roughly £1billion is of the same order to, but somewhat larger than, annual losses due to flooding averaged over recent years. Some of the inconsistency is explained by reporting of recent flood events and by assumptions in the model (particularly the exclusion of emergency repair works). The reasonably good correspondence between model and observations indicates that the model does provide a sound basis for comparative evaluation of future scenarios.

The method is computer-intensive, and 2002 analysis took several weeks to compute, with separate computers being dedicated to each region of the Environment Agency of England and Wales. The computational aspects, in particular the interaction with the GIS database, have since been refined, so that each scenario analysis reported here took about a week to compute.

In addition to the national-scale risk modelling of flooding from rivers and the sea, quantified analysis was made of the effects of long-term change on the frequency of urban flooding. The approach adopted was based on analysis of three typical cities: a market town in northern England, and inland city with major watercourses in Scotland and a coastal city in Wales. Results from these locations were then up-scaled based on asset data from water service providers. This present-day analysis was combined with scenarios of rainfall depth, duration, and frequency; asset deterioration; urbanization; and changing vulnerability.

The models outlined above were used to analyse the long-term change by making appropriate changes to the model parameters to reflect the time and scenario under consideration. The four scenarios listed in Table 3 were analysed for the 2080s and chosen to coincide with the years for which climate scenarios were available (Hulme et al., 2002). The input data required by the risk assessment models do not correspond exactly to the information provided in either in climate change or socio-economic scenarios. It was therefore necessary to construct approximate relationships between the variables for which scenarios information was available and the variables required for flood risk analysis. A summary of the relationships adopted in the analysis of risks from river and coastal flooding is provided in Table 4. A quantified estimate was made of the effect in each scenario that a given change, for example urbanisation, would have on the relevant variables in the risk model (Table 4). The cumulative effect of each of the changes in the given scenario was then calculated. Where feasible, regional variation was applied to these adjustments in order to take account of, for example, regional differences in climate or demographic projections. There is no unique mapping between a scenario, which is an inherently vague entity, and a realization of the risk model. In other words, there is not a unique representation of the scenario in the risk model. The quantified analysis presented here is one of many equally plausible representations of the same four scenarios. Whilst no claim is made to the uniqueness of these results, they do illustrate some striking contrasts between different scenarios of change and provide the basis for exploring responses to flood risk that are robust across plausible futures. The approach is summarised in Fig. 4. The final step in Fig. 4 represents a cross-check with the expert analysis of drivers described below.

Future flood risk is greatly influenced by flood management policy and practice, perhaps more so than it is by changes outside the control of the flood manager, such as climate change or economic growth. However, in the analysis described here, current flood dike alignment and levels of investment in maintenance and renewal were kept the same across all scenarios. Clearly, flood management policy will change in the future and will tend to reflect the nature and public expectations of future society, i.e., flood management is scenario-dependent. However, the aim of the current study was to inform present-day policy makers and, in order to do that, the present day flood management policy was subjected to particular scrutiny by analysing its effectiveness in a range of scenarios. Changing scenarios were super-imposed on this fixed flood management policy (including the current pattern of expenditure and technical approach), in order to assess the capacity of the current policy to cope with long-term changes.

2.4. Expert analysis of drivers

The quantified analysis of future flood risk described above provides an impression of how risk may change in future under a range of different climate change and

Table 4
Representation of risk drivers in quantified analysis

Variable used risk model	Explanation	Changes that may be represented with this variable
Standard of Protection (SoP) of flood defences	The return period at which the flood defence (or where none exists the river bank) is expected to overtop.	Climate change[a] Changes in land use management (which may change run-off and hence river flows and water levels) Morphological change (that may also influence the conveyance of the river and hence water levels)
Condition grade of flood defences	An indicator of the robustness of the defences and their likely performance when subjected to storm load	Morphological changes Maintenance regimes
Location of people and properties in the floodplain	Spatially referenced database of domestic and commercial properties. Census data on occupancy, age, etc.	Demographic changes Urbanisation Commercial development
Flood depth–damage relationships	Estimated flood damage (in £ per house or commercial property) for a range of flood depths	Changes in building contents Changes in construction practices
Social flood vulnerability indices[b]	An aggregate measure of population vulnerability to flooding, based on census data	Changes in demographics (e.g. age) Changes in equity
Agricultural land use classification in the floodplain	Agricultural land grade from 1 (primearable) to 5 (no agricultural use)	Changed agricultural practices Agricultural land being taken out of use
Reduction factors	Measures that will reduce total flood damage, e.g. flood warning and evacuation can be reflected by factoring the estimated annual average damage	Flood warning (including communications technologies) and public response to warning Evacuation Community self-help

[a] For example a scenario in which if climate change is expected to increase water levels by 20% is represented by reducing the SoP of flood defences by an appropriate increment.
[b] Tapsell et al. (2002).

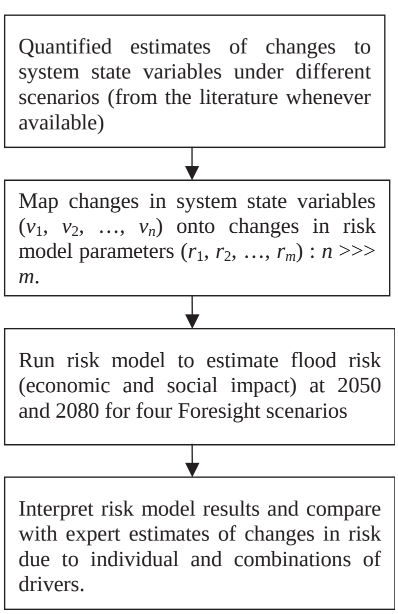

Fig. 4. Overview of methodology for implementation and interpretation of national-scale flood risk analysis.

socio-economic scenarios. However, it does not provide specific insights into the contribution that different drivers of change make to the total risk. To do so would require a large number of sensitivity runs, which were not feasible in the context of the present study given the considerable computational expense of each national-scale flood risk assessment model run. Moreover, the approximate risk analysis tools described above could not resolve the effects of all of the potential drivers of change.

In order to provide an insight into the importance of individual drivers to the overall flood risk, a ranking methodology, based on expert judgement, was employed. First, the drivers of changing flood risk were identified in a brainstorming session and clustered into a manageable number of driver sets (Table 5). The future change in each driver was described and, where possible, quantified using evidence from the literature. As in the quantified flood risk analysis described above, flood management activities were assumed to remain constant and were excluded from the analysis.

Drivers were ranked according to an expert assessment of their impact on total flood risk in England and Wales at two specified times in the future (2050s and 2080s) under four scenarios, relative to present day flood risk. For the purposes of this analysis, flood risk was defined as the product of the likelihood and consequences of flooding, and an aggregate measure of

Table 5
Summary of drivers of changing flood risk

Driver Set	Drivers	SPR classification	Explanation
Catchment runoff	Precipitation	Source	Quantity, spatial distribution of rainfall and intensity. Rain/snow proportion
	Urbanisation	Pathway	Changes in land surface (e.g. construction of impermeable surfaces and storm water drainage systems)
	Rural land management	Pathway	Influences the function of surface and sub-surface runoff. Changes include the proportion of conservation/recreation areas and wetlands
Fluvial Processes	River morphology and sediment supply	Pathway	Changes in river morphology that influence flood storage and flood conveyance
	River vegetation and conveyance	Pathway	Changes in river vegetation extent and type, for example in response to climate change or due to changed maintenance or regulatory contraints
Coastal processes	Relative sea level	Source	Increases in mean sea level due to climate change. Uplift/subsidence of land
	Waves	Source	Wave height and direction
	Surges	Source	Temporary increases in sea level above astronomic tide level, resulting from reduced atmospheric pressure and the action of strong winds
	Coastal morphology and sediment supply	Pathway	Changes in the nearshore seabed, shoreline and estuaries. May be the consequence of anthropogenic activities such as dredging, reclamation and coastal protection
Societal changes	Public behaviour	Pathway	Behaviour of floodplain occupants before, during and after floods can significantly modify their severity
	Social vulnerability	Receptor	Changes in social vulnerability to flooding, for example due to changes in health and fitness, equity and systems of social provision
Economic changes	Buildings and contents	Receptor	Changes in the cost of flood damage to domestic, commerical and other buldings and their contents (e.g. due to increasing vulnerability of domestic and commerical goods or increasing domestic wealth)
	Urban vulnerability	Receptor	Changes in the number and distribution of domestic, commerical and other buildings in floodplains
	Infrastructure	Receptor	Systems of communication (physical and telecommunication), energy distribution, etc. Changes in the extent to which society is dependent on these systems
	Agriculture	Receptor	Changes in the intensity and seasonality of agriculture, including removal of agricultural land from production and hence changes vulnerability to flood damage

economic and health/social consequences was adopted. Environmental consequences were excluded and are discussed separately below. Drivers that influence the sources or pathways in the flooding system change the likelihood of flooding. Drivers that influence the receptors in the flooding system change the consequences of flooding. The effect of the driver was expressed as a multiple of present day risk. Thus, climate change that increased the frequency of flooding by a factor of 1.9 on average nationally would be scored as having an impact of 1.9 on the likelihood of flooding. A driver that increased the quantity of assets at risk in the floodplain by a factor of 1.6 on average nationally would be scored as having an impact of 1.6 on the consequence of flooding.

Some drivers are spatially distributed in their impact. For example, sea level rise only impacts upon coastal floodplains, which currently contribute 26% of expected annual damage in England and Wales, rising to an estimated 46% by the 2080s. In order to compare drivers, the impact score was factored according to the spatial extent of the driver's influence. Suppose that without consideration of spatial extent, a driver affecting only coastal floodplains (for example sea level rise) is estimated to increase the present day risk in coastal floodplains by a multiple c in the 2080s, then the corresponding multiple n to flood risk nationally is given by $n = 1 + 0.46(c - 1)$.

Elicitation of ranking values began with circulation of a protocol explaining the ranking methodology to each of the 15 experts. Their expertise overlapped so each driver was the subject of the judgement of multiple experts. First, each driver was evaluated independently. These scores were then presented, discussed, and if necessary amended in a group moderating session. Finally, the scores were further reviewed when compared with the results of the quantified risk analysis introduced above and then subjected to wider peer review via two workshops with 21 and 34 attendees, one open meeting attended by 131 people, and electronic publication of draft results.

3. Results and discussion

3.1. Quantified flood risk assessment

The results of national-scale flood risk assessment are summarised in Table 6. Large increases in the number of people occupying the floodplain in the UK are envisaged in the relatively loosely regulated World Markets and National Enterprise scenarios. Floodplain occupancy is kept stable in the Global Sustainability and Local Stewardship scenarios. However, increasing flood frequency, primarily due to climate change means that even with stable numbers of people in the floodplain, the number of people at risk from flooding more frequently than 1:75 years will increase in all scenarios, assuming that current flood defence systems are continued into the future. Greater climate change by the 2080s, together with the increased floodplain occupancy noted above means that the World Markets and National Enterprise scenarios will see more than twice the number of people at risk from flooding more frequently than 1:75 years.

In all scenarios other than the relatively low growth Local Stewardship scenario, annual economic flood damage is expected to increase considerably over the next century assuming the current flood defence policies are continued into the future. A roughly 20-fold increase by the 2080s is predicted in the World Markets scenario, which is attributable to a combination of much increased economic vulnerability (higher floodplain occupancy, increased value of household/industrial contents, increasing infrastructure vulnerability) together with increasing flood frequency.

Change in the ratio of flood risk to per capita GDP provides an indication of how severe or harmful (in economic terms) flooding will be when compared with economic growth over the next century. In the World Markets and National Enterprise scenarios, flooding is expected to remove a greater proportion of national wealth than it currently does (and thus merit a greater investment to reduce risk). In the Local Stewardship and Global Sustainability scenarios, flooding is predicted to remove a lesser proportion of national wealth since these scenarios tend to be less vulnerable to flood damage and are expected to be subject to somewhat less climate change.

The pattern for flood damage to agriculture is rather different to the pattern from economic damage as a whole. At present, agricultural losses account for only about 0.5% of economic damage due to flooding. This loss is very small in economic terms, but can represent considerable impact on the rural economy. In the globalized World Markets scenario, the proportion of agricultural losses is projected to decrease, since a greater proportion of agricultural products are being imported (though the effect of climate change on agriculture globally has not been considered) and low-grade agricultural land is being taken out of production. Agricultural damage in the more self-sufficient National Enterprise and Local Stewardship scenarios is expected to be more significant.

By way of baseline, the spatial distribution of flood risk based on 2002 data is presented in Fig. 5. Highest economic risk is located in floodplain areas of high economic value, notably Greater London despite very high standards of flood protection. A number of areas of high coastal flood risk are located along the South, East, and North-West coasts of England. The distribution of the increase in expected annual economic damage for the World Markets 2080s scenario, relative to 2002, is illustrated in Fig. 6. Increasing risk is predicted to be concentrated in broadly the same areas as where it is currently highest. London and the Thames Estuary (due to rapid urbanisation), the South East coast (due to rising relative sea levels), and urban areas of Northern England (due to high predicted increases in intense rainfall) stand out as areas where the growth in economic risk will be greatest.

Table 6
Summary of flood risk assessment for England and Wales (excluding sewer flooding)

	2002	World markets 2080s	National enterprise 2080s	Global sustainability 2080s	Local stewardship 2080s
Number of people within the indicative floodplain (millions)	4.5	6.9	6.3	4.6	4.5
Number of people exposed to flooding (depth > 0 m) with a frequency > 1:75 years (millions)	1.6	3.5	3.6	2.4	2.3
Expected annual economic damage (residential and commercial properties) (£billions)	1.0	20.5	15.0	4.9	1.5
Annual economic damage relative to GDP (%)	0.10	0.14	0.31	0.06	0.05
Expected annual economic damage (agricultural production) (£millions)	5.9	34.4	41.3	43.9	63.5

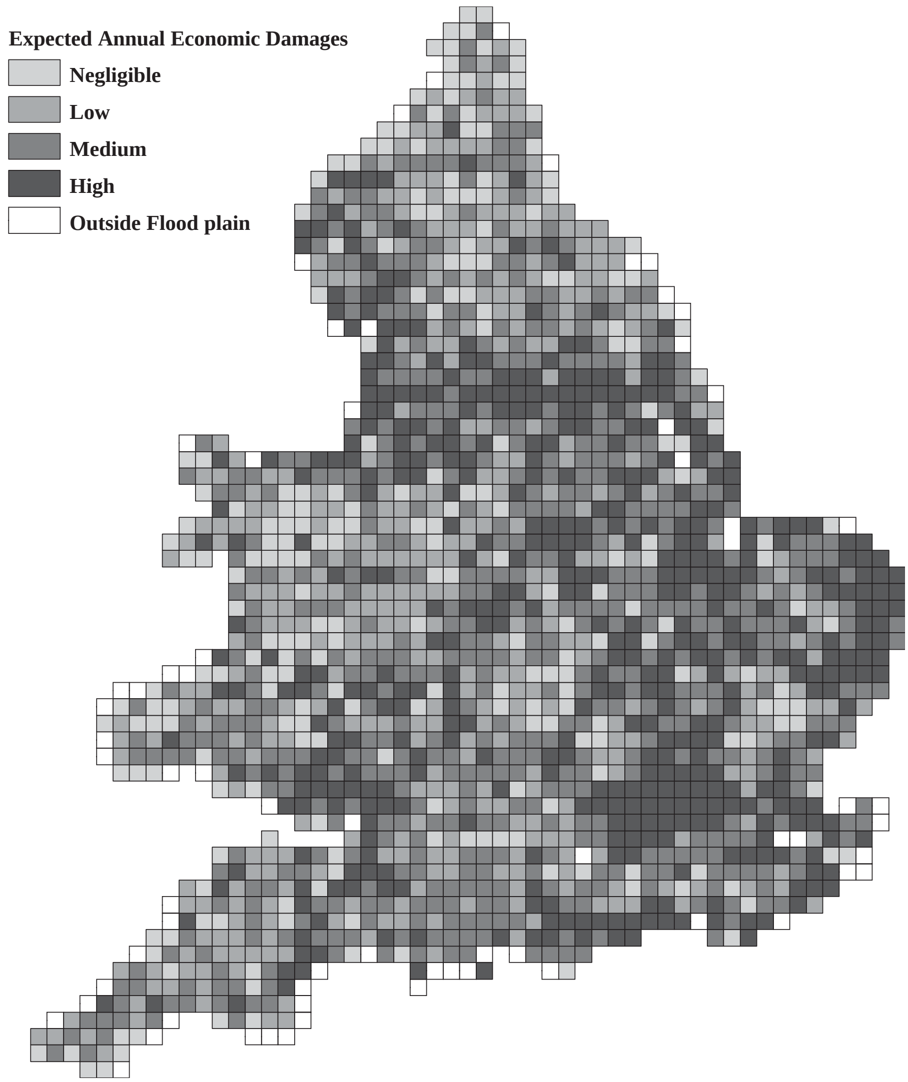

Fig. 5. Annual average economic damage: 2002.

The annual economic cost of property flooding from sewers is currently estimated to be £270million. This damage is expected to increase considerably due to increasing rainfall frequency and intensity, limited capacity of ageing sewer infrastructure, and increasing urban density and economic vulnerability to flooding (Table 7). The figures listed in Table 7 are in addition to the risk estimates due to flooding from main rivers and the sea (Table 6).

The environmental impacts of the changes to flooding outlined above need to be set in the context of major human-made modifications of rivers and coasts in the UK in the past, particularly during the 20th Century. Flood and coastal defences (and associated land drainage) have been a major contributory factor to the loss of fluvial and coastal ecosystems. Ecosystem changes over the period 2030–2100 are expected to be most obvious on the coast. Coastal grazing marsh is predicted to be the most threatened coastal habitat under all four scenarios, as inter-tidal losses are likely to be offset by planned and unplanned coastal abandonment (Nicholls, 2001). On river floodplains, removal of agricultural land from production (which will be widespread in some locations under some scenarios) will yield environmental benefits. The environmental status of many ecosystems will depend on the (scenario-dependent) regime of environmental regulation and protection.

3.2. Expert analysis of drivers

The scores for each driver are presented in Table 8 as increases (in terms of a multiple) of present day national flood risk that will be attributable to the given driver on the time-scales and in the scenarios indicated. The total effect of all drivers will depend on the interactions between them, but the implied increases in economic risk of flooding, assuming

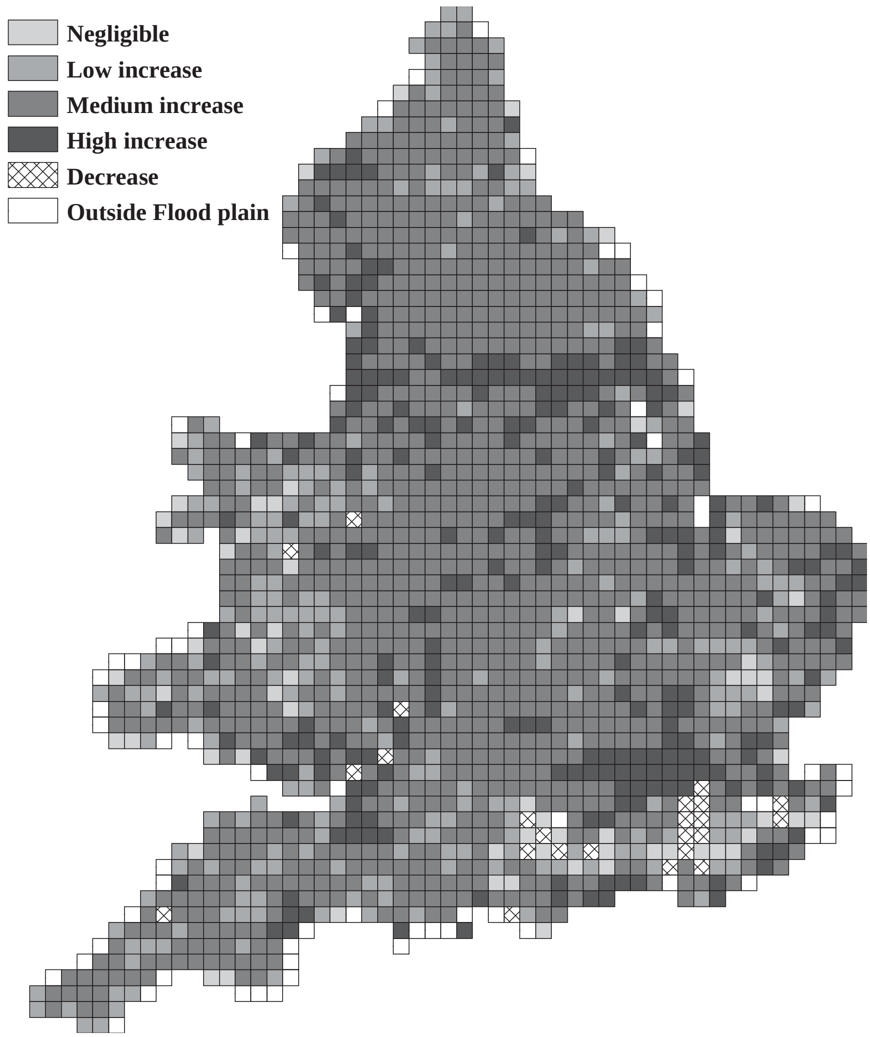

Fig. 6. Increase in annual average economic damage: World Markets scenario, 2080s compared with 2002.

Table 7
Estimated annual cost of sewer flooding

	2002	World markets 2080s	National enterprise 2080s	Global sustainability 2080s	Local stewardship 2080s
Properties at risk of flooding in 1 in 10 year event (thousands)	82	380	340	300	320
Expected annual damage (£ million)	270	7880	5055	1870	740
Uncertainty range on expected annual damage (£ million)	100–500	3500–15,000	2000–10,000	900–3600	350–1400

full dependence and independence between drivers in all cases, bound the predicted increase from the flood risk modelling reported above, other than in the Local Stewardship scenario, so besides this case the results are consistent. The purpose of these scores was to identify the drivers that are most influential in changing flood risk, in order to target policy responses. It would be unrealistic to develop a complete ordering of drivers. The drivers are labelled in Table 8 as being of 'high', 'medium', or 'low' significance, depending on their rank position in the range of scenarios.

Of the drivers of increased flood frequency, precipitation and relative sea level rise are identified as being the most influential. Even though relative sea level rise influences only 46% of floodplains, the sensitivity of the frequency of flooding to changes in mean sea level means that sea level rise will be an important driver of flood risk nationally. The effect of increasingly relative sea levels interacts with (rather more

Table 8
Summary of driver impacts on flood risk

Driver name	F, C, or A[a]	P or C[b]	World markets		National enterprise		Global sustainability		Local stewardship		Lowest rank position	Highest rank position	Driver significance
			2050s	2080s	2050s	2080s	2050s	2080s	2050s	2080s			
Precipitation	F	P	3	3.6	2.2	2.7	1.7	2.0	2.2	2.7	9	3	High
Urbanisation	F	P	2.2	2.7	2.2	2.7	0.8	0.7	0.8	0.7	12	3	Medium
Rural land management	F	P	1.3	1.6	1.3	1.6	0.8	0.8	0.8	0.7	13	8	Low
River morphology and sediment supply	F	P	1	1.6	1	1	1.3	2.0	1.7	2.7	14	4	Medium
River vegetation and conveyance	C	P	1	1.2	1	1.2	1.7	3.6	1	1.6	14	3	Low
Relative sea level	C	P	2.4	9.6	2	6.4	1.7	3.7	1.7	5.1	6	1	High
Waves	C	P	1.7	5.1	1.3	2.8	1	1.5	1	1.9	13	6	Medium
Surges	C	P	2.4	9.6	1.7	4.6	1	1.5	1.3	2.8	13	2	Medium
Coastal morphology and sediment supply	A	P	2.4	5.1	2.0	3.7	1.3	1.5	1.7	2.4	8	4	Medium
Public behaviour	A	C	2	2.8	0.5	0.3	0.3	0.2	0.3	0.2	9	1	High
Social vulnerability	A	C	6.0	19.8	2.2	3.6	2.2	3.2	3.0	6.1	6	1	High
Buildings and contents	A	C	4.0	6.4	3.2	4.5	1.5	1.9	0.9	0.7	10	1	High
Urban vulnerability	A	C	1.6	2.0	1.4	1.6	1.1	1.1	1	1	14	10	Low
Infrastructure	A	C	4.7	9.0	3.2	5.2	1.5	1.5	0.9	0.7	10	1	High
Agriculture	A	C	1	1	1	1	1	1	1	1	15	12	Low

[a] F: only influence fluvial flood risk, C: only influences coastal flood risk, A: influence fluvial and coastal flood risk.
[b] P: changes probability of flooding, C: changes consequences.

speculative) predictions of increasing storminess and continuing reduction in sediment volumes at the coast with the consequence that coastal waters become deeper, allowing larger waves to penetrate near the coast. As a consequence of increasing water levels and wave heights, coastal flood defences will be overtopped more frequently and will be more costly to maintain.

Precipitation is the leading driver of increasing fluvial flood frequency, though it should be noted from the spatially explicit analysis presented in the previous section, that the increase in rainfall frequency and intensity is not projected to be uniform across England and Wales (though the spatial distribution of changes in precipitation is very uncertain). Increasing precipitation (particularly intense downpours) will potentially have a very major impact on urban flooding given the physical limits to discharge in enclosed urban drainage infrastructure. The influence of river morphology, vegetation, and conveyance on flood risk is scenario dependent. In Global Sustainability and Local Stewardship scenarios regulatory restrictions on channel maintenance and the wish to re-naturalise rivers will reduce channel conveyance and hence increase flood frequency unless further measures are taken to increase channel cross-sections or flood storage volumes. Rural land management and its consequent impact on runoff is predicted to have only a small impact on flood frequency, a result that is derived from more detailed quantitative studies (Reynard et al., 2001).

The influence of drivers that are a direct consequence of climate change (precipitation, waves, surges, and relative sea levels) differs across scenarios, depending on the climate projections. These drivers are most influential in the World Markets scenario, which corresponds to high greenhouse gas emissions.

The rising economic impacts of flooding are driven by increasing wealth and hence increasingly valuable contents and fabric of domestic and commercial buildings and increasingly vulnerable infrastructure. These increases are particularly marked in the World Markets scenario. However, as noted in the previous section, the increase in flood damage as a proportion of national wealth will be much smaller, and is projected to decrease in Global Sustainability and Local Stewardship scenarios.

The effect of increasing urbanisation on flood risk will be relatively low, since even in the 2080s, the majority of flood risk will be located in urban areas that exist now. However, in those rural areas that are urbanised the increase in risk is dramatic and practically irreversible. Flood impacts on infrastructure are recognised as an important driver in societies that will be increasingly dependent on these infrastructures, which, due to increasing use of technology, may become increasingly vulnerable to flood damage. Infrastructure failure during major floods may have considerable knock-on effects, disrupting warning, evacuation, and recovery.

Social vulnerability to flooding is expected to increase across all scenarios. Also, the expert elicitation indicated that certain public behaviours may have a considerable impact on flood risk.

In keeping with the results presented in the previous section, agricultural impacts are predicted to be negligible in national economic or social terms (though their local impacts will be significant).

4. Policy implications

The quantified analysis of flood risk has demonstrated that if the current flood defence policy is continued unchanged in the future, there will be very significant increases in the frequency with which people and property suffer flooding with potentially very large impacts in economic and social terms. Whilst some drivers of increasing flood risk stand out as being particularly influential, on the whole, the projected increases in flood risk for all scenarios depends on the cumulative and interacting affect of multiple drivers influencing both the probability and the consequences of flooding. Attempts to control the increase in flood risk (if it is deemed to be desirable to do so) will need to address these multiple drivers in an integrated manner. There are clear spatial patterns to the distribution of flood risk and the location of its projected increases. Packages of policy response need to be tailored to reflect the characteristics of particular localities.

Coastal flooding makes an increasing contribution to total flood risk, increasing from 26% in 2002, to 46% in the 2080s. The increasing probability of overtopping the Thames Barrier and adjoining dikes that protect central London makes a significant contribution to this increase in risk. At many coastal sites (including major industrial and infrastructure facilities), there is very limited scope to retreat inland without major economic and/or social implications. The increasing frequency and severity of loading of coastal flood defences means that they will be increasingly costly to repair or replace. Continued reduction in sediment supply to coasts will be reflected in a narrowing of beaches and deterioration in amenity and ecological value of coasts.

Urban flooding makes a significant contribution to the economic impacts of flooding and it is the flooding that members of the public experience most frequently. The finite capacity and ageing condition of much urban drainage and sewer infrastructure is at odds with policy commitments to increase the density of urban habitation in England.

Analysis of fluvial flooding processes has indicated that regulatory pressure to restore river habitats under some scenarios will reduce channel conveyance and lead to increasing flood risk. This effect may be mitigated by retreat from current flood dike alignment and restoring larger areas of the floodplain to their natural state—a policy with both flood management and ecological benefits.

Other than specific areas of particularly rapid projected development in South East England, the majority of vulnerable buildings are a legacy of existing rather than future development. Thus, urbanisation makes a fairly modest contribution to increases in flood risk nationally. However, there are still considerable benefits to be gained locally in avoiding the increase in vulnerability that is brought about by floodplain urbanisation.

The agricultural impacts of flooding are very small in economic terms and are projected to decrease under scenarios where support for agricultural production is expected to decrease. Measures to protect agricultural land from flooding will be a reducing economic priority. However, some farming communities will be very vulnerable. Measures to reduce flood risk by better managing runoff from agricultural land are only projected to have a small impact on total flood risk.

Calculated in real terms, a major driver of increasing flood risk is the increasing value of domestic and commercial buildings and their contents. However, all of this loss may not be perceived to be real, in that damage due to flooding as a proportion of total wealth will grow much more slowly. The extent to which losses are perceived to be harmful will determine willingness to pay to reduce risk through taxation or measures provided by the market (insurance, subscription flood defence, flood proofing, etc.). The effects of flood damage and disruption to infrastructure are difficult to estimate. However, it is projected that unless specific measures are taken to reduce the vulnerability of existing and in particular new high technology infrastructures, then flood damage will be significant and could impact upon a large proportion of the population, including many who do not live in floodplains. Changes in social vulnerability to flooding and the potential impacts of public behaviour on modulating flood risk, signal a need to attend to these social issues.

The risk analysis described in this paper has not estimated the risks of loss of life due to flooding. The increasing economic risks estimated here are likely to be accompanied by increasing risk of loss of life, though this will be mitigated depending on the effectiveness of flood warning and evacuation measures.

5. Conclusions

The purpose of the analysis described in this article was to form a basis for long-term flood risk management policy by assessing the scale and drivers of flood risk over a period of 30–100 years. The analysis focussed upon current flood management policy, projected unaltered into the future, in order to identify strengths, weaknesses, and particular areas of vulnerability. To this end, a risk-based analysis framework has been established within which two separate types of analysis fit coherently: spatially explicit quantified flood risk analysis, and expert appraisal and ranking of the drivers of changing future flood risk. In both cases change in risk was analysed by (implicit or explicit) consideration of the influence that projected climate and socio-economic change would have on the state variables describing the flooding system and the impact that changes in state variables would have on risk in a Source-Pathway-Receptor framework.

The expert analysis provided an assessment of the relative contribution of different drivers to overall change in flood risk, without having to resort to exhaustive sensitivity analysis within the quantified risk model, which would have been prohibitively expensive. The expert ranking indicated that in the absence of changes to flood management policy, climate change would be the main driver of changing flood frequency. However, overall, increase in risk is influenced more by socio-economic drivers than by climate change.

Socio-economic and climate scenarios have been used in combination in order to generate self-consistent projections of potential future variation in flood risk, assuming stable flood management policy. In all scenarios the frequency of flooding is projected to increase, more so on the coast than on rivers. The increase is greatest in High-emission scenarios, particularly in the latter half of the 21st century. The risk of flooding is strongly modified by societal vulnerability and the scenarios analysis demonstrates how widely that vulnerability may vary according to the trajectory of socio-economic change. The risk that actually prevails in the future will be further modified by flood management activity, which will itself be a reflection of society's values and expectations.

Analysis of environmental and socio-economic phenomena over a timescale of 30–100 years in the future involves formidable uncertainties. Model uncertainties in climate projections up to the 2050s exceed the differences between emissions scenarios. There is considerable disagreement about the spatial patterns of climate change down-scaled to the UK. Changes in some climate variables, for example extreme sea levels and short, high intensity rainfall events are particularly difficult to predict. Socio-economic change, which on a global scale leads to changing greenhouse gas emissions trajectories and, on the UK scale, also determines economic and social vulnerability to flooding, is even more difficult to predict and, it is argued, succumbs only to a scenarios-based approach that can merely illustrate some of the potential range of variation between different futures. The uncertainty is reflected in this analysis in that we have only proposed a partial ranking of drivers, rather than a complete ranking. Precise results have been quoted for the quantified risk analysis but they have been interpreted merely as providing an indication of the magnitude, rate, and spatial distribution of potential change rather than being firm predictions.

Notwithstanding the uncertainties in the analysis, it provides important new insights for policy-makers. 'Business as usual' in flood risk management over the next century will be accompanied by large increases in flood damage, the magnitude of which will depend on the trajectory broader socio-economic change. The analysis demonstrates how the increase in flood risk will be a function of multiple interacting drivers. Climate change makes a contribution to this process but the severity of its impacts are modulated by socio-economic context, not to mention adaptive capacity, which has not featured in the current analysis. The situation is particularly severe on the coast, where the proportion of flood losses, relative to fluvial flooding, is projected to increase in the future.

Policy response will need to involve packages of measures, tailored to specific localities. Flood risk on the coast and in urban areas presents a particular challenge, though the uncertainties associated with these two sectors are high. Changes in the economics of agriculture represent an opportunity in flood management terms. Increasing dependence on technology will make society more vulnerable to damage by flooding but also presents the potential for innovative flood management solutions.

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