Pluvial (rain-related) flooding in urban areas: the invisible hazard

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This report assesses how many people in urban areas are at risk from pluvial flooding (surface water flooding resulting from intense rainfall). It projects the increase in risk due to climate change and population growth, examines the exposure of vulnerable social groups, and reviews the main policy developments to manage surface water.

Flooding and flood risk management have moved up the policy agenda in the last decade, with key legislation introduced since 2009. Meanwhile, changes in insurance provision may lead to higher premiums and flood cover may become less available in flood risk areas. This report provides the first estimates of current and future populations at risk and their social characteristics. It reviews the main policy developments to manage surface water and identifies obstacles to effectiveness.

The report:

• estimates the current and future population at risk from pluvial flooding;

• assesses the social characteristics of areas at risk; and

• reviews the main policy developments to manage surface water and the obstacles to effectiveness.

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Contents

List of figures and tables

Figures

Tables

Executive summary

Key findings and conclusions

- An interdisciplinary approach is required to better understand social vulnerability to flood risk, incorporating engineering, natural sciences and social sciences.

- From a social justice perspective, it is important to know the population at risk and its characteristics, not just the number of properties at risk, as has been the focus of existing risk assessments.

- Pluvial flood risk accounts for approximately one-third of flood risk from all sources in the UK.

- Approximately 2 million people in UK urban areas (settlements with a population over 10,000) are exposed to an annual pluvial flood risk of 0.5 per cent or greater ('1 in 200-year' event).

- An additional 1.2 million people in urban areas could be put at risk by 2050 from a combination of climate change (300,000) and population growth (900,000).

- Settlements across the UK with higher rainfall also tend to have greater levels of social deprivation, although the differences are small.

- Census data covering the entire population indicates that vulnerable groups are over-represented in areas at pluvial flood risk within Belfast, and also within Glasgow and Luton but to a lesser extent.

- Changes to the cost and availability of insurance in the future have the potential to alter the socio-economic composition of flood risk areas and/or to blight certain areas.

- Recent flood management legislation around the UK has improved the priority given to pluvial flood risk, although challenges remain in terms of governance arrangements.

- Pluvial flood risk can be heavily mitigated in new developments through a combination of avoiding the highest risk locations, investment in drainage systems, flood proof building design and surface water management involving 'green' and 'blue' space and 'blue' corridors.

- A key challenge remains for existing built-up areas at high risk, although gradual upgrading of drainage systems and surface water management can ameliorate risk when opportunities for redevelopment arise.

- Further research is required in a number of areas, in particular: prediction of future extreme rainfall probabilities under climate change scenarios; real-time prediction of pluvial flooding to enable warnings to be issued; assessment of patterns of urban development and surface water management in areas at risk; appraisal of the housing and land market responses to flood risk – particularly the impact of rising insurance premiums in high risk locations.

Background and scope of research

The most common source of flooding is when water levels in rivers rise so that the rivers overtop their banks ('fluvial' flooding). Another familiar source of flooding along coasts results from a combination of high tides and stormy conditions. Less well known by the general public, and less well understood, are 'pluvial' (rain-related) floods which occur following short intense downpours that cannot be quickly enough evacuated by the drainage system or infiltrated to the ground. Pluvial floods often occur with little warning in areas not obviously prone to flooding – hence the term 'invisible hazard'.

Pluvial floods have recently been identified as the type most likely to increase in severity as a result of climate change. They are also the most difficult to manage because they are difficult to predict and it is challenging to provide adequate warning times. Following severe pluvial flooding in Glasgow in 2002, and across Hull and other parts of the UK in 2007, pluvial flooding is now given more attention by policy-makers than in the past.

This project aims to:

- provide the first estimates of population (rather than properties, as in previous work) most at risk from pluvial flooding in urban areas, both now and in 2050, by UK region, taking into account climate change and population growth;

- assess the socio-economic composition of urban areas nationally with the highest levels of extreme rainfall now and in the future, and provide more detailed socio-economic profiles of areas identified as at risk from pluvial flooding in three localities (Belfast, Glasgow and Luton); and

- engage with key stakeholders (at both local and national levels) to assess current awareness and responses to pluvial flood risk and help inform appropriate policy responses across contrasting jurisdictions (England, Scotland and Northern Ireland).

The main elements of this research were:

- use of the UK Climate Projections 2009 (UKCP09) Weather Generator to estimate the scale of climate change on extreme rainfall events over key urban areas;

- topographic modelling of pluvial flood risk in three settlements (Belfast, Glasgow and Luton) for baseline and climate change scenarios;

- use of population projections and 2001 Census of Population data to estimate the population at risk from pluvial flooding in urban areas now and in 2050;

- use of the Index of Multiple Deprivation (IMD) and 2001 Census of Population to assess the distribution of vulnerable social groups in relation to pluvial flood risk in urban areas;

- interviews with key stakeholders in central and local government, environmental and water regulators, water companies, insurers, industry experts and third sector organisations; and

- documentary research into the legislative arrangements around the UK in relation to pluvial flooding and local responses.

Extensive pluvial flooding is more likely to occur in urban areas because of the greater prevalence of impermeable surfaces. In addition, it is likely to have greater consequences in urban areas because of the density of buildings and people. This research therefore focuses on urban areas, defined as settlements with a population over 10,000.

Despite pluvial flooding moving up the policy agenda in recent years, important gaps or uncertainties in knowledge remain – in particular, the number of people and properties at risk; the impact that climate change is likely to have on the extent and pattern of pluvial flooding; the distribution of different social groups to the hazard; the ability to forecast pluvial flooding and issue warnings; and the governance arrangements required to deliver effective surface water management.

A formidable range of concepts, methods and data needs to be brought to bear to help us better understand current and future flood vulnerabilities. The complexity of conducting analyses of current and future flood vulnerabilities is therefore considerable. Nevertheless, there is merit in specifying research broadly to capture the full range of factors that influence flood vulnerability.

How many people are at risk from pluvial flooding?

We estimate that almost 2 million people in urban areas (settlements with a population over 10,000) face an annual 0.5 per cent probability ('1 in 200-year') of pluvial flooding. This represents around 5 per cent of the urban population, and around one-third of flood risk from all sources.

This estimate is based on the size of the UK's urban population; the proportion of the urban population that lives in areas at risk (identified from surface flow and ponding modelling in local case studies); and the proportion of the urban population with accommodation at street level or below.

How many people could be at risk by 2050?

By 2050, 3.2 million people in urban areas could be at risk from pluvial flooding, an increase of 1.2 million. This increase is composed of an additional 300,000 as a result of climate change and 900,000 as a result of population growth.

However, surface water management, investment in drainage systems and planning regulations in flood risk areas have the potential to limit this increase and even reduce current numbers at risk. To have a substantial impact, these measures would require significant changes in policy and practice.

Are vulnerable groups over-exposed to pluvial flood risk?

Our analysis across settlements reveals that towns and cities with higher intensities of extreme rainfall also have higher levels of social deprivation, as measured by the government's Index of Multiple Deprivation (IMD), although the differences are relatively small. This primarily reflects the fact that northern and western locations in the UK tend to have higher levels of deprivation as well as having wetter climates. Detailed analysis of the pattern of pluvial flood risk within three case study settlements (Belfast, Glasgow and Luton) indicates that vulnerable groups (as identified in previous survey work after floods: for example, Werritty *et al.*, 2007) are over-represented in the areas at risk. Again, the differences are small but remarkably consistent across these three very contrasting settlements.

Nevertheless, the distribution of social groups in relation to flood risk (including, but not restricted to, the vulnerable groups identified in previous survey work) is remarkably consistent across the three settlements. This suggests there are systematic processes that lead to potentially vulnerable groups being over-exposed to the hazard. A likely mechanism is older, smaller terraced housing being more prevalent in low lying flat areas, close to a river, that tended to be developed first during industrialisation. As towns and cities expand outwards, development is more likely to be on elevated land and tends to be characterised by larger, more expensive housing.

An increase in insurance premiums in flood risk areas – which some insurers are already implementing – has the potential to alter the social characteristics of high risk locations. Increased premiums may make more sought-after areas the preserve of the rich; in other areas, such increases may lead to falls in house prices and subsequent filtering of lower income groups into these areas. The withdrawal of insurance altogether would be likely to blight areas of new development and cause problems for the resale of existing properties.

What can be done to reduce pluvial flood risk?

Sustainable Urban Drainage Systems (SUDS), surface water management plans and flood proofing of developments have the potential to limit the increase or even decrease the number of people and properties at risk. Separate storm water and foul water systems can increase drainage capacity and reduce the likelihood of sewage mixing with pluvial flood water.

There remains a major issue, however, with existing properties and combined foul/storm water drainage systems which will remain a part of the urban fabric for many decades to come. Here, greater use needs to be made of identifying and exploiting opportunities to 'retro-fit', for example as part of major urban redevelopment projects or, in the case of flood proofing, when buildings in high risk locations are being renovated.

Local authorities have an important role to play in leading the partnership approach to surface water management. However, lack of powers, funding and capacity, and constraints on skills, conspire to make this difficult to achieve.

Recommendations

Social justice and vulnerability

1   Environmental regulators and local authorities should incorporate information on the number of households with a ground floor into flood risk assessments. This is particularly important in London and Scotland where significant proportions of the urban population live above street level so are not directly at risk from flooding.

2   Local authorities should provide emergency planners with lists of addresses that receive personal care services, and give those responsible for flood risk assessment a count of the numbers of people in small areas who receive personal care.

Insurance and housing markets

3   The governments of the UK and the Association of British Insurers should work together to make adequate provision to protect vulnerable groups and maintain a high level of geographical coverage in currently developed areas.

4   Responsible bodies should increase the take up of contents insurance among vulnerable groups through 'pay-with-rent' schemes in the social rented sector, for example by introducing an 'opt out' rather than an 'opt in' arrangement.

5   Regulators should publish indicative pluvial flood risk maps.

What can be done about pluvial flood risk?

6 Local authorities (and, where appropriate, water companies) should develop a strategic approach to dealing with high risk areas:

    a currently developed areas – retro-fit when possible, identify and improve 'pinch points' in the drainage system, and manage the micro-topography to create safe flow routes;

    b currently undeveloped areas with development pressure – insist on effective SUDS, flood proof design and surface water management plans;

    c currently undeveloped areas with less pressure for development – identify opportunities for landscaping that incorporates 'green' and 'blue' space, supported through land use planning and, if necessary, compulsory purchase.

7 Local authorities, regulators and water companies should engage with the public regarding surface water and drainage issues, promoting the preservation of porous surfaces and capture of rainwater at household level.

8 Local authorities and water companies should make more use of opportunities to de-couple existing combined clean and foul water drainage systems: for example, when areas are undergoing major redevelopment.

9 Local authorities should extend surface water management plans where possible by integrating them with wider urban regeneration and landscape design plans that incorporate 'green' and 'blue' spaces.

10 Local authorities should enhance their capacity and skills to fully incorporate surface water issues into flood risk management, for example through pooling of expertise and knowledge across neighbouring authorities.

11 The governments of the UK should improve guidance and policies to ensure that resilience to the 1 in 200-year pluvial flood risk is designed into areas at risk and new developments.

12 Responsible bodies should clearly define responsibility for 1 in 30- to 1 in 200-year flood risk.

Areas for further research

1 Refine existing estimates of sub-daily duration rainfall on a 1 km (or better) grid.

2 Improve understanding of spatial and temporal variation in rainfall within extreme events.

3 Improve existing forecasting of extreme rainfall in real time.

4 Develop better methods for measuring socio-economic variation at spatial scales commensurate with data on flood risk, thereby enhancing existing flood risk assessments.

5 Better identify which social groups are most vulnerable to the impacts of a flood and how this varies with the geographical scale of a flood.

6   Examine socio-economic change and housing market impacts in light of flood events.

7   Examine changes in the cost and availability of insurance (building on ongoing work by the Association of British Insurers) and their implications for social justice, vulnerability and urban development.

8   Investigate through case studies the options for handling extreme floods, particularly in larger towns and cities.

1 Introduction

Our approach

Engineering and natural sciences have recently made an enormous contribution to understanding flood risk and the development of flood risk management and policy. Now the challenge is to better understand how economic and social systems will respond and interact with climate change and adaptation policies in reinforcing existing welfare outcomes and inequalities, and creating new ones.

Those with least opportunity to adapt, for example because of low income, poor health, location or housing tenure, may be disproportionately affected by the social impacts of flooding and flood risk. Current assessments of flood risk have emphasised the hazard itself and its economic impacts, with treatment of social vulnerability and adaptive capacity much less developed. This is a necessary first step but only provides part of the picture. That the bulk of research to date has been done on the hazard and its economic impacts partially reflects the fact that these aspects are more tangible and therefore easier to measure. Social vulnerability, resilience and adaptation to flooding and flood risk at individual, institutional and national levels are critical areas that need to be better understood.

The team behind this research comprises experts in a range of disciplines, spanning urban geography and social inequality (Houston), hydrology and flood risk management (Werritty), civil engineering and drainage (Bassett and McMillan), population (Geddes) and town planning (Hoolachan). Our view is that a genuinely interdisciplinary approach incorporating engineering, natural sciences and social sciences is essential to understanding and responding to future flood risk and vulnerability to flooding. This will require a greater involvement of social science perspectives in the development of flood adaptation policies than has hitherto been the case.

Contribution of this research

Perhaps our most significant empirical finding is that by 2050 national population growth is likely to put around three times more people at risk from surface water flooding than climate change. However, there are significant regional differences in the scale of increase in urban population at risk, and in the relative importance of population growth versus climate change. This emphasises that risk is the product of both the natural hazard and the exposure of the population to that hazard.

It is not our intention to downplay the potential impact of climate change (and environmental change more generally) on human welfare during this century and beyond. We simply highlight that climate change is only part of the story of vulnerability to flooding, and that in the short and medium term other forces are likely to have greater impacts.

This report includes the first estimate of the population at risk. Existing work has focused on estimating the number of properties, which is essential in order to estimate economic damages. However, from environmental justice and emergency planning perspectives, it is crucial to know how many people are at risk and the characteristics that may make them particularly vulnerable or resilient.

The research reveals that socially deprived areas are at slightly higher risk of pluvial flooding. This is particularly the case in cities on a sizeable river because deprived inner city neighbourhoods tend to be located in low lying areas. Some of these neighbourhoods are also at risk from river or coastal flooding.

Anticipating the future inevitably confronts uncertainty. Current techniques in climate modelling can estimate with some confidence (subject to carbon emission assumptions) likely overall future levels of rainfall and broad seasonal and regional patterns in its distribution. However, estimating with accuracy the future probability of extreme rainfall events is more challenging. Similarly, it is difficult to predict how urban development in flood risk areas will progress and how current planning policy will play out. Also poorly understood is how housing markets will respond to flood risk, particularly given rising insurance premiums for flood cover. Key stakeholders we interviewed in the course of this research have provided useful insights but it is important that further research is conducted on these issues.

A formidable range of concepts, methods and data needs to be brought to bear to help us better understand current and future flood vulnerabilities. For example, the inputs to the quantitative analysis in this report alone span rainfall data for baseline conditions; UK Climate Projections (UKCP09) rainfall projections for various scenarios, timescales, durations and locations; digital elevation models; 2001 Census of Population data disaggregated by location and social group; and future population projections by region.

The complexity of conducting analyses of current and future flood vulnerabilities is therefore considerable. Nevertheless, there is merit in specifying research broadly to capture the full range of factors that influence flood vulnerability. Only this broad approach will reveal the relative order of magnitude of the various drivers of future flood vulnerability, which is critical to developing effective and equitable adaptation policies. Policy development that focused mainly on understanding the hazard would omit crucial economic and social forces affecting exposure, vulnerability and resilience to flooding.

Research aims

This project aims to:

- provide the first estimates of population (rather than properties, as in previous work) most at risk from pluvial flooding in urban areas, both now and in 2050, by UK region, taking into account climate change and population growth;

- assess the socio-economic composition of urban areas nationally with the highest levels of extreme rainfall, now and in the future, and provide more detailed socio-economic profiles of areas identified as at risk from pluvial flooding in three localities (Belfast, Glasgow and Luton); and

- engage with key stakeholders (at both local and national levels) to assess current awareness and responses to pluvial flood risk and help inform appropriate policy responses across contrasting jurisdictions (England, Scotland and Northern Ireland).

Preparing this report

This research has drawn on a complex and diverse range of data spanning climate, drainage, topography, population and social deprivation, as well as qualitative material on policy and management. Much of the technical detail, for example our methodology, is presented in the appendices with only a summary and the key issues retained in the main body of this report.

The remainder of the report is organised in the following chapters:

- background;

- research methods;

- climate change and extreme rainfall;

- current urban population at risk;

- future urban population at risk; and

- understanding and responding to pluvial flood risk.

The report concludes with a summary of the key findings and offers recommendations for policy-makers and areas for further research.

2 Background

What is pluvial flooding?

Floods can arise from a variety of causes. The best understood floods occur when, following intense or prolonged rainfall, water levels in rivers rise and the rivers overtop their banks (fluvial flooding). Also well known are coastal floods caused by storm surges and wave action superimposed on high water levels generated during the diurnal cycle of tides (Ball *et al.*, 2008). Flooding can also occur from ground water rising to the surface of the land, usually associated with prolonged periods of heavy rainfall. Less well understood by the general public are pluvial floods which often occur unexpectedly in locations not obviously prone to flooding and with minimal warning – hence the term an 'invisible hazard'.

Pluvial flooding occurs when rainfall that is usually converted into run-off, which can be evacuated by the drainage system, remains on impermeable surfaces and flows overland or into local depressions and topographic lows to create temporary ponds. Pluvial flooding only occurs when the rainfall rate exceeds the capacity of storm water drains to evacuate the water and the capacity of the ground to absorb water. This is usually associated with short-duration storms (of up to three hours) and with rainfalls > 20–25 mm/hour. It can also occur following lower intensity rainfalls (~ 10 mm/hour) over longer periods, especially if the ground surface is impermeable by being developed, saturated or frozen.

In older developments, when combined systems (storm water and foul water sewers) are overwhelmed, the foul water sewers surcharge onto the streets. The resulting flood is a mixture of surface water and untreated sewage which produces a more severe health hazard. Although new urban drains are designed to evacuate the 1 in 30-year run-off, poor maintenance, the lower design standard of highway drains, and blockages at entrances and outfalls typically result in their actual capacity being substantially lower. In addition, urban 'creep' (for example, paving over gardens, extensions to properties and urban 'in-fill' development) serves to increase surface run-off gradually.

Depending on the location and local setting, pluvial flooding can also be combined with river flooding or coastal flooding. When this happens, promoting sustainable flood management becomes an even bigger challenge (Scottish Government, 2010).

Current methods for managing pluvial flooding are focused on the introduction of Sustainable Drainage Systems (SUDS) and Surface Water Management Plans (SWMPs) usually designed and operated by local authorities. These typically involve enhanced infiltration of water into the soil by retaining significant 'green spaces' and introducing permeable paving, slowing down flow of water into storm water drains (via grassy swales and detention and storage ponds). The sub-surface management of water is mainly the responsibility of the water utilities (publicly owned in Scotland and Northern Ireland and privatised in England and Wales) for waste water and run-off from rooftops, while local authorities are responsible for highway drainage. Both can help reduce the incidence and severity of pluvial floods by upgrading their urban drainage systems.

What is the scale of the risk?

Pluvial flooding is challenging to predict and plan for as it does not have an easily defined 'floodplain' like rivers and the sea. Buildings, street furniture, kerb heights and drainage capacity all have an impact on surface water flow, making it complex to map and manage. Given the multitude of factors coming

together to produce pluvial flooding, it is correspondingly difficult to produce consistent estimates of the extent of pluvial flood risk. Results vary with the data and methods used to produce flood maps, for example assumed drainage capacity, rates of ground infiltration, the depth of water that is considered likely to pose a risk, and the probability/return period considered.

An estimated 3.8 million properties are thought to be at risk from pluvial flooding in England (Environment Agency, 2009). This represents around 10 per cent of all properties (including those not at risk). In Scotland, some 15,000 properties have been estimated to be at pluvial flood risk (Scottish Environment Protection Agency, 2011). The Scottish figure represents 0.6 per cent of all properties, a substantially lower proportion than in England. This difference can be partially accounted for by differences in methodology. In particular, the figure for England does not take account of drainage into sewers during a storm (the Environment Agency's most recent surface water maps released to local authorities make an allowance for drainage capacity but a national estimate of properties at risk has not yet been produced). In addition, the Digital Terrain Model (DTM) used in the Environment Agency work in England was of a greater vertical resolution and thus would detect more depressions in topography likely to be prone to pluvial flooding.

The 3.8 million properties deemed to be at risk in England compare with 2.4 million at risk from fluvial or coastal flooding (and 1.7 million at risk from ground water). Of the 3.8 million identified as at pluvial risk, 1 million are also at risk from fluvial or coastal flooding. Excluding ground water, this suggests that pluvial flooding accounts for over half of all flood risk in England (3.8 million of a total of 6.2 million properties). The Northern Ireland Preliminary Flood Risk Assessment estimates 2,300 properties at risk per annum from pluvial flooding, compared with 3,000 for fluvial and 1,000 for coastal flooding. Pluvial flooding therefore accounts for around one-third of flood risk from all sources. In Scotland, the proportion is much lower; just over 13 per cent of all properties are at risk of being flooded (Scottish Environment Protection Agency, 2011).

These significantly different estimates by the environmental regulators for different parts of the UK may result from differences in data and methods rather than actual regional differences in pluvial flood risk. This underlines the difficulty and uncertainty in estimating pluvial flood risk.

What social issues arise?

Some social groups are more vulnerable to the effects of flooding than others, for example those on lower incomes, older people and disabled (Whittle *et al.*, 2010). The concept of vulnerability has a long history dating back at least to 1970s neo-Marxist critiques of capitalist development which arguably increased the exposure of the poor to a range of environmental risks, in particular famine (Watts and Bohle, 1993; Wisner *et al.*, 1994). The term 'vulnerability' was adopted by researchers examining natural disasters in the 1990s and developed into the 'hazard:exposure:susceptibility' framework in use today (Cutter, 2006).

In academic use, 'hazard' refers to the likelihood, location, scale and nature of a hazard, for example flood water. 'Exposure' refers to the location of 'receptors' in relation to the hazard, for example population, buildings, and critical infrastructure and services. 'Susceptibility' refers to the ability of receptors to withstand, recover from, or adapt to a hazard (Kelly and Adger, 2000).

Recent literature emphasises resilience rather than vulnerability, arguing that 'adaptive capacity' is the crucial aspect of maintaining welfare in response to long-run environmental change (Nelson *et al.*, 2007) and similar thinking has been applied in helping communities respond to flooding (Environment Agency, 2011). However, the resilience literature has been criticised for assuming a relatively high capacity to adapt at individual and community levels, which in practice is often highly constrained by powerlessness and poverty (Galaz, 2005).

The conceptualisation and definition of vulnerability is important but in developing a framework in which to assess vulnerability it is crucial to ask what outcomes are considered important and how they are impacted by different hazards or events. These two issues are developed in Lindley *et al.* (2011), who state:

Vulnerability is a matter of those features of a person or group that are relevant to the conversion of external events into welfare outcomes … the significant debate between the different approaches is not about the definition of vulnerability, but rather the richness of the accounts offered of welfare outcomes and conversion factors and of the degree to which vulnerability is hazard specific. (p. 6)

Some attempts have been made to define and measure vulnerability to flooding, such as the Social Flood Vulnerability Index based on social deprivation, being an older person, having poor health and being lone parents (Tapsell *et al.*, 2002). However, the impacts of floods on individuals, households and communities are complex and multifaceted, and are difficult to capture in simple indices. The typology (see Table 1) developed by Smith (1996) makes a helpful distinction between direct impacts (which are immediate and can partly be assessed quantitatively) and indirect impacts (which emerge over months and years, are less clearly defined and are problematic in terms of quantitative assessment).

The direct tangible economic impacts (damage to property and contents, loss of income and so on) can readily be calculated using standard methods (Flood Hazard Research Centre, 2010) and are routinely used in benefit–cost analyses for project appraisal for flood protection schemes. The direct intangible social impacts (including disruption to family life, stress of dealing with insurers and builders, anxiety, impacts on physical and mental health, and loss of personal and family memorabilia of sentimental value) are much more difficult to assess (Werritty *et al.*, 2007) and have only recently been added in project appraisal for flood protection schemes. At present, the evaluation of indirect impacts is still in its infancy, with only hints as to the true long-term economic and social impacts of floods.

The concepts of 'vulnerability' and (its corollary) 'resilience' are firmly embedded in the modern flood risk management literature and underpin recent policy (Scottish Government, 2010; Environment Agency, 2011). When combined with concepts of 'exposure' and 'susceptibility', these greatly enrich our current understanding of the term 'flood risk' (see Figure 1). Flooding as a 'hazard' solely involves the actual characteristics of an event (depth, velocity, duration and water quality). Flood 'risk' involves adding to this the likelihood of an event occurring plus the exposure and vulnerability of individuals, households and property.

An individual or a household is vulnerable if, on being exposed to flooding, they struggle and possibly fail to cope with or adapt to the resulting impacts. By contrast, an individual or a household is resilient if, drawing on a personal or societal coping strategy, they recover from or adapt relatively rapidly to the impacts of flooding.

Those on low incomes are thought to be more vulnerable, particularly if they do not have insurance (Crichton, 2007). Werritty *et al.* (2007) conducted an extensive survey across Scotland into the self-reported impacts of being flooded, with follow-up focus groups. Those without a car were found to be more vulnerable to disruption if they were rehoused at some distance from work, school or family and friends. Renters were found to be more vulnerable than home-owners, although renters and owners are highly differentiated. For example, of all housing tenures, social renters reported the highest impact of

Table 1: Typology of flood impacts (after Smith, 1996)

Direct impacts (immediate)
Tangible: physical damage to property, costs of restoration and rebuilding
Intangible: ill-health of flood victims (including mental trauma), coping with post-flood recovery
Indirect impacts (delayed and longer lasting)
Tangible: disruption of economic and social activities (lost industrial and agricultural production, damage to retail sector and transport infrastructure)
Intangible: increased vulnerability of survivors, planning blight and out migration

Figure 1: The influences on flood risk
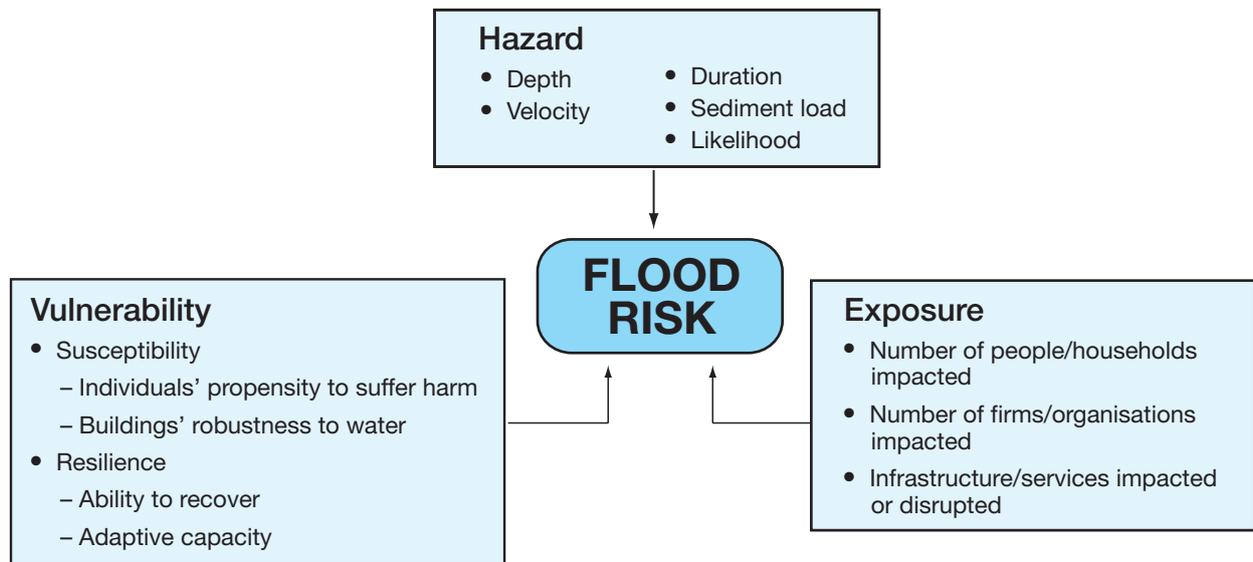
Source: Derived from McLaughlin, 2011

being flooded and private renters the lowest. Social renters reported being rehoused in 'sink' estates, but private renters had little difficulty finding suitable alternative accommodation (cf. Whittle *et al.*, 2010). Similarly, those who owned their home outright reported low impacts of being flooded compared with those who had a mortgage. This linked to concerns over negative equity and, in some cases, requirements from mortgage lenders for re-valuations which could affect mortgage terms.

When few properties are flooded, the options for rehousing people adequately are much greater. When a large proportion of a town or city has been flooded (such as in Hull in 2007), there are many more households seeking accommodation and few unaffected areas in which to rehouse them. This appears to explain the fact that Werritty *et al.* (2007), studying a series of relatively small floods in Scotland, found that private renters reported the lowest impact of being flooded. In the widespread flooding in Hull, private renters reported significant problems finding alternative accommodation in Hull (Whittle *et al.*, 2010).

Ways of reducing vulnerability include actions by the public or private sector to reduce exposure (for example, by upgrading urban drainage) and actions by individuals to minimise losses (for example, by having a flooding action plan, flood proofing a property and taking out insurance). This latter strategy can prove difficult for those on low incomes or in high risk areas where insurance may not be affordable.

Private insurance companies absorb the bulk of the financial burden of flooding, which considerably reduces the vulnerability at individual household level (at least for those with insurance). The current Statement of Principles between the Association of British Insurers and governments of the UK ensures that insurance is generally available (although in recent years those who are flooded or who change insurer may have premiums or excesses for flooding increased). The Statement of Principles requires insurance cover to be provided for flood damage at no higher premium in flood risk areas. In return, the government is committed to building defences to a 1 in 75-year level and providing the insurance industry with information on levels of risk. The Statement of Principles is due to lapse in 2013. It is imperative that it is replaced by a new agreement guaranteeing affordable insurance, especially for the most vulnerable members of society.

The concept of 'vulnerability' is therefore about who is most susceptible to the effects of flooding. The concept of 'environmental justice' is also relevant, although it differs from vulnerability in that it is concerned with the fairness of particular patterns of exposure to hazards. The term 'social justice' is often used to judge the fairness of the distribution of various welfare outcomes (for example, income, health

and education) across social groups. Key criteria by which the fairness of distribution is judged include equality, need, those most deserving and total societal welfare (Rawls, 1971). 'Justice' can also refer to the process by which outcomes are produced: for example, whether all voices are given equal opportunity to influence decisions (Dobson, 1998).

Environmental justice applies the concept of fairness to the exposure of different social groups to various environmental 'goods', such as green space, and to environmental 'bads', such as traffic fumes, noise or industrial contamination (Dobson, 1998). Lower income groups tend to be over-represented in polluted areas, often the result of market forces meaning that those who can afford to live in cleaner, greener places, do so (Gatrell, 2002). In terms of climate change, justice issues arise not only from the impacts of climate change itself (such as flooding) but also as a consequence of mitigation and adaptation responses which may disproportionately affect those on low incomes (Lindley *et al.*, 2011), such as carbon-based taxes and increased insurance premiums for flood cover.

A situation in which lower income groups were systematically over-exposed to flood risk would be of questionable fairness on the grounds of equality (Walker *et al.*, 2006). Also important is whether lower income groups have less resilience to the effects of a flood (Fielding and Burningham, 2005). For example, lower income individuals are less likely to have insurance, may have less disposable income to assist with their recovery and are more likely to suffer from poor health, all of which may exacerbate the impacts of being flooded.

Previous research has found that areas at risk from river flooding tend to have slightly lower levels of deprivation than areas not at risk, although there is regional variation in this relationship (Walker *et al.*, 2006). This is explained by riverside locations tending to offer high quality residential amenity that attracts higher income groups who can afford to live there. In contrast, coastal areas at risk from flooding are associated with higher levels of deprivation than areas not at risk, which can be explained by the co-location of industrial land uses and low-income housing (Werritty *et al.*, 2007). Lower income groups have lower awareness of flood risk and less preparedness, meaning there can be a 'double whammy' in some locations of both over-exposure and low awareness (Fielding, 2009).

However, until now no research has been conducted on the distribution of pluvial flood risk across social groups. Four mechanisms have the potential to produce adverse distributions of pluvial flood risk. First, pluvial flooding is primarily an urban phenomenon, and larger urban areas have higher proportions of residents in deprived categories. Second, higher density neighbourhoods may be more prone to pluvial flooding because they have fewer porous surfaces, and social deprivation is strongly correlated with urban density. Third, elevated locations in towns and cities are often characterised by larger houses affording panoramic views, while older, smaller terraced houses and flats are more likely to be built on lower value land that is flatter, lower lying and poorly drained. Fourth, market forces and development pressures may enable higher income groups to avoid living in areas at risk from pluvial flooding (assuming that information on risk is freely available).

What will climate change mean?

An increase in the risk of flooding is widely reported as one of the most likely impacts of climate change across the UK (Evans *et al.*, 2004; Werritty with Chatterton, 2004; CCRA, 2010). This is a direct result of the physical principle that a warmer atmosphere holds higher amounts of water vapour and UK regional climate models (UKCP09) predict increased winter rainfall (especially in the north and west) and more intense, highly localised summer rainfall (especially in the south and east). These predictions also accord with recent changes in rainfall over the period 1961–2006 (Jenkins *et al.*, 2008) which have seen many parts of the UK affected by severe and highly damaging floods, most notably in Yorkshire, Hull, the Severn-Avon basin and Belfast in 2007. Whilst no single flood can unequivocally be attributed to climate change, there is evidence that the probability of floods (in this instance, the regional floods affecting England and Wales in 2000) is increasing as a result of anthropogenic greenhouse gas emissions (Pall *et*

al., 2011). As we examine later, the precise link between increased rainfall and urban flooding remains complex, but there is now little doubt that a warmer and wetter UK will experience more floods with greater impacts in urban areas.

What is the policy response around the UK?

Hitherto, undefined roles and responsibilities in relation to pluvial flooding have been an issue. However, the recent flood management legislation has clarified responsibilities for some tasks. For example, environmental regulators are generally responsible for producing and reporting on national flood risk assessments[1], while local authorities are responsible for designing and implementing local flood risk management strategies.

At the local level, however, the implementation of flood management plans and strategies straddles a range of responsible authorities, making co-ordination difficult. Key players include planning authorities; water companies; internal drainage boards (England only); developers; highway authorities; and environmental regulators. In England, the key driver for co-operation by the water companies is the Water Industry Act 1991 which requires them to co-operate with relevant authorities in relation to surface water and combined sewers. The key here is in managing urban flooding at the interface between underground (minor systems) and above ground (major systems) as recommended by Digman *et al.* (2006).

The implementation of the Metropolitan Glasgow Strategic Drainage Plan (founded by Glasgow City Council, Scottish Water, the Scottish Environment Protection Agency and Scottish Enterprise) is providing evidence of how co-operation can be delivered at this key interface in managing pluvial floods. However, as already noted, the management of flood risk varies across the UK. This arises from the different jurisdictions which determine how this devolved power is exercised and how European Union (EU) directives are transposed into locally enforced statutes. We therefore now outline the key legislative context for flood risk management in different jurisdictions around the UK.

England and Wales[2]

Until recently, the responsibility for managing flood risk in England and Wales was variously shared between the Department for Environment, Food and Rural Affairs (Defra, the national strategic authority), internal drainage boards (low lying rural areas), the Environment Agency (responsible for 'main rivers' and sea flooding) and local authorities (for 'non-main rivers' and coastal protection). But at a more local scale, the responsibility for surface water flooding (shared between local authorities, water companies, internal drainage boards and private owners) has lacked comparable clarity.

Following the severe flooding in England in 2007, the Pitt Report (Cabinet Office, 2008) made a number of recommendations designed to promote a more co-ordinated and sustainable approach to managing flood risk (especially in terms of local floods associated with surface water). The ensuing Flood and Water Management Act 2010 clarified the roles of the key agents that manage local flood risk (including surface run-off, ground water and ordinary water course components) across England and Wales. In terms of managing flooding, the Act allocates an overview of all flood and coastal erosion risk to the Environment Agency and gives unitary and county councils the lead in managing local flood risks, which is to result in a national strategy for England. In addition, the EU Floods Directive requires member states to assess, map and plan for flood risk. In England, the Flood Risk Regulations 2009 transposed these requirements into statute.

For local flood risk, the Act specifies that a unitary local authority or county council will be the Lead Local Flood Authority charged with bringing together all relevant bodies (district councils, internal drainage boards, highway authorities, water companies and the Environment Agency) to help manage local flood risk. The Act enables such partnerships to be developed but does not specify what local arrangements

should look like. The Lead Local Flood Authority, in collaboration with other relevant bodies, is required to develop, maintain, apply and monitor a strategy for local flood risk management in its area. This local strategy, which includes surface run-off, ground water and ordinary water courses, must include consultation with other relevant bodies and the public and must be consistent with the national strategy. A key component of the strategy is that it is risk-based and promotes resilience in affected communities. More specifically, the local strategy must identify the relevant management authorities and their respective functions. It must specify objectives with measures to achieve them, together with associated costs and benefits and a timetable for implementation.

SUDS are a key element in managing local flood risk. The intention is that a SUDS Approving Body is to be set up in each Lead Local Flood Authority, with the responsibility for approving proposed new drainage schemes in new developments and redevelopments. The right to connect drainage (in the form of SUDS) from a private development to the public sewerage system will be conditional on the surface water drainage system being approved by the approving body in compliance with national standards. For the first time in England and Wales, developers are required to incorporate SUDS into new developments.

Once in operation, the SUDS will be adopted and maintained by the relevant local authority. Only surface water drainage can be connected to the sewerage system. Foul water connections will continue to require approval by the relevant water and sewerage company. In existing urban areas, flooding often involves the discharge of sewage as a result of sewers surcharging within properties and onto highways during severe rain storms. Sewer flooding is covered in the Act when wholly or partly caused by rainwater entering the sewer system and water companies have responsibilities to manage sewer flooding. Solutions, such as keeping rainwater out of sewers, will be linked to local authorities' management of surface water run-off. It is anticipated that, over time, well-maintained SUDS will help reduce the risk of both surface and sewerage flooding.

In summary, the Flood and Water Management Act 2010 has clarified and strengthened the roles of the diverse authorities responsible for managing surface water run-off in urban areas. A key component in managing local flood risk will be the future requirement that SUDS accompany all new developments. Given that SUDS have not historically been required in England and Wales, there will be many existing urban areas where SUDS do not exist and where the challenge will be to retro-fit them as circumstances and resources allow. This historical legacy means that the hazard of surface water flooding, most notably experienced in Hull in 2007, is likely to exist in some areas well into the future.

Scotland

The current and future management of flooding in Scotland differs markedly from that in England and Wales (Werritty, 2006). Prior to the Flood Risk Management (Scotland) Act 2009, local authorities were the only public bodies with powers to undertake flood risk management which, for the most part, they did by engineered structural defences to protect properties adjacent to main rivers (although Scottish Water also had powers prior to the 2009 Act to alleviate sewerage flooding). However, with the transposition of the EU Floods Directive into Scots law in the 2009 Act (Ball *et al.*, 2009), flood risk management in Scotland has greatly broadened its scope to include coastal, pluvial and ground water flooding and has embraced sustainability as a key driver. The Scottish Environment Protection Agency (SEPA) has been designated the competent authority to deliver the Act with local authorities and Scottish Water as the main responsible authorities for specific measures. SEPA has now taken on a strategic role with responsibility for the Preliminary Flood Risk Assessment (by 2011), Flood Hazard and Flood Risk Maps (by 2013) and a Flood Management Plan (by 2015) and is already providing an enhanced flood warning service via its Floodline.

Local authorities, sometimes grouped together to cover the larger river basins, are developing local flood risk management programmes. They continue to implement specific measures designed to

reduce flood risk, vet planning applications in flood risk locations and provide support, along with the emergency services, during major flooding incidents. Scottish Water is responsible for managing sewerage floods and increasingly works alongside local authorities in dealing with pluvial floods.

Prior to the severe flooding in the east end of Glasgow in 2002, pluvial flooding had not been identified as a separate form of flooding in urban areas. However, following that event, and especially with the creation of the Metropolitan Glasgow Strategic Drainage Partnership (founded by Glasgow City Council, SEPA, Scottish Water and Scottish Enterprise in 2003), this type of urban flooding has attracted increasing attention across Scotland. As now implemented in England and Wales, a key policy instrument to reduce the pluvial flood risk is the promotion of SUDS. These have been required by SEPA in the east of Scotland since 1996 and, following the Water Environment and Water Service (Scotland) Act 2003, they are now enforced across Scotland with Scottish Water taking over their maintenance once properties on developments are sold.

Northern Ireland

The management of pluvial flooding in Northern Ireland is mainly shared between the Rivers Agency, the Department for Regional Development (DRD) Roads Service, the Northern Ireland Water and Planning Service and the Northern Ireland Environment Agency (Rivers Agency, 2011). The Rivers Agency (an executive agency of the Department of Agriculture and Rural Development) is the statutory drainage and flood defence authority and the competent authority for delivering the EU Flood Directive. It also provides emergency flood response and maintains open water courses and culverted systems. The DRD engages with pluvial flooding via its responsibility as the Northern Ireland roads authority and its development of policy relating to water and sewerage services via arms-length bodies. The Planning Service (an executive agency within the Department of the Environment) provides guidance to local authorities for managing flood risk via the Planning Policy Statement (PPS) 15 *Planning and Flood Risk*, but at present this does not explicitly address the risk of pluvial flooding. The Northern Ireland Environment Agency (another agency within the Department of the Environment) chairs the Northern Ireland Working Party on SUDS.

Recent policy development specific to managing pluvial flooding includes implementing European legislation, regulating Northern Ireland Water, development of Surface Water Flood Maps and proposals for promoting SUDS:

- The EU Floods Directive has been transposed into local legislation by the Water Environment (Floods Directive) Regulations (Northern Ireland) 2009. Implementation is vested in a steering group which comprises Emergency Planning, Northern Ireland Environment Agency, Department of Environment Planning and Emergency Policy, Planning Service, DRD Water Policy Unit, Roads Service and Northern Ireland Water. A stakeholder group has also been formed to reflect the interests of other governments, local government, the voluntary sector, emergency response authorities, the business community and environmental interests.

- The first major task for ensuring compliance with the EU Floods Directive is the production of a Preliminary Flood Risk Assessment (PFRA) by December 2011. Its compilation in Northern Ireland has much in common with the approach being developed in Scotland and provides, for a given location, the number of people affected together with their health characteristics as a surrogate measure of vulnerability (Rivers Agency, 2010). The term 'health' in this context focuses on easily identifiable buildings in which vulnerable people are likely to be located (hospitals, care homes, health centres). In terms of surface water management, inundation maps (which include pluvial flooding) are being prepared both in terms of current baseline conditions and with an allowance for climate change.

- Current guidance to Northern Ireland Water focuses on environmental protection and the treatment of waste water rather than managing pluvial flooding. Under the current Water and Sewerage Services (Northern Ireland) Order 2006, the drainage system does not have to be designed to cope with extreme events (in excess of 1 in 30 years), although the company is responsible for flooding caused by failures arising from inadequate maintenance of its pumping stations or sewerage network.

- Once the Surface Water Flood Maps have been published, the Planning Service will update PPS15 to incorporate pluvial flood risk explicitly in spatial planning.

- Following a consultation on *Managing Stormwater: a Strategy for Promoting the Use of Sustainable Drainage Systems in Northern Ireland* (2009), a working party (chaired by the Northern Ireland Environment Agency) has recommended SUDS as the preferred approach for managing surface water flooding caused by land development.

3 Research methods

The research we carried out was divided into three phases, each with its own sub-components. The three main phases were assessments of:

- the impact of climate change on pluvial flood hazard;

- urban population vulnerability to pluvial flooding; and

- current responses to pluvial flood risk.

Pluvial flooding is more likely to occur in urban areas, where its consequences are also likely to be greater and this research therefore relates primarily to urban areas. The coverage of urban areas varies across different elements of the research. Analysis of projected changes in extreme rainfall under different emissions scenarios, and for different timescales, was restricted to the largest settlement in each region of the UK, which we refer to as 'Tier 1' settlements. More detailed analysis of spatial and seasonal patterns was conducted for the medium emissions scenario to the 2050s for 44 key settlements (the largest settlements in the UK, while ensuring a regional spread). We refer to these as 'Tier 2' settlements. National estimates of the urban population at risk now and in 2050 are based on all settlements in the UK with a population over 10,000 in the 2001 Census of Population.

The remainder of this chapter provides an outline of the research methods used. More detailed technical accounts can be consulted in the Appendices which cover the results from climate modelling based on UKCP09 software (Appendix I); methods for deriving future rainfall using the UKCP09 Weather Generator and selection of urban areas (Appendix II); inundation modelling of flood outlines (Appendix III); estimating socio-economic profiles of areas at risk (Appendix IV); and details of interview coverage (Appendix V).

Phase 1: The impact of climate change on pluvial flood hazard

National and regional assessment of current and future wettest day over key urban areas using UKCP09 software

The UK-wide assessment of extreme rainfall which causes pluvial flooding is based on maps of the wettest day in winter and summer under the current climate, and projected wettest day rainfalls under future climates (2030s, 2050s and 2080s) across three emission scenarios (low, medium and high). The outputs for current wettest day rainfall are reported across a 25 km grid which covers the whole of the UK. Although pluvial flooding is dependent on the intensity of sub-daily storms, the spatial pattern of the hazard can be assessed from these maps given the likely association between the severity of daily and sub-daily rainfall (for example, pulses of intense short-duration rainfall within very wet days). The future hazard requires modelling for selected 25 km squares which cover key urban areas. This is done using the Weather Generator within the UKCP09 software. The nationwide patterns of future pluvial flooding can then be examined for given emission scenarios, along with trends from the 2030s to the 2080s.

Local assessments of current and future wettest hour (Belfast, Glasgow, Luton, Wigan) using UKCP09

More detailed assessment of the pluvial flood hazard requires the modelling of extreme rainfall over periods of less than 24 hours. The UKCP09 Weather Generator can also be used to determine maximum 1-hour rainfalls under future emission scenarios from the 2030s to the 2080s. This level of detail is necessary to understand inundation maps prepared using short-duration rainfalls. Local assessments of current and future wettest hour rainfalls are developed for four urban areas with contrasting urban histories and morphologies (Belfast, Glasgow, Wigan and Luton). The UKCP09 Weather Generator failed to produce stable and robust estimates of extreme 1-hour rainfall (Appendix I). Given this finding, the likely range of uplift in rainfall intensity due to climate change was modelled by performing runs of baseline rainfall plus 10 per cent and baseline plus 20 per cent.

Translating rainfall into pluvial flood outlines

Pluvial flood risk was mapped using JFLOW, 2-D raster-based modelling software developed by JBA Consulting. The inputs to the model are rainfall data and topographical information for the area of interest. The model produces a map of pluvial flood depths and velocities across the study area. Flood outlines of depth > 0.1 m were mapped in order to identify areas deemed to be at risk. A full account of the methodology is provided in Appendix III but the key aspects are outlined below.

The Flow Model
The model progresses in a series of temporal steps, with water moving between 5 m horizontal cells driven by gravity. Thus, rainfall is routed to low lying areas where it forms ponds until the water level is high enough to spill into surrounding cells. The model is run beyond the end of the period of rainfall in order to allow water to continue to run off across the ground surface to create final flood depths. An allowance for drainage capacity is subtracted from the rainfall profile equivalent to the locally relevant 1 in 5-year rainfall in each settlement. (The design standard is theoretically 1 in 30-year rainfall but in practice blockages and bottlenecks diminish operating capacity.) Finally, water is allowed to be lost off the edge of the modelled area.

The Digital Terrain Model (DTM)
Most of the study areas have elevation data available from light detection and ranging (LiDAR) coverage, which provides 1 m horizontal resolution to 20 cm vertical accuracy. In areas where LiDAR was not available, we used elevation data from Ordnance Survey and NEXTMap at 5 m horizontal resolution and lower vertical accuracy. In order to represent water flow accurately, buildings from Ordnance Survey digital maps are 'stamped' onto the DTM at arbitrary 5 m height (water flows around buildings and not through them); bridges, underpasses, tunnels and culverts are 'opened' in order to allow water to flow through or under. Roadside kerbs are assumed to be 0.1 m in order to allow water to flow down roads.

Rainfall input
For each settlement, *Flood Estimation Handbook* (Institute of Hydrology, 1999) depth–duration–frequency relationships were used to generate 'baseline' 0.5 per cent annual probability (1 in 200-year) rainfall for 1.1 hour and 10.5 hours' duration. The flood outlines produced from each duration were combined in order to identify areas at risk. As outlined above, the likely range of uplift was modelled by performing runs of baseline plus 10 per cent and baseline plus 20 per cent.

Phase 2: Urban population vulnerability to pluvial flooding

The risk posed by flooding is the result not only of the natural hazard (in the case of pluvial flooding, extreme rainfall over urban areas) but also of the distribution of the population and of particularly vulnerable groups such as older people. The second phase of the research therefore considered the distribution of the urban population, as well as a number of potentially vulnerable groups, in relation to the distribution of the hazard.

As with the hazard in phase 1, population vulnerability was assessed at two spatial scales: national and local. Both produced estimates of the number of people in urban areas exposed to the hazard. The national assessment was disaggregated by region, while the local assessment was conducted for flood risk and non-risk areas within three settlements, Belfast, Glasgow and Luton.[3]

National assessment of urban population vulnerability

Urban population at risk: baseline (pre-climate change)
We established an approximate baseline number of people in urban areas at risk from pluvial flooding using the following steps:

1   identify the UK's total urban population;

2   calculate the proportion of urban residents who live in areas prone to pluvial flooding;

3   calculate the proportion of urban residents who have living accommodation at or below street level; and

4   apply the proportions from steps 2 and 3 to the UK's total urban population.

Step 1: we identified the UK's total urban population using 2001 Census of Population data for urban areas.[4]

Step 2: the proportion of urban residents who live in areas prone to pluvial flooding was derived from our analysis of the distribution of population in relation to modelled pluvial flood outlines in Belfast, Glasgow and Luton (see next chapter and Table 3).

Step 3: we calculated the proportion of urban residents who have living accommodation at or below street level through an analysis of information on the lowest level of accommodation occupied by households in the 2001 Census of Population.

Step 4: after regional disaggregation of the data from steps 1 and 3, regional and UK estimates of the population at risk from pluvial flooding were calculated. These estimates relate to the 2001 population exposed to the 1 in 200-year pluvial flood risk under the 'baseline' (1961–90) climate.

Urban population at risk under climate change
We estimated the population that could be at risk from pluvial flooding in 2050 using the following steps:

1   establish the current urban population at risk (see steps above);

2   identify the rate of population growth from national population projections;

3   identify the percentage increase in extreme rainfall over key urban areas (based on UKCP09 wettest day: note that sub-daily duration is preferable but UKCP09 is unable to produce robust sub-daily extreme rainfall projections. See Appendix I);

4   calculate the 'exposure:hazard response ratio' ([% change in population exposed]/[% change in intensity of hazard]); and

5   apply the proportions from steps 2, 3 and 4 to the current urban population at risk.

Step 1: the current urban population estimated to be at risk by region was taken from the 'baseline' calculations (see above).

Step 2: population projections produced by the relevant government statistical agencies around the UK were obtained and used to calculate rates of population growth. Population projections are available to (and beyond) 2050 for the UK as a whole but regional projections are only available to 2033.

Step 3: ideally, extreme rainfall magnitudes of sub-daily duration would be used since this is the type of rainfall most likely to produce pluvial flooding. However, the UKCP09 Weather Generator is unable to produce reliable projections for extreme sub-daily rainfall. We have therefore used the projected percentage change in wettest day over urban areas under the medium emissions scenario. Since short pulses of rain often occur within longer periods of rainfall, change in wettest day severity is likely to give an indication of the scale of change to shorter duration events.

Step 4: depending on local topography and the distribution of population within specific settlements, a given percentage change in rainfall intensity may not necessarily translate to a similar proportionate change in population flooded. We have therefore calculated the exposure:hazard response ratio based on the results from our detailed modelling in local settlements (see phase 1 and next chapter). We have defined this ratio as [% change in population exposed]/[% change in intensity of hazard].

Step 5: the proportions calculated in steps 2, 3 and 4 were then applied to the UK urban population estimated to be at risk from pluvial flooding in the 'baseline' (pre-climate change) scenario.

Socio-economic distribution of risk: baseline and climate change

We analysed the socio-economic profile of 44 key urban areas (see Appendix II) across the UK according to their intensity of wettest day rainfall, firstly under 'baseline' (pre-climate change) conditions and then under climate change (reported in chapters 5 and 6 of this report). To ensure comparability with results under climate change, we used Weather Generator baseline data. We repeated this analysis using rainfall intensities for 2050 under the medium emissions scenario. In both baseline and climate change scenarios, we classified the severity of the wettest day rainfall in each urban area as 'low' (< 17 mm), 'medium' (17–23 mm) or 'high' (> 23 mm).

The socio-economic profiles were assessed using three measures: the Index of Multiple Deprivation (IMD), self-reported health, and occupational status. Other socio-economic indicators were also analysed, but none revealed a pattern in relation to intensity of wettest day rainfall.

Local assessment of urban population vulnerability

We were able to carry out detailed assessments of the distribution of vulnerable groups in relation to areas at risk from pluvial flooding within the three settlements for which pluvial flood risk modelling had been conducted. Here, we estimated the distribution of population in relation to areas at risk (see

Appendix IV) and created socio-economic profiles of flood risk and non-risk areas. This was done by intersecting predicted flood extents (depth > 0.1 m) with Census Output Areas (COAs, the smallest spatial units for which detailed Census data is available, which therefore gives the best match to pluvial flood outlines which are often very small).

The local socio-economic profiles consisted of those in the following potentially vulnerable categories: older people (75+); ethnic minority; limiting long-term illness; poor health; unemployed; lower socio-economic group; households with no car; owners with a mortgage; social renters; private renters; overcrowding; single pensioners; lone parents; and households at or below street level. We hoped to analyse the IMD in the local analysis but this proved impossible as it is not available for COAs. Because our analysis was limited to population data, this list should not be considered exhaustive of all aspects of vulnerability to flooding. For a more comprehensive list of domains associated with flood vulnerability, incorporating physical and social characteristics of place and ability to avoid, recover from and adapt to flooding, see Lindley *et al.* (2011).

Phase 3: Current responses to pluvial flood risk

Our assessment of current responses to pluvial flood risk has mainly involved interviews with key stakeholders and experts. In addition, we have conducted some documentary research and attended flood risk management conferences.

We interviewed a total of 20 stakeholders in pluvial flooding issues in the course of the research (see Appendix V). Interviews lasted between 30 and 90 minutes. Face-to-face interviews were recorded and expansive notes subsequently written up. A smaller number of interviews were conducted by telephone, with detailed notes being made during and immediately afterwards.

Interviews were conducted at national and local levels, in order to gain an understanding of the critical issues and responses at different levels of governance, including policy formulation, strategy development and implementation. National interviews included officials with central government departments and agencies, water regulators, water companies, insurance companies and relevant charitable organisations. Local interviews included drainage engineers, planners, emergency planners and others responsible for flood management.

National interviews covered key organisations with responsibility for flood management in the three UK jurisdictions with primary legislative competence for flooding: England, Northern Ireland and Scotland. Local interviews covered local government officials and water companies operating in Belfast, Glasgow and Luton.

Textual material from the interviews was thematically coded using a grounded theory approach. This involved an initial open reading of the material in order to identify the main findings contained within the interviewees' responses. A second reading identified common themes, which informed the organisation of the write-up of the interview material in this report. Specifically, these themes were: vulnerability, insurance, governance, surface water management and investment.

Selecting local case study settlements

In selecting settlements (shown in Table 2), it was deemed important to have a cross-section of various factors, including: urban form; whether there is a recent history of pluvial flooding; whether there is a surface water management plan in place; age of infrastructure; socio-economic characteristics; and country of jurisdiction within the UK. All settlements have a moderate or high existing level of flood risk.

Table 2: Case study settlements

City	Recent history of pluvial flooding	Surface water management plan	Urban form	Age of infrastructure	Socio-economic characteristics	Jurisdiction	Miscellaneous
Belfast	Yes	No	Victorian industrial	Victorian	Post-industrial, slow regeneration	Northern Ireland	Religious segregation
Glasgow	Yes	Yes	Victorian industrial	Victorian	Post-industrial, regeneration	Scotland	Sustainable regeneration
Luton	Yes	Yes	New town	Post-war	Vibrant	England	Ethnic diversity
Wigan	No	No	Victorian industrial	Victorian	Post-industrial, regeneration	England	Part of Greater Manchester flood management plan

4 Climate change and extreme rainfall

See Appendices I and II for further detail.

Current extreme rainfall

In general, more rainy days occur in winter and autumn than in summer. The north and west are the wettest areas of the UK, a pattern that is also reflected in maximum 1-day rainfalls occurring once in two years. But this regional pattern does not apply for more extreme 1-day rainfalls (which are most closely associated with pluvial flooding) with a 50 mm event (1 in 50-year storm) occurring virtually anywhere in the UK in the summer. This pattern is even stronger for 1-hour rainfalls with falls > 14 mm/hour (1 in 10-year storm) and > 31 mm/hour (1 in 100-year storm) occurring across the whole of the UK except for eastern Scotland and Northern Ireland (see Figure 2). Note the contrast in numerical scales in Fgure 2.

Overall, whilst there is a marked north-west–south-east gradient in the maximum 1-day rainfall, in the autumn and winter this is typically reversed for the maximum 1-hour rainfall where consistently higher values are reported for the south and east with lower values in eastern Scotland and Northern Ireland.

Figure 2: Comparison of 1-hour rainfall (mm) 10-year return period and 100-year return period
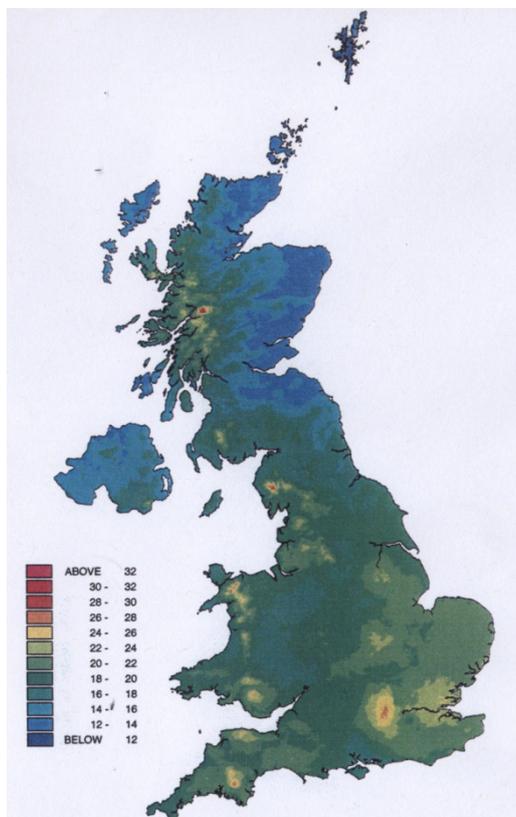
a) 1-hour rainfall (mm) 10-year return period
b) 1-hour rainfall (mm) 100-year return period
Source: Institute of Hydrology, 1999
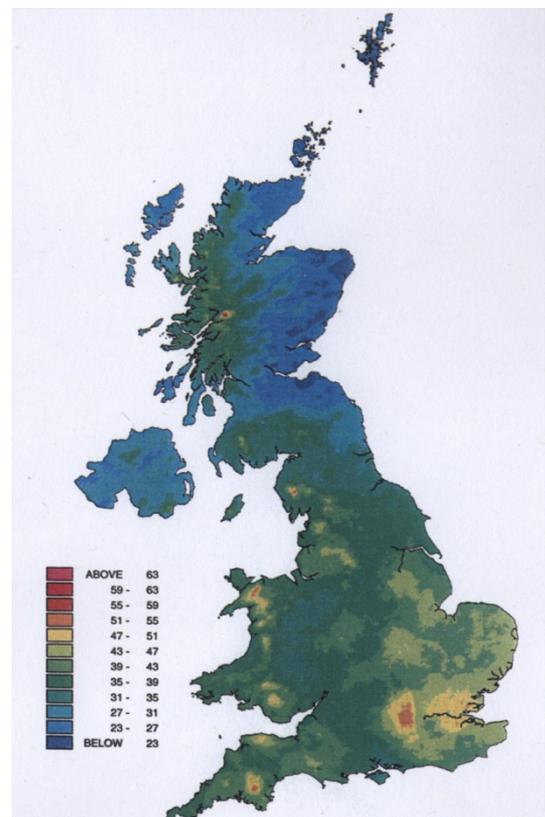
Future extreme rainfall

The UKCP09 projections for future rainfalls predict that during the twenty-first century the UK will have wetter, warmer winters (particularly in the north and west) and hotter, drier summers (particularly in the south and east). Further detail is provided by UKCP09 by season under low, medium and high emission scenarios across three time periods (see Figure 3).

Figure 3: Changes in rainfall for wettest day in winter and summer (high emissions for 2080s) across a range of probability levels

Change in precipitation (%) on the wettest day of winter for the 2080s, high emissions scenario

Change in precipitation (%) on the wettest day of summer for the 2080s, high emissions scenario
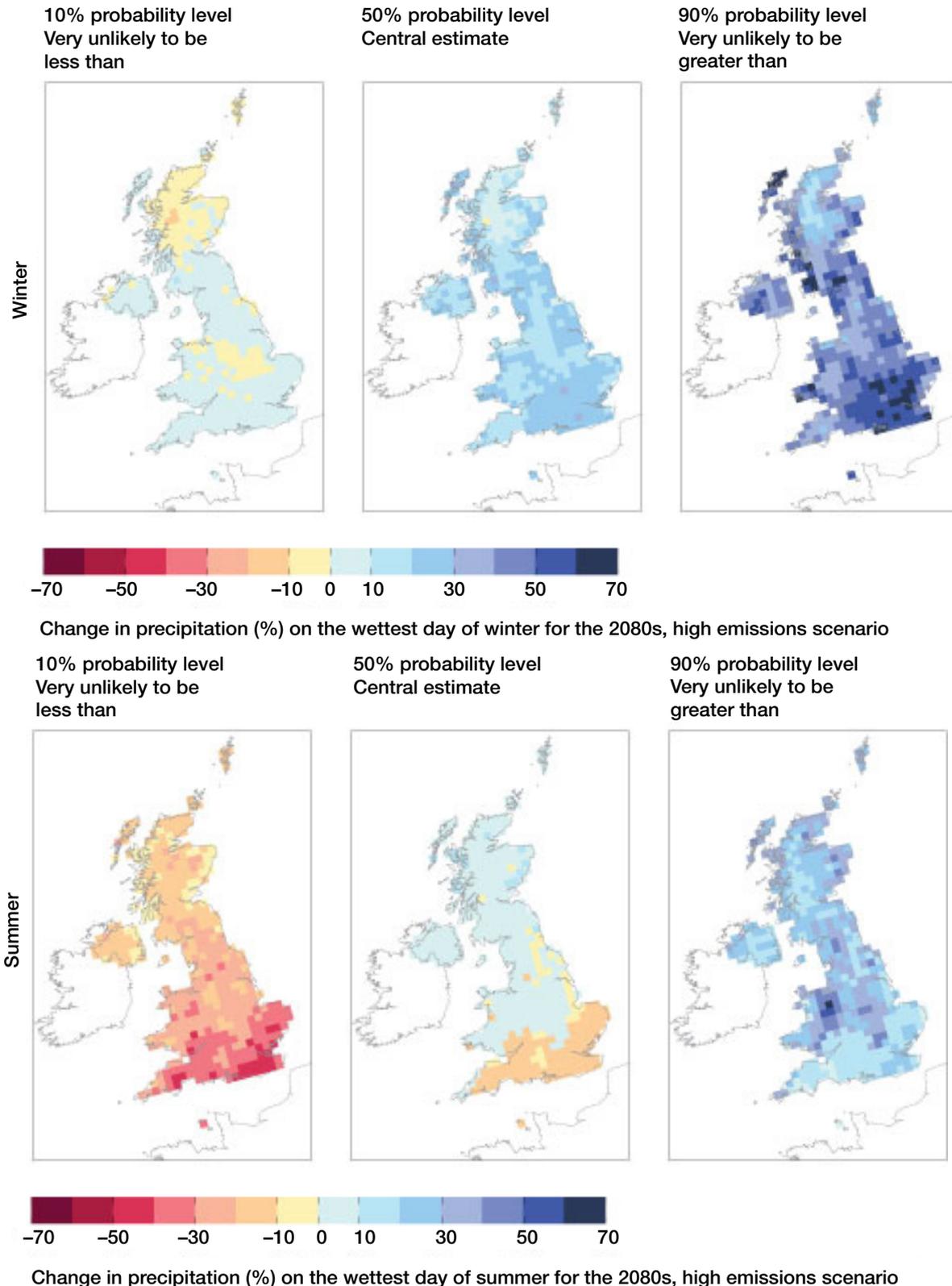
Source: UKCP09

Taking the high emissions scenario by the 2080s (see Figure 3), much of the UK will experience up to a 20 per cent increase in winter wettest day rainfall ('central estimate') and, locally across much of south and eastern England, up to a 50 per cent increase (with a 1 in 10 chance). In summer the pattern changes markedly with most of southern England seeing at least a 10 per cent decrease ('central estimate'). There is a 1 in 10 chance this could be up to a 10 per cent increase in southern England and up to a 40 per cent increase in parts of northern England. This range of possible outcomes reflects a high degree of uncertainty over estimates of future rainfall due to the complexity of atmospheric processes. Thus some frontal storms can extend over large areas and last several days whilst convective summer storms tend to be highly localised and short lived.

Retaining the same 25 km grid, we used the UKCP09 Weather Generator to predict extreme rainfall for a medium emissions scenario for the 2050s using the 44 urban areas selected for this report. Since the Weather Generator output is reported as a percentage change, the Met Office rainfall for the baseline period (1961–90) was used to convert these percentage changes into a 2050s wettest day (mm) and uplift (mm).

In terms of the 2050s wettest day, no consistent pattern emerges (see Figure 4) with the five highest values straddling Scotland (Glasgow), Wales (Cardiff and Swansea) and England (Sheffield and Plymouth). However, the five lowest values are consistently in eastern England (Norwich, Gillingham, Southend-on-Sea, Peterborough and Ipswich) and there is a slight west–east gradient when all values are taken into account. However, when the uplift values are examined (see Figure 4), only Swansea, Glasgow, Brighton and Worthing remain in the top ten. They are now joined by Crawley, Portsmouth, Southampton, Bristol and Reading – a group drawn exclusively from southern England. This implies that, in general, the hazard of extreme daily rainfall will increase more rapidly in southern England than in other parts of the UK, a finding that is consistent with the map of the current 1 in 100-year 1-hour rainfall (see Figure 2b). This is also consistent with the general prediction that convective storms and cells within frontal storms are likely to become more severe and intense (UKCP09). This is significant in relation to pluvial flooding, since the south-east of England is heavily urbanised and non-porous surfaces in urban areas make towns and cities more susceptible to pluvial flooding than rural areas.

Given that most pluvial floods are caused by short-lived events, and inundation modelling is based on storms of one to three hours' duration, the ideal rainfall prediction is the maximum 1-hour fall. As explained below, at present the Weather Generator cannot produce robust and reliable estimates for 1-hour falls. But since a 1 in 100-year daily rainfall is likely to include intense and short-lived pulses of rain which will generate pluvial flooding, the above analysis of the 1 in 100-year wettest day rainfall provides a useful surrogate for where future pluvial flooding is likely to be most severe.

Turning from spatial to temporal patterns in future extreme rainfall, we now report on the wettest days over three periods (2020s, 2050s and 2080s) and across three emission scenarios (see Figure 5), but only for the twelve Tier 1 urban areas (see next chapter for definition). The key findings are that:

- there will be a steady increase in both uplifted rainfall and wettest day rainfall for all urban areas throughout the twenty-first century, reflecting the high regional uplifts in the south;

- as emissions increase, there will be an increase in wettest day rainfall and uplifted rainfall for all urban areas; and

- the absolute but not the percentage increases are smaller in urban areas with lower wettest day rainfalls.

Figure 4: Wettest day baseline and uplift (2050s, medium emissions) across key urban areas

Key

- Wettest day rainfall (cm)
- Uplift in rainfall (mm)

1. Swansea
2. Glasgow
3. Cardiff
4. Sheffield
5. Plymouth
6. Manchester
7. Preston
8. Brighton
9. Stockport
10. Worthing
11. Crawley
12. Belfast
13. Bournemouth
14. Bristol
15. Southampton
16. Blackpool
17. Bolton
18. Londonderry
19. Portsmouth
20. Woking
21. Edinburgh
22. Liverpool
23. Reading
24. Swindon
25. Birmingham
26. Sunderland
27. Newcastle upon Tyne
28. Slough
29. Nottingham
30. Greater London
31. Oxford
32. Derby
33. Coventry
34. Leeds
35. Stoke-on-Trent
36. Hull
37. Leicester
38. Middlesbrough
39. Luton
40. Norwich
41. Gillingham
42. Southend-on-Sea
43. Peterborough
44. Ipswich

Note different scales

Figure 5: Wettest day for Tier 1 urban areas: low, medium and high emissions
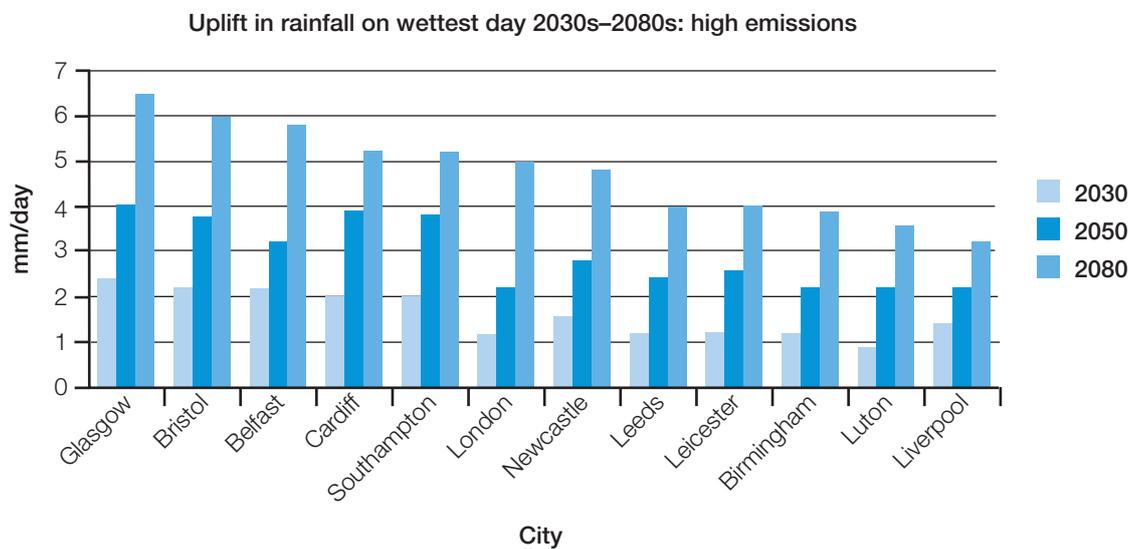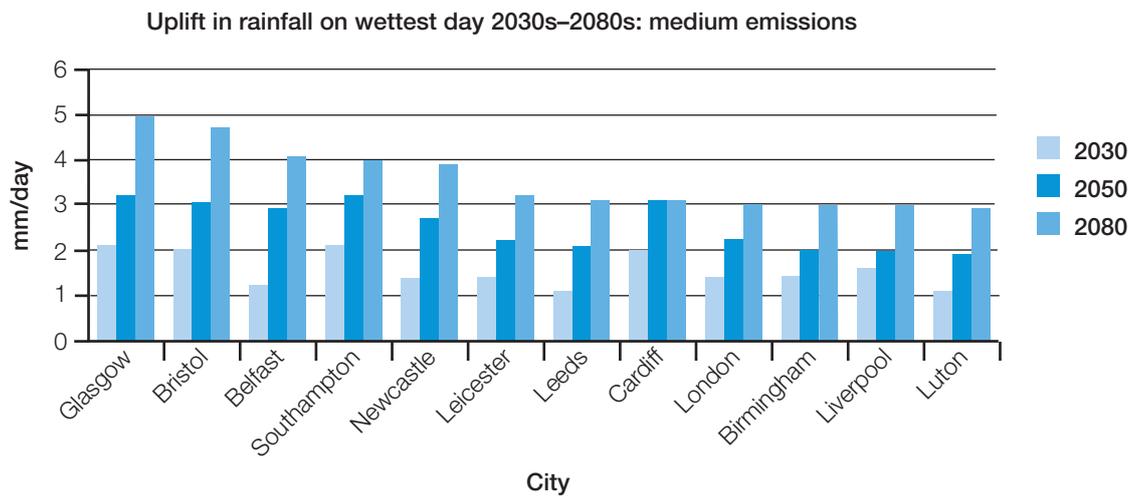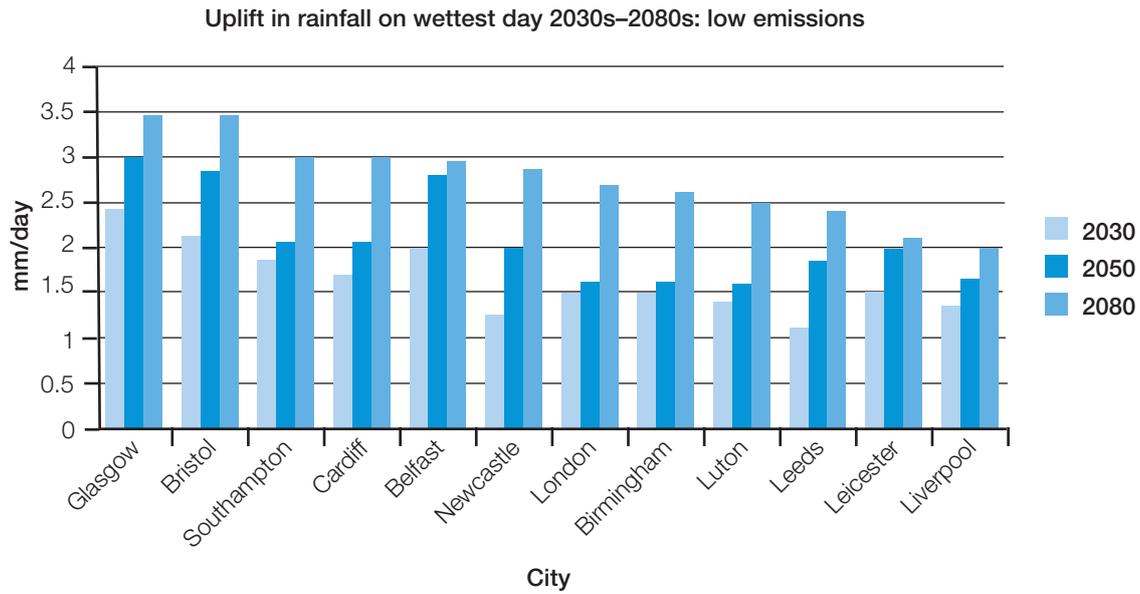
Uplift in rainfall on wettest day 2030s–2080s: low emissions

Uplift in rainfall on wettest day 2030s–2080s: medium emissions

Uplift in rainfall on wettest day 2030s–2080s: high emissions

Glasgow, Belfast, Cardiff and Bristol (all located in the west of the UK) record the highest wettest day rainfall and absolute uplift in rainfall in nearly all scenarios by the 2080s, followed by Southampton and London in the south. Liverpool is consistently at the lower end of the rank order in Figure 5 with relatively low uplifted rainfall. This may reflect its location close to the dry Cheshire plain with an annual rainfall of only 850 mm.

The seasonality of rainfall on the wettest day is now explored using the Weather Generator for London and Glasgow, two urban areas with contrasting rainfall profiles for medium emissions across the 2030s, 2050s and 2080s (see Figure 6).

A strong seasonal signal is present throughout for both locations. With the exception of summer, the rainfall on the wettest day increases across all three time periods. By contrast, summer rainfall in London decreases in all time periods. London also reports higher percentage increases but this is against a lower absolute rainfall than for Glasgow, meaning that the impact on the scale of pluvial flooding may be less in London than in Glasgow despite the higher percentage increase.

It has already been noted that changes in 1-hour rainfall will be most important in terms of future urban flooding. The Weather Generator was used to derive the maximum 1-hour rainfalls for Luton, Belfast, Glasgow and Wigan (see Appendix II for details). The results failed to produce consistent or credible results, with only Glasgow reporting an increase (of 16 per cent) – see Table 15, Appendix I.

Belfast shows a reduction of 1.9 per cent and Luton and Wigan larger reductions of 6.9 per cent and 4.6 per cent respectively. The markedly different results for Belfast and Glasgow – two cities relatively close to each other with similar climates – raise a question about the robustness of these results. Further analysis into the distribution of extreme values and the frequency of storms with varying rainfall intensities failed to clarify these inconsistencies in uplift values by the 2080s.

Conclusion

Currently, extreme rainfall of 1-hour duration is most intense in the autumn and winter in the north and west, but during the summer months is most intense in the south and east. Uplifts due to climate change are likely to be greatest in percentage terms in the south and east, and greatest in absolute terms in the north and west.

We conclude that the Weather Generator cannot provide robust and reliable results for maximum 1-hour rainfall at high return periods and note the accompanying guidance which cautions use beyond a return period of 1 in 10 years (Jones *et al.*, 2009).

Figure 6: Seasonal changes in rainfall on wettest day: London and Glasgow

Percentage uplift in rainfall: medium emissions
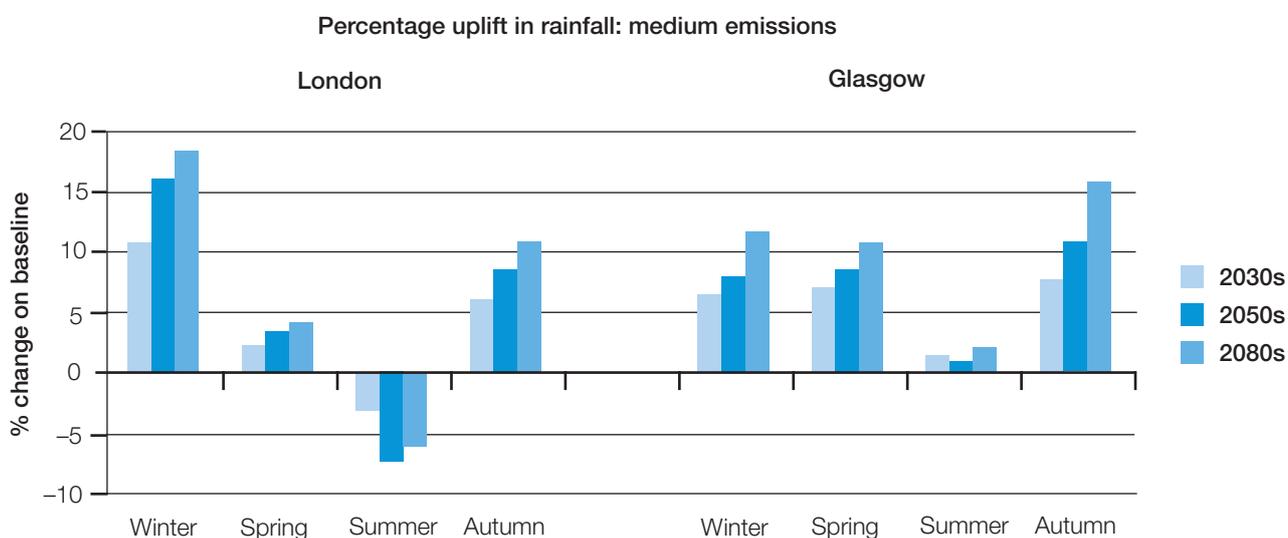
In the modelling of inundation for Belfast, Glasgow and Luton (see Appendix III), we have used uplift values of plus 10 per cent and plus 20 per cent which we anticipate are likely to be well within the likely window of future extreme rainfalls and thus not seriously damaging to the findings reported later. Following improvements to the Weather Generator or subsequent alternatives, we recommend that these values be re-examined.

5 Current urban population at risk from pluvial flooding

This chapter assesses the numbers of people living in urban areas that may be at risk from pluvial flooding. It then goes on to assess some of their social characteristics.

Current urban population at risk

We have established an approximate baseline number of people at risk from pluvial flooding in urban areas, using the following steps:

1   identifying the UK's total urban population (settlements with a population of 10,000 or greater);

2   calculating the proportion of urban residents who live in areas prone to pluvial flooding (0.5 per cent annual probability rainfall minus drainage capacity, > 0.1m flood depth);

3   calculating the proportion of urban households that have living accommodation at or below street level; and

4   applying these proportions to the UK's total urban population.

According to urban–rural definitions developed by the jurisdictions across the UK (see chapter 3), almost 45 million people in the UK lived in urban areas in 2001. The 2001 Census of Population reveals that 87 per cent of households in urban areas across the UK have living space on or below street level. While households above street level are not immune to all the impacts of a flood (for example, damage to cars, sheds and garages, and disruption during an actual flood event), they are unlikely to have to be rehoused for any length of time compared with those with extensive damage to the interior of their home. It is on this basis that we consider it appropriate to exclude those living above street level from estimates of numbers at risk.

We assume that 5 per cent of the urban population is at risk from pluvial flooding. This proportion was derived from our analysis of the distribution of population in relation to modelled pluvial flood outlines in Belfast, Glasgow and Luton. We have cautious confidence in extrapolating nationally from these three towns, on the basis that the local modelling is best current practice (see Appendix III) and the proportion identified as at risk in each town was remarkably similar despite very different urban structures (see Table 3). Over the three towns, 5.6 per cent of the population was identified as at risk. However, we opted to be conservative and assumed a slightly lower figure nationally (5 per cent) in order to minimise the possibility of falsely over-estimating the scale of the risk posed from pluvial flooding in urban areas.

Just under 2 million people across the UK are estimated to be at risk of pluvial flooding in urban areas larger than 10,000 population (see Table 3).[5] This figure is the total urban population of 45 million multiplied by 0.05 (the proportion in areas at risk) multiplied by 0.87 (the proportion of households in urban areas at or below street level).

Regional patterns

The preceding chapter provided an estimate of the number of people at risk from pluvial flooding in urban areas across the whole of the UK. There are, however, regional patterns to urbanisation and therefore to the population at risk.

Since we are assuming a nationally uniform 5 per cent of urban population at risk from pluvial flooding, the regional pattern reported (see Table 3) reflects the size of each region's urban population and the proportion of households with living space at or below street level.

The three regions with the largest urban populations are London, the South East and the North West. Together, these regions account for over two-fifths of the UK's urban population and over 750,000 people at potential pluvial flood risk. Adding the West Midlands accounts for the majority of the UK's urban population and takes the total number of people at potential risk to almost 1 million.

The proportion of each region's total population at potential risk varies from 2.6 per cent in Scotland and Wales to 3.7 per cent in the North West and West Midlands. The lower proportion in Scotland is driven by a low proportion of urban residents living at or below street level, a function of Scotland's distinctive 'tenement' flats. The low proportion in Wales is driven by low levels of urbanisation (although the definition of urban differs in Wales, which may partially account for this). London also has a significant share of its population living above street level, but this is counteracted by being almost entirely urbanised so that the overall share of London's population at potential risk (3.4 per cent) is similar to the UK average (3.3 per cent).

Table 3: Regional distribution of potential pluvial flood risk in urban areas over 10,000 population

Region	Population, 2001	Urban pop. (% of total pop.)	Urban pop. in areas at risk from pluvial flooding (% of urban pop.)	Street level or below (% of urban pop.)	Urban pop. at potential risk from pluvial flooding	Pop. at potential risk from pluvial flooding (% of total pop.)
South East	8,000,645	75.1%	5.0%	89.2%	267,942	3.3%
North West	6,729,764	80.9%	5.0%	91.9%	250,334	3.7%
London	7,172,091	98.3%	5.0%	70.2%	247,348	3.4%
West Midlands	5,267,308	80.9%	5.0%	91.1%	193,958	3.7%
East of England	5,388,140	70.4%	5.0%	91.2%	172,992	3.2%
Yorkshire & The Humber	4,964,833	75.4%	5.0%	92.0%	172,199	3.5%
South West	4,928,434	68.4%	5.0%	89.9%	151,613	3.1%
East Midlands	4,172,174	69.9%	5.0%	93.9%	136,955	3.3%
Scotland	5,062,011	68.1%	5.0%	75.4%	129,901	2.6%
North East	2,515,442	78.9%	5.0%	91.4%	90,740	3.6%
Wales	2,903,085	56.3%	5.0%	92.2%	75,332	2.6%
Northern Ireland	1,686,700	63.0%	5.0%	93.8%	49,873	3.0%
UK	**58,790,627**	**76.1%**	**5.0%**	**87.1%**	**1,939,187**	**3.3%**

The higher proportions at risk in the North West and West Midlands are driven by high levels of urbanisation. These are the only two regions outside London that are more than 80 per cent urbanised.

However, regional differences should not be over-emphasised. Except for Scotland and Wales, both at 2.6 per cent, all regions fall within a relatively small range (3.0–3.7 per cent) of their total population at potential risk.

National socio-economic profile of urban areas at potential risk

We analysed the socio-economic profiles of key urban areas according to their intensity of wettest day rainfall. To ensure comparability with results under climate change, we used Weather Generator baseline data. The socio-economic profile was assessed using three measures: the IMD, self-reported health, and occupational status. The severity of the wettest day rainfall in each urban area was classified as 'low' (< 17 mm), 'medium' (17–23 mm) or 'high' (> 23 mm). Other socio-economic indicators were also analysed, but none revealed a pattern in relation to the severity of the wettest day.

Urban areas with the highest wettest day rainfall also have the highest multiple deprivation score (see Table 4). Urban areas with a wettest day greater than 23 mm have an IMD score of 29.6, compared with an IMD score of 27.3 for urban areas with a wettest day less than 17 mm.

Health showed a similar 'regressive' relationship, with wetter urban areas having higher levels of poor health. Urban areas in the 'high' wettest day category had 10.5 per cent of their residents reporting poor health, compared with 9.2 per cent in the 'low' wettest day category.

There is no systematic relationship between occupational status and wettest day severity. The wettest urban areas actually had the lowest proportion of residents unemployed or in manual occupations, and there is no consistent gradient in this proportion against wettest day severity.

Local socio-economic profile of areas at pluvial flood risk

Across the three local case study settlements (Belfast, Glasgow and Luton), 5.6 per cent of the settlements' populations live in areas at risk from pluvial flooding (see Table 5). There is little difference in this proportion between the three settlements. However, Glasgow has a high proportion of its population living above street level (over a third, compared with around 10 per cent in Belfast and Luton), which means that a lower proportion of Glasgow's population is at direct risk from pluvial flood water actually entering the home: 3.4 per cent in Glasgow versus 5.2 per cent in Belfast and 5 per cent in Luton once those living above street level are discounted.

The characteristics of populations in flood risk and non-risk areas are important, since some socio-demographic groups are more vulnerable to the impacts of a flood than others. We have picked out for analysis the main groups that previous research has identified as more vulnerable than others to the

Table 4: Socio-economic profile of urban areas by 30-year wettest day rainfall: baseline

Socio-economic indicator	Severity of 30-year wettest day[†1]		
	High > 23 mm	**Medium** 17–23 mm	**Low** < 17 mm
Index of Multiple Deprivation (IMD)	29.6	28.0	27.3
Poor health (%)[†2]	10.5	10.3	9.2
Low occupational status (%)[†3]	13.1	14.7	13.8

[†1] Mean of 30-year 99th percentile wettest day rainfall over key urban areas. Source: UKCP09 Weather Generator

[†2] Source: 2001 Census of Population

[†3] Percentage long-term unemployed or in routine or semi-routine employment. Source: 2001 Census of Population

Table 5: Local populations at risk: baseline

Settlement	Population of areas at risk	% of total population	Population of areas at risk at street level or below	% of total population at risk
Belfast	33,126	5.7%	30,088	5.2%
Glasgow	63,927	5.5%	39,411	3.4%
Luton	10,593	5.7%	9,185	5.0%
Average (pop. weighted)	–	5.6%	–	4.3%

impacts of a flood. We have calculated the percentage of the population (or, in some cases, households) that falls into different socio-demographic groups for flood risk areas and non-risk areas (see Table 6). A comparison of the proportion of flood risk and non-risk areas in each socio-demographic group identifies whether a particular group is over-represented in flood risk areas.

The results indicate that all the vulnerable groups in Table 6 are over-represented in flood risk areas, with the exception of owners with a mortgage and households living at street level or below. Although of different magnitudes, the pattern is almost identical across all three settlements, despite differences in location, size, age, urban structure and ethnic composition. This suggests a systemic and systematic process producing a slightly regressive distribution of pluvial flood risk.

Table 6: Local socio-demographic profiles: baseline

Socio-demographic indicator	Belfast			Glasgow			Luton		
	Flood risk areas	Non-risk areas	Diff.	Flood risk areas	Non-risk areas	Diff.	Flood risk areas	Non-risk areas	Diff.
Older people (75+)	7.4%	6.8%	0.6%	6.8%	6.9%	0.0%	5.3%	5.1%	0.3%
Ethnic minority	1.2%	1.1%	0.1%	3.7%	3.7%	0.0%	29.8%	28.0%	1.8%
Limiting long-term illness	22.9%	21.6%	1.3%	24.0%	23.8%	0.2%	15.9%	15.3%	0.7%
Poor health	13.3%	12.2%	1.1%	13.7%	13.5%	0.3%	8.4%	8.0%	0.4%
Unemployed	4.8%	4.3%	0.5%	4.9%	4.8%	0.2%	4.1%	3.8%	0.2%
Lower socio-economic group	39.2%	36.7%	2.5%	28.7%	27.9%	0.8%	30.0%	29.2%	0.7%
Households with no car	37.6%	33.4%	4.2%	48.0%	46.5%	1.5%	27.8%	26.3%	1.4%
Owners (with a mortgage)	35.5%	39.0%	-3.5%	36.4%	36.9%	-0.5%	43.4%	46.4%	-3.1%
Social renters	29.2%	25.7%	3.6%	35.7%	35.1%	0.6%	17.0%	16.4%	0.6%
Private renters	8.3%	7.2%	1.1%	4.7%	4.6%	0.1%	11.2%	10.5%	0.7%
Overcrowding	8.2%	7.2%	1.0%	18.0%	18.0%	0.0%	12.4%	11.5%	0.9%
Single pensioner households	15.9%	14.6%	1.3%	15.8%	15.6%	0.2%	11.4%	11.1%	0.4%
Lone parent households	9.6%	9.3%	0.3%	9.4%	9.1%	0.3%	6.9%	6.8%	0.0%
Households at street level or below	90.8%	92.6%	-1.7%	61.6%	63.8%	-2.1%	86.7%	88.7%	-2.0%

There are, however, differences between the settlements in the magnitude of the over-representation of vulnerable groups in flood risk areas. In Glasgow and Luton, the differences in socio-demographic profile of flood risk and non-risk areas are very small. The differences in Belfast, while still quite small, are larger. For example, 37.6 per cent of households in flood risk areas in Belfast have no car compared with only 33.4 per cent in non-risk areas. Similarly, social renters comprise 29.2 per cent of households in flood risk areas but only 25.7 per cent in non-risk areas.

Conclusions

- Around 5 per cent of the urban population is at risk from the 0.5 per cent probability (1 in 200-year) pluvial flood.

- Regional variation in risk is driven by the level of urbanisation and the proportion of households living above street level.

- The greatest proportions of population at risk are in the North West and West Midlands regions, while the lowest are in Scotland and Wales; the three regions with the greatest number of people at risk are the South East, North West and London.

- Social deprivation and poor health are more prevalent in urban areas with the highest wettest day intensity.

- Potentially vulnerable groups are over-represented in parts of urban areas at greatest risk from pluvial flooding.

6 Future urban population at risk from pluvial flooding

The previous chapter of this report established an approximate current (2001) urban population at risk from pluvial flooding. More significant from the point of view of understanding the implications of climate change for social vulnerability is the scale of increase in the urban population at risk. This chapter therefore presents evidence on the likely future urban population at risk and its social characteristics.

Future urban population at risk

Our analysis reveals that the urban population at risk on current trends may increase substantially – up from 2 million in 2001 to 3.2 million by 2050. The main driver of this is population growth, which accounts for three-quarters of the projected increase, with more people expected to be living in areas at risk of pluvial flooding. Climate change will significantly worsen this situation by broadening the impact of pluvial flooding to an estimated further 300,000 people (the remaining 25 per cent).

It is important to note that population growth will not necessarily increase the proportion of the population at risk. In contrast, other things being equal, climate change is likely to increase the proportion at risk – based on our estimates, up from approximately 5 per cent of the population to around 6 per cent by 2050. From economic and insurance points of view, the proportion of the population at risk is more important than the total number at risk.

Of course, there are many uncertainties and complexities in projecting forward estimates of this kind. Climate change and population growth, while both important, are of course not the only factors influencing the urban population at risk of pluvial flooding. Other factors include changes in the distribution of population in relation to flood risk areas, for example through the implementation of planning policies to reduce flood risk, investment in urban drainage schemes, surface water management and changes in the resilience of buildings and people to flooding.

It is not possible to know how all these factors will develop in the future, but it is possible to project population change with a degree of confidence. Population projections are based on observed birth and death rates for different age groups, applied to future age cohorts as they grow older. Assumptions about net migration are also factored into population projections. National population projections are available to 2080, although the latest regional projections only go to 2033 because of uncertainties regarding future internal migration patterns.

Alongside climate change, population growth may have a significant influence on the number of people facing flood risk. The UK population is projected to increase by 45 per cent between 1991 and 2051. Over the same period, the magnitude of the wettest day rainfall over key urban areas is projected to increase by 12.3 per cent (see Chapter 2 and Appendix I). Whilst this will not translate into a proportionate increase in pluvial flooding (see detail in Appendices I and II), an uplift in the wettest day rainfall will in general result in an increase in flood hazard.

Assuming population growth in areas at risk of pluvial flooding is no greater or less than the UK average (although in practice growth in flood risk areas may be less than this if planning policy to reduce exposure to flood risk is effective), population growth alone has the potential to increase the population at risk of pluvial flooding by almost half (45 per cent) between 1991 and 2051. A given increase in rainfall,

however, may not necessarily translate to a similar proportionate increase in the population flooded, as this depends on local topography and population distribution.

Our analysis of a 10 per cent uplift in rainfall intensity in our modelling in Belfast, Glasgow and Luton translated to a 13 per cent increase in the population flooded on average (see Table 7). In other words, the exposure:hazard response ratio is 1.3 (0.13/0.10). Therefore, a national increase in rainfall intensity of 12.3 per cent due to climate change could be expected to increase the population exposed to flood hazard by 16 per cent (12.3 * 1.3).

Applying these figures to our estimate of 2 million people in urban areas at risk from pluvial flooding suggests that by 2050 approximately an additional 1.2 million will be at risk. Population growth accounts for 900,000 of this increase while climate change accounts for 300,000. This increase would take the total urban population at risk from pluvial flooding to 3.2 million by 2050.

In reality, of course, population growth and associated patterns of development in areas at risk from pluvial flooding may be either greater or less than the national average. Patterns of development therefore have the potential to influence greatly the number of people at risk from surface water flooding, either for better or for worse. A sanguine reading of future urban development could argue that a significant proportion of population growth will be accommodated in new developments with higher drainage capacity and SUDS, thus serving to diminish the hazard itself. Similarly, if carbon reduction targets are met worldwide, climate change may not be as adverse in terms of extreme rainfall in the UK as currently predicted. Despite these uncertainties about the future, it is nevertheless important to consider the possible relative magnitudes of change in risk attributable to climate change versus population growth.

Regional patterns

The previous chapter assessed the scale of likely impacts from climate change and population growth on the numbers at risk by 2050 in urban areas across the UK as a whole. However, there are regional patterns to both climate change and population growth (see Table 7) which should be borne in mind by local authorities and others in assessing future risk. Note that in Table 7 regional population projections are only available as far as 2033 rather than 2050 as reported in the national analysis above.

Regions with the greatest projected increases in population are the East of England, South West, London, East Midlands and South East. All these regions have projected population growth in excess of 25 per cent between 2001 and 2033. The East of England tops the table at just over 31 per cent. These regions fall exclusively in the south and east of the UK. By contrast, northerly and western regions – without exception – have projected population growth below the UK average. The North West has the lowest projected population growth, followed by Scotland, the North East and then Wales. However, the population of all regions is projected to increase.

High population growth in the London and South East regions will exacerbate the problem of existing high numbers of people at potential risk from pluvial flooding in those regions. Low population growth in the North West will limit the rate of increase in the already high number of people at risk in that region, but the number of people at risk in the North West will nevertheless continue to increase as a result of population growth, albeit less rapidly than in the South East and London.

The baseline 30-year wettest day rainfall also displays a regional pattern, with the most westerly regions (including Northern Ireland and Scotland) experiencing the highest values and the East of England the lowest. Projected increases in wettest day due to climate change over key urban areas do not show a consistent regional pattern, ranging from 10.3 per cent in the North West to 14.5 per cent in Scotland.

Table 7: Projected change in population and wettest day

Region	Urban pop. at potential pluvial risk, 2001	Pop. growth 2001–33 (%)	Wettest day: baseline[†1] (mm)	Wettest day: 2050s[†1] (mm)	Change in wettest day, 1990–2050 (%)	Change in pop. at risk due to climate change[†2] (%)
South East	267,942	25.6%	20.2	23.2	14.9%	19.4%
North West	250,334	9.0%	23.2	25.6	10.3%	13.4%
London	247,348	28.1%	18.8	21.1	12.2%	15.9%
West Midlands	193,958	16.1%	18.9	20.9	10.4%	13.5%
East of England	172,992	31.1%	16.2	18.1	11.6%	15.1%
Yorkshire & The Humber	172,199	22.4%	21.2	23.7	11.6%	15.1%
South West	151,613	28.3%	22.6	25.5	13.0%	16.9%
East Midlands	136,955	27.8%	18.6	20.7	11.5%	15.0%
Scotland	129,901	9.4%	23.9	27.3	14.5%	18.9%
North East	90,740	12.5%	18.5	20.9	13.1%	17.0%
Wales	75,332	15.3%	30.5	34.6	13.1%	17.0%
Northern Ireland	49,873	19.6%	22.3	24.7	10.6%	13.8%
UK	**1,939,187**	**21.1%**	**21.2**	**23.9**	**12.3%**	**16.0%**

†1 Mean of 30-year 99th percentile wettest day rainfall over key urban areas

†2 Percentage change in wettest day * 1.3 (observed hazard:exposure response ratio, see Table 8)

Nationally across the UK, demographic change and climate change in combination have the potential to put an additional 1.2 million people at risk from pluvial flooding by the middle of the twenty-first century. On current trajectories, demographic change is set to have three times the impact of climate change. However, the relative importance of demographic change and climate change varies across regions, with climate change actually having a slightly greater impact than population growth in Scotland and northern England due to low population growth in these regions (see Figure 7). Looking to the future, regions with high population growth could be expected to require higher levels of new build, which is likely to be equipped with greater drainage capacity and better surface water attenuation (for example, via SUDS).

National socio-economic profile of urban areas at potential risk

As with the baseline situation reported previously, we analysed the socio-economic profile of key urban areas according to the severity of the wettest day rainfall, for the 2050s medium emissions climate change scenario (see Table 8).

Under climate change, the 'regressive' relationship identified in the baseline analysis between health and wettest day is amplified. In the 2050s climate, the current (2001) distribution of poor health in the population would mean 10.7 per cent of residents in the wettest urban areas having poor health but only 8.6 per cent of residents in the driest urban areas.

Figure 7: Change in urban population at potential risk from pluvial flooding by source of change
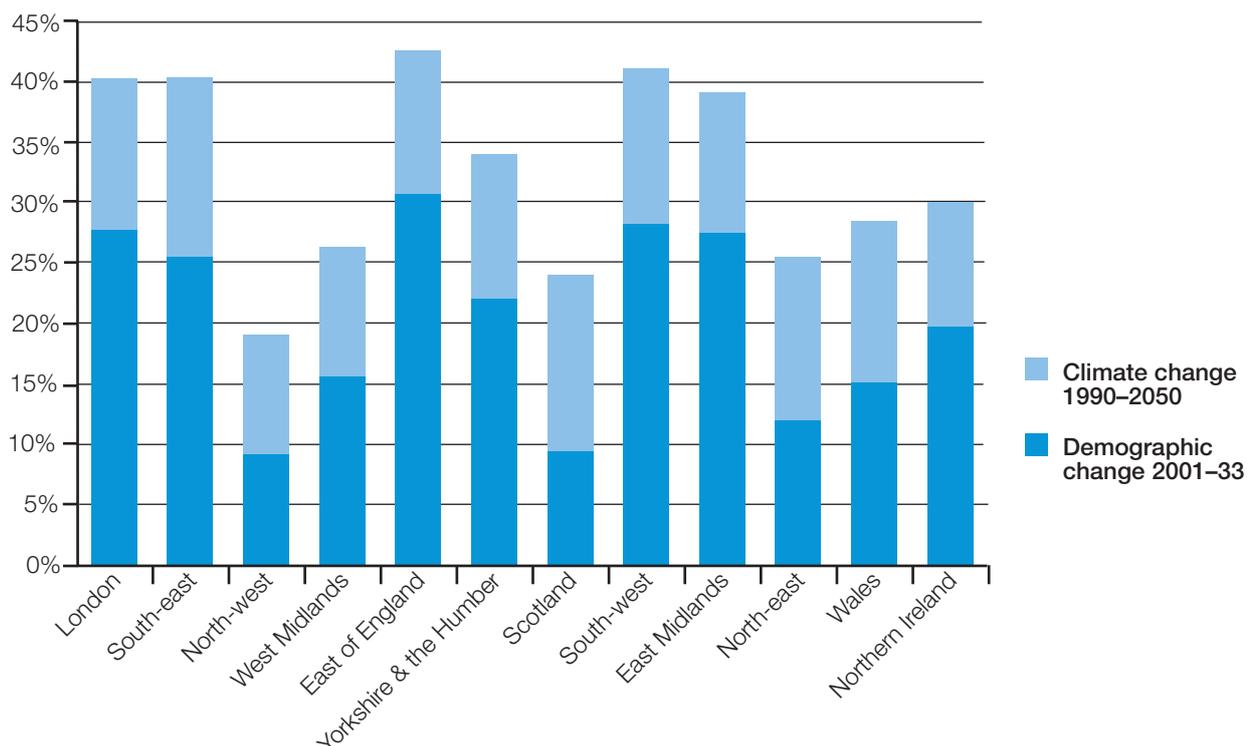

Table 8: Socio-economic profile of urban areas by 30-year wettest day severity: 2050s

Socio-economic indicator	Severity of 30-year wettest day[†1]		
	High > 23 mm	**Medium** 17–23 mm	**Low** < 17 mm
Index of Multiple Deprivation (IMD)	27.5	28.9	24.9
Poor health (%)[†2]	10.7	9.7	8.6
Low occupational status (%)[†3]	13.3	14.9	14.6

†1 Mean of 30-year 99th percentile wettest day rainfall over key urban areas. Source: UKCP09 Weather Generator

†2 2001 Census of Population

†3 Percentage long-term unemployed or in routine or semi-routine employment, based on 2001 Census of Population

However, changes to the wettest day mean that by the 2050s the current distribution of population would no longer display a consistent relationship between the IMD and wettest day. Finally, under this climate change scenario, as currently, there is no relationship between occupational status and wettest day.

Local socio-economic profile of areas at pluvial flood risk

Two climate change scenarios were tested in the detailed local modelling work: baseline plus 10 per cent and baseline plus 20 per cent in rainfall intensity. Across the three study settlements, a 10 per cent increase in wettest day rainfall translates to a 12.9 per cent increase in population at risk (see Table 9). Thus, the exposure:hazard response ratio is 1.29 (0.129/0.100). This ratio is dependent on the local topography and local pattern of population distribution. The ratio is similar in Belfast and Glasgow (12.6 per cent and 12.3 per cent respectively) but higher in Luton (16.6 per cent), possibly because a flatter topography in Luton causes flood water to spread more widely.

Table 9: Local populations at risk: climate change (+10%)

Settlement	Pop. of areas at risk at street level or below	% of total pop.	% increase on baseline
Belfast	33,872	5.8%	12.6%
Glasgow	44,260	3.8%	12.3%
Luton	10,706	5.8%	16.6%
Average (pop. weighted)	–	4.8%	12.9%

A 20 per cent uplift in rainfall wettest day translates to a 25.6 per cent increase in population at risk (see Table 10). Again, Luton has a higher exposure:hazard response than Belfast and Glasgow. In the 20 per cent uplift case, the exposure:hazard response ratio is 1.28 (0.256/0.200), almost identical to the 10 per cent uplift ratio.

We analysed the socio-demographic profiles of flood risk and non-risk areas in all three towns under the plus 20 per cent climate change scenario. The resulting profiles were virtually identical to the baseline profiles (except, of course, that more people of all socio-economic groups are at risk under climate change but no group faces a greater increase in risk than others). In the interests of space and clarity, we have therefore not reported the climate change profiles in this report.

Conclusions

* The number of people exposed to pluvial flood risk on current trajectories may increase by up to 1.2 million by 2050, up from 2 million in 2001.

* Population growth has the potential to put three times more people at risk from pluvial flooding by 2050 than climate change.

* Regional differences in projected population growth mean the increase in numbers at risk also varies by region, being greatest in the south and east and lowest in the north and west.

* Population growth would not increase the proportion of the population at risk, but climate change would.

* The planning system and flood risk management have the potential to limit increases in the numbers at risk.

Table 10: Local populations at risk: climate change (+20%)

Settlement	Pop. of areas at risk at street level or below	% of total pop.	% increase on baseline
Belfast	37,600	6.5%	25.0%
Glasgow	49,001	4.2%	24.3%
Luton	12,180	6.6%	32.6%
Average (pop. weighted)	–	5.4%	25.6%

7 Understanding and responding to pluvial flood risk

Chapter 2 sets out the key vulnerability, social justice and policy issues arising in relation to pluvial flooding. This chapter fleshes out the vulnerability and justice issues and goes on to consider the opportunities and constraints within the governance arrangements for dealing with pluvial flood risk. Finally, we look at how surface water management is practised and assess what can be done to mitigate risk.

This chapter of the report draws on the key findings from 20 interviews with stakeholders working in areas relating to surface water management and flooding. Interviews focused on current practice, understanding and response to flood vulnerability and the management of surface water and pluvial flooding. Appendix V provides a list of those interviewed, which spans central and local government, environmental and water regulators, water companies, insurance companies and the 'third' sector.

Flood vulnerability

Interviewees stressed a number of dimensions to vulnerability, in particular impacts on economic, social and cultural/heritage spheres of life. Most of these are reflected in the criteria used throughout the jurisdictions of the UK in assessing flood risk.

Economic vulnerability

Economic impacts include physical damage, disruption to businesses and lost earnings. Damage to buildings and interiors can be substantial, with a large proportion of the costs being borne through insurance companies. Infrastructure can also be damaged, for example roads and electricity sub-stations. Disruption to businesses can arise due to flooded premises and damage to equipment and stock. Flooding to roads may prevent the delivery of supplies and the dispatch of goods, as well as preventing employees or customers from accessing premises.

All these types of economic impact are differentiated by varying degrees of vulnerability of property and infrastructure, businesses, households and individuals. For example, timber-framed houses tend to suffer greater flood damage than stone or brick. Similarly, buildings with concrete or stone floors suffer less flood damage than those with timber flooring. There are regional differences in construction materials and techniques; for example, timber-framed houses are more common in Scotland.

Social vulnerability

A number of interviewees, particularly those working in the charitable sector, who often had experience of supporting flood victims, stressed the range of social impacts of being flooded and how certain individuals were more susceptible than others. Social vulnerability is wide ranging and includes emotional impacts, psychological issues, strains on relationships and families, and disruption to schooling and social activities. An individual's sense of safety and security can be harmed by their home being flooded – having to leave the familiarity of home behind and live elsewhere while their property is repaired can leave

some people with a permanent sense of loss. This can be exacerbated by individuals being overwhelmed by events and losing control over daily routines.

People can also feel overwhelmed by the process of recovery, and this is particularly the case in areas of widespread flooding, where builders, decorators and fitters are all working under contract to insurance companies, and there is severe time pressure to refit large numbers of properties. Emotional impacts can also arise from the loss of sentimental items in a flood, particularly family photographs. Anxiety about future flooding can become a permanent feature in some individuals' psychology, while mental stress and strains on relationships can arise in the immediate aftermath of a flood and subsequent rehabilitation phase. Disruption arising from being temporarily housed can also have significant social impacts. For example, children may have to change schools or face long journeys, and social contact and social networks may be restricted (or, more positively in some locations, brokered).

Diverse groups and individuals are affected differently by the social impacts of being flooded. Most people we interviewed mentioned older people and care home residents as being particularly vulnerable because of difficulties in evacuation during a flood event. Also mentioned were people with low mobility, poor health, isolation and, in some cases, low income. One interviewee observed that local authorities tend to be good at identifying collective vulnerable groups, such as those in care homes and hospitals, but are much less good at identifying vulnerable individuals in the community. One possible solution, suggested by the same interviewee, is for local authorities (with approval from the Data Commissioner) to provide emergency planners with lists of people or addresses receiving personal care services and to provide counts of the number of individuals receiving personal care to those responsible for conducting flood risk assessment.

Insurance

Insurers we interviewed reported nervousness about uncertainty in the scale and location of flood risk. This anxiety has caused some larger companies to commission independent assessments of flood risk. Based on this information, some companies are taking a gradual, incremental approach to increasing premiums for existing policy holders. Some companies are implementing higher premiums (and excesses for flood damage) for new customers in the highest risk locations, although insurers are wary of charging more than the market will bear and generating bad public relations if they were to charge full actuarial premiums. Other companies are seeking to reduce risk in their portfolios by avoiding providing cover in high risk locations. This has the consequence of raising the risk in other companies' portfolios, potentially storing up problems for them in the future.

The industry is aware of the likely public relations and political backlash to full actuarial premiums in flood risk areas. In addition, some insurers are held back from introducing full actuarial premiums by awareness that they would complicate price structures and make it less easy to advertise and advise customers of likely premiums. Insurers are taking some steps to encourage flood proofing measures, such as flood guards, although there are difficulties in making these conditions of cover. Take up by policy holders has been low. Cost adjusters are reluctant to pay for flood proofing measures to be installed after a flood, as this would be seen as improvement rather than reinstatement.

Larger insurers tend to seek to increase premiums and flood excesses rather than withdraw cover altogether. Nevertheless, some smaller companies operating on smaller margins are trying to minimise risk in their portfolios by turning down high risk properties. Some insurance companies are forming alliances within which they share liability for customers' flood damages – this is done in order to minimise the scale of a financial 'hit' if there is widespread flooding in an area in which a particular company is over-exposed. In addition, the re-insurance market spreads risks so that individual insurers get a degree of insulation from unidentified risk within their portfolio.

Flood governance

Many interviewees indicated that, in the past, pluvial flooding had been a 'Cinderella' to fluvial and coastal flooding in terms of research, risk assessment and legislation. This has improved greatly in recent years, although many interviewees reported that precise roles and responsibilities in relation to pluvial flooding remain unclear, even after the recent legislation, and can hinder working in effective partnerships.

Partnership working

At some institutional interfaces, relatively effective partnership working has developed. On the whole, local authorities and water companies co-ordinate their activities quite well, but inevitably there is regional and local variation. This co-operation is assisted by the fact that some interests coincide: for example, local authorities are obliged to manage surface water run-off and they pay water companies to minimise the flow of surface water into sewers. However, an obstacle to co-ordination can be different planning and budgetary horizons: for example, local authorities often work on a one-year horizon but water companies plan investments over longer periods. This can make it difficult to align capital investment programmes.

At other institutional interfaces, partnership working is less effective or not fully established. In particular, highway authorities and, in some locations, Network Rail are critical to managing surface water run-off yet they are often not represented on drainage boards and other flood management forums. Here, interests less obviously coincide. It suits highway authorities and other infrastructure providers, in order to minimise costs, to route their surface water into urban drainage systems. However, from the water companies' point of view, this reduces drainage capacity at times of peak run-off and, in cases of combined sewerage–drainage systems, increases the volume of water to be treated. Separate drainage and sewerage systems reduce this problem to some degree, but the issue of water companies not having full control over the volume of surface water flowing into their drainage systems remains. To adequately address this issue, there would need to be an expansion of surface water drainage networks ('blue corridors') within urban areas.

The emphasis on partnership working in the UK flood management legislation was strongly supported in principle by almost all interviewees. When partnerships work well, they have the potential to deliver good outcomes. However, there are a number of challenges in making partnerships operate effectively. Mistrust and resentment can develop and no one partner has the responsibility to ensure effective flood risk management continues after a partnership ceases to operate effectively. Although there are instances of good practice (for example, the Metropolitan Glasgow Strategic Drainage Partnership), in many circumstances it is difficult to make partnerships work well. Part of the difficulty relates to 'buy in' at senior management level across the organisations and agreeing the level of partnership that is envisaged.

Uncertainty and competing demands

Many interviewees were of the view that local authorities, particularly through the planning system, have a pivotal position in instigating and enforcing change in the practices of developers. However, local authorities are also central to balancing competing priorities, so in some instances reducing flood risk may come quite far down the list after, for example, economic regeneration or affordable housing. If faced with the choice between a developer's 'planning gain' coming in the form of affordable housing units or SUDS investment, the pressures to take the affordable housing will often be intense, both politically and from other local authority departments.

Uncertainty about locations at risk and difficulty in determining levels of risk and return periods make planning and risk appraisal for surface water flooding difficult. Where there is uncertainty over the level of flood risk, this serves to weaken the negotiating position of local authorities and strengthen that of developers.

Capacity

Low awareness is another factor that contributes to pluvial flood risk often being sidelined in planning, as are limited expertise and restricted capacity to respond within local authorities. Interviewees reported that this is likely to be exacerbated by the loss of senior, experienced drainage engineers in local authorities as a result of public sector cutbacks over the next few years. It is hoped that Defra's skills strategy currently being developed will address this need.

Despite these challenges, new partnership arrangements, where effective, can represent powerful 'communities of practice' in which information and understanding are shared and created. Legislation and regulations relating to flooding around the UK are still quite new and working relationships are still developing, so there is room to be cautiously optimistic that partnership working will continue to improve.

Jurisdictional contrasts

Given contrasts in the governance and recent history of surface water management in England and Wales, Scotland and Northern Ireland, management of pluvial flooding is inevitably evolving along different pathways in each jurisdiction. However, it should prove possible for practitioners in different jurisdictions to benefit by exchanging best practice.

In England, sustained investment in renewing urban drainage assets, following the privatisation of water utilities in England in 1989, should have removed many of the 'pinch points' in urban drainage systems by now. This has resulted in an average age of 65 years for sewer networks, but a significant number of very old sewers remain. The major challenge in England now is the delivery of local flood risk management across a large number of organisations which previously have not always worked in partnership. Recent experience from Scotland suggests that effective co-operation, and ultimately co-ownership, can take many years to develop. The number of responsible authorities involved in England is larger than elsewhere in the UK and the need to involve a SUDS approving body in decisions on urban drainage will add considerable complexity to the decision-making process, but may improve adoption of drainage systems by the relevant body.

Scotland, having first invested in SUDS in 1996, already has considerable expertise in managing urban surface water. Since the Water Environment and Water Services (Scotland) Act 2003, additional technical expertise has been developed within local authorities and Scottish Water in approving and maintaining SUDS. Several local authorities also view surface water management as fundamental to urban renewal projects. Since its creation in 2002, Scottish Water has undertaken an extensive renewal of its urban drainage assets. But the rate at which this proceeds may be constrained by Scottish Water's continued public sector status, ever-tighter regulation by the Water Industry Commission and an inability to raise private capital on the money markets.

Northern Ireland has the advantage of a more centralised system for delivering pluvial flood risk management and benefits from having already mapped this hazard via its Surface Water Flood Maps and inclusion in its Preliminary Flood Risk Assessment. Set against this is a weakness in governance, that no explicit duty is placed on Northern Ireland Water to manage the impacts of heavy rainfall on its sewerage systems, and SUDS are an aspiration yet to be converted into practice.

Flood practice: surface water management

Compared with coastal and fluvial flooding, pluvial flooding is more amenable to mitigation through careful urban design. It is, in principle at least, possible to design urban environments in which water from rainfall is unlikely to accumulate in areas that pose a threat to property or infrastructure. Climate change merely adds to this challenge.

The principles of sustainable development emphasise the responsible utilisation of natural resources, where appropriate, and recycling or reuse. Water, while potentially a hazard, is also a resource. In urban areas water is used for drinking, cleaning, manufacturing and recreation/amenity. It is wasteful to allow rainwater to flow from buildings and streets into drainage systems and then be subject to costly treatment. Clearly, drinking and bathing water in homes needs to be purified, but many uses of water in urban areas, such as irrigation of gardens and some manufacturing uses, do not. A change in ethos therefore lies at the heart of a new, more sustainable, approach to surface water management, seeing rainwater in urban areas as a resource, not solely a hazard. These principles are captured within the concept of SUDS, an approach favoured by interviewees.

Some surface water run-off in urban areas can be collected for direct use through butts on residential and some commercial properties. Such 'grey water' can be used for watering gardens and other non-potable uses. Increasing porous surfaces in urban areas in order to infiltrate and attenuate run-off during a storm is also a key component of SUDS, for example by increasing green space and blue space and the introduction of gravel filtration beds. Green and blue space have the added benefits of increasing biodiversity, improving air quality and providing amenity that can improve physical and mental wellbeing. As well as helping attenuate run-off, gravel filtration beds remove coarser physical contaminants from water, reducing costs and demands on purification plants.

Managing water on the surface is a more adaptive way of responding to climate change than building ever-larger sewers. During intense rainfall, there will inevitably be excess run-off and this is when surface water management plays a crucial role. Managing water on the surface requires buy in from the public and acceptance of safe flow routes for excess surface water and spaces that can flood with limited damage or disruption. Surprisingly small and inexpensive alterations to the micro-topography of urban environments can create relatively safe flow routes for surface water. For example, raised kerbs at roadsides can channel water along the road network to designated flood ponds or into rivers.

A key design feature to reduce the hazard of flood water is to have separate storm and foul water drainage systems. If a drainage system's capacity is exceeded during intense rainfall, it is important to reduce the chances of sewage finding its way out of the sewers. Recent design standards require all new developments to have separate storm and foul water disposal. However, in many instances, a storm water discharge from a new development will ultimately feed into an older combined sewerage–drainage system. Retro-fitting entire towns and cities will clearly be prohibitively expensive and disruptive. Managing rainwater at source and via SUDS systems will be important. In addition, opportunities need to be exploited to use permeable paving and retro-fit key choke points in combined systems when city centres are resurfaced and roads are dug up for other works.

In some towns and cities, it will be possible to avoid new developments in the highest risk locations. Urban planners, designers, developers and architects – and indeed some dwellers – will need to learn to live with floods and flood risk. This is particularly true in areas of development pressure where preventing development even in high flood risk areas will come at an economic and social cost, for example in terms of urban regeneration, jobs and housing.

Nevertheless, the majority of those interviewed indicated that urban design that is resistant and resilient to flooding can mitigate the worst impacts of flood water. For example, properties can be built with concrete or stone floors and sealed wall coverings, with raised electrical installation. Where cost permits, buildings can be built on stilts. This need not be wasted space, but can be used for car parking or storage, such as recycling facilities.

However, existing buildings in flood risk areas will continue to pose problems for some time. Existing built-up areas, particularly at high density, are difficult and costly to retro-fit, in terms of either flood proofing properties or incorporating SUDS into the built environment.

8 Discussion and recommendations

Key findings

This research has revealed that socially deprived areas are at slightly higher risk of pluvial flooding. This is particularly the case in many British cities built on a sizeable river where deprived inner city neighbourhoods tend to be located in low lying areas. Some of these neighbourhoods are also at risk from river or coastal flooding.

Perhaps our most significant finding, however, is that national population growth has the potential to put around three times more people at risk from pluvial flooding by 2050 than climate change. There are significant regional differences in the scale of increase in urban population at risk, and in the relative importance of population growth versus climate change, driven mainly by high population growth in the south and east and low population growth in the north and west. These regional differences emphasise that risk is the product of both the natural hazard and the exposure of the population to that hazard.

It is possible that the impact of population growth on numbers at risk will be mitigated by effective planning policy, enhanced drainage capacity and SUDS on new developments. Similarly, although population growth has the potential to increase the number at risk from fluvial and coastal flooding, it can be hoped that planning policy will direct new development to lower risk areas. The extent to which population growth can be accommodated in low risk contexts remains to be seen, however.

It is not our intention to downplay the potential impact of climate change (and environmental change more generally) on human welfare during this century and beyond. We simply highlight that climate change is only part of the story of vulnerability to flooding, and that in the short and medium term other economic, demographic and social forces may have greater impacts. This underlines the need for a greater engagement of social scientists and policy analysts with genuinely interdisciplinary research on the implications of climate change alongside the natural sciences and engineering.

Uncertainty

There is significant uncertainty about the projected changes to rainfall and therefore flood hazard. This is particularly the case for pluvial flooding, which is often the product of short, very intense downpours or convective storms. Such storms are usually produced by conditions that are highly localised in both space and time and, as UKCP09 notes, it is difficult to establish a relationship between their magnitude and frequency and the broader changes to climate in terms of temperature and average rainfall.

In general terms, climate change projections for the UK indicate that winters will become wetter and summer rainfall will occur with greater severity, at least when considering maximum rainfall over a 24-hour duration. However, at present it is not possible to represent extreme rainfall events of sub-daily duration accurately in climate models. This reflects the fact that the Weather Generator in UKCP09 does not adequately model convective rainfall. Nevertheless, given that a wet 24-hour period will also contain pulses of heavier rainfall of shorter duration, it seems likely that projected uplifts in rainfall over a 24-hour period will be associated with an uplift in the severity of sub-daily duration rainfall.

In order to capture this uncertainty, we have performed sensitivity analysis of the impact on populations at risk from pluvial flooding associated with 10 per cent and 20 per cent uplifts in maximum 1-hour rainfall. Both scenarios correspond with slightly greater proportionate increases in the population at risk.

There also remains a degree of uncertainty in how rainfall will respond to the built environment and where exactly it will accumulate in 'ponds'. First, spatial and temporal variation in rainfall intensity during a storm over a city is difficult to represent accurately. Second, although an allowance is made for the capacity of the drainage system to remove surface water, this is usually done by subtracting a uniform quantity of water falling on the ground. The specific capacity in different parts in the drainage network, and interaction between the drainage network and surface flow, is not included in existing models of pluvial flooding. Finally, it is not possible to capture variation in infiltration rates depending on land cover and antecedent conditions (for example, ground saturation). Despite these uncertainties, large areas of ponding can be identified with sufficient confidence that flood maps can be produced for surface water management.

In order to reduce this uncertainty, we recommend that further research be undertaken:

- to refine existing estimates of sub-daily duration rainfall on a 1 km (or better) grid;

- to improve understanding of spatial and temporal variation in rainfall within extreme events; and

- to improve existing forecasting of extreme rainfall in real time.

Social justice and vulnerability

It is difficult to get accurate information on the population in flood risk areas because the areas at risk can be small and/or cover only a segment of COAs, the smallest units for which population data is available (average population of around 120). This is a particular problem in relation to pluvial flooding because many individual areas of 'ponding' are so small, in contrast to larger more contiguous areas that get inundated by fluvial or coastal flooding.

In this research we have intersected COAs with flood risk outlines in three towns (Belfast, Glasgow and Luton) in order to calculate the proportion of each COA's area that is at risk. We then used that proportion to calculate the population at risk in each COA, and summed the COA populations at risk across each settlement. This method assumes a uniform distribution of population across each COA.

Analyses using coarser spatial units run the risk of achieving a poor match between the actual locations of population in relation to flood risk outlines. Furthermore, the spatial structure of towns and cities can resemble a socio-economic mosaic, often varying markedly over relatively short distances. Consequently, coarse spatial analysis can conceal pockets of social deprivation because of the fine granularity of some urban structures.

Our own 25 km grid analysis of national patterns did not find that towns and cities experiencing higher extreme rainfall events, or greater uplifts in extreme rainfall events due to climate change, had significantly different levels of social deprivation from other towns and cities. However, the populations of cities with higher rainfall did tend to register higher levels of poor health (which may itself be partly caused by a wetter and colder climate).

Our finer-grained empirical analysis in Belfast, Glasgow and Luton revealed that areas in towns and cities at risk from pluvial flooding have slightly higher levels of potentially vulnerable groups, although the differences are small. Nevertheless, these small differences are robust on the basis that the Census of Population covers the entire population and therefore is not subject to sampling error. Households with no car, and social and private renters, were particularly over-represented in areas at risk from pluvial flooding.

The differences between flood risk and non-risk areas were larger in Belfast than in Glasgow and Luton. This is significant because Belfast has a similar urban structure to most English towns and cities (terraced housing on low lying land, often close to a river). Although the magnitudes varied between the towns, the patterns were remarkably consistent, suggesting a set of processes systematically exposing potentially vulnerable groups to higher risk.

More generally, some socio-demographic groups are likely to be more vulnerable to the impacts of a flood, irrespective of whether they are over- or under-exposed to the hazard in terms of probability. Particularly vulnerable groups appear to be those with disabilities, but in some instances also those with large loan:value ratio mortgages, and social renters. In the case of large scale widespread flooding, private renters can also be particularly adversely affected because of a lack of alternative accommodation available in the aftermath.

Current understandings of social vulnerability to flooding assume that the social groups used to measure general deprivation are most susceptible to the effects of flooding, most notably: renters, non-car owners, those on low incomes, lone parents and older people. While clearly some of these groups are often more susceptible to the impacts of a flood than others, this is not always the case and some counter-intuitive groups have been identified with specific vulnerabilities to flooding. For example, home-owners with a mortgage report high impacts of being flooded, possibly due to concerns about insurance, mortgage conditions and negative equity. Likewise, self-employed people who depend on a vehicle for their livelihood will suffer a high impact if the vehicle is damaged by a flood (Werritty *et al.*, 2007).

It is our view that measures of vulnerability to flooding could be improved by incorporating a wider range of factors relating to resilience and adaptive capacity (Lindley *et al.*, 2011; Twigger-Ross and Orr, 2011) and by taking greater account of existing evidence about the social groups that are most susceptible to the impacts of being flooded and how that varies with the scale of a flood (for example, Werritty *et al.*, 2007; Whittle *et al.*, 2010).

The scale of a flood appears to magnify impacts on some groups more than others. For example, many private renters appear not to be badly affected by small scale localised floods because they can find permanent alternative accommodation with relative ease. However, private renters (and social renters) can be badly affected by a large scale widespread flood when it may not be possible for them to be rehoused in the same town. This can be particularly problematic for those without a car.

In order to understand the nature of social vulnerability and flood risk better, we recommend that:

1   Environmental regulators and local authorities incorporate information on the number of households with a ground floor into flood risk assessments. This is particularly important in London and Scotland where significant proportions of the urban population live above street level so are not directly at risk from flooding.

2   Local authorities provide emergency planners with lists of addresses that receive personal care services, and give those responsible for flood risk assessment a count of the numbers of people in small areas who receive personal care.

We recommend that further research be undertaken:

• To develop better methods for measuring socio-economic variation at spatial scales commensurate with data on flood risk, thereby enhancing existing flood risk assessments.

• To identify better the social groups that are most vulnerable to the impacts of a flood and how this varies with the scale of the flood.

Insurance and housing markets

Changes to the availability and affordability of insurance cover for flooding, as well as changes to the operation of housing markets in high risk locations, have the potential to affect the social composition of flood risk areas in the long run. The Association of British Insurers is currently renegotiating with UK governments a sustainable solution for when the Statement of Principles expires in 2013. This agreement

has ensured a certain level of investment in flood defence from the government in return for guaranteed continuation of cover, provided that defences are planned within five years. Some insurers are already charging higher premiums or imposing higher excesses for flood damage in high risk locations, and this trend may increase in the future. If full actuarial premiums were charged for flood risk, high flood risk locations (coastal and fluvial as well as pluvial) could become the preserve of the rich.

An alternative scenario is that insurers withdraw cover from the highest risk locations altogether or impose unaffordable excesses for flood damage. In this case, home buyers may be unable to secure mortgages for properties in such locations. This in turn would reduce demand for property and prices would fall, blighting areas of new development and investment in existing housing stock. In this scenario, households that are not in need of a mortgage would be more likely to live in such locations: chiefly renters and pensioners, who are also potentially more vulnerable to the impacts of flooding. If pockets of land in cities under pressure for development become uninsurable, situations may arise in which planning gain agreements associated with adjacent developments result in development of social housing or care homes in the areas at risk.

Although perhaps relatively unlikely scenarios, these possible sets of circumstances underline the importance of achieving a favourable outcome in the current negotiations between the Association of British Insurers and UK governments. It is inevitable that the future will be different and that the provision of insurance protection against flooding will change because of the twin effects of climate change and government policy following the principles of sustainable flood management by moving away from hard engineered flood defences. However, what is important is that a new agreement makes provision for the adequate protection of vulnerable groups who may not be able to afford cover in higher risk locations. In addition, it is important that insurance cover is available in all currently developed areas in order to prevent the blighting of communities. In return, the government needs to address insurers' concerns that they are not receiving timely information on levels of risk and the provision of new flood defences.

To date, the housing market has remained unresponsive to flood risk and even to actual flood events (Lamond and Proverbs, 2006). However, this has been in a context of widespread affordable insurance availability in high risk locations, and relatively low levels of information and public awareness of flood risk – particularly in relation to pluvial floods. Increased levels of public awareness may affect housing markets, but thus far there is little evidence of this. For example, the publication of indicative flood risk maps for coastal and fluvial flood risk has arguably not had a big impact on housing markets (Pryce *et al.*, 2011).

There is therefore good justification for publishing maps of pluvial flood risk with impacts on house prices and insurance availability, and poor justification for not providing existing residents and potential home buyers (and renters) with information about levels of risk. It would appear only fair and just to enable people to make informed decisions about property purchases and rental decisions in relation to the level of flood risk. Greater transparency of information on flood risk may foster greater co-operation and ultimately risk-sharing between government and insurers, and between insurers themselves.
In order to enhance the availability and take up of insurance, we recommend that:

3   The governments of the UK and the Association of British Insurers work together to make adequate provision to protect vulnerable groups and maintain a high level of geographical coverage in currently developed areas.

4   Responsible bodies increase the take up of contents insurance among vulnerable groups through 'pay-with-rent' schemes in the social rented sector, for example by introducing an 'opt out' rather than an 'opt in' arrangement.

5   Regulators publish indicative pluvial flood risk maps.

We recommend that further research be undertaken:

- to examine socio-economic change and housing market impacts in light of flood events; and

- to examine changes in the cost and availability of insurance (building on ongoing work being done by the Association of British Insurers) and their implications for social justice, vulnerability and urban development.

What can be done about pluvial flood risk?

SUDS, surface water management plans and flood proofing of developments all have the potential to limit the increase or even to reduce the number of people and properties at risk. Separate storm and foul water systems increase drainage capacity and reduce the likelihood of sewage mixing with pluvial flood water. Recently introduced requirements in law for new developments to include SUDS where possible, and the empowerment of flood authorities to withhold permission for developments to connect to the sewerage system (in England and Wales), are important steps forward in mitigating future pluvial flood risk.

A major issue remains, however, with existing properties and poor capacity sewerage systems which will remain a part of the urban fabric for many decades to come. Here, greater use needs to be made of identifying and exploiting opportunities to retro-fit, for example as part of major urban redevelopment projects or, in the case of flood proofing, when buildings in high risk locations are being renovated. For example, major urban regeneration in the east end of Glasgow, including developments associated with the 2014 Commonwealth Games, has provided an opportunity to rethink surface water in this part of Glasgow with extensive use of green and blue space as well as investment in drainage infrastructure. Although the Metropolitan Glasgow Strategic Drainage Plan is visionary and partly implemented, public sector cuts and associated rationalisation within local government and elsewhere may hamper its delivery.

An important question is what to do with high risk land that is not currently developed. In areas of development pressure, a combination of SUDS, surface water management plans and flood proofing of buildings during construction can mitigate the worst impacts of pluvial flooding. In areas where there is less pressure for development, and where such measures may make development commercially unviable, compulsory purchase could be used and land reconfigured and incorporated as green and blue space within surface water management plans.

There is a need for greater public awareness of water issues in general and pluvial flooding in particular. Public awareness of coastal and fluvial flood risk has increased in recent years in response to some major floods and extensive media coverage. However, public awareness of pluvial flooding lags behind. Raising awareness about the value of porous surfaces in gardens and of collecting surface run-off for use around the home and garden would be beneficial, if only to promote awareness and an ethos of responsible water use as much as attenuating run-off. Water companies are keen to promote public awareness about the drainage and sewerage systems in general, and in particular the importance of not disposing of non-degradable items down drains.

Local authorities have a pivotal role to play in leading the partnership approach to surface water management. However, lack of powers, funding and capacity, and skills constraints, conspire to make this difficult to achieve. We therefore make the following recommendations in relation to surface water management:

6   Local authorities (and, where appropriate, water companies) develop a strategic approach to dealing with high risk areas:

a   in currently developed areas – retro-fit when possible, identify and improve 'pinch points' in the drainage system, and manage the micro-topography to create safe flow routes;

b   in currently undeveloped areas with development pressure – insist on effective SUDS, flood proof design and surface water management plans; and

c   in currently undeveloped areas with less pressure for development – identify opportunities for landscaping that incorporates 'green' and 'blue' space, supported through land use planning and, if necessary, compulsory purchase.

7   Local authorities, regulators and water companies engage the public about surface water and drainage issues, promoting the preservation of porous surfaces and capture of rainwater at household level.

8   Local authorities and water companies make more use of opportunities to de-couple existing combined clean and foul water drainage systems: for example, when areas are undergoing major redevelopment.

9   Local authorities extend surface water management plans where possible by integrating them with wider urban regeneration and landscape design plans that incorporate 'green' and 'blue' spaces.

10 Local authorities enhance their capacity and skills to fully incorporate surface water issues into flood risk management, for example through pooling of expertise and knowledge across neighbouring authorities.

11 The governments of the UK improve guidance and policies to ensure that resilience to the 1 in 200-year pluvial flood risk is designed into areas at risk and new developments.

12 Responsible bodies clearly define responsibility for 1 in 30- to 1 in 200-year flood risk.

Further research could usefully be conducted to investigate, through case studies, the options for handling extreme floods, particularly in larger towns and cities.

Appendix I

Climate change impacts on pluvial flood risk

1 Current extreme rainfall, including regional and season patterns

Information for extreme UK rainfall is available from the UKCP09 *A Climatology of Extremes for the UK* (Brown *et al.*, 2008) and Volume 2 of the *Flood Estimation Handbook* (Institute of Hydrology, 1999). The former provides a series of maps derived from Met Office 1-day observations 1958–2004, upscaled to the UKCIP 2008 25 km grid. For durations of 1, 5 and 30 days, quantiles have been estimated using standard extreme value analysis. The 1-day duration rainfall is directly relevant to the cells of rainfall that generate pluvial floods.

Figure 8: Seasonal fraction of wet days (precipitation > 1.0 mm/day) for the period 1858–2004
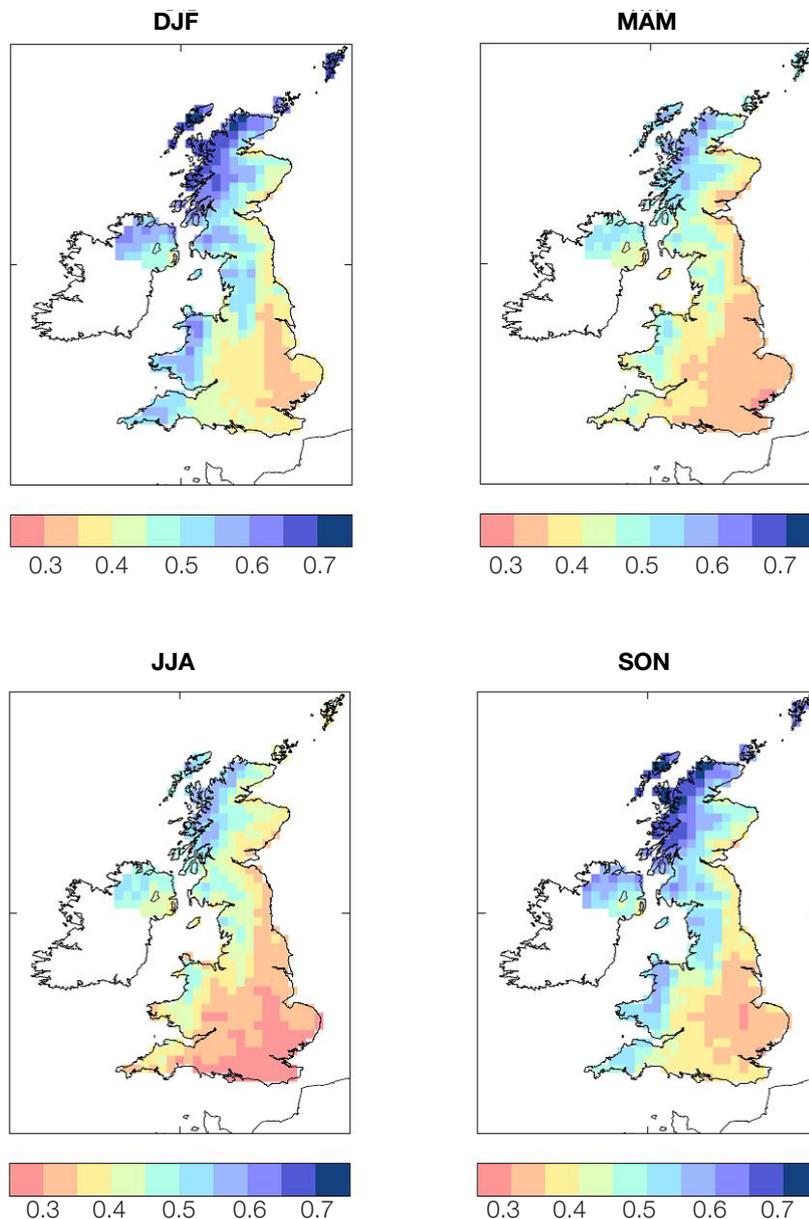

Source: Brown *et al.*, 2008

Across the UK, more rainy days occur in winter and autumn than in summer (see Figure 8) reflecting the fact that winter (DJF) and autumn (SON) are far wetter seasons than summer (JJA).

This pattern does not hold for all 1-day rainfalls (see Figure 9). Whilst the west continues in general to be wetter, for more extreme events (1 in 50-year return value) higher values are more widespread across the UK, especially in summer. Thus, in the summer, a 1 in 50-year daily rainfall > 50 mm can be expected across the whole of the UK except in the South East.

Figure 9: Rainfall (mm/day) for 2-year and 50-year return periods for winter (DJF) and summer (JJA) 1-day rainfall for the period 1958–2004

DJF, 1-day duration
2-year return value

DJF, 1-day duration
50-year return value

JJA, 1-day duration
2-year return value

JJA, 1-day duration
50-year return value
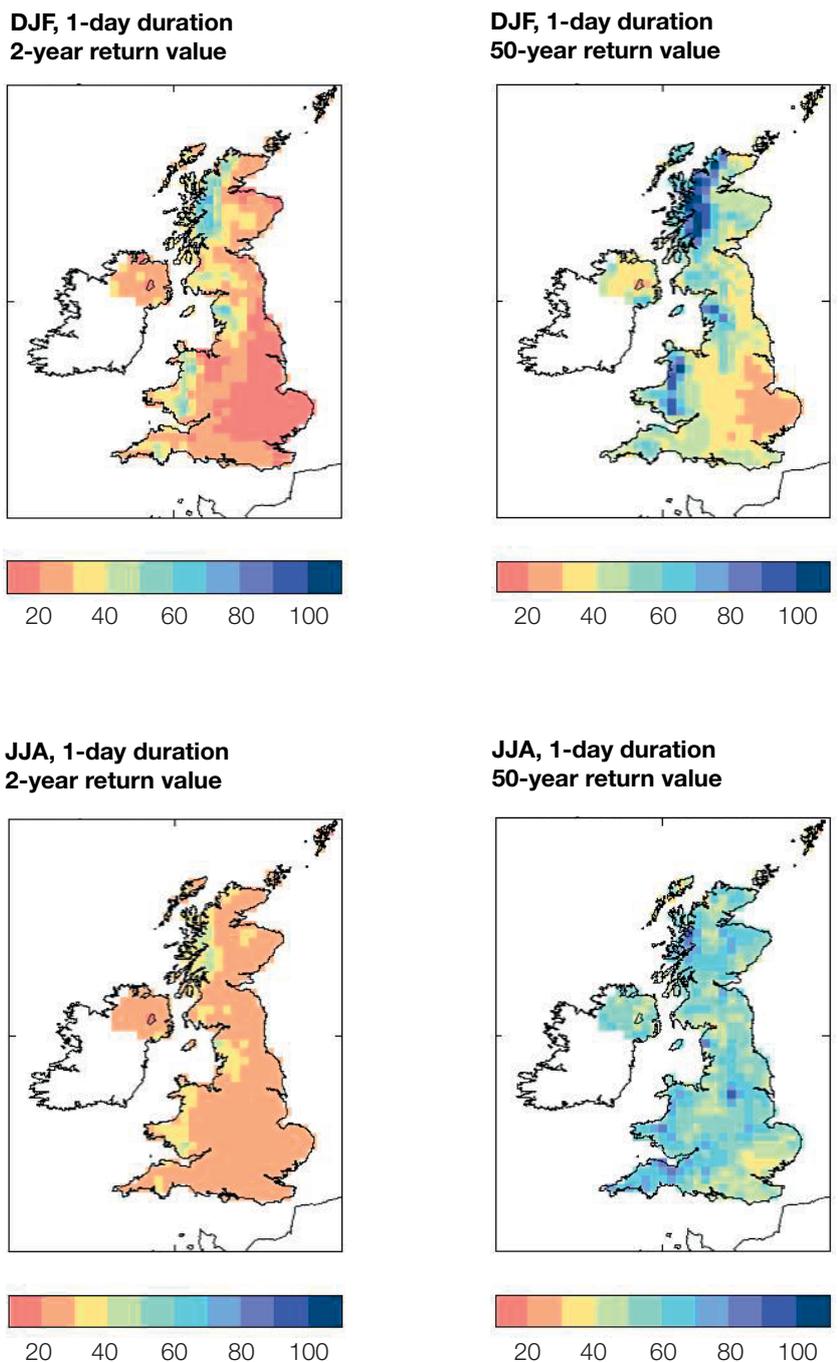
Source: Brown *et al.*, 2008

Figure 10: Comparison of 1-hour rainfall (mm) 10-year return period and 1-hour rainfall (mm) 100-year return period
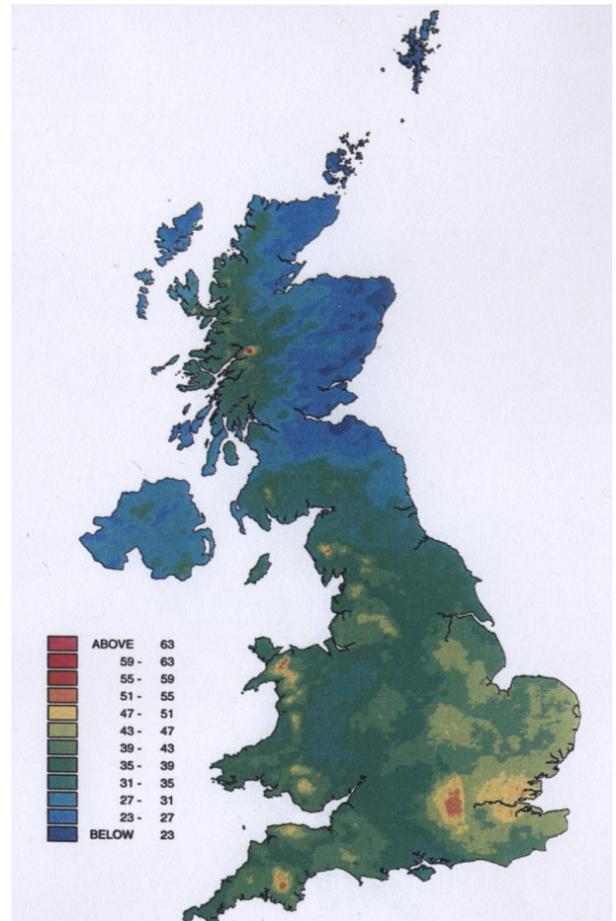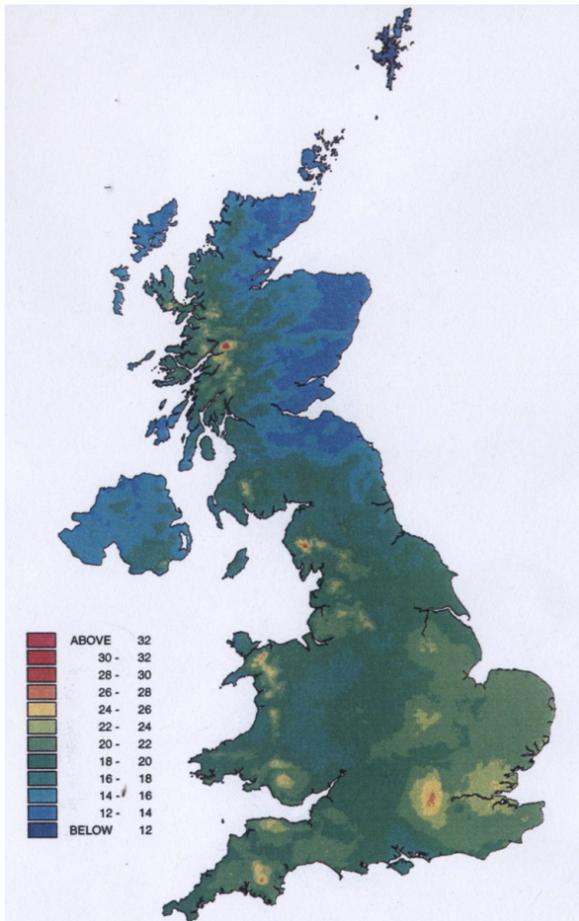
a) 1-hour rainfall (mm) 10-year return period

b) 1-hour rainfall (mm) 100-year return period

Source: Institute of Hydrology, 1999

This pattern becomes even more pronounced for 1-hour rainfalls (Figures 10a and 10b). Note the contrast in numerical scale. For 1 in 10-year events, falls > 14 mm/hour are recorded across the whole of the UK except for eastern Scotland and Northern Ireland, with even higher values locally from north-west Scotland to central southern England. Virtually the same pattern obtains for 1 in 100-year events, where falls of > 31 mm/hour can be found across the UK except for eastern Scotland and Northern Ireland. Although these maps derived from the Flood Studies Report (Institute of Hydrology, 1999), they provide no breakdown by season. It is likely that the very high values reported across southern and eastern England mostly occur during the summer when convective activity is at its maximum.

In summary, whilst maximum 1-day rainfall likely to occur once in two years is during the autumn and winter with a marked north-west (high) to south-east (low) gradient, this pattern alters markedly for more extreme rainfall of shorter duration. Thus the pattern for the maximum 1-hour rainfall likely to occur once in 100 years almost displays a reverse pattern with consistently higher values in the south and east and lower values in eastern Scotland and Northern Ireland.

## 2 Future extreme rainfall under climate change for the whole of the UK

In terms of overall future climate, the UK Climate Projections 2009 (UKCP09) estimates that the UK is likely to experience wetter, warmer winters (particularly in the north and west) and hotter, drier summers (particularly in the south and east). Further detail is provided by the UKCP09 for all four seasons under low, medium and high emission scenarios across three time periods.

Figure 11: Changes in rainfall for wettest day in winter and summer (low emissions for 2020s) across a range of probability levels

10% probability level
Very unlikely to be less than

50% probability level
Central estimate

90% probability level
Very unlikely to be greater than

−70   −50   −30   −10   0   10   30   50   70

Change in precipitation (%) on the wettest day of winter for the 2020s, low emissions scenario

10% probability level
Very unlikely to be less than

50% probability level
Central estimate

90% probability level
Very unlikely to be greater than

−70   −50   −30   −10   0   10   30   50   70

Change in precipitation (%) on the wettest day of summer for the 2020s, low emissions scenario

Source: UKCP09

Figure 12: Changes in rainfall for wettest day in winter and summer (high emissions for 2080s) across a range of probability levels

Winter

10% probability level
Very unlikely to be
less than

50% probability level
Central estimate

90% probability level
Very unlikely to be
greater than

−70   −50   −30   −10   0   10   30   50   70

Change in precipitation (%) on the wettest day of winter for the 2080s, high emissions scenario

Summer

10% probability level
Very unlikely to be
less than

50% probability level
Central estimate

90% probability level
Very unlikely to be
greater than

−70   −50   −30   −10   0   10   30   50   70

Change in precipitation (%) on the wettest day of summer for the 2080s, high emissions scenario

Source: UKCP09

For extreme rainfall projections, UKCP09 provides maps at a 25 km grid covering the whole country. Maps depicting rainfall on the wettest day in either the winter or summer are available across a range of emission scenarios (low, medium and high) for the 2020s, 2050s and 2080s. The results are reported at three probability levels extending from 10 per cent ('very unlikely to be less than', or a chance of 1 in 10) through 50 per cent ('central estimate') to 90 per cent ('very unlikely to be more than', or a chance of 1 in 10). The end members of the estimates for low emissions in the 2020s and high emissions in the 2080s are reported in Figures 11 and 12 respectively.

It is important to note that the changes are reported in percentage terms and not as absolute values. Given the strong regional trends in absolute wettest day rainfall, care must be taken in interpreting these percentage changes. For a low emissions future (see Figure 11), the wettest day rainfalls in winter are set to increase by up to 10 per cent ('central estimate') or by up to 20 per cent across much of eastern and southern England (with a 1 in 10 chance). The 2020s pattern for the summer is broadly similar, although some coastal areas in England could see a 10 per cent decrease and selected locations in England could see an increase as high as 30 per cent. By the 2080s under a high emissions scenario (see Figure 12), much of the UK will experience up to a 20 per cent increase in winter wettest day rainfall ('central estimate') and, locally across much of south and eastern England, up to a 50 per cent increase (with a 1 in 10 chance). In summer, the pattern changes markedly with most of southern England seeing at least a 10 per cent decrease ('central estimate') but with a 1 in 10 chance this could be up to a 10 per cent increase in southern England and up to a 40 per cent increase in parts of northern England.

In summary, the seasonal and regional pattern of wetter winters (particularly in the north and west) and drier summers (particularly in the south and east) is broadly reflected in projected trends in rainfalls on the wettest day, with the largest percentage increases in the winter in the north and west. However, projected 'central value' changes in wettest day rainfall show the greatest increase in the south in the winter, and even a reduction in wettest day summer rainfall in the south.

It is important to note a high degree of uncertainty in these estimates of future rainfall: hence they are reported across a range of probabilities. This arises because the atmospheric processes that generate rainfall are highly complex. Whilst some frontal storms can extend over large areas lasting for days, other convective storms are highly localised and last less than an hour. A further complication is that slow moving frontal storms can have embedded cells of high intensity rainfall, as occurred over Hull in 2007. Current climate change models struggle to incorporate this complexity across a range of scales. This uncertainty is reflected in the range of results for high emissions in the 2080s, with the wettest day rainfall in summer very unlikely to be reduced by more than 30 per cent or increased by more than 10 per cent, and with a central estimate of a 10 per cent reduction.

The customised maps across the whole of the UK do not extend to rainfalls of less than 24 hours' duration. For the specific urban areas targeted in this project, and for durations of less than 24 hours, the UKCP09 Weather Generator was used to provide greater detail on future pluvial flooding.

3 Future extreme rainfall under climate change for selected urban areas

The Weather Generator in UKCP09 was used to generate absolute and percentage changes in future extreme rainfall. It provides estimates of the maximum daily rainfall at a grid scale of 25 km. Appendix II provides details on how this was undertaken. The Weather Generator output is referred to below as the 'wettest day' rainfall.

Percentage and absolute changes in rainfall on the wettest day in the year

UK-wide patterns
The Weather Generator enables simulation of a range of future rainfalls across diverse time periods under three contrasting emission scenarios. However, each simulation takes many hours to complete when

Table 11: Wettest day rainfall and projected uplift in rainfall by urban area: 2050s medium emissions

Urban area	Wettest day rainfall (mm)	Urban area	Uplift in rainfall (mm)
Swansea	38.8	Swansea	5.0
Glasgow	30.8	Crawley	3.8
Cardiff	30.3	Brighton	3.5
Sheffield	30.2	Worthing	3.5
Plymouth	29.4	Glasgow	3.3
Manchester	28.6	Portsmouth	3.2
Preston	28.3	Southampton	3.2
Brighton	27.0	Bristol	3.1
Stockport	26.8	Cardiff	3.1
Worthing	26.2	Reading	3.0
Crawley	25.9	Swindon	3.0
Belfast	25.7	Sheffield	2.9
Bournemouth	25.2	Woking	2.9
Bristol	25.2	Bournemouth	2.8
Southampton	24.9	Oxford	2.8
Blackpool	24.1	Belfast	2.8
Bolton	24.0	Blackpool	2.8
Londonderry	23.6	Sunderland	2.7
Portsmouth	23.4	Manchester	2.7
Woking	23.2	Plymouth	2.6
Edinburgh	22.7	Newcastle-upon-Tyne	2.6
Liverpool	22.1	Preston	2.5
Reading	22.0	Slough	2.5
Swindon	22.0	Nottingham	2.4
Birmingham	21.7	Edinburgh	2.4
Sunderland	21.6	Bolton	2.4
Newcastle-upon-Tyne	21.6	Coventry	2.4
Slough	21.4	Greater London	2.3
Nottingham	21.3	Leeds	2.2
Greater London	21.1	Hull	2.2
Oxford	20.9	Gillingham	2.2
Derby	20.9	Southend-on-Sea	2.2
Coventry	20.7	Leicester	2.2
Leeds	20.7	Stockport	2.2
Stoke-on-Trent	20.2	Birmingham	2.0
Hull	20.1	Liverpool	2.0
Leicester	19.9	Middlesbrough	2.0
Middlesbrough	19.6	Luton	1.9
Luton	18.5	Londonderry	1.9
Norwich	18.3	Norwich	1.8
Gillingham	18.0	Peterborough	1.8
Southend-on-Sea	18.0	Derby	1.8
Peterborough	17.9	Ipswich	1.7
Ipswich	17.7	Stoke-on-Trent	1.5

post-run processing of the raw data is also taken into account. Given resource constraints on this part of the project, we decided to standardise the Weather Generator simulations on the 2050s, using a medium emissions scenario for all urban areas. In part, this choice reflects government preference for this decade and scenario when setting targets and developing climate change policy.

The findings for each of the 44 urban areas studied are listed in Table 11, in which the wettest day rainfall and uplift in rainfall by the 2050s (medium emissions) are reported in rank order. Since the Weather Generator output is reported as a percentage change, the Met Office rainfall for the baseline period (1961–90) is used to convert these percentage changes into a 2050s wettest day (mm) and uplift (mm). It is important to note that some urban areas with lower uplift values may report higher wettest day values. In terms of the 2050s wettest day rainfall, no consistent spatial pattern emerges with the five highest values straddling Scotland (Glasgow), Wales (Cardiff and Swansea) and England (Sheffield and Plymouth). However, the five lowest values are consistently in eastern England (Norwich, Gillingham, Southend-on-Sea, Peterborough and Ipswich) and there is a slight west–east gradient when all values are taken into account.

When the list of uplift in rainfall is compared with wettest day rainfall, some striking differences emerge. Only Swansea, Glasgow, Brighton and Worthing remain in the top ten, now joined by Crawley, Portsmouth, Southampton, Bristol and Reading – a group drawn exclusively from southern England. Given that care has been taken to obtain a representative sample of urban areas across the UK, this result implies that, in general, the hazard of extreme daily rainfall will increase more rapidly in southern England than in other parts of the UK. With the exception of Glasgow, this distribution accords well with the map of the more extreme 1 in 100-year 1-hour rainfall (see Figure 10b) produced by the *Floods Study Report* (Institute of Hydrology, 1999). This result is consistent with the general prediction that, given climate change in the UK, convective storms and cells within frontal storms are likely to become more severe and intense.

The relationship between maximum daily rainfalls and pluvial flooding is complex as most urban floods are caused by events lasting only a few hours and most inundation maps involve modelling storms of one to three hours' duration. Nonetheless, a 1 in 100-year daily rainfall is likely to include intense and short lived pulses of rain which cause pluvial flooding. These pulses of rain either can occur in isolated convective cells (typically in the summer) or be embedded within frontal storms (which can occur throughout the year). In our view, the projected increase in the 1 in 100-year wettest day rainfall by the 2050s across parts of southern England is likely to increase the pluvial flood hazard.

## Figure 13: Wettest day for Tier 1 urban areas: low emissions

Uplift in rainfall on wettest day 2030s–2080s: low emissions
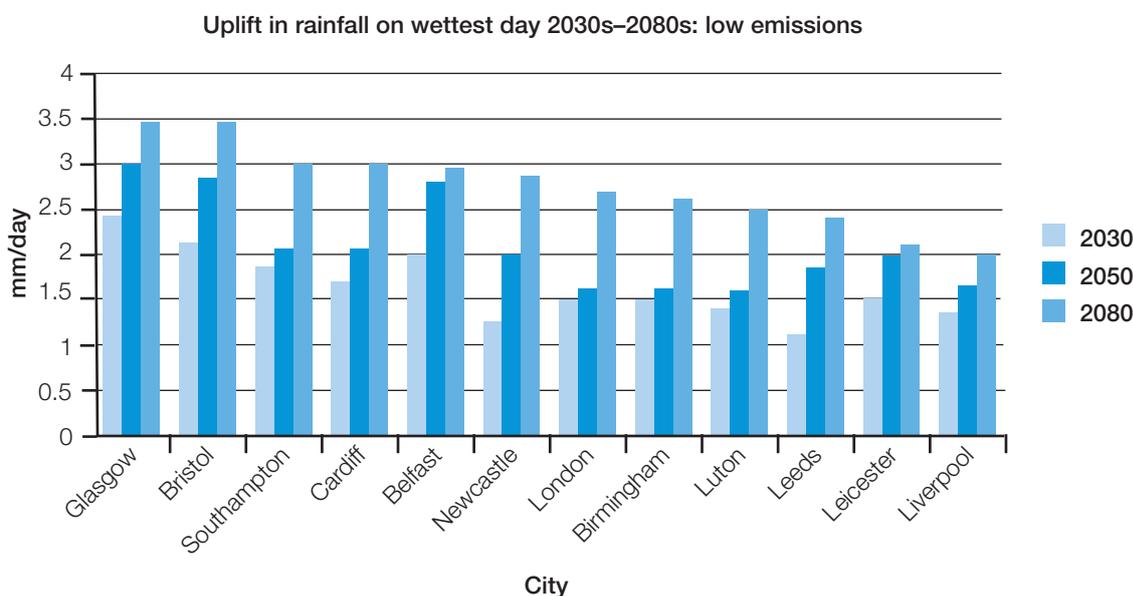
Figure 14: Wettest day for Tier 1 urban areas: medium emissions

Uplift in rainfall on wettest day 2030s–2080s: medium emissions
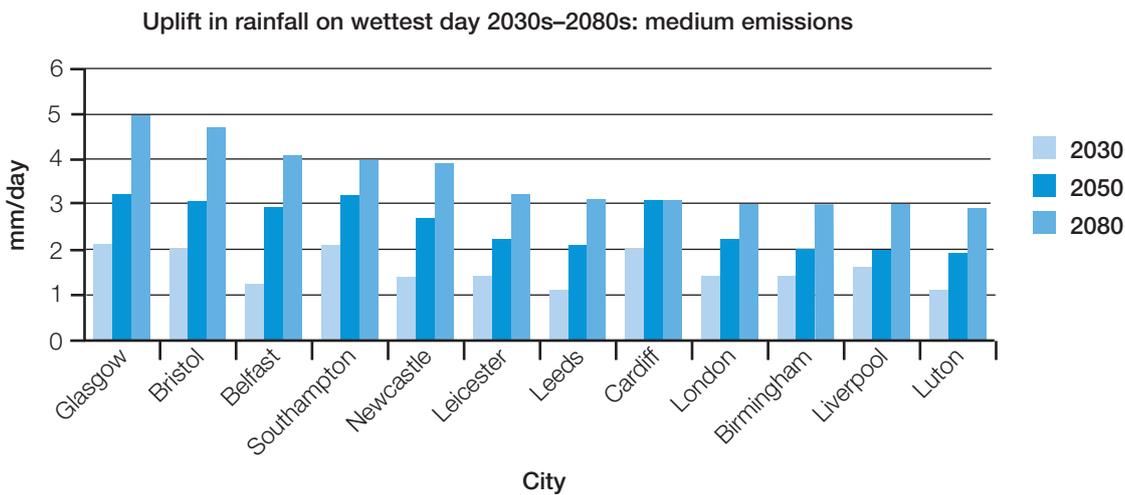
Figure 15: Wettest day for Tier 1 urban areas: high emissions

Uplift in rainfall on wettest day 2030s–2080s: high emissions
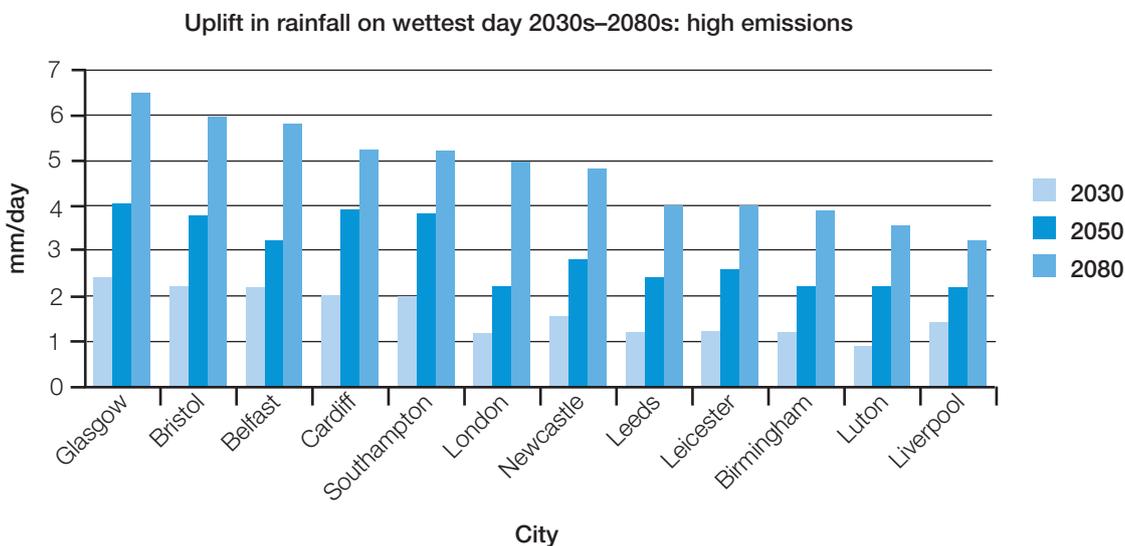
Trends over time

Having examined the spatial variation in the wettest day, both now and for a fixed period (the 2050s), temporal variation in the wettest day is examined over three periods (2020s, 2050s and 2080s) and across three emission scenarios. Calculating the results for all possible permutations of the 44 urban areas exceeded the resources available. Accordingly, only the results from Tier 1 urban areas (the largest settlement each region of the UK) are reported in Figures 13, 14 and 15 (with the urban areas reported in rank order for the 2080s scenarios) and Table 12.

The key findings are that:

* There is a steady increase in both uplifted rainfall and wettest day rainfall for all urban areas throughout the twenty-first century.

* As emissions increase, there is an increase in wettest day rainfall and uplifted rainfall for all urban areas.

* The increases are smaller in urban areas with lower wettest day rainfalls.

Appendix I: Climate change impacts on pluvial flood risk

Table 12: Projected uplift and wettest day rainfalls (mm): Tier 1 urban areas, time periods and emission scenarios

Uplift in rainfall (mm)				Wettest day rainfall (mm)			
Low emissions	**2030**	**2050**	**2080**	**Low emissions**	**2030**	**2050**	**2080**
Glasgow	2.4	3.0	3.4	Glasgow	29.9	30.4	30.9
Bristol	2.2	2.8	3.4	Cardiff	28.9	29.3	30.2
Southampton	1.8	2.1	3.0	Belfast	24.9	25.6	25.8
Cardiff	1.7	2.1	3.0	Bristol	24.3	24.9	25.5
Belfast	2.0	2.7	2.9	Southampton	23.5	23.9	24.8
Newcastle	1.2	2.0	2.8	Birmingham	21.1	21.3	22.3
London	1.5	1.7	2.7	Liverpool	21.4	21.8	22.1
Birmingham	1.5	1.7	2.6	Newcastle	20.2	21.0	21.8
Luton	1.4	1.6	2.5	London	20.3	20.6	21.6
Leeds	1.1	1.8	2.4	Leeds	19.6	20.3	20.9
Leicester	1.5	2.0	2.1	Leicester	19.2	19.6	19.8
Liverpool	1.3	1.7	2.0	Luton	18.0	18.2	19.0
Medium emissions	**2030**	**2050**	**2080**	**Medium emissions**	**2030**	**2050**	**2080**
Glasgow	2.3	3.3	4.9	Glasgow	29.7	30.8	32.4
Bristol	2.1	3.1	4.6	Cardiff	29.3	30.3	30.3
Belfast	1.3	2.8	4.1	Belfast	24.2	25.7	27.0
Southampton	2.2	3.2	4.0	Bristol	24.2	25.2	26.7
Newcastle	1.4	2.6	3.8	Southampton	24.0	24.9	25.8
Leicester	1.4	2.2	3.2	Liverpool	21.7	22.1	23.0
Leeds	1.2	2.2	3.1	Newcastle	20.5	21.6	22.8
Cardiff	2.1	3.1	3.1	Birmingham	21.0	21.7	22.5
London	1.4	2.3	3.0	London	20.2	21.1	21.9
Birmingham	1.4	2.0	2.9	Leeds	19.7	20.7	21.6
Liverpool	1.6	2.0	2.9	Leicester	19.1	19.9	20.8
Luton	1.1	1.9	2.8	Luton	17.7	18.5	19.4
High emissions	**2030**	**2050**	**2080**	**High emissions**	**2030**	**2050**	**2080**
Glasgow	2.4	4.1	6.5	Glasgow	29.8	31.5	33.9
Bristol	2.2	3.8	6.0	Cardiff	29.2	30.1	32.6
Belfast	2.1	3.3	5.7	Belfast	25.0	26.2	28.6
Cardiff	2.0	2.9	5.4	Bristol	24.2	25.9	28.1
Southampton	2.0	2.9	5.3	Southampton	23.7	24.7	27.0
London	1.3	2.4	5.0	Newcastle	20.5	21.8	23.8
Newcastle	1.5	2.8	4.8	London	20.2	21.3	23.8
Leeds	1.2	2.4	4.0	Birmingham	21.0	21.9	23.5
Leicester	1.4	2.6	4.0	Liverpool	21.6	22.4	23.4
Birmingham	1.3	2.3	3.9	Leeds	19.6	20.9	22.5
Luton	0.9	2.2	3.6	Leicester	19.1	20.3	21.6
Liverpool	1.5	2.3	3.3	Luton	17.5	18.7	20.2

- Glasgow, Belfast, Cardiff and Bristol (all located in the west of the UK) record the highest wettest day rainfall and uplifted rainfall in nearly all scenarios by the 2080s.

- Liverpool is consistently at the lower end of the rank order in Figures 13–15, with relatively low uplifted rainfall. This may reflect its location with an annual rainfall of only 850 mm.

Seasonality

Rainfall data on the wettest day by season was not available from the Met Office baseline data (1961–90), but it has proved possible to generate percentage change on the wettest day by season using the Weather Generator. Here we report on the findings for London and Glasgow – representative of urban areas with contrasting rainfall profiles (see Table 13 and Figure 16).

There is a striking seasonality in the wettest day under a medium emissions scenario for all three time periods. In London there is a decrease in the summer wettest day rainfall in all three time periods. In Glasgow the rainfall in the summer wettest day very slightly increases for all three time periods but the actual pattern mirrors that for London. London is predicted to have generally higher percentage increases in winter than Glasgow, but this is against a lower absolute rainfall.

Table 13: Projected percentage change by season and time period, London and Glasgow: medium emissions

	London winter	London spring	London summer	London autumn	Glasgow winter	Glasgow spring	Glasgow summer	Glasgow autumn
Projected % change								
2030 medium	10.7	2.7	-3.2	6.3	6.5	6.8	0.7	8.1
2050 medium	16.6	4.2	-7.1	8.5	7.9	8.7	0.6	10.3
2080 medium	18.5	4.6	-6.2	10.9	11.6	11.1	1.5	15.7

Figure 16: Seasonal changes in rainfall on wettest day: London and Glasgow

Percentage uplift in rainfall: medium emissions
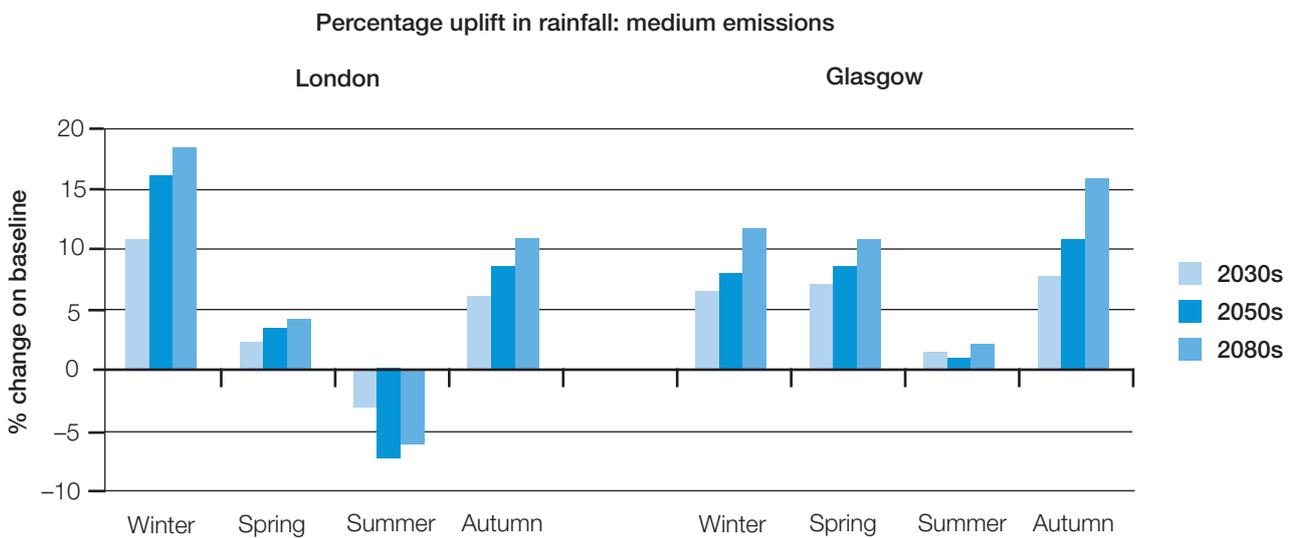
Changes in 1-hour rainfall

Given the significance of sub-daily rainfall in generating pluvial floods, we now examine patterns in 1-hour rainfalls. Because of the uncertainty in projecting future 1-hour rainfall for all three time periods, and across three emission scenarios, the Weather Generator only permits simulations of up to 30 years' length. This partly reflects the added challenge of working at a 5 km grid scale and partly the difficulty of capturing the full complexity of the processes that produce such extremely localised rainfall.

As in the UK-wide analysis of future wettest day rainfall, the Weather Generator was used to determine the maximum 1-hour rainfall for Luton, Belfast, Glasgow and Wigan (see Appendix II for details of how this was done). The Weather Generator outputs are referred to below as the 'maximum 1-hour rainfall' (see Figure 17 and Table 14).

Only Glasgow of the four urban areas reports an increase in the maximum 1-hour rainfall under climate change. Belfast shows a reduction of 1.9 per cent and Luton and Wigan larger reductions of 6.9 per cent and 4.6 per cent respectively. The markedly different results for Belfast and Glasgow – two cities relatively close to each other, with similar climates – raise a question about the robustness of these results. We conclude that the Weather Generator cannot provide robust and reliable results for maximum 1-hour rainfall at high return periods and note the accompanying guidance which cautions use beyond a return period of 1 in 10 years.

Figure 17: Maximum 1-hour rainfall, 2080s: four urban areas

Rainfall in wettest hour (max of 30 ranked medians)
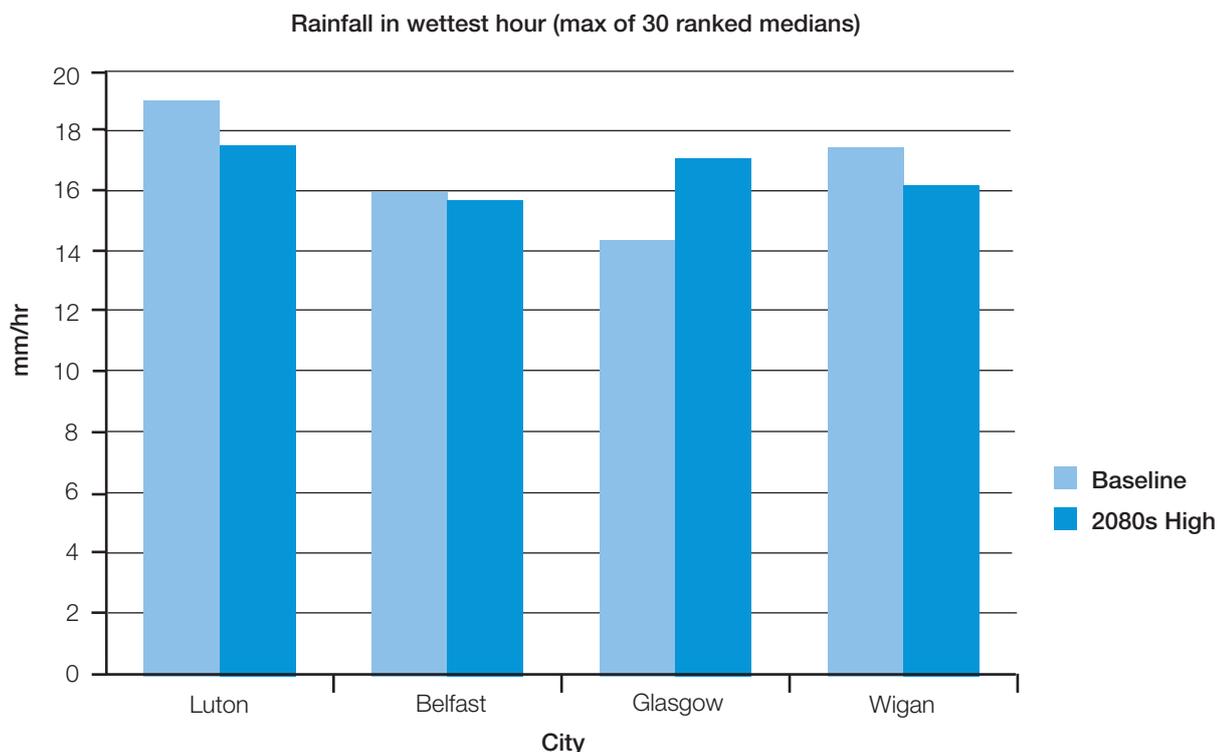
Table 14: Maximum 1-hour rainfall and uplift by 2080s: high emissions (maximum of 30 ranked medians)

	Luton	Belfast	Glasgow	Wigan
Baseline rainfall (mm)	18.9	16.0	14.7	17.4
2080s high (mm)	17.6	15.7	17.1	16.6
Uplift (mm)	-1.3	-0.3	2.4	-0.8
Uplift (%)	-6.9%	-1.9%	16.0%	-4.6%

1-hour rainfall: distribution of extreme values

We now explore the possibility that this unexpected result is caused by a small number of extreme values. Rather than relying solely on the highest median of each 30-year series, we plotted all 30 medians of the 99th percentiles of the simulated 1-hour maxima in rank order to examine their distribution. These are reported in Figure 18 and, with the exception of Glasgow, which has the highest uplift of 16.1 per cent, the ranked 30 medians show a consistent pattern for observed and 2080s extreme rainfalls across all ranks. From this we infer that in three out of four cases, extreme rainfalls share a common pattern under current and projected future conditions. The inconsistent pattern in uplift is thus not due to a few aberrant extreme values.

It is clear from the above that the Weather Generator cannot be used to derive robust estimates of future 1-hour rainfalls.

1-hour rainfall: frequency

An alternative explanation for these findings is that climate change affects not just the most extreme 1-hour rainfalls, but also the frequency of storms. This would account for the increases in wettest day rainfall we have observed at the 25 km resolution. But analysis of rainfall frequency shows similar trends to rainfall intensity (see Table 15). Under 2080s high emissions, there is an increase in all four urban areas for falls > 50 mm/day (daily data), but no overall or consistent pattern for falls > 12 mm/hour (hourly data).

Figure 18: Ranked medians from 100 runs for observed and 2080s high emissions scenarios

Distribution of ranked medians
BELFAST

Distribution of ranked medians
LUTON

Distribution of ranked medians
GLASGOW

Distribution of ranked medians
WIGAN
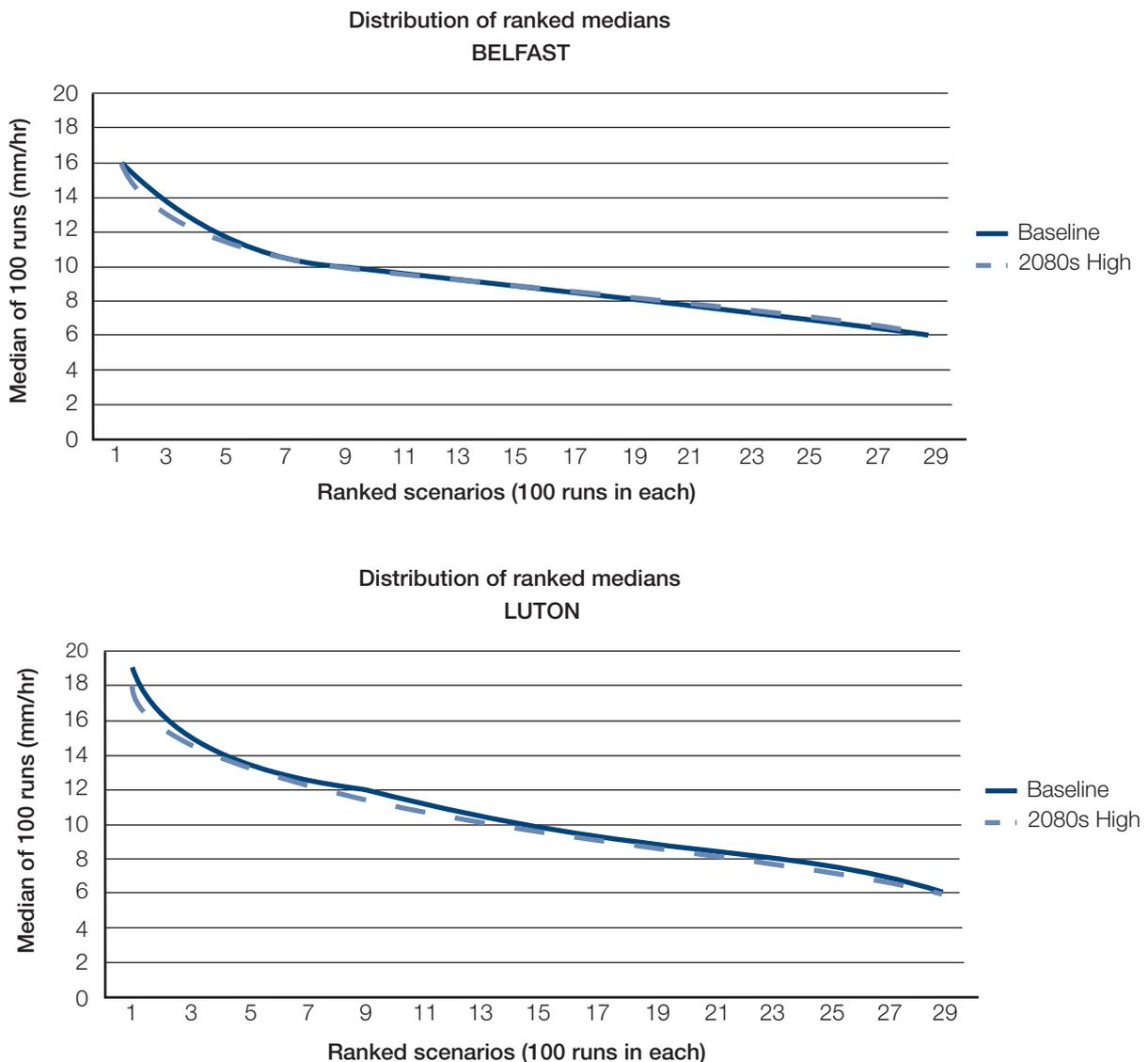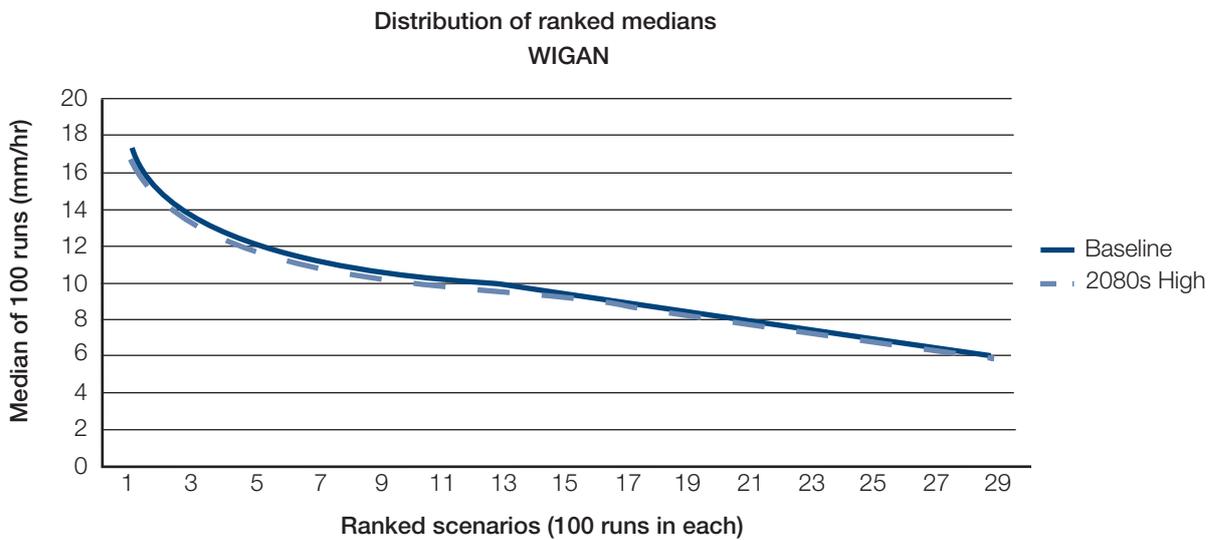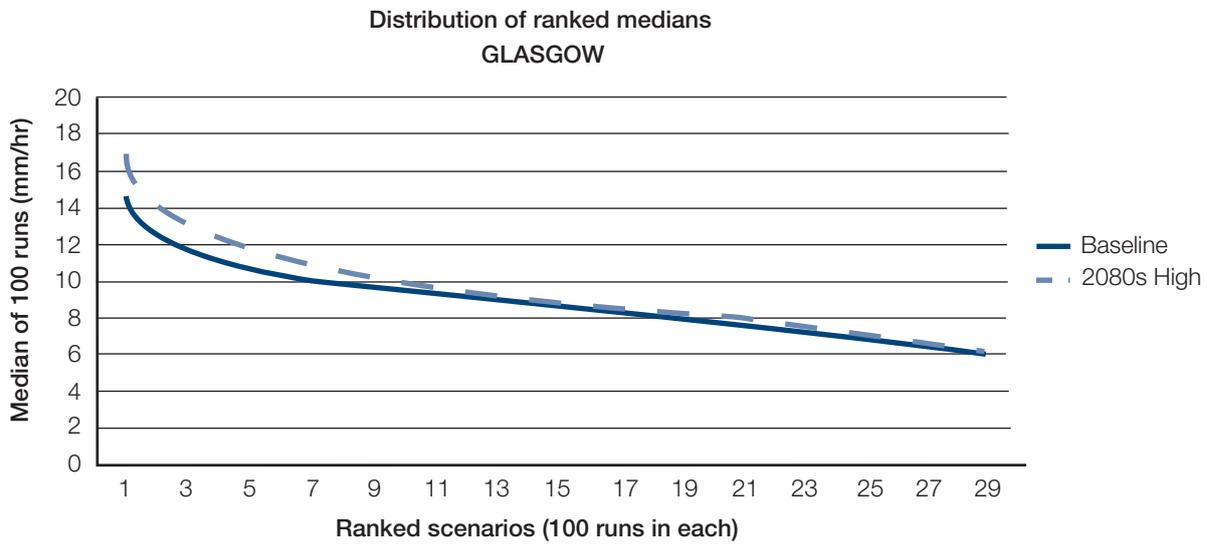
Table 15: Frequency of daily rainfall > 50 mm/day and hourly rainfall > 12 mm/hour

Daily

Number of years with daily maxima > 50mm over a 100-year period				
	Luton	**Belfast**	**Glasgow**	**Wigan**
Observed	93	93	96	92
2080s high emissions	100	100	97	95
Change	7	7	1	3

Hourly

Number of years with hourly maxima > 12mm over a 100-year period				
	Luton	**Belfast**	**Glasgow**	**Wigan**
Observed	6	4	3	6
2080s high emissions	5	3	5	5
Change	-1	-1	2	-1

Appendix II

Estimating extreme rainfall events under climate change

Phase 1a: Impact of climate change on national patterns of extreme rainfall

Much current work on the impact of climate change on rainfall and flooding assumes a 20 per cent uplift from climate change. Using UKCP09 outputs, we provide a more precise analysis of national variation in the uplift of extreme rainfall which can lead to pluvial flooding.

The key stages to the national analysis comprised:

1   Select relevant urban areas (since pluvial surface water flooding primarily occurs in urban areas).

2   Derive wettest day rainfall predictions for selected urban areas from UKCP09.

3   Analyse results in terms of time period, emissions scenario, geographic pattern and season.

Selecting urban areas

Resource constraints in selecting and extracting urban-based UKCP09 grid squares meant that all urban areas across the UK could not be analysed. To ensure a representative sample, the largest settlement in each of the 11 regions of the UK was selected, followed by the next largest settlements in each region in proportion to the region's share of the UK total population. This process resulted in the selection of 44 urban areas across the UK.

Deriving wettest day rainfall predictions for selected urban areas from UKCP09

The Weather Generator interface in UKCP09 was used to identify the 25 km output square that sat over the centre of each urban area. This was done visually with the choice of square usually being clear cut. Only two urban areas, Gillingham and Southend-on-Sea, shared the same square.

The Weather Generator was then used to derive projections of the wettest day for each 25 km square. The wettest day statistic reported by the Weather Generator is based on the 99th percentile of daily rainfall data over a 30-year period (that is, 10,950 values), disaggregated by season.

The Weather Generator wettest day output only relates to the percentage change on the baseline value. In order to analyse the results in terms of the absolute projected increase in mm, we obtained baseline wettest day data from the Met Office for the relevant 25 km squares for the standard period 1961–90. Unfortunately, this baseline data was reported annually and not disaggregated by season.

The Weather Generator produces simulated raw weather for a selected number of years. Because it is based on probabilistic climate models, different simulations produce different results. It is therefore necessary to aggregate a certain number of runs in order to obtain a reliable estimate of the central climate change. In the national analysis for each 25 km square, we ran each simulation 1,000 times for a given urban area to ensure robust results, and took the median value of the 1,000 runs.

Analysing results by time period, emissions scenario, geographic pattern and season

Wettest day data for each urban area was obtained for three time periods (2030s, 2050s and 2080s) and three emissions scenarios (low, medium and high) by season. However, it would have been beyond our resources to run all emissions scenarios and all time periods for all 44 urban areas. Accordingly, the urban areas were divided into two 'tiers':

• the largest urban area in each of the UK's twelve regions (Tier 1); and

• all other 32 selected urban areas (Tier 2).

The following climate change scenarios were run for the two tiers:

• Tier 1: nine separate scenarios for each city; low, medium and high emissions in the 2030s, 2050s and 2080s. The nine separate scenarios allowed us to analyse changes over time and by emissions scenario in all regions.

• Tier 2: one scenario for each city; medium emissions in the 2050s. Because of the greater number of Tier 2 cities, we could more accurately assess changes over space and by season in all regions.

Phase 1b: Impact of climate change on local extreme rainfall

In assessing pluvial flood risk, the national analysis can only identify urban areas with the greatest projected uplift in daily rainfall. It cannot predict where 'ponding' would actually occur during an extreme rainfall event. It thus identifies areas of potential risk. Whether and where actual flooding occurs, in response to extreme rainfall, is determined by local topography, land cover and the capacity of the urban drainage. Future 1-hour rainfalls were used as the input to JBA Consulting's JFLOW inundation model to produce fine-grained flood hazard maps at 5 m horizontal resolution (see Appendix III).
     The two key stages to the local analysis of extreme rainfall under climate change were:

6   Derive 1-hour rainfall predictions for four urban areas from UKCP09.

7   Analyse results in terms of storm intensity, duration and frequency.

Deriving 1-hour rainfall predictions for urban areas from UKCP09

In order to access the most detailed outputs possible from the Weather Generator, we derived data for the 5 km square directly over the centre of each urban area. Unlike the summary output at 25 km resolution, the 5 km level provides access to raw weather data from the Weather Generator. This not only increases geographic precision, but also enables greater flexibility in how the data can be analysed.
     The same scenario was chosen for each urban area: high emissions, 2080s. This was based on the 'worst case scenario' so that the relative risk between urban areas would be sharply exposed.
     Given the much greater processing time required, we based our analysis of 1-hour rainfalls on 100 runs rather than 1,000 as for the national analysis. To test the reliability of 100 runs, we selected 50 of the 100 runs at random and recalculated results, finding virtually no difference. This indicates that 100 runs are sufficient to produce robust results.
     Pluvial flooding is usually produced by short bursts of intense rainfall falling over a period of between one and three hours. Thus, the ideal would be to extract data from the Weather Generator on

rainfall events of around three hours' duration. However, the Weather Generator only permits daily or hourly data to be derived and UKCP09 cautions against using it for hourly rainfall in general and beyond a 5- to 10-year return period in particular. We therefore initially opted for data on daily duration.

For each urban area, we derived 100 years of simulated raw weather data at a 24-hour temporal resolution. To ensure that the results were not strongly influenced by outliers, and to be consistent with usual modelling practice, we calculated annual maxima for each of the 100 years in each of the 100 runs. We then took the median of the 99th percentile values across the 100 runs. This can be considered analogous to the 1 in 100-year return period for daily rainfall.

Having run the 1 in 100-year daily rainfall through JFLOW for central Belfast, it became apparent that, after making an allowance for urban drainage, this 24-hour rainfall would produce minimal flooding.

We therefore re-ran the Weather Generator at an hourly rather than daily temporal resolution. The generator will only produce 30 years of hourly data (because of limits to processing time and the size of data file produced). We calculated 30 annual maxima from these data for each of the 100 runs for each of Belfast, Glasgow, Wigan and Luton. The annual maxima for each run were extracted and the median determined for the 100 values in each rank position, 1 to 30. This produced a single series of 30 annual maxima of 1-hour rainfall. However, the results were inconsistent both in the direction and magnitude of change.

Given this lack of robustness in the projected 1-hour rainfalls, it was agreed with the Project Advisory Group not to use the Weather Generator 1-hour rainfall values. Instead, estimates of the present day 1 in 100-year 1-hour rainfall, based on the *Flood Estimation Handbook*, were determined for Belfast, Glasgow, Wigan and Luton, plus uplifts of 10 per cent and 20 per cent in order to assess sensitivity of flood outlines to changes in 1-hour rainfall intensity. Flood outline maps are based on a combination of the ponding occurring from 1-hour and 10-hour storm durations.

Analysing results by rainfall intensity, duration and frequency

It was originally proposed to examine any change in 1-hour rainfall potentially attributable to climate change. However, the 1-hour results were inconsistent with a 6.9 per cent reduction in Luton, a 16 per cent increase in Glasgow, and very little change in Belfast and Wigan.

These counter-intuitive results illustrate two issues. First, the Weather Generator cannot reliably predict extreme rainfall of sub-daily duration. Second, climate change may increase the frequency and/or geographic size of storms rather than their severity. The Weather Generator cannot examine the geographic size of storms as each grid square is modelled separately. However, it does allow the calculation of the frequency of a given intensity occurring.

Appendix III

Modelling pluvial flood risk

Project scope

The scope of pluvial mapping in this study was as follows:

- coverage of the defined urban areas for Belfast, Glasgow and Luton;

- simulation of the baseline 0.5 per cent annual probability (200-year) return period event, using 1.1-hour and 10.5-hour storm durations; and

- simulation of the 0.5 per cent annual probability (200-year) return period event, using 1.1-hour and 10.5-hour storm durations, with two different allowances for climate change based on percentile uplifts.

Description of model

Pluvial modelling utilises JFLOW modelling software, a specialist tool for assessing pluvial flood risk. JFLOW is a 2-D flood routing model which uses a raster-based approach driven by the underlying DTM. Water movement between cells is driven by gravity and depends on the ground level and water depth in adjacent cells. Velocity is also influenced by the roughness coefficient specified for the cells. Thus blanket rainfall applied across the study area will be routed according to the topography to low lying areas, where it will pond until the water level is high enough to spill to surrounding cells. JFLOW incorporates full implementation of the Shallow Water Equations providing reliable flood depth and velocity modelling.

Model set up

The maximum number of cells that can be used in a JFLOW simulation at one time is approximately 1,500,000. Each study area was therefore divided into run tiles of approximately 5 x 5 km using a 5 m grid. As Belfast is situated on the coast, some of the tiles at the edge of the Belfast run area were smaller than this, at 2.5 x 2.5 km or 1.25 x 1.25 km as required. Table 16 shows the number of individual run tiles for each city, derived from this method.

In order to smooth the interface between run areas, a 500 m buffer was included around each tile giving a 1 km overlap between run areas. The results within these overlapping areas were then combined to ensure a contiguous results grid.

Model assumptions

The following assumptions apply to the JFLOW model:

- Filtered LiDAR and NEXTMap data used in the DTM gives an accurate representation of the ground surface and presence of streamlines and low topography.

- Flow will pass around buildings rather than through them (no volume accommodated within buildings).

- Flow along roads is constrained by kerbs of approximately 0.1 m height.

Table 16: Number of JFLOW run tiles per city

City	No. of run tiles
Belfast	36
Glasgow	35
Luton	6

- A Manning's 'n' coefficient of 0.1 is used as a blanket surface roughness.

- The capacity of the urban drainage systems can be represented by applying a general reduction to the rainfall estimates equating to the 20 per cent annual probability (5-year) return period rainfall.

- Water is lost from the model at the edges of the DTM (volume lost is recorded).

- The model run time extends beyond the end of the input hydrograph in order to allow water to continue to run off across the ground surface to create final flood depths. The model run continues for six times the hyetograph length (standard multiplier for JFLOW).

Study areas

The three cities chosen to be mapped in detail were Belfast, Glasgow and Luton. The extent of the area to be mapped in each case was provided, based on metropolitan, urban and settlement areas available from local government information. The extent of mapping in Luton was also constrained by the availability of LiDAR data.

As JFLOW runs on the basis of 5 x 5 km tiles, each study area was divided into run tiles using a standard grid. For coastal areas of Belfast, a smaller grid size was used where applicable (2.5 x 2.5 km or 1.25 x 1.25 km). The study areas are shown in Figures 19 to 21.

Plans of study areas

Figure 19: Belfast study area
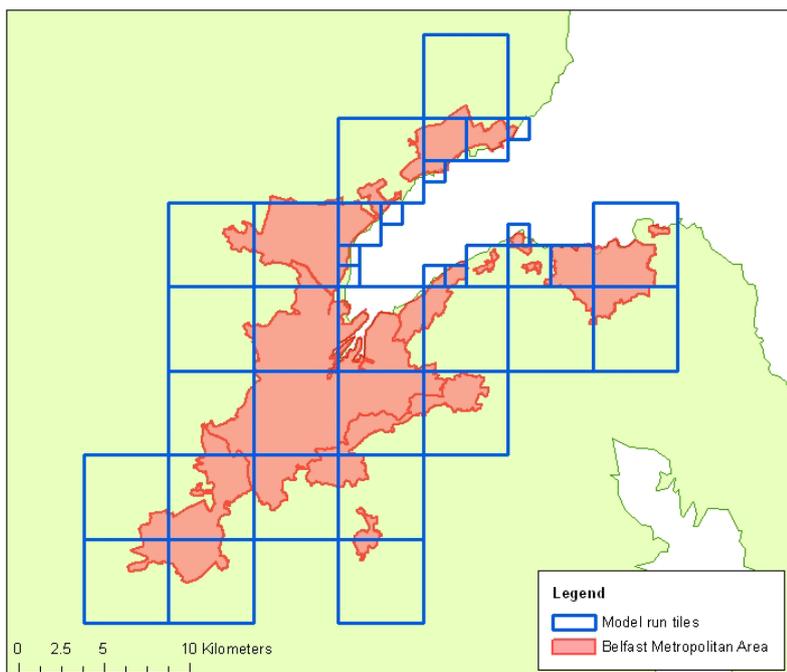
Source: UK Borders

Figure 20: Glasgow study area
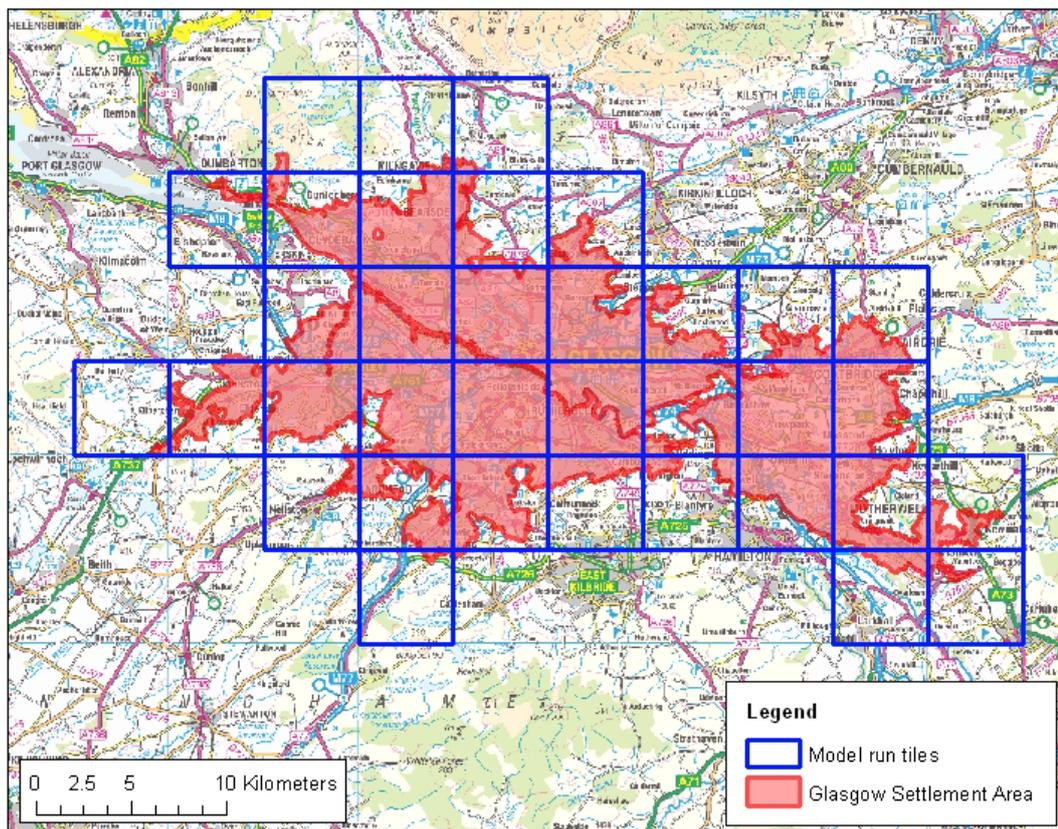
Source: UK Borders

Figure 21: Luton study area
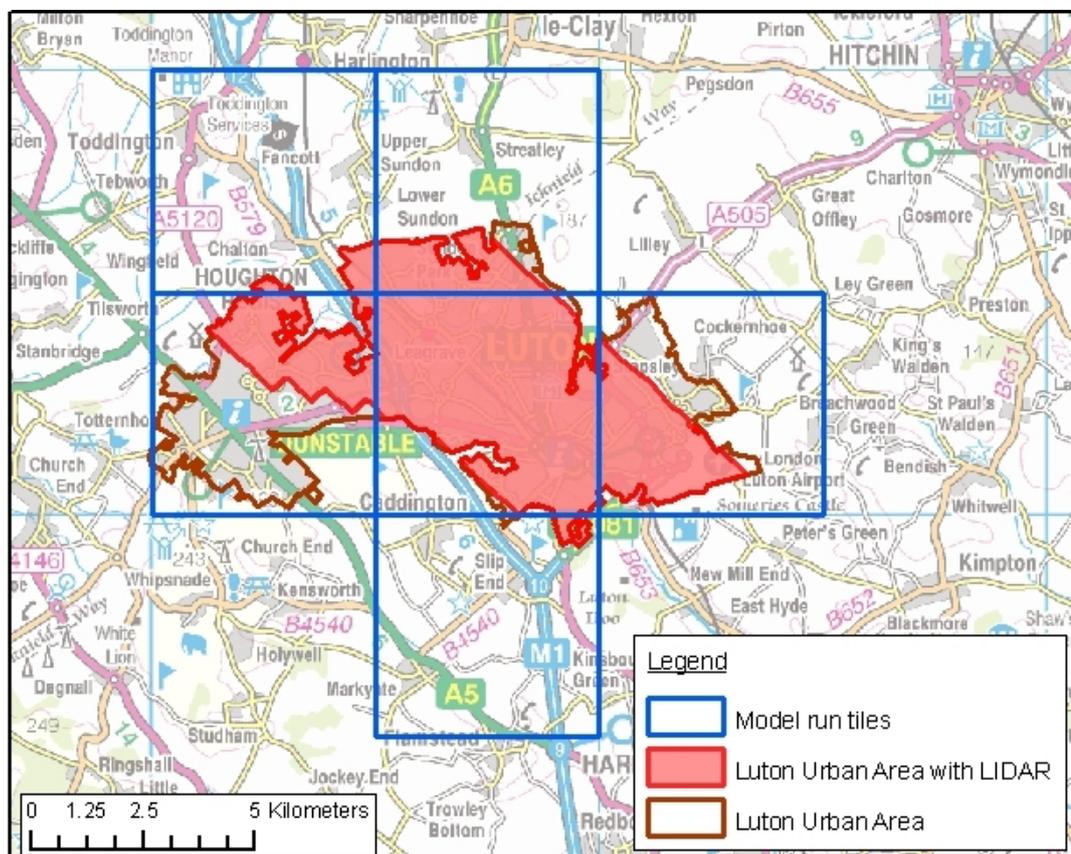
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Digital terrain model

Pluvial modelling uses a 2-D raster approach to simulate rainfall run-off over the topography of the study area. For this purpose a DTM is required. This chapter outlines the methodology for preparing DTMs for use in JFLOW.

Data type and availability

Where available, LiDAR data provides topographical data of generally high quality and precision (1 m cell size and vertical accuracy of approximately 20 cm is standard). However, LiDAR data is only available for some areas of the UK. For Belfast and Glasgow, areas not covered by LiDAR were supplemented by available Ordnance Survey of Northern Ireland (OSNI) or NEXTMap data (generally 5 m cell size and lower vertical accuracy). Table 17 describes the topographical data available for each of the study areas.

Combining DTM datasets

For Belfast and Glasgow, where two types of DTM data were available, they were combined by stamping the LiDAR data onto the NEXTMap/OSNI DTM. Given the more reliable accuracy of LiDAR, this dataset was used in preference.

The interface between the two datasets was smoothed to ensure no false changes in level remained as a relic of the merging process. This smoothing was undertaken using a feathering method which interpolates between the LiDAR and NEXTMap levels within a buffer zone 100 m wide. This interpolated raster strip is then stamped over the boundary between the two datasets to provide a smooth interface.

Editing the DTM

LiDAR, NEXTMap and OSNI DTMs are based on elevation data from air-based surveys (light detection and ranging, interferometric synthetic aperture radar and photogrammetry respectively). Therefore the levels returned capture high points including bridges and embankments. The presence of such features may distort the results due to levels within the DTM that do not represent potential low points and flow routes. Figure 22 shows an example where flows routed along the low levels of a river valley would, without editing of the DTM, come up against a barrier to flow where the DTM picks up the level of bridge decks crossing the watercourse. In reality, there would be a culvert or opening to allow flow to continue under the bridge. Features of this sort need to be edited to allow more realistic flowpaths.

Table 17: Data availability

City	LiDAR coverage	Other data
Belfast	Partial	OSNI
Glasgow	Partial	NEXTMap
Luton	Partial	None made available

Figure 22: Example of DTM editing
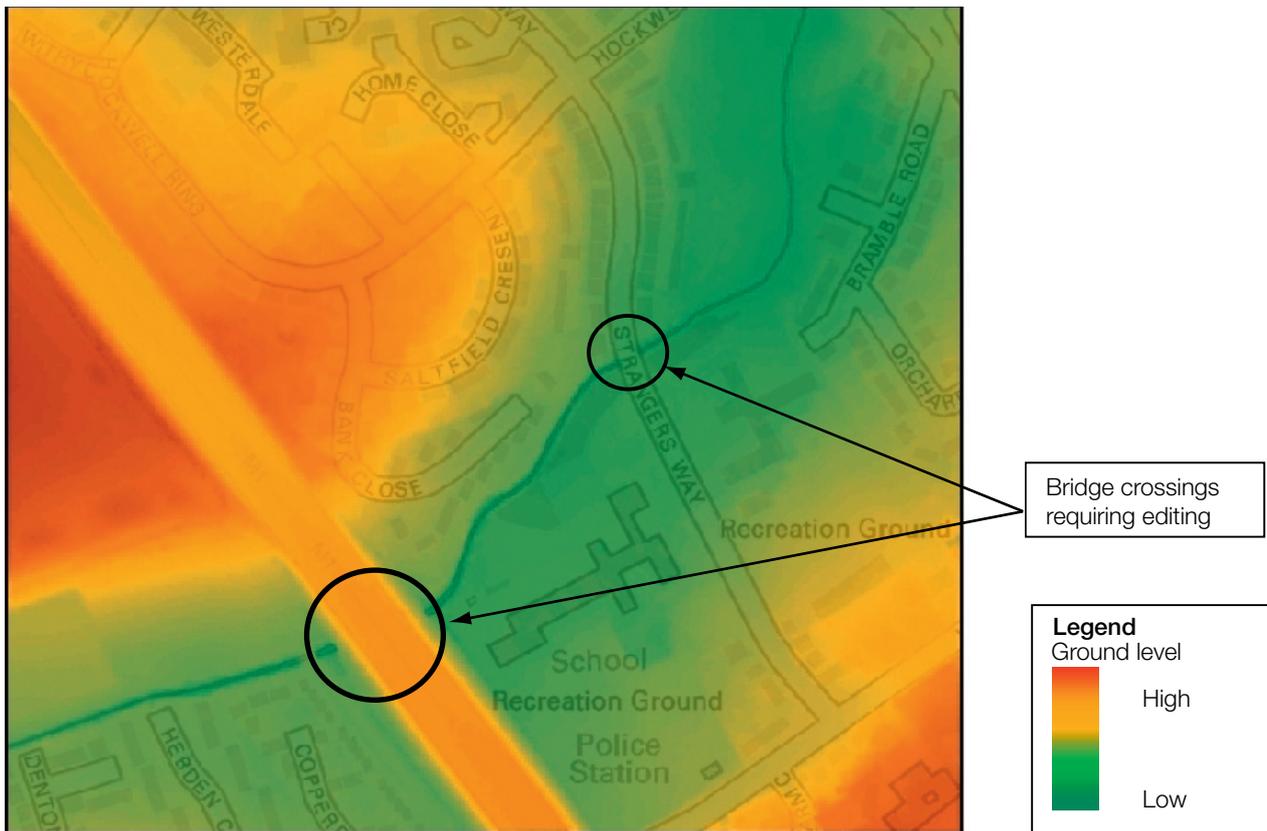
Licence reference number: Z10351
Contains Ordnance Survey data © Crown copyright and database right 2011

Features of this type which require editing include:

- bridges across roads and railway lines;

- underpasses beneath embankments;

- tunnels;

- river crossings; and

- culverted sections of watercourse.

These features were edited using a tool that allows features to be cut through from a defined start and end point in the DTM. The tool creates a cut at a specified width (a multiple of 5 m), based on levels interpolated between the defined start and end point of the cut line. These edits are stamped onto the DTM to create a terrain model fit for purpose for the pluvial model.

Adding buildings to the DTM

The filtered LiDAR and NEXTMap/OSNI data available for this study has had buildings removed and represents 'bare earth' terrain models. However, in pluvial mapping, the flow routes taken by surface water run-off are strongly influenced by the presence of buildings as these are likely to act as an obstruction to flow. In order to recreate realistic flow paths within the model, it is therefore appropriate to incorporate building shapes into the DTM.

Figure 23: Adding buildings to the DTM

a) 'Bare earth' DTM (no buildings)   b) 'Stamped' DTM (incorporates buildings)
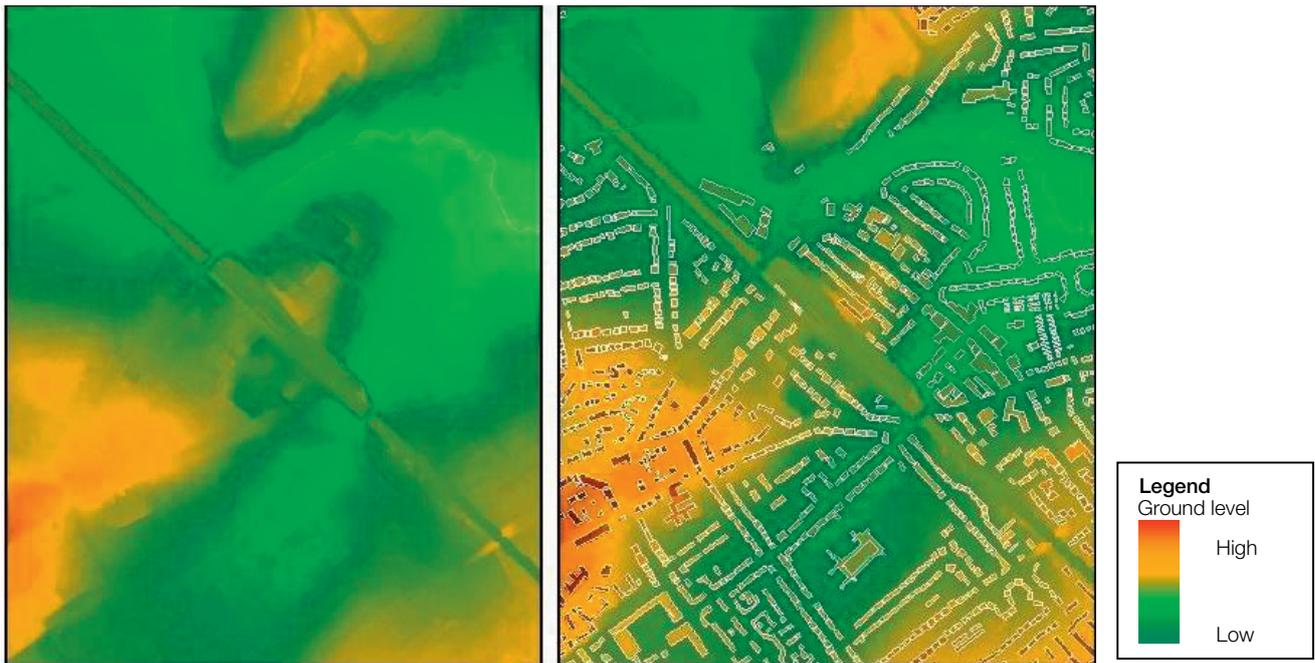
Licence reference number: Z10351
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To achieve this, building outlines were extracted from the freely available Ordnance Survey Street View mapping for Glasgow and Luton, and OS MasterMap data which was available for Belfast. The buildings were then converted to a format compatible with the DTM (including abstraction of their shape to the 5 m cell size used in the DTM), assigned an arbitrary height of 5 m and stamped onto the DTM. This ensures surface run-off across the DTM will follow flow paths around rather than through the buildings (see Figure 23).

Rainfall methodology

The hydrological input required by JFLOW pluvial modelling is a depth-time hyetograph to represent the storm's rainfall profile, which is applied as a blanket rainfall over the run area.

Rainfall depth

For the purposes of this project, rainfall estimations were generated using the *Flood Estimation Handbook* (Institute of Technology, 1999). Its depth–duration–frequency (DDF) modelling was used to generate baseline rainfall, and an uplift factor to represent the impact of climate change was then applied. These methods are summarised below.

DDF model

The *Flood Estimation Handbook* can be used to generate DDF curves for any 1 km grid point. A DDF curve relates storm duration to total rainfall depth, with different curves representing different return periods of event (see Figure 24).

Figure 24: Example of DDF curves
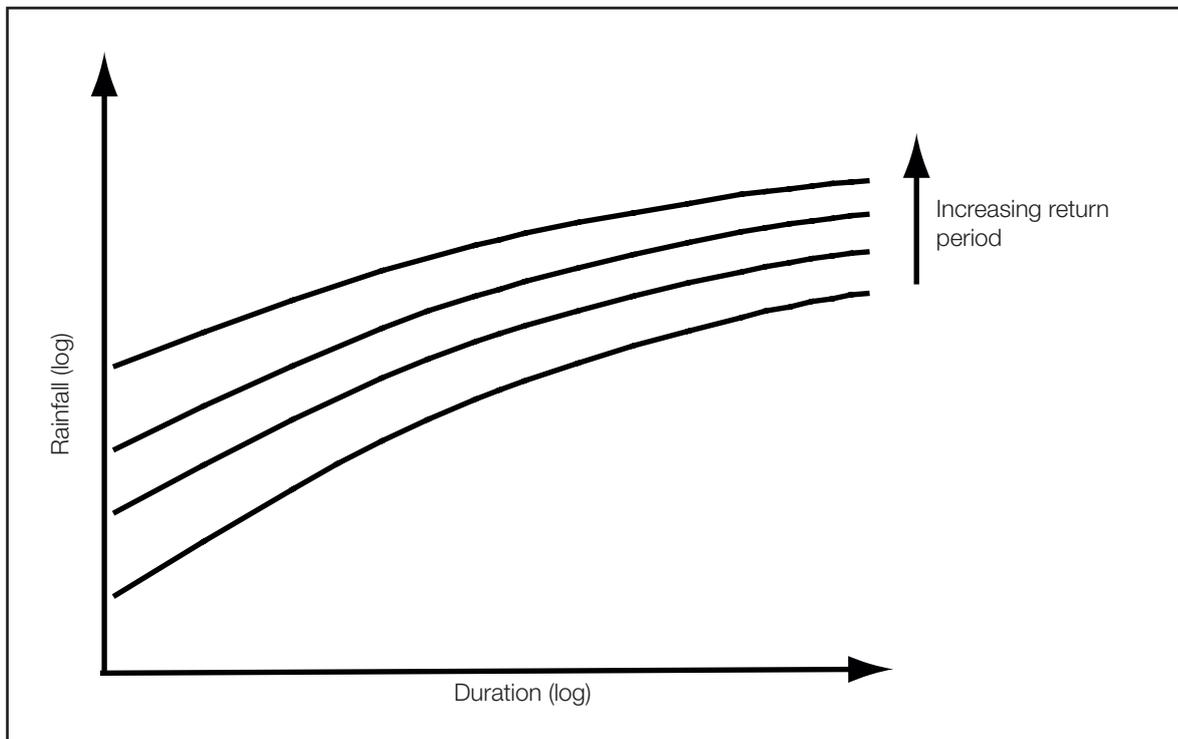
Since DDF parameters are defined for each km point, this method for calculating rainfall depths allows incorporation of their spatial variability in the pluvial study.

As discussed, a single run of the JFLOW pluvial model covers an area of approximately 5 x 5 km. For each run, a single rainfall profile is required which is applied as a blanket rainfall over the whole area. DDF parameters were therefore extracted for the grid point closest to the centre of each JFLOW run area to create a rainfall profile. This allows the broad scale spatial variation in rainfall over each city to be represented in the model.

Uplift for climate change

A percentage increase in rainfall was used to represent the potential impact of climate change. Due to the limitations associated with the ability of the UKCP09 Weather Generator to generate sub-daily rainfall (as was required for this study) for high return period events, it was decided to test the impact of a 10 per cent and 20 per cent increase in rainfall across each city. These percentage increases were applied to each rainfall profile prior to the subtraction of the drainage allowance.

Rainfall profile

To create the inputs required by the JFLOW model, the total rainfall depth for each scenario needs to be converted into a rainfall profile which varies over time. In order to do this, a standard profile shape was applied, as described in the *Flood Estimation Handbook* (Vol. 2). Two profiles are given: summer and winter. Both profile shapes are symmetric, single-peaked and bell-shaped, and do not vary with duration or location.

The 'summer' profile has a more pronounced peak, representative of the convective storms more common in summer, and is recommended for application to urban catchments where a shorter period of high intensity rainfall is generally more critical (see Figure 25). The parameters of the summer storm profile were therefore used to generate a rainfall hyetograph by dividing the total rainfall depth over the storm duration with the relative proportions of the summer profile.

Figure 25: *Flood Estimation Handbook* standard profile shapes
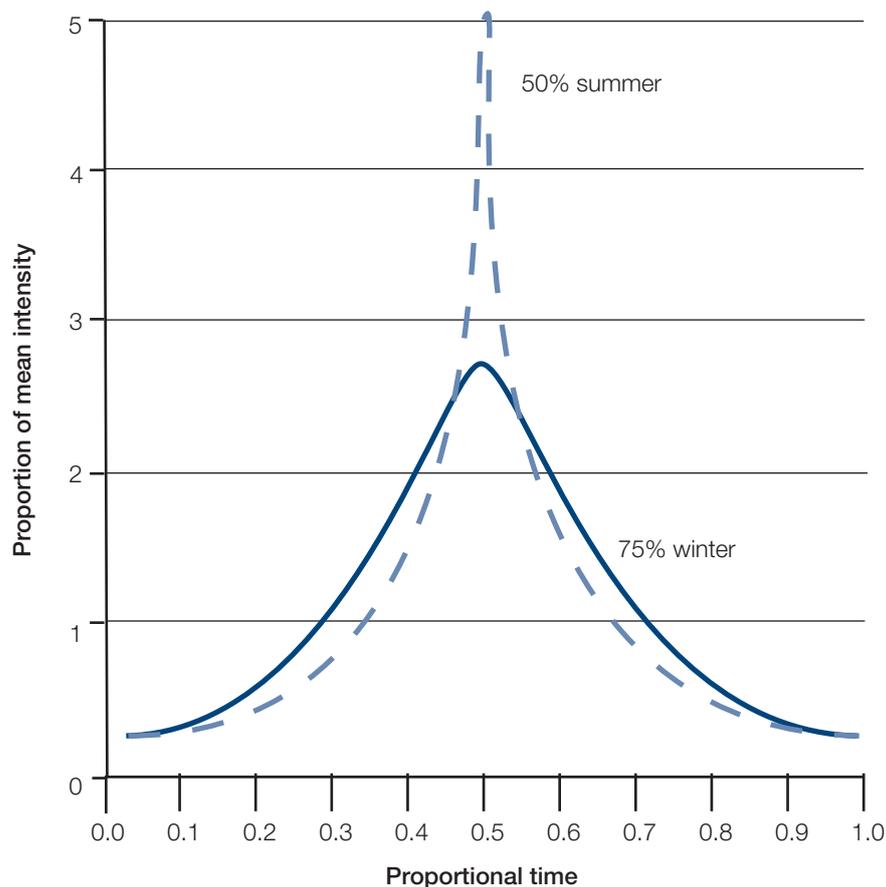
Effect of urban drainage

Drainage systems in urban areas remove some pluvial run-off volume from the ground surface. Within urban areas, the capacity of the drainage system will vary substantially between locations and, to account for drainage, use of a standardised approach is therefore appropriate. Research by JBA Consulting during other national pluvial mapping exercises has suggested that a standardised allowance equating to the 20 per cent annual probability (5-year) event is appropriate for most UK cities following testing against historical datasets. This allowance for drainage is therefore considered suitable for application to the three study settlements.

Figure 26 shows an example of the rainfall profiles created for central Luton for the baseline and climate change scenarios, for the 0.5 per cent annual probability (200-year), 1.1-hour duration event with drainage allowance subtracted.

Rainfall duration

Previous pluvial studies conducted by JBA Consulting have suggested that the duration of the event that is used has a significant influence on the areas and depths of pluvial flooding predicted by the model. Its recent research suggests that shorter rainfall event durations are more critical for steeper topography, with longer duration events more critical for flatter topography that is subject to ponding.

In order to capture this effect, it was decided to model two durations of flood events: 1.1-hour and 10.5-hour, which is consistent with JBA's approach to national flood mapping (the decimals give an odd number of values in the hyetograph). The results can be merged to produce a final outline for each scenario.

Figure 26: Example rainfall profiles, Luton, 200-year, 1.1-hour event: baseline and climate change scenarios
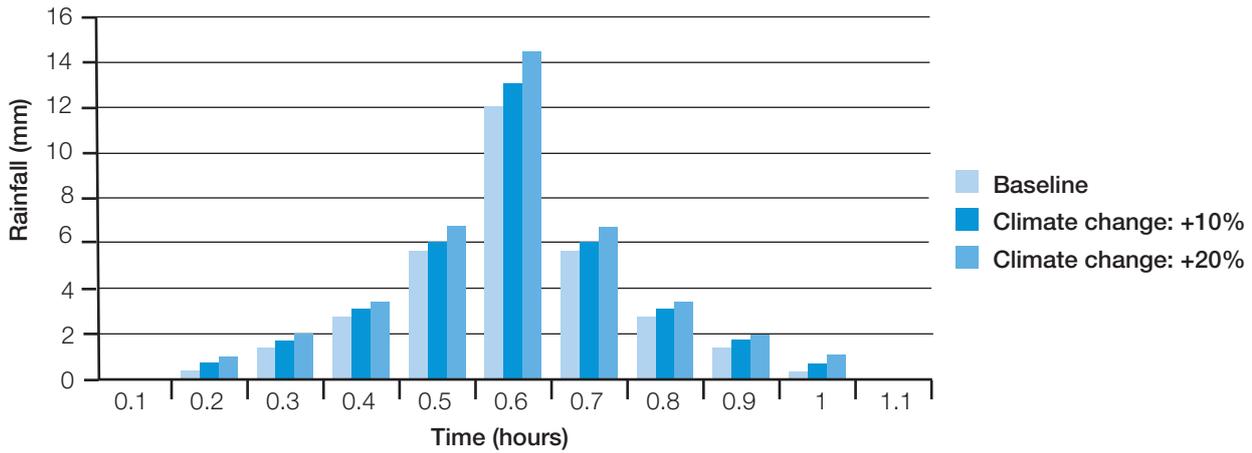
Design rainfall profiles

The final choice of design rainfall for this study is therefore:

- 0.5 per cent annual probability (200-year) return period;

- baseline rainfall estimated using the *Flood Estimation Handbook* depth–duration–frequency modelling method;

- estimated uplift for climate change of 10 per cent and 20 per cent;

- 1.1-hour and 10.5-hour durations; and

- 20 per cent annual probability (5-year) allowance for urban drainage subtracted.

Results

JFLOW output

The output from the pluvial model is a raster of final flood depths across each run tile. The results for each tile were mosaicked together to produce a raster with full coverage for each study area.

The depth raster was used to generate filtered flood outline polygons. Depths of less than 0.1 m were removed from the flood outline as standard. Isolated areas of pluvial flooding of less than 200 m² in size were also removed from the outline (note that the latter applies to the polygon but not the raster). These are standard procedures developed by JBA Consulting during nationwide pluvial modelling work.

For the final maps, water bodies including watercourses and lakes were masked to differentiate them from the pluvial outlines. Examples of the different outputs are shown in Figure 27.

Figure 27: Example pluvial outlines for baseline and climate change events

a) Baseline event

b) Climate change event

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Legend

▮ (pink)	Baseline pluvial outline
▮ (blue)	Climate change pluvial outline
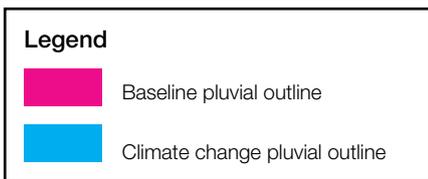
Appendix IV

Methodology for local socio-economic profiling of areas at risk from pluvial flooding

Choice of urban area definitions

Urban areas vary in their spatial extents and may be defined using different criteria for different reasons. An initial task was therefore to agree definitions for Luton, Belfast and Glasgow that were suitable for the present analysis and within which the pluvial modelling work was to be performed.

The definitions for Luton, Belfast and Glasgow adopted for this study are derived from official national classifications of urban areas defined separately for England and Wales, Northern Ireland and Scotland. These classifications are similar, as one might expect, although the precise definitions and terminology adopted are not identical. The most important points are as follows:

- In the case of Luton, flood modelling was limited to the Luton sub-urban area (rather than the larger Luton-Dunstable urban area) because of the availability of digital elevation data required for the pluvial modelling (see Appendix III). Correspondingly, the socio-economic profile that was developed subsequently also relates to the Luton sub-urban area rather than the entire Luton-Dunstable urban area.

- For Belfast, it was practicable to perform flood risk modelling for all parts of the area covered by Belfast metropolitan urban area, encompassing Belfast itself and twelve adjacent urban settlements. The latter tend to be relatively small settlements and were easy to include in the flood modelling without significantly adding to the modelling time or cost.

- What we refer to as 'Glasgow' is defined as the General Register of Scotland's defined 'settlement' of Greater Glasgow, which – in addition to the City of Glasgow – includes 36 other smaller localities and over 1.1 million people.

Modelling socio-economic variations within urban areas

The pluvial flood modelling work conducted for this study – using high resolution elevation data – produced extremely detailed flood outlines. In many cases, flood outlines are very small, down to a fraction of a hectare in size.

Conversely, socio-economic data tends to be available at coarser levels of spatial detail. Even COAs – the smallest size of area available for reporting Census of Population data – tend to be much larger than the flood outlines resulting from the flood modelling work. This presents a challenge in estimating the population at risk. To select all COAs, including those only partially covered by a flood outline, would substantially over-estimate population at risk. Similarly, to select only COAs that are completely inundated would miss all smaller areas of flood risk. It would in principle be possible to set an arbitrary threshold for inclusion (for example, 50 per cent coverage of a COA with flood outline), but this would introduce considerable random error.

We have addressed this problem by identifying the proportion of each COA that is covered by a flood outline, then calculating the same proportion of the COA's population. The population deemed to be at risk in each COA is then summed across the whole of each settlement. This proportion has also been

applied to each population sub-group in order to produce the socio-economic profiles for flood risk and non-risk areas in each settlement.

Alternative approaches to modelling population distribution

In reality, however, population is rarely distributed evenly across COAs and in some cases may be highly concentrated within particular locations: for example, if a large area of open space falls within a particular COA. Awareness of this has led to increased attention to alternatives to COAs for population distribution mapping.

One such approach is modelling COA population data in the form of a density surface represented by a regular geographical grid. This is achieved through a process of spatial redistribution between COA centroids. Unlike COAs, which vary considerably in size and the way their boundaries are drawn, the cells in such a grid are of a uniform size which helps to remove the effects of 'modifiable' geography in understanding population distribution. Limitations of this approach, however, are that population is still allocated to open spaces (unless open spaces can be masked) and that the spatial interpolation process can take considerable computation time.

A second approach is to utilise the information on Census population counts that is available for areas smaller than COAs (such as unit postcodes) and then use this to estimate the distribution of population sub-groups. This assumes that the spatial distribution of sub-groups replicates that of the total population. This second approach is more feasible because of links to the unit postcode geography developed in planning COAs, and because of availability of population and household counts for unit postcodes. A limitation, however, is that population sub-groups will often not follow the distribution of the total population: that is, some COAs are not spatially homogenous in terms of socio-economic profile. Another limitation is the computation time taken to assign population sub-group data from COAs to the smaller units.

Mainly because of the excessive demands on computation time, we opted in this research to use COAs to estimate population at flood risk (although still employing the 'proportionate area' technique). However, in order to assess the sensitivity of results to the method of local population estimation, we have calculated the population at risk in Belfast for the baseline scenario using all three methods outlined.

The lowest result suggests 29,149 at risk, using 100 m cells for which population counts have been made available by the Northern Ireland Statistics and Research Agency. In other parts of the UK, the smallest areas for which Census population and household counts are available are unit postcodes. The highest result is 33,126 at risk, using COAs (the method employed for the local risk analysis and socio-economic profiling in this report). This represents a variation of 13.6 per cent from the lowest estimate. The results are:

- COAs: 33,126 at risk;

- surface redistribution: 31,318 at risk; and

- 100 m cells: 29,149 at risk.

Appendix V

Interviews

Organisation	Role of organisation	Position/role of interviewee
AVIVA	Insurance company	Underwriting Manager
Belfast Resilience Forum	Third sector charity	Programme Manager
Department for Environment, Food and Rural Affairs (Defra)	Central government department	Project Manager
Department for Regional Development (DRD) Road Services	N. Ireland government agency	Maintenance, Eastern Division
Environment Agency	Central government's environmental management agency	Senior Advisor, Flood and Coastal Risk Management
Flood Guards	Private company manufacturing and marketing flood guards	Partner
Luton Borough Council	Local government	Transport Strategy Officer
Luton Borough Council	Local government	Strategy and Sustainability Team Leader
Luton Borough Council	Local government	Strategy and Sustainability Officer
Metropolitan Glasgow Strategic Drainage Partnership (MGSDP)	Body that co-ordinates drainage and related urban redevelopment in Greater Glasgow	SEPA representative on MGSDP
NIG Insurance	Insurance company	Underwriting Manager
Northern Ireland Rivers Agency	N. Ireland Drainage and Flood Defence Authority	Director of Development
Northern Ireland Rivers Agency	N. Ireland Drainage and Flood Defence Authority	Mapping and Modelling Unit
Scottish Environment Protection Agency (SEPA)	Scottish government agency for environmental management	National Flood Risk Assessment
Scottish Flood Forum	Supports and represents flood victims and those at risk	Chairman
Scottish Water	State water company	Flood Risk Management (Asset Strategy)
Thames Water	Water company	Asset Manager
University of Abertay	Education and research institution	SUDS and urban drainage expert
University of Dundee	Education and research institution	Insurance expert
Wigan Council	Local government	Group Manager, Planning Policy
Wigan Council	Local government	Senior Assistant Engineer
Women's Royal Voluntary Service	Third sector charity	Head of Resilience

Glossary

blue space	Urban area set aside for storing water or conveying storm water to drains
blue corridor	Planned safe flow route for excess surface run-off during extreme rainfall, usually making use of kerbed highways
Census Output Area (COA)	Smallest geographic unit for which 2001 Census of Population data is released, typically representing around 120 people/50 households
emissions scenario	Projection of possible levels of greenhouse gas emissions throughout the twenty-first century (low, medium and high) used by UKCP09
environmental justice	Fairness of a pattern of exposure to environmental hazards across social groups (see also social justice)
Defra	Department for Environment, Food and Rural Affairs (England and Wales)
DRD	Department for Regional Development (N. Ireland)
Digital Terrain Model (DTM)	Digital model that gives a detailed representation of the surface of terrain
EU	European Union
exposure	Number of people, households, businesses, infrastructure and services that can potentially be impacted by floods
green space	Non-built up vegetated areas within a settlement
hazard	Occurrence with the potential to cause harm
impermeable surface	Surface that does not permit the infiltration of water and therefore generates surface water run-off during periods of rainfall
IMD	Index of Multiple Deprivation
JFLOW	Software used by JBA Consulting to generate surface water inundation maps
LiDAR	Light Detection and Ranging: remote sensing technology for terrain mapping
NEXTMap	Digital elevation model covering the UK from airborne radar (lower resolution than LiDAR)
OSNI	Ordnance Survey of Northern Ireland
pluvial flooding	In England, usually referred to as urban flooding 'caused by rainfall overwhelming drainage capacity' (Parliamentary Office of Science and Technology, 2007, p. 1) In the Pitt Review, referred to as surface water flooding, attributed to 'extreme rainfall and the inability of the water to drain away quickly enough' (Cabinet Office, 2008) In Scotland, defined as 'flooding that results from overland flow which has been generated by rainfall before the run-off enters any watercourse or sewer. This is also referred to as surface water flooding' (Scottish Government, 2010, p. 48) In N. Ireland, the Rivers Agency equates pluvial flooding with surface water flooding: 'surface water or pluvial flooding occurs as a result of high intensity rainfall which overwhelms natural or engineered drainage systems resulting in water flowing overland and ponding in depressions in the ground' (Rivers Agency, 2011, p. 3)
PPS	Policy Planning Statement (N. Ireland)

population projection	Projection into the future of anticipated population derived by applying age-specific birth and death rates to the current population age structure, with age cohorts rolling forward (e.g. 10-year-olds in 2010 become 50-year-olds in 2050, minus anticipated deaths); assumptions are made about net international and internal migration
resilience	Ability to withstand, recover from or adapt to an external event such as a flood (see also vulnerability)
risk	Combination of the likelihood and consequences of a hazard occurring
return period	Probability that a flood of a specified size will occur within a given period. Thus the probability that a 1 in 100-year flood will occur is 0.01 each year
run-off	Component of rainfall which, on reaching the ground, fails to infiltrate the soil and flows across the surface
SEPA	Scottish Environment Protection Agency
social justice	Set of principles (chiefly: need, desert, equality, freedom, power and total collective welfare) against which to judge the fairness of processes or outcomes (see also environmental justice)
storm water drainage	Part of urban drainage systems designed to evacuate storm water (gullies along the edge of roads, drains and sub-surface pipe systems)
sustainable flood management	Flood risk management that meets human needs while preserving the environment so that needs can also be met for future generations
Sustainable Drainage Systems (SUDS)	Set of techniques designed to slow the flow of water, which can contribute to reducing flood risk by absorbing some of the initial rainfall and then releasing it gradually. This reduces the flood peak and helps to mitigate downstream problems, making a useful contribution to flood management
Surface Water Management Plan (SWMP)	Plan for managing the component of pluvial flooding directly caused by extreme rainfall
sewerage flooding	Flooding caused by a blockage or overflowing in a sewer or urban drainage system
UK Climate Projections 2009 (UKCP09)	Up-to-date estimates of future climate across the UK throughout the twenty-first century
vulnerability	Susceptibility to harm resulting from the probability of exposure to a hazard, mitigated by resilience to that hazard (see also resilience)
Weather Generator	Computer program within UKCP09 that enables end-users to customise future climates for specific time periods and emissions scenarios
2-D	Two-dimensional model enabling depth as well as areal extent of floods to be reported

Notes

1   There is a significant distinction between practice in England and Wales, and Scotland. Whereas the national flood risk assessment includes pluvial flooding in Scotland, it does not in England and Wales.

2   In this chapter on the governance of flooding in England and Wales, the terms 'local flood' and 'surface water flood' are used rather than 'pluvial flood'. This reflects both the current usage in England and Wales and contrasts in how flooding in urban areas is managed. For further details, see the Glossary.

3   Wigan was also included as a case study town (see Table 2) but unfortunately was dropped from the modelling work. This difficult decision was reached because the additional (unplanned) surface flow model runs required to perform sensitivity analysis of uplift in extreme rainfall meant the number of runs required for all four towns was beyond our capacity. Belfast, Glasgow and Luton were retained in order to maintain a spread of towns around the jurisdictions of the UK.

4   As defined by government statistical agencies around the UK. The main criteria used are contiguous high density areas of more than 10,000 people. It is important to stress that these areas bear no relation to local authority jurisdictions, including the three settlements in which we have conducted detailed analysis (Belfast, Glasgow and Luton).

5   This figure is substantially lower than the Environment Agency's original 3.8 million properties because of improvements in methodology since the Environment Agency produced its figure. More refined risk maps are now issued to local authorities (see Chapter 2 for more details).

References

Ball, T., Werritty, A., Duck, R. W., Edwards, A., Booth, L. and Black, A. (2008) *Coastal Flooding in Scotland: A Scoping Study*. Report to SNIFFER, Edinburgh

Ball, T., Hendry, S., Werritty, A. and Spray, C. J. (2009) *Flood Risk Management (Scotland) Act 2009*. Sweet and Maxwell Statutes Annotated

Brown, S., Boorman, D., Buonomo, E., Burke, E., Caesar, J., Clark, R., McDonald, R. and Perry, M. (2008) *A Climatology of Extremes for the UK: A Baseline for UKCP09*. Exeter: The Met Office Hadley Centre

Cabinet Office (2008) *Learning Lessons from the 2007 Floods*. London: Cabinet Office

CCRA (Climate Change Risk Assessment) (2010) A*ssessment for the Devolved Administrations, Scottish Tier 2 List of Impacts*, CEOSA 0901

Crichton, D. (2007) *The Growing Risks of Climate Change on Households in England*. Paper presented to the British Insurance Brokers' Association Conference, May 2007

Cutter, S. (2006) 'Vulnerability to Environmental Hazards'. In Cutter, S. (ed.) *Hazards, Vulnerability and Environmental Justice*. London: Earthscan, pp. 71–82

Digman, C., Balmforth, D., Kellagher, R. and Butler, D. (2006) *Designing for Exceedance in Urban Drainage: Good Practice*. CIRIA report C635

Dobson, A. (1998) *Justice and the Environment. Conceptions of Environmental Sustainability and Theories of Distributive Justice*. Oxford: Oxford University Press

Environment Agency (2009) *Flooding in England: A National Assessment of Flood Risk*

Environment Agency (2011) *Understanding the Risks, Empowering Communities, Building Resilience: The National Flood and Coastal Erosion Risk Management Strategy for England*

Evans, E., Ashley, R., Hall, J., Penning-Rowsell, E., Saul, A., Sayers, P., Thorne, C. and Watkinson, A. (2004) *Future Flooding, Scientific Summary Volume 1*. Foresight programme. London: Office of Science and Technology

Fielding, J. L. (2009) 'Double Whammy? Are the Most at Risk the Least Aware? A Study of Environmental Justice and Awareness of Flood Risk in England and Wales'. In Samuels, P. *et al.* (eds) *Flood Risk Management: Research and Practice*, pp. 965–72

Fielding, J. and Burningham, K. (2005) 'Environmental Inequality and Flood Hazard'. *Local Environment*, 10(4), pp. 379–95

Flood Hazard Research Centre (2010) *The Benefits of Flood and Coastal Risk Management: A Handbook of Assessment Techniques – 2010*. Flood Hazard Research Centre, Middlesex University

Galaz, V. (2005) 'Social-ecological Resilience and Social Conflict: Institutions and Strategic Adaptation in Swedish Water Management'. *Ambio*, 34(7), pp. 567–72

Gatrell, A. C. (2002) *Geographies of Health*. Oxford: Blackwell

Institute of Hydrology (1999) *Flood Estimation Handbook* (5 volumes). Wallingford: Institute of Hydrology

Jenkins, G. J., Perry, M. C. and Prior, M. J. (2008) *The Climate of the United Kingdom and Regional Trends*. Exeter: The Met Office Hadley Centre

Jones, P. D., Kilsby, C. D., Harpham, C., Glenis, V. and Burton, A. (2009) *UK Climate Projections Science Report: Projections of Future Daily Climate for the UK from the Weather Generator*. University of Newcastle

Kelly, P. M. and Adger, W. N. (2000) 'Theory and Practice in Assessing Vulnerability to Climate Change and Facilitating Adaptation'. *Climatic Change*, 47(4), pp. 325–52

Lamond, J. and Proverbs, D. (2006) 'Does the Price Impact of Flooding Fade Away?' *Structural Survey*, 24(5), pp. 363–77

Lindley, S. J., O'Neill, J., Kandeh, J., Lawson, N., Christian, R., O'Neill, M., Steiner, H., Starkey, R. and Anderson, K. (2011) *Justice, Vulnerability and Climate Change: An Integrated Framework*. York: Joseph Rowntree Foundation

McLaughlin, M. (2011) *Flood Risk Management (Scotland) Act: National Flood Risk Assessment*, talk at SNIFFER Flood Risk Management Conference, February 2011, Edinburgh

Nelson, D. R., Adger, W. N. and Brown, K. (2007) 'Adaptation to Environmental Change: Contributions of a Resilience Framework'. *Annual Review of Environment and Resources*, 32, pp. 395–419

Pall, P., Aina, T., Stone, D. A., Stott, P. A., Nozawa, T., Arno, G. T., Hilberts, D. L. and Myers, R. A. (2011) 'Anthropogenic Greenhouse Gas Contribution to Flood Risk in England and Wales in Autumn 2000'. *Nature*, 470, pp. 382–5

Parliamentary Office of Science and Technology (2007) *Urban Flooding*, POSTNOTE, 289, Westminster, London: UK Parliament

Pryce, G., Chen, Y. and Galster, G. (2011) 'The Impact of Floods on House Prices: An Imperfect Information Approach with Myopia and Amnesia'. *Housing Studies*, 26(2), pp. 259–79

Rawls, J. (1971) *A Theory of Justice*. Boston, Mass: Harvard University Press

Rivers Agency (2010) *Introduction to the Preliminary Flood Risk Assessment*. Belfast: N. Ireland Rivers Agency

Rivers Agency (2011) *Surface Water Management Roles and Responsibilities Report*. Belfast: N. Ireland Rivers Agency

Scottish Environment Protection Agency (2011) *Properties at Risk*. Personal communication

Scottish Government (2010) *Delivering Sustainable Flood Risk Management: A Consultation*. Edinburgh: Scottish Government

Smith, K. (1996) *Environmental Hazards: Assessing Risk and Reducing Disaster* (2nd edition). London: Routledge

Tapsell, S., Penning-Rowsell, E. C., Tunstall, S. M. and Wilson, T. L. (2002) 'Vulnerability to Flooding: Health and Social Dimensions'. *Philosophical Transactions of the Royal Society of London Series A: Mathematical, Physical and Engineering Sciences,* 360, pp. 1511–25

Twigger-Ross, C. L. and Orr, P. R. (2011) *Social Vulnerability to Climate Change Impacts: An Evidence Review Undertaken as Part of the UK Climate Change Risk Assessment (CCRA)*. London: Department for Environment, Food and Rural Affairs (Defra). Collingwood Environmental Planning Ltd

UKCP09 (2009) *UK Climate Projections*. UK Climate Impacts Programme, Defra. www.ukcip.org.uk [Accessed 25 August 2011]

Walker, G., Burningham, K., Fielding, J. and Smith, G. (2006) *Addressing Environmental Inequalities: Flood Risk*. R&D Technical Report, SC020061/SR1. Bristol: Environment Agency

Watts, M. and Bohle, H. (1993) 'The Space of Vulnerability: The Causal Structure of Hunger and Famine'. *Progress in Human Geography*, 17(1), pp. 43–67

Werritty, A. (2006) 'Sustainable Flood Management: Oxymoron or New Paradigm?' *Area*, 38, pp. 16–23

Werritty, A. with Chatterton, J. (2004) *Future Flooding Scotland*. Foresight Flood and Coastal Defence Project, Office of Science and Technology, Department of Trade and Industry

Werritty, A., Houston, D. S., Ball, T., Tavendale, A. and Black, A. R. (2007) *Exploring the Social Impacts of Flooding and Flood Risk in Scotland*. Edinburgh: Scottish Executive

Whittle, R., Medd, W., Deeming, H., Kashefi, E., Mort, M., Twigger-Ross, C., Walker, G. and Watson, N. (2010) *After the Rain: Learning the Lessons from Flood Recovery in Hull*. Final project report for 'Flood, Vulnerability and Urban Resilience: A Real Time Study of Local Recovery Following the Floods of June 2007 in Hull'. Lancaster, UK: Lancaster University. Available at: http://www.lec.lancs.ac.uk/cswm/Hull%20 Floods%20Project/HFP_%20outputs.php [Accessed 25 August 2011]

Wisner, B., Blaikie, P., Cannon, T. and Davis, I. (1994) *At Risk: Natural Hazards*, *People's Vulnerability and Disasters*. Abingdon: Routledge

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