Submission to the Senate Standing Committee on Environment and Communications inquiry into recent trends in and preparedness for extreme weather events

Professor Rod Keenan
Director of the Victorian Centre for Climate Change Adaptation Research
Melbourne School of Land and Environment, the University of Melbourne

16 January 2013

Introduction

Climate change will increase the frequency and intensity of extreme weather events and generate new types of weather events beyond recent human experience. Adapting to climate change presents new challenges for policy makers and the community. Managing the risks associated with increasing incidence of extreme weather events requires assessment of hazards and the sensitivity, exposure and adaptive capacity in communities, industries and ecosystems. Building resilience and responding effectively to climate related impacts will require foresight and leadership, strategic planning, collaboration and effective communication.

Improved management of extreme events involves development of the enabling environment and specific implementing measures to manage risks. For example, with floods, enabling includes routine monitoring, flood forecasting, data exchange, institutional reform, bridging organizations, contingency planning for disasters, insurance and legal incentives to reduce vulnerability. All such activities are 'low regret' in that they yield benefits regardless of future climate but are not cost-free. Implementing measures that address climate change related effects can include climate safety factors for new build, upgrading resistance and resilience of existing infrastructure, modifying operating rules, development control, flood forecasting, temporary and permanent retreat from hazardous areas, periodic review and adaptive management.

This submission presents some key messages from research being undertaken through the Victorian Centre for Climate Change Adaptation Research and others at the University of Melbourne. It also draws on broader experience from engagement with local government. The case is made for continuing investment in research to support improved decision for investment in preparedness and improved coordination of research across institutions and jurisdictions to support effective management of climate risks.

Key points

1. Preparing for extreme weather events requires a sound understanding of current and future risks, sensitivities to these risks in communities, infrastructure and the built and natural environments, and the costs and benefits of preparation and response options.
2. The potential impacts of climate change vary across different regions, industries and different sectors of the community. Analysis needs to be targeted specifically for different state and local governments and industry sectors.

3. Continued investment in well targeted research is required. This can reduce the cost of extreme weather events by providing sound climate science and improved understanding of potential impacts and adaptation options. This research needs to be better coordinated at local, state and national levels.
4. Collaborative networks are required at state and regional levels. These networks should include state emergency management, land management, health, human services, planning and transport agencies, infrastructure managers, regional natural resource management bodies, local government and community groups. These networks can foster resilience through development of informal interactions, building common understanding, organisational flexibility and sharing capacity and resources to prepare for, and respond to, climate risks. These partnerships could facilitate greater information sharing between different levels of government and with researchers, industry and the community.
5. Adaptation measures, indicators or benchmarks are required that can be used to assess the benefits of adaptation investment. This requires a systems framework for linking the different components of climate impacts and adaptation responses
6. Local governments are at the forefront of adaptation and climate risk management. There is a need to invest in support for local government decision making on climate related issues, including improved strategic planning frameworks, scenario analysis, improved information on potential impacts and response options and increased capacity to utilise technical inputs for local planning needs.
7. The science and understanding of climate change and its impacts will continually evolve. A strategic, flexible, and integrated national approach is needed to provide the basis for local government to incorporate the latest science into hazard overlays and other planning processes.
8. There is a need to invest in analysis to determine ways to incorporate potential future climate change impacts into asset management, maintenance and replacement through the development of financial and accounting tools.

Background

Adapting to climate change risks presents new challenges for policy makers and the community. Roles and responsibilities between levels of government and between government bodies are therefore uncertain. Adaptation involves more than just consideration of climate-related hazards. Responding to the risks of climate change involves assessment of the sensitivity, exposure and adaptive capacity in communities, industries and ecosystems. Adapting to the impacts of extreme events is the outcome of social learning. It requires an understanding of sense of place, a capacity for individuals and the broader society to identify potential future impacts and what these mean for themselves as individuals, their families, their communities or their companies. Building resilience and responding effectively to climate related impacts require agreement on common goals. Developing these goals requires foresight and leadership, strategic thinking, resourcefulness, collaboration and effective communication. Government needs to foster meaningful conversations within communities about what they value and wish to maintain and what they might be willing to let go to prepare effectively for future disasters effectively.

The Victorian Government has recognised the need for decision makers to be better informed about the risks and the options to adapt to climate change. In 2009 it funded the establishment of the Victorian Centre for Climate Change Adaptation Research as a partnership among Victorian universities. This submission was developed in consultation with partner universities.

The Centre's research program involves multi-disciplinary and multi-institutional research teams to address priorities identified by the Victorian Government. As well as supporting innovative new research, it conducts regional think-tanks, stages an annual forum and supports a visiting fellowship program. Researchers work closely with all levels of government and the community to ensure that research results make a difference to policy and practice. The submission presents relevant learning from VCCCAR activities on key questions raised in the issues paper.

The Centre's research program and other activities are an example of effective networking and collaboration at the state and regional level. The aim of this submission is to briefly present some of the most important messages from this work and from broader experience in local government. These can be encapsulated in three areas: framing responses to climate risks, improved decision making under uncertainty through scenario planning, building leadership and networked capacity and preparing for and responding to extreme events. The submission also makes the case for continuing investment in, and improved coordination of, research and development in disaster risk reduction and climate change adaptation.

Climate change adaptation in context: framing responses to climate risk

Framing occurs when people with different knowledge, experiences and personal backgrounds consider an activity or a challenge. Framing is a way of making sense of a topic (like climate change) from an individual perspective but it can also be used to arrive at a shared meaning and sense of purpose in addressing the challenge.

Early research activity has focused on different climate change assessment methodologies and how these can potentially influence potential pathways. Through this activity, the study has identified the following ways of framing adaptation:

1. **A disaster response approach**. This natural disasters frame has been an important consideration in government policy discussion on climate change.
2. **A risk management approach**. This is the dominant, organisational practice for dealing with risks to assets or legal liabilities in local government and the private sector.
3. **A vulnerability approach**. This focuses on who or what will be affected and in what way.
4. **A resilience approach**. This is the ability of groups or communities to cope with external stresses and disturbances as a result of social, political, or environmental change. The concept originated in ecology but is now being translated and applied to human systems.

Understanding and managing risks depends to a large extent on what approach different people use to frame the response to climate change. The project also found that:

- Adaptation will often be context specific, not only influenced by different climate impacts but also the vulnerability and exposure of the 'system' in question;
- Further institutional complexity is introduced when considering the large number of organisations and people affected. Each bring different values, perceptions of risk, motivations, levels and types of knowledge, roles and responsibilities, and even cultural background;
- When assessing the problem to be addressed, even the choice of climate change assessment methodology can be considered a framing influence. Taking two examples; risk assessments can be characterised as top-down expert driven approaches whereas vulnerability assessments tend to be bottom-up processes which encourage the greater inclusion of multiple stakeholder voices;

- Being more explicit about these framings as part of local adaptation processes can benefit a shared understanding of the fundamentals of climate risks and adaptation options, lead to more flexible, adaptive management approaches to responding to climate change.

Climate change adaptation is often framed in policy and practice, as an ‘environment’ or ‘sustainability’ issue. It is better regarded as a business risk (such as occupational health and safety) that, if well-managed, will result in lower long-term costs to the economy and the society.

For example, recent analysis of the implications sea level rise and coast and catchment flooding indicates a high cost for a 'wait and see' approach, particularly given rapid growth in coastal populations and a strong drive for further coastal development. Current infrastructure and planning policy is inadequate even without any further change in climate or sea level impacts.

Planning

Victorian local Councils are working with Victorian Government Departments to identify the most appropriate way to incorporate the risks associated with sea level rise and increased rainfall inundation into planning schemes. The City of Melbourne and City of Port Phillip are assembling available climate change information. However a consistent statewide or national approach would be superior to planning decisions by individual Councils.

The science and understanding of climate change and its impacts will continually evolve. A strategic, flexible, state or national approach is needed to provide the basis for local government to incorporate the latest science to into hazard overlays and other planning processes.

Planning frameworks also need to consider equity and diversity in managing climate risks. For example, the Western region of Melbourne has one of the largest residential growth areas in the country is one of the most diverse cultural regions in the metropolitan region with over 90 different nationalities. It also has some of the most disadvantaged socio economic groups. These factors combined with the physical setting and the lack of vegetation cover and other forms of ‘green infrastructure’ can lead to very high exposure and sensitivity to specific risks. A spatial vulnerability analysis of urban populations to extreme heat events by Monash University showed that most areas of the Western region of Melbourne have high vulnerability to the increasing temperatures. Consequently, the long term effects of climate change on the Western Metropolitan communities are likely to be more severe and create greater hardship than other areas of Metropolitan Melbourne. To maintain liveability in many communities, there is a need to ensure appropriate support and planning that recognises cultural diversity and socio-economic status.

While many reforms to planning frameworks may involve little cost, there is a need for sound analysis to support planning decisions (see for example, http://www.buildingfutures.org.uk/assets/downloads/Facing_Up_To_Rising_Sea_Levels.pdf). Local governments need increased technical capacity to adequately assess potential impacts on coastal settings, existing infrastructure and advice and guidance on appropriate essential infrastructure for newly emerging coastal communities. Providing consistent support and advice will lead to better opportunities for coastal living in other areas along Victoria's coastline and put less pressure on existing growth regions.

There is a lack of institutions to support local government decision making. The private sector is not filling the requirement. There is potentially a role for the Federal Government in providing funding for this type of analysis and increased capacity to utilise technical inputs and undertake local assessments that is aimed at meeting local planning needs.

Assets and infrastructure

In many areas of Victoria there are aging assets that will become increasingly vulnerable in relation to extreme weather events. Exposed coastal assets (both private and public) have been identified as highly vulnerable to extreme events, flooding and sea level rise. There is a need for analysis to determine the most appropriate way to incorporate potential future climate change impacts into asset management, maintenance and replacement and the development of financial and accounting tools to support this.

For example, analysis of drainage capacity and coastal planning and protection measures in coastal councils indicates that current infrastructure is severely limited and is inadequate for dealing with the future risks under a changing climate. Local government requires increased support and strategic guidance from the Federal and State government to engage in localised and strategic hazard and vulnerability analysis in order to make appropriate and sound investment decisions in this area.

There are already indications that the insurance industry is moving to reduce liability in this area and increase premiums. For example, there a levy of $50, 000 has been placed on local governments to cover the costs of recent flood events. There is anecdotal evidence to suggest that there has been a reduction in some areas of compensation.

Science, monitoring, education and warning systems

There is a clear need to generate improved information that is relevant to decision making on different types of weather and climate related risks in different parts of the country. This needs to driven by the information required to support investment and management decisions being taken by government and industry (see Wilby and Keenan 2012, attached).

Most preparation and response actions will be taken by individuals, households and businesses. A resilient community requires clear and credible information about risks, responsibilities and available services. This information will need to be provided in a clear, consistent and timely manner. Engagement and education of businesses and households will require targeted programs which identify the needs of stakeholder groups and how to effectively engage with them. Government and non-government organisations involved in supporting communities need to coordinate programs to ensure businesses and households have the information they require to effectively adapt.

Decision makers must also be supported in applying information in climate risks and decision tools. Personal attitudes and beliefs of people in senior positions can determine the motivation and willingness within an organisation to consider climate risks and provide resources to implement climate adaptation plans.

Information on future climate risks also needs to be targeted for different industry sectors. The effects of climate change will differ between sectors. At VCCCAR events we have found that the capacity to consider and respond to extreme weather events varies considerably across industry sectors and between scales. Small and Medium scale enterprises are generally found to have limited capacity. There is a need for improved strategic thinking and planning in this regard (see scenario planning section below).

These frameworks and tools also need to extend to local government. Training is needed on understanding risk and risk management approaches, such as scenario and design-related approaches, to ensure decisions about future development, particularly in areas highly exposed to extreme weather events do not increase risk through greater creating exposure to hazards.

Increases in extreme weather events, both in Australia and overseas, has the potential to cause severe disruption to supply chains that will have negative impacts on local industry. A strategic response framework is required to maintain logistics and local supply chains to limit disruption to local industry, ensure continuity and maintain productivity. Greater interaction between business and government to can identify and address critical vulnerabilities along industry supply chains

Increases in the number of days with excessive heat can impact directly upon productivity in areas such as construction and manufacturing. Working in hot conditions can result in a number of adverse health effects - ranging from discomfort to serious illness, which are generally grouped together as heat stress. In extreme circumstances this can be fatal. While there is some advice available to industry to address these issues, identifying the future financial impacts of changing climate for industry sectors will be important in ensuring the risk to industry sectors from climate change is able to be appropriately and effectively managed.

Maintaining investment in locally and regionally focused research and building local expert capacity will enable review and interpret lessons from climate-related events, build a culture of commitment to excellence and generation and testing of new ideas, and provide the evidence base for adoption of improved responses to climate risks. Well-resourced, local research communities such as the VCCCAR can also rigorously test interstate and international methods and best practices for adoption in the local context.

The need for adaptive and social learning processes

Building adaptable, resilient and responsive communities, institutions and organisations is a social learning process. It is a continuing process that evolves in response to new information and changing environmental, economic and social circumstances, as well as the availability of new technologies.

Monitoring and evaluating responses is critical. Effective adaptation requires planning, monitoring, review and updating of plans.

Policies are required to build collaborative networks at state and regional levels that develop resilience through maintaining redundancy, organisational flexibility and the availability of resources to respond to climate risks. These should have wide membership, including agencies and organisations not necessarily regarded as part of ‘disaster response’ (for example VicRoads, Transport and community sector organisations and municipal councils). This will require commitment by agency leaders and strong incentives for participation and collaboration. These can be built through regular dialogue, social events, shared training, staff exchanges and clear branding.

Experts (from universities, CSIRO, BOM and other organisations) also need to be involved in these networks.

Such networks can be used to establish agreed responsibilities and decision making prior to events occurring and identification and protection of key infrastructure, built and natural assets and vulnerable sectors of the community. This requires investment in communication processes up and down and across organisations and with different parts of the community to inform people of potential risks and their role in disaster preparation and response.

Local governments also need effective knowledge networks to ensure that they have access to the right information that enable good decision making. Small councils who have less resources are more likely to find it harder to be able achieve this and this has the potential to lead to long term inequity and limited capacity to build organisational resilience in relation to climate change.

Managing extreme events requires organisations that work at the boundary between science and policy or practice. Such organisations operate over longer time frames to build high levels of trust with partners and provide for sustained commitment and capacity in advising on climate impacts and adaptation options (international examples include the UK Climate Impacts Program or the CMAS program in the USA). The development of this type of organisation in different parts of Australia is highly desirable.

In the short time it has been in operation, VCCCAR has played an important role in network development across state government agencies, universities, local government, industry and various sectors of the community. Through various activities, the Centre is providing opportunities for creative discussion and engagement between these different groups to build common understanding about climate risks.

Decision making under uncertainty

Understanding and managing complexity and uncertainty is one of the greatest challenges facing policy makers and practitioners in emergency management. Traditional linear planning and 'pre-formed' decision making have developed from an approach that assumes expert knowledge and analysis can be used to anticipate or define future conditions. This approach is not so relevant in rapidly changing and uncertain conditions. Climate change will occur over a long time frame, with diverse potential impacts and a high complexity of interacting social, economic, political and environmental drivers, these traditional approaches are unlikely to be effective. Scenario-based approaches are therefore being used across a range of Victorian Government departments as a key tool for decision making under uncertainty in the emergency management context.

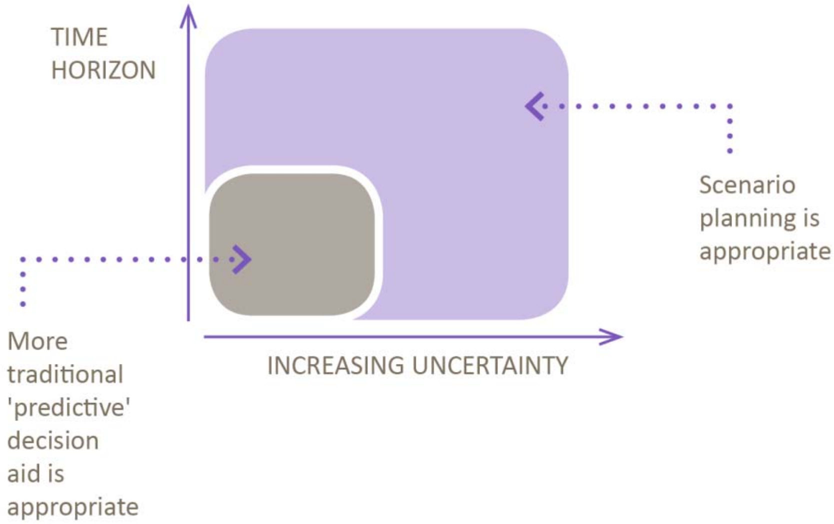

Figure 3: When is scenario planning appropriate?

Scenario planning has been a valuable tool for addressing climate change adaptation objectives in Victoria. However, there was substantial variation in the goals of the exercise, types of scenarios used and the approach to scenario planning. In general, scenario approaches have stimulated constructive dialogue and informed strategic planning or policy making processes.

The following key points emerged from the research:

1. **Scenario planning supports a shift from 'enhanced prediction' to 'robust decision making' under uncertainty.**
   Many scenario processes are driven by a desire to determine the 'most likely' future scenario consistent with a 'predict-then-act' model of problem solving. Yet, fundamental to scenario planning is the capacity to overcome 'predictive' mindsets and engage with potential futures beyond the 'status quo'. Scenarios are not predictions. The major strength of scenario planning is the exploration of possibilities and making 'robust' decisions that recognise future uncertainties. Emergency preparation could incorporate the use of scenarios into.

2. **Scenario planning can be a powerful platform for exploring and integrating diverse sources of knowledge and stimulating imaginative ideas and responses.**
   Knowledge and opinions from diverse groups of people can be integrated using scenario planning techniques. Scenario processes also help uncover and explore different 'world-views' and build shared understanding. Creative approaches can be particularly effective for capturing the imagination of different people about what the future might look and feel like. Exercises that integrate across different government departments can increase the range of world views and perspectives involved and results in more 'joined up' approaches to policy development or implementation.

3. **Maximising the benefit of scenario planning for climate adaptation decision making requires a clear linkage between scenario outcomes and specific decisions.**
   Scenario processes should be embedded within specific decision making situations and structured in a way that ensures the relevance of the outcomes is clear to decision makers.

Processes such as state adaptation planning and planning for regional development or implementation of policies such as Living Victoria may benefit from adopting a scenario-based approach.

4. **Effective adoption of scenario planning requires building and supporting organisational cultures and communities of practice.**
   There is significant potential benefit to be realised from establishing ongoing support and learning networks around scenario planning. The Victorian Government should consider the development of these cross-department networks that share knowledge and capacity in scenario approaches.

Costing climate change impacts and adaptation options

Estimating the costs of climate impacts is an important step in evaluation of adaptation options. Impacts of climate change in Victoria are already being felt and are likely to intensify in the future. Some effects of climate change could be positive, for example potential increases in agricultural production or reduced human deaths due to decreasing incidence of extreme cold in some regions; but many impacts are likely to be negative, particularly with the projected increase in intensity and frequency of extreme events.

From a public policy perspective there is a demand for an economic analysis of the costs and benefits of climate change impacts that can then be compared with the costs of potential preparation, avoidance or response actions. These are important for assessing potential risks and making the case for government intervention. However assessing the economic impacts of climate change is challenging and resource intensive and there are a variety of potential approaches that can be used to make these assessments.

Key concerns and issues in assessing the costs of climate events and adaptation options include: (1) the valuation of impacts on intangibles (such as the environment or amenity values); (2) the selection of an appropriate discount rate; (3) incorporation of uncertainty, 4) the analysis of low probability though high impact events; and (5) the distributional impacts between different parts of the community. These challenges highlight the importance of transparency regarding assumptions in the way these issues are treated, the sensitivity of results to these assumptions, and the combining of quantitative and qualitative data.

In one example, the work of the current Coastal Adaptation Pathways project for Port Phillip Bay is showing clear indication that the cost to the City of Port Phillip and the City of Melbourne of coastal and catchment floods and inundation has the potential to be very high even with when low sea level rise scenarios are applied.

Research

Continued research is required to identify and analyse the type and extent of the impacts of future We require clear strategic actions from the Federal Government on the science on sea level rise and catchment inundation and its potential impacts for each region and clear indication of what this means for future planning policy and provision in this area. Our analysis at the LGA level indicates that it is now clear that the risk of impacts from a changing climate over even the short to medium is real, and the liability of no action lies with the Federal Government.

Research is required to determine appropriate indicators of adaptation and response to disaster events and testing these for incorporation into state reporting and planning. These may be based around loss of life, injuries, property or natural assets as a result of climate change and the extent of these in relation to the incidence and intensity of future events.

Some other key questions emerging from discussions with government and industry include:

- What risks and liabilities are governments currently exposed to as a result of current changes in climate and to what extent do these risks and liabilities arise from Victorian legislation and regulation?
- What legislative and planning changes are required to ensure that risks and potential liabilities arising from the impacts of climate change should reside with the entity best placed to manage those risks?
- Can alternative governance and institutional structures more effectively manage these risks?
- What are the climate change related risks for government assets and essential services infrastructure, when and how are these risks likely to present themselves and what are the alternative options for managing risks to infrastructure or services (including legal contracts, insurance, building design or planning)?
- What is the nature of vulnerability and adaptive capacity in 'vulnerable' communities, how can it be measured or assessed and how are future social and economic changes likely to affect this vulnerability?
- What specific types of climate events are vulnerable sectors of the community most exposed to and when are these effects likely to be felt? Are there particular temperature, rainfall or other thresholds when community exposure and impacts will markedly increase and when are they likely to be felt?
- What options (including planning, behavioural, regulatory and structural changes) could be considered by government for reducing community vulnerability? How can these options be demonstrate both cost effectiveness and effectiveness against outcomes?
- How can/ should government engage with communities about future climate risks and to facilitate effective adaptive behaviour and how can responsibilities for adapting to climate related risks be shared between government and the community?
- What are the responsibilities of those who intend to support vulnerability reduction (primarily in the community and not-for-profit sector), what is their capacity to support adaptation and how can they be better equipped to do so?

In the process of addressing these questions there needs to be better coordination research activity in this field. There are a wide range of research funding and management arrangements around climate adaptation, including the National Climate Change Adaptation Research Facility, the CSIRO Climate Adaptation Flagship, the Bushfire Cooperative Research Centre and as well as various projects within state government agencies and partnership projects with universities. Improving understanding, linkages and management of the breadth of research being undertaken across the country would build greater capacity to inform policy and practice.

Supporting information

See a range of VCCCAR publications at http://www.vcccar.org.au/content/views/publications

In particular:

Framing adaptation in the Victorian context
http://www.vcccar.org.au/content/framing-adaptation-victorian-context

Scenarios for climate adaptation
http://www.vcccar.org.au/content/scenarios-climate-adaptation

Costing climate adaptation
http://www.vcccar.org.au/files/vcccar/Framing_project_workingpaper2_240511.pdf

A spatial vulnerability analysis of urban populations to extreme heat events. School of Geography and Environmental Science, Monash University.
http://www.health.vic.gov.au/environment/downloads/heatwaves_hotspots_project.pdf

Climate Change Risks to Coastal Buildings and Infrastructure - A Supplement to the First Pass National Assessment http://www.climatechange.gov.au/publications/coastline/climate-change-risks-to-coastal/climate-change-risks.aspx

Supporting Victorian Local Governments Manage Climate Risks and Plan for Change, MAV.
http://www.sustainability.mav.asn.au/counciloperations/Supporting_Victorian_Local_Government_Manage_Climate_Risks_and_Plan_for_Change-6287

Article

Progress in Physical Geography
36(3) 348 378

DOI: 10.1177/0309133312438908
ppg.sagepub.com
SAGE

Adapting to flood risk under climate change

Robert L. Wilby
Loughborough University, UK

Rod Keenan
University of Melbourne, Australia

Abstract

Flooding is the most common natural hazard and third most damaging globally after storms and earthquakes. Anthropogenic climate change is expected to increase flood risk through more frequent heavy precipitation, increased catchment wetness and sea level rise. This paper reviews steps being taken by actors at international, national, regional and community levels to adapt to flood risk from tidal, fluvial, surface and groundwater sources. We refer to existing inventories, national and sectoral adaptation plans, flood inquiries, building and planning codes, city plans, research literature and international policy reviews. We distinguish between the *enabling* environment for adaptation and specific *implementing* measures to manage flood risk. Enabling includes routine monitoring, flood forecasting, data exchange, institutional reform, bridging organizations, contingency planning for disasters, insurance and legal incentives to reduce vulnerability. All such activities are 'low regret' in that they yield benefits regardless of the climate scenario but are not cost-free. Implementing includes climate safety factors for new build, upgrading resistance and resilience of existing infrastructure, modifying operating rules, development control, flood forecasting, temporary and permanent retreat from hazardous areas, periodic review and adaptive management. We identify evidence of both types of adaptation following the catastrophic 2010/11 flooding in Victoria, Australia. However, significant challenges remain for managing transboundary flood risk (at all scales), protecting existing property at risk from flooding, and ensuring equitable outcomes in terms of risk reduction for all. Adaptive management also raises questions about the wider preparedness of society to systematically monitor and respond to evolving flood risks and vulnerabilities.

Keywords

adaptation, climate change, flood, natural hazards, risk, Victoria, vulnerability

I Introduction

Reported global economic losses from natural hazards such as storms, tropical cyclones and floods are increasing due to growth in populations, and the amount of capital at risk (Bouwer, 2011). At the same time, patterns of development in areas of flood risk combined with changing demographics (including rapid urbanization in developing countries and ageing populations in developed countries) are increasing overall vulnerability. For example, between the 1970s and 2000s, the proportion of the world's gross domestic product (GDP) annually

Corresponding author:
Robert L. Wilby, Department of Geography, Loughborough University, Loughborough LE11 3TU, UK
Email: r.l.wilby@lboro.ac.uk

exposed to tropical cyclones rose from 3.6% (US$525.7 billion) to 4.3% (US$1.6 trillion) with the economic loss risk rising fastest in high-income countries (UNISDR, 2011). As the 2011 floods in Australia, China, Germany and the United States demonstrate, even high- and middle-income countries struggle to cope with weather extremes. Although the absolute direct costs of disasters may be greatest for high-income countries, the economic impact (expressed as a proportion of GDP) is larger for middle-income countries because of their rapidly expanding asset bases yet relatively immature risk management systems (World Bank/United Nations, 2010). However, when expressed as absolute and proportionate mortality, developing nations in the Asia-Pacific region are most impacted (Shultz et al., 2005).

There is widespread concern that shifts in extreme weather events associated with climate change could exacerbate damages or even reverse development gains in some regions (UNDP, 2007). The prospect of needing to adapt becomes more likely the longer governments fail to curb emissions (M.S. Smith et al., 2011) and the global population at risk of flooding is expected to rise with temperature (Hirabayashi and Kanae, 2009). There is also growing recognition that national governments have high risk exposure (in terms of public goods and services, stability of the tax base and economy) as well as moral and legal obligations to ensure the well-being of their citizens. For instance, under the Hyogo Framework for Action 2005–2015 governments have agreed to: (1) ensure that disaster risk reduction (DRR) is a national and a local priority with a strong institutional basis for implementation; (2) identify, assess and monitor disaster risks and enhance early warning; (3) use knowledge, innovation and education to build a culture of safety and resilience at all levels; (4) reduce the underlying risk factors; (5) strengthen disaster preparedness for effective response at all levels (UNISDR, 2005).

This paper reviews the steps being taken by actors at international, national, regional and community levels to adapt to flood risk from tidal, fluvial, surface and groundwater sources. Flooding is singled out because worldwide it is the most common natural hazard and third most damaging (after storms and earthquakes) (World Bank/United Nations, 2010). Flooding is already the most costly natural hazard in Europe and South Asia, but future risk projections are much less certain than for drought and heatwave (Dankers and Feyen, 2008; Kundzewicz et al., 2010). Although there is an expectation that anthropogenic climate change will increase the magnitude and frequency of extreme precipitation events, the consequences for inland flooding depend on the generating mechanism, and a host of site-specific factors, not least land-use changes. Furthermore, some assert that there is already a discernible human fingerprint in the risk of widespread fluvial flooding (Kay et al., 2011; Pall et al., 2011). Coastal flooding may be more certain given that all climate model projections show rising sea levels, but the rate of change is, again, highly location specific and the rate, and ultimate peak, of sea level rise is a function of the future trajectory of greenhouse gas emissions. In both cases, it is clear that traditional engineering solutions founded on the assumption of a stationary climate are no longer applicable (Milly et al., 2008).

Here we examine measures for adapting to future flood risk in a realm of deep uncertainty. There is considerable merit in building a 'pool of good practice' no matter where it is found (European Environment Agency, 2009: 4). We begin with a brief overview of adaptation typologies and inventories, then describe our approach to categorizing measures drawn from a search of scientific, governmental and professional literature. The review is split into those activities that broadly *enable* adaptation, and those that *implement* specific measures to reduce vulnerability to flood risk(s). We ground our inventory by referring to responses to the

2011 flooding in Victoria, Australia, and consider the extent to which these might build adaptive capacity. The concluding section identifies several key challenges ahead and offers suggestions for further research.

II Adaptation typologies and inventories

Adaptation to environmental change has occurred throughout human history but is achieving greater prominence as societies recognize their vulnerability to the pace and direction of anthropogenic climate change. The theoretical and practical basis for how communities adapt has been reviewed before (Adger et al., 2007). It is clear that adaptation has social limits, and is both place and scale dependent (e.g. Adger et al., 2003, 2009; Burton, 1996). As the number of adaptation plans has proliferated, so have attempts to catalogue and define the measures that would characterize a 'well-adapting' society. A brief overview of some of the schemes is provided below.

Smit et al. (2000) described one of the earliest 'anatomies' of adaptation based on three attributes: the climatic-stimuli; the system that is adapting; and the method of adaptation. They also recognized that adaptation strategies can be grouped by timeframe of interest, types of behaviour, sector, scale and level of governance. The EU Adaptation and Mitigation Strategies (ADAM) project catalogued options according to hazard type and whether the measure was technological, soft engineering, management best practice, planning and design, legal/regulatory, insurance/financial or institutional (McEvoy et al., 2010). Wilby et al. (2009) identified eight adaptation categories according to their differential requirements for climate risk information: new infrastructure; operational adjustment; retrofit; behaviour change; regulation and codes of practice; sector-wide planning; education; and financial risk transfer. Hallegatte (2009) began with the premise that the climate outlook is so uncertain that only robust measures should be considered. These strategies were classified as 'no-regret', reversible and flexible, incorporating safety margins, employing 'soft' solutions, or reducing decision timeframes. Conversely, Barnett and O'Neill (2010) described five types of mal-adaptation – interventions that are intended to increase adaptation in one sector but inadvertently increase vulnerability by, for example, increasing carbon emissions or transferring risks from one group to another.

Several studies have compiled inventories of adaptation options for specified regions and/or sectors. For example, McGray et al. (2007) collected examples of efforts drawn from the developing world to highlight synergies between adaptation and development goals. Likewise, Hellmuth et al. (2007) find value in showcasing practical experiences of ongoing climate risk management and DRR in Africa. Others are more concerned with ranking individual options according to their cost-effectiveness, urgency, contribution to mitigation, and wider benefits. De Bruin et al. (2009) assembled then ranked 96 adaptation options across seven sectors (agriculture, nature conservation, water management, energy and transport, housing and infrastructure, health, and recreation and tourism). According to the chosen criteria, integrated nature and water management policies were ranked most highly, followed by measures to climate-proof housing and infrastructure (primarily against heatwaves). Although the inventory was originally conceived for the Netherlands several options were incorporated within a Europe-wide assessment of the water sector (EEA, 2009).

Some inventories have been developed with a view to measuring the extent to which tangible actions are being taken by a range of actors at national and institutional levels. Tompkins et al. (2010) conducted an exhaustive search for early adopters of adaptation practice in the UK and, even by 2005, identified over 300 examples. They grouped the cases by sector and type of adaptation, and found that the highest levels of adaptation activity were in the capital-intensive water supply and flood defence sectors. As with Urwin and Jordan (2008) they show that the public sector is leading adaptation practice in the UK, driven in part by formal requirements for monitoring and review under the National Adaptation Strategy. Wilby and Vaughan (2011) proposed a more qualitative set of 'hallmarks' for measuring adaptation *within* institutions. Their metrics included evidence of visionary leadership, objective setting, risk and vulnerability assessment, guidance for practitioners, organizational learning, low-regret adaptive management, multi-partner working, monitoring and reporting progress, and effective communication with stakeholders. Similarly, the UK's Adaptation Sub Committee considers organizations are moving towards desirable adaptation outcomes if there is first proof of awareness raising and capacity building, then recognition of climate impacts in decision-making, then tangible action to reduce those risks (ASC, 2010).

III Approach

The previous section demonstrates that there are different ways of defining and grouping adaptation actions. We began by compiling examples of flood risk management activities drawn from:

- existing reviews of adaptation options (e.g. Botzen et al., 2010; De Bruin et al., 2009; EEA, 2009; McEvoy et al., 2010; Tompkins et al., 2010; Wilby, 2009);
- national risk assessments and adaptation plans (e.g. Australia, Bangladesh, Canada, Djibouti, Finland, Norway, UK, Yemen);
- city adaptation plans (e.g. Dhaka, Ho Chi Minh City, London, Mexico City, Mumbai, New York);
- flood, development control and insurance sector plans (e.g. Botzen and van den Bergh, 2008; Defra, 2011a; Victoria State, 2007);

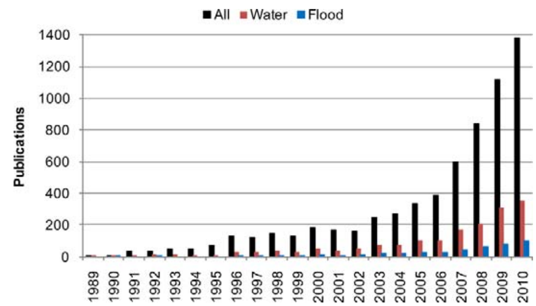

Figure 1. Annual number of peer-reviewed publications addressing all aspects of adaptation to climate change, water-sector issues (including flooding), and flooding (only)

- national building and spatial planning codes (e.g. Arnbjerg-Nielsen, 2008; DCLG 2006, 2007; Ihringer, 2004; Stevens, 2008);
- river basin management planning (e.g. Dawson et al., 2011; EC, 2009; Huntjens et al., 2010; Krysanova et al., 2010; Payne et al., 2004);
- coastal zone risk assessment and management (e.g. Abel et al., 2011; Defra, 2005a; EC, 2009; Hinkel et al., 2010; Rosenzweig et al., 2011; Tribbia and Moser, 2008; US CCSP, 2009);
- post-flood inquiries (e.g. Pitt, 2007; QFCI, 2011);
- international policy reviews and syntheses (e.g. Biesbroek et al., 2010; Cheong, 2011; Ford et al., 2011; IPCC, 2012; UNISDR, 2005).

We then extended the sift to research literature using keywords such as 'climate', 'adapt*', 'flood*', 'risk', 'measure', 'option', 'inventory'. (The number of peer-reviewed publications held in the Web of Science is growing rapidly; Figure 1. Water-sector papers account for about 25% of the volume, and flooding 7%. Since 1989, over 500 research papers have addressed aspects of climate change, adaptation and flooding alone.) Finally, we solicited the views of sector experts and community leaders in Australia, North America, South Asia and Europe. We acknowledge that this is an imperfect sample; however, the intention was to build a pool of case studies illustrating different adaptation types rather than a definitive list.

We applied a straightforward definition of adaptation as any *adjustment of behaviour to limit harm, or exploit beneficial opportunities, arising from climate change* (ASC, 2010: 60). In some regions, strategies for coping with present climate variability and flooding may fall short of good practice. In these cases, there is already an 'adaptation deficit' that needs to be addressed (Burton, 2006). For example, inappropriate or unregulated development within floodplains increases exposure to flood hazards regardless of climate change. Large floodplain assets may remain in place for decades to centuries, thereby committing resources and institutions to pathways that reduce flexibility in the face of uncertain climate outlooks (Barnett and O'Neill, 2010). In this case, development control is legitimately defined as an adaptation measure because of the potential to limit future harms. However, a new flood wall that does not include a climate change safety margin might reduce the current adaptation deficit, but would not be regarded as anticipatory adaptation.

As noted before, there are many ways of categorizing adaptation examples such as: near-versus long-term actions; urban versus rural versus coastal; hard (engineering) versus soft (planning); private versus public. We chose to make a clear distinction between the broader *enabling environment* for adaptation and specific *implementing measures* to manage flood risk. The former includes the production and dissemination of climate risk information, as well as the institutional structures for legislation and mobilizing resources before, during and after flooding. The latter captures practical steps that can be taken to defend against, live with or withdraw from flood risk. This recognizes that integrated flood risk management involves more than local measures; bridging organizations and institutions are needed to deal with transboundary and multi-jurisdictional issues.

IV Enabling environment for adaptation

International bodies and national governments are largely responsible for creating the legal, economic and policy environments in which different actors respond to climate variability and change. Enabling measures can take many forms ranging from regional cooperation on monitoring, forecasting and data exchange, through thematic research programmes, institutional reform and capacity building, to local contingency planning for disaster management. The enabling activities in Table 1 are 'low regret' in the sense that they yield benefits regardless of the climate outlook but are not cost-free. We presume that these are all entry-level requirements for integrated flood risk management but identify three themes for deeper analysis: information provision, institutional arrangements, and improving preparedness. These are mutually interdependent since improved preparedness cannot be achieved without information on hazards and vulnerability, or institutional structures to demark lines of responsibility and protocols for delivery. However, the following examples show that their relative importance is context specific.

1 Information provision

Climate risk information is arguably the single most important asset for adaptation planning. This mainly refers to routine monitoring of physical, hydrological and socio-economic drivers of flood risk (and associated impacts). Climate change projections, while potentially important for longer-term infrastructure and other types of planning decisions are of lesser importance in dealing with shorter-term adaptation deficit issues and managing risks associated with changing landscape, social or economic

Table 1. Enabling environment for adapting to flood risk

Information	National data platforms • Baseline data: climate and socio-economic indicators • Topographic surveys (floodplains, coast) • Scenarios of long-term drivers of flood risk (climatic and non-climatic) Monitoring and surveillance networks Maps of risk and vulnerability (by gender, social group, etc) Educational programmes to raise awareness of risks and responses Research programmes
Institutions	Bridging agencies • Transboundary cooperation (riparian states) • Cross-sectoral planning and cooperation • Information exchange between scientists and stakeholders Legal structures • Building codes, design standards, planning rules • Periodic review and adaptive management • Budgets, responsibilities, accountabilities • Public participation, transparency • Economic analysis of adaptation benefits • Insurance (household to sovereign level)
Preparedness	Public and household contingency planning (pre-, during, post- event) Multi-actor and agency coordination • Assigned roles, responsibilities, resources (standing orders) • Agreed jurisdictions (regional, national, international) • Role-play exercises

factors. Much can be achieved in addressing current and future risk through cooperative approaches to hazard assessment and warning systems. Governments and neighbouring states may share data or agree to integrate flood hazard management and align research programmes. Such arrangements are expected to be vital as hydrological regimes shift and the adaptation responses of one riparian have the potential to impact others. The Global Climate Observing System (GCOS) was established to secure data for broad-scale climate system monitoring, climate change detection and response monitoring, development of national economies, and research. A 2009 review of GCOS found that the overall decline of the global meteorological network witnessed during the 1990s had been halted or reversed, but observational coverage remains sparse and uneven across some regions (e.g. Africa and South Asia). Without basic meteorological information and data on flood impacts it is impossible to detect emerging flood risks, or to benchmark adaptation interventions. This is why international donors such as the World Bank have been encouraging governments in the Middle East and North Africa (MENA) region to expand their hydrometric networks.

Some nations have bilateral arrangements to exchange near real-time meteorological and hydrological data for flood control. For example, China and India have been sharing data for the Yarlungzambo/Brahmaputra River since 2002. Likewise, India and Nepal, Bhutan and India, Bangladesh and India, Pakistan and India, and Bangladesh and Nepal all secure upstream data for downstream flood forecasting and warning systems. The Kosi Treaty (1954) and Gandak Treaty (1959) make provision for coordinated action on flood control, irrigation and hydroelectric power generation between India and Nepal; elsewhere in Central Asia river management is far from integrated (e.g. Wegerich, 2008). Some contest that historically the most significant constraints to integrated flood management in Asia have been social and political rather than technical (Ahmad and Ahmed, 2003; Chowdhury and Ward, 2007; Mirza et al., 2003). Others call for much more transparency and public scrutiny of how governments plan to adapt to transboundary water hazards (Lebel et al., 2010b).

National agencies have traditionally supplied climate change scenarios but there are now calls for greater international coordination and sharing of supercomputing resources to deliver higher-resolution information and climate services under an adaptation pretext (Shukla et al., 2010). Some claim that climate models were not originally conceived to solve adaptation problems and are far from 'prime time' (Kundzewicz and Stakhiv, 2010). Others assert that climate model projections have utility for specific classes of decision and that greater discernment is required on the part of users on the value of particular projections for their decision context (Wilby et al., 2009). McNie (2007) believes that scientists are *producing too much of the wrong kind of information*, whereas Tribbia and Moser (2008) show that coastal managers want climate scenarios translated into more relevant variables (e.g. rates of coastal erosion and retreat rather than sea level rise; groundwater recharge and levels rather than rainfall). Hulme and Dessai (2008) claim that high-resolution climate change scenarios actually serve a range of purposes: pedagogic, motivational and practical.

Although the saliency of climate projections (i.e. suitability for actual user needs) is open to debate, few would argue that regional, national and local hydro-meteorological data are critical for flood forecasting (section V(2) below) and disaster management (Auld, 2008a). Routine monitoring networks capture real-time data to support forecasts (Figure 2), as well as long-term trends in physical drivers and socio-economic consequences of flooding. However, more intensive field measurement may be justified when dealing with particularly hazardous situations. For example, remote sensing and in situ surveys help identify potential glacial lake outburst floods (GLOFs) in the Himalayas and direct emergency engineering works as required (Meenawat and Sovacool, 2011; Quincey et al., 2007). Likewise, concerns about a potential failure of the Howard Hanson Dam in Washington State following a major storm in January 2009 prompted an intensive campaign of surface and upper atmosphere monitoring. These data supported long-lead hydrologic outlooks and real-time information for emergency managers and the public (White et al., 2012). In other cases, data may be gathered on socio-economic impacts following catastrophes such as the summer 2010 monsoon floods in Pakistan (Warraich et al., 2011). Enhanced surveillance during and after floods improves understanding of the epidemiology of waterborne disease (Auld et al., 2004; Lau et al., 2010) or long-term mental health impacts (Berry et al., 2011). This demonstrates that disparate sources of information (including public health data) are needed to judge the societal impact of flooding and risk-reduction measures (Keim, 2008).

High-resolution topographic surveys of coastal change and floodplain elevations are essential for simulating areas of inundation and associated damages (e.g. US CCSP, 2009; Ward et al., 2011; Webster et al., 2004). The resulting flood maps are of interest to many stakeholders: the prospective house-buyer, insurers, spatial planners, utilities managing critical water and energy assets, and those coordinating emergency responses. Whereas detailed maps of fluvial flood risk are widely available in North America and Europe, risk maps for surface water flooding in built environments are much rarer in other regions. This type of flood mapping requires detailed information on urban drainage systems, street levels and property characteristics. Even small features in the urban landscape (such as curb levels and street

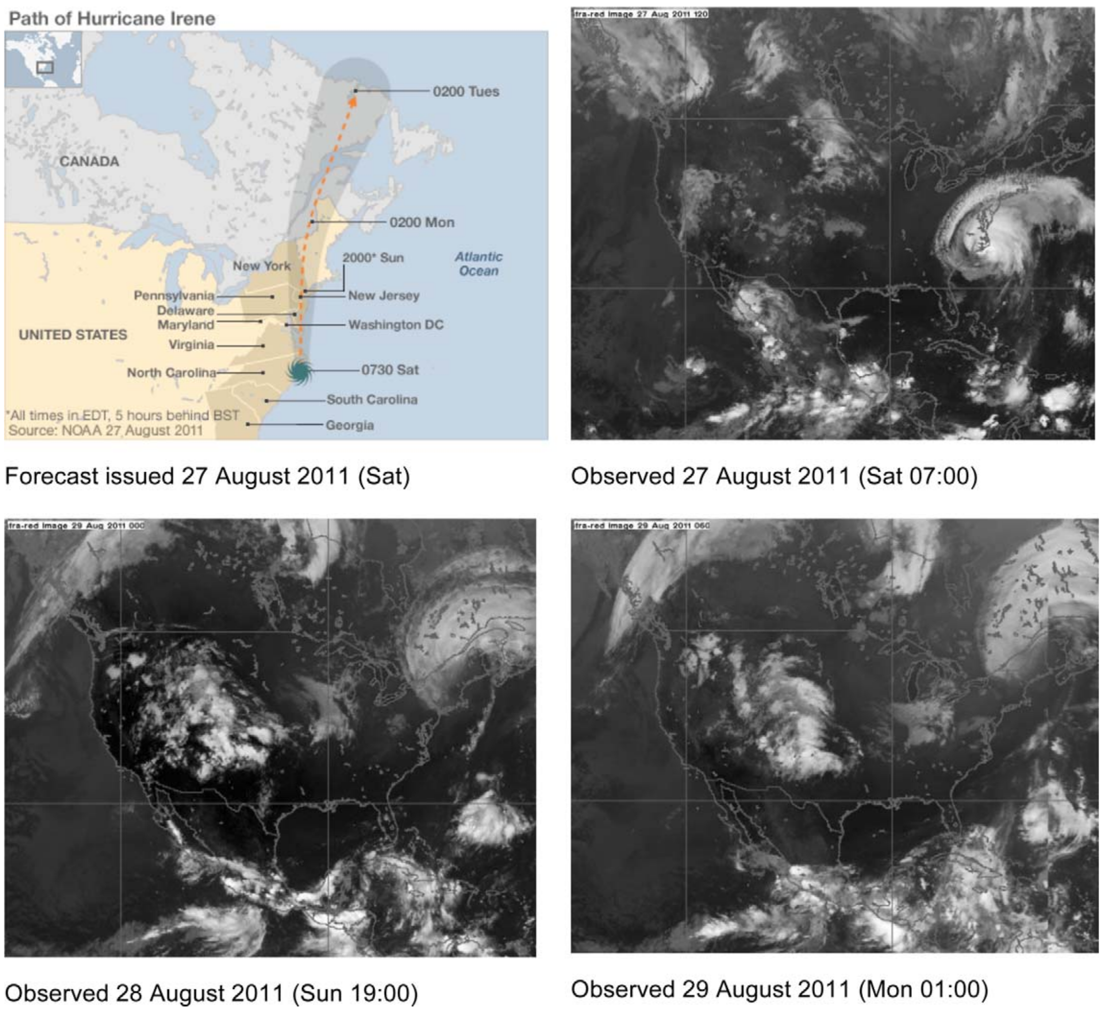

Figure 2. The widely acclaimed forecast (National Weather Service) and actual path of hurricane Irene, 27–29 August 2011 (all times in EDT)
Source of satellite imagery: http://www.metoffice.gov.uk/weather/satellite

orientation) can affect predicted water levels and water levels may often depend on the extent of maintenance and serviceability of drainage infrastructure. Therefore, maps of flood risk under climate change are particularly contentious given the large uncertainty in future flood volumes and depths combined with the evolving character of built areas.

Notwithstanding the above limitations, flood mapping is useful for identifying existing social inequalities or differences in attitude toward risk and/or vulnerability (Walker and Burningham, 2011). For example, a vulnerability assessment of urbanized and less urbanized districts in Ho Chi Minh City revealed gender variations in flood risk exposure (Tu and Nitivattananon, 2011). Another vulnerability assessment in the Netherlands found that people in areas unprotected by dykes tend to underestimate their risk of flooding (Botzen et al., 2009b). Projected flood areas and depths may then be superimposed on maps of vulnerability to identify

Table 2. UK indicators for assessing preparedness for flood risk in land-use planning (*source*: ASC, 2011)

Indicator	Trend in indicator	Change in vulnerability
Damages from climate hazards		
Insurance claims for weather-related causes	None apparent	None
Number of properties flooded	No data identified	
Development in flood risk areas		
Number of buildings constructed in areas prone to river, coastal and surface water flood risk, not accounting for flood defences (2001–2011)	Increasing	Increasing
Number of buildings at low, moderate and significant likelihood of river and coastal flooding, accounting for flood defences (2001–2011)	Increasing	Increasing
Proportion of new dwellings built in areas of high flood risk (1989–2009)	None apparent	Increasing
Factors affecting risk of surface water flooding		
Change from 'natural' to 'man-made' surfaces (2001–2011)	Increasing	Increasing
Change in area of urban green space	No data identified	
Catchment/neighbourhood-level measures		
Resolution of Environment Agency flood risk planning objections	Increasing	Reducing
Number of properties with 'increased protection' from flood risk	Increasing	Reducing
Uptake of sustainable drainage and permeable paving measures	None apparent	Reducing
Property-level measures		
Uptake of measures to increase resilience and resistance to flood risk in new development	Increasing	Reducing
Uptake of measures to manage surface water runoff rates in new development	None apparent	Reducing

'hot-spots' and to evaluate the economic benefits of urban planning or upgraded flood defences (Hallegatte et al., 2011; Hanson et al., 2011). Multi-criteria land-use modelling frameworks can also help test alternative adaptation strategies linked to specific climate change narratives (e.g. Hansen, 2010).

Agencies are beginning to collate data on insurance claims, patterns of construction and planning decisions to track performance against national metrics of flood risk. For example, Table 2 lists indicators used by the UK Adaptation Sub-Committee to measure changing preparedness for flood risk. Some opposing trends emerge: the number of new buildings in flood-prone areas continues to rise (increasing overall exposure), as does the number of neighbourhoods and households adopting flood resilience measures (reducing vulnerability). Insurance claims for weather-related causes are harder to interpret since they reflect risk transfer for the householder (less vulnerability). On the other hand, insurance arrangements that provide cover in flood-prone situations may promote moral hazard that encourages further development in floodplains (more vulnerability) or reduces incentives on the part of householders to implement risk-reduction measures (Wamsler and Lawson, 2011). Clearly, a holistic view of flood risk metrics (including socio-economic trends) is necessary to fully understand the net vulnerability of populations living in flood-prone areas.

Furthermore, the actuarial challenge of deriving fair insurance rates for rare, severe flood events cannot be understated.

2 Institutional arrangements

Institutional arrangements determine the extent to which adaptive capacities for flooding may be mobilized in the private and public sector through policy frameworks and regulation, incentives, allocation of resources, and better coordination. Traditional, top-down, short-term, target-driven departmental management arrangements may not be well suited to managing 'wicked' problems such as climate change (Hulme, 2009). Given the inherent uncertainties in projected flood risks, institutional flexibility and openness to new knowledge are highly regarded attributes (RCEP, 2010); conversely, regulatory barriers or misaligned policies may constrain action. For example: uptake of sustainable urban drainage systems (SUDS) may be confounded by ambiguity about legal responsibility for their ownership and maintenance (ASC, 2010); planning regulations that deter development in floodplains may be thwarted by other policies to regenerate brown-field sites; fragmented powers and/or responsibilities for data collection or risk assessment may mean that a coherent view of flood risks fails to emerge; fear of legal challenge over land-zoning may deter authorities from producing flood maps; poorly adapted, flood-prone housing may be constructed to meet pressing demands for more homes (RECP, 2010).

A growing number of studies highlight the need for institutional structures that encourage community engagement to assimilate local knowledge into coastal and flood risk management (e.g. McEvoy et al., 2010; Naess et al., 2005; T.F. Smith et al., 2011). Others assert that the river basin is the logical administrative unit for taking a more unified and structured approach to adaptation planning (Wilby et al., 2006). Furthermore, policy frameworks provided by international legislation such as the EU Water Framework Directive – through periodic review processes and stakeholder consultation – ensure that river basins are adaptively managed. As noted before, this level of integration is needed to ensure that climate risks are not transferred from one group to others. The International Upper Great Lakes Study is a good example of both a bottom-up and top-down, adaptively managed strategy (Brown et al., 2011). Their 'dynamic management plan' is based on stakeholders' definitions of 'coping zones' (lake levels that they consider to be acceptable, survivable or intolerable). Through carefully designed monitoring, the performance of the lake regulation plan will be continually evaluated against the coping zones, tested against climate model outputs, and modified as required.

Some suggest that more radical institutional reforms may be needed to overhaul national capacities in flood risk management (Eakin et al., 2011), to avoid path dependencies in infrastructure development (Garrelts and Lange, 2011), to deliver coherent policies, procedures and regulations for integrated coastal zone management (Storbjork and Hedren, 2011), or to safeguard the needs of socially vulnerable groups (Ford et al., 2011; Lebel et al., 2010a). Tompkins et al. (2008) believe that long-term adaptive capacity (in the Cayman Islands and NE Brazil) can only be built if all the mechanisms of good governance are in place – namely, stakeholder participation, access to knowledge, accountability and transparency. McEvoy et al. (2010) suggest that there should also be plenty of formal and informal opportunities for individuals to reflect on knowledge about climate change impacts and adaptation in collaboration with others.

There are many international examples of shared watersheds across jurisdictional boundaries where exchange of information and cooperation in monitoring and management can reduce flood risks and improve management responses. These can also occur at subnational levels in river basins that cross state or provincial boundaries. Bridging agencies facilitate cross-sectoral cooperation and vertical integration through different levels of governance. As noted above, multinational arrangements will be increasingly needed to strengthen adaptation capacities in flood forecasting and to develop shared management plans for large river basins. For example, the South Asia Water Initiative (SAWI) is a strategic alliance of seven countries intent on more cooperative management of waters that drain the Himalayas. Another international example in Southeast Asia is the Mekong River Commission, which aims to develop cooperative approaches to managing water resources in the lower Mekong. Subnational examples include the Murray Darling Basin Commission (now Authority) in southeastern Australia. To date, these two have focused more on issues of water allocation and quality and maintenance of environmental assets than on managing floods.

At national levels, bridging agencies help to raise awareness of risks and to mainstream ‘climate smart’ approaches within institutional decision-making. For example, the UK Climate Impacts Programme (UKCIP) stimulated much participative knowledge and two-way information exchange between stakeholder and scientific communities (Hedger et al., 2006). Early studies included translating national climate change scenarios into potential flood impacts for London (e.g. LCCP, 2002). Other bodies such as Environment Canada have been central to the production and dissemination of high-resolution climate change information used by a broad constituency, including for national assessment (e.g. Lemmen et al., 2008). These kinds of activity can be particularly important for small organizations with limited in-house capacities for climate risk screening.

Legal institutions incentivize and enforce national standards (e.g. for building codes and planning permission), transpose international to national law (e.g. EU Flood Directive), empower agencies and assign budgets (Llosa and Zodrow, 2011). The planning system is an area in which adaptation can occur in ad hoc ways. Barnett et al. (2011) describe how six decisions made by the Victorian Civil and Administrative Tribunal (VCAT) on appeals are shaping approaches to climate vulnerability assessment and coastal development in East Gippsland, Australia. Likewise, RCEP (2010) consider the legal aspects of coastal protection in the UK. They note that provision of flood and coastal defences is a discretionary power rather than a duty, and that the process for dispersing resources is dominated by cost-benefit analysis (including social well-being and cost distribution). However, tensions emerge when local communities feel excluded from a national process of resource allocation, or strategic abandonment of hard defences. Legal liabilities are complicated under these circumstances: depending on context, common law, and even the Human Rights Act 1998, may be invoked. Statutory liability is easier to establish for an engineering work that causes flooding or erosion than liability for a failure to act, which falls under common law. In Queensland, low uptake of State Planning Policy (SPP) 1/03 is attributed to fear that identifying natural hazard management areas means owning the management of that risk. These two cases illustrate how legal considerations may influence adaptation policies involving managed retreat of the coastline, or whether or not flood hazard maps are provided for developers. Government authorities or companies holding large land banks could be particularly susceptible to abandonment of defences or re-zoning of flood risks.

Flood insurance can be both an incentive and a barrier to adaptation. As noted above, insurance can foster a degree of complacency about flooding (Wamsler and Lawson, 2011) and encourage continued occupation of floodplains (Burby, 2001). Others claim that social welfare improves (in the Netherlands) when insurance companies take responsibility for part of the risks associated with climate change (Botzen and van den Bergh, 2008). Clearly, the outcome partly depends on the way in which the insurance is structured. In the USA there are calls for 30-year insurance policies – linked to mortgage lifetime and tied to the property – to ensure continuity of coverage even if the resident moves (Kunreuther and Michel-Kerjan, 2009). Some analysts suggest that low-cost measures (e.g. oil tank protection) should be made mandatory through building codes in the Elbe and Danube catchments with financial incentives within insurance contracts to further motivate households to mitigate flood risk (Kreibich et al., 2011). Schwarze and Wagner (2004) advocate mandatory insurance policies that provide cover up to the 100-year flood; the state would intervene for losses associated with more extreme events.

Extreme flood events can have fiscal consequences that place substantial stress even on government budgets. Flood 'hot-spot' countries such as Austria, Hungary and Romania have significant disaster contingent liabilities for post-event relief and reconstruction (Mechler et al., 2010). The EU Solidarity Fund (EUSF) was established after the catastrophic Central Europe flooding of August 2002 to make provisions for governments in these circumstances through support to national insurance systems, compensation and loss-sharing (Aakre et al., 2010). However, there are concerns that the very existence of the fund acts as a disincentive for risk-reduction measures in post-disaster assistance (Hochrainer et al., 2010). Mexico and some countries in the Caribbean include contingent liabilities in their national budgets, and even transfer part of the public-sector catastrophe risk to international markets (Cardenas et al., 2007). As with household insurance, national governments have to strike a delicate balance between financing risk-transfer as opposed to risk-reduction measures. Challenges of managing this balance were also evident following the flood events of 2010/11 in Australia when the Government of Queensland, which had chosen to 'self-insure' against flood risks to infrastructure, found that the size of the impact meant that it had to pass the risk on to Federal Government (which then imposed a one-off levy through the tax system to higher income earners to pay for an estimated A$7 billion in costs to repair and replace infrastructure damaged in these floods).

3 Improved preparedness

Climate change has the potential to change the frequency and types of flooding. Growth of urban areas combined with increased intensities of heavy precipitation mean that flash flooding, surface runoff and waterlogging may become more commonplace. Alternatively, higher winter rainfall could increase the risk of widespread fluvial and groundwater flooding. Since responsibility for managing flood emergencies extends beyond government authorities to communities and individuals, the evolving pattern of flood hazards needs to be reflected in contingency planning and public preparedness.

Following widespread summer flooding in the UK, the Pitt Review (Pitt, 2007) identified 15 urgent actions, of which at least 10 could be defined as enabling. These included a national flood emergency framework to be set up by Defra, and for flood warning schemes to be extended to all homes and businesses liable to flooding. The public are now urged to take greater responsibility for their own personal state of readiness, including assembly of a flood kit comprising emergency supplies and contact numbers. An emphasis on improved preparedness and emergency response was also reflected in the 175 recommendations of the Queensland Floods Commission Inquiry (2011). For example, the inquiry recommended that every local government susceptible to flooding should prepare and publish a disaster management plan, and that training is provided for all local disaster coordinators. Plans for improved community education to assist preparedness and understanding of flood warnings appeared in both inquiries.

It is recognized that the way in which climate change is framed and communicated affects perceptions of risk and hence levels of motivation of households and businesses to take precautionary measures (Howe, 2011; Kreibich, 2011; Pontee and Morris, 2011). This is a sensitive issue: some communities are concerned that alarmist language might blight areas facing sea level rise and disengage citizens who are knowledgeable of their local environment (Barnett et al., 2011). During flood events it is also important that warnings are issued in ways that are meaningful to individual communities. The Pitt Review (Pitt, 2007) noted that most people do not use river height in watercourses as their point of reference and find it hard to understand how information relating to specific river gauging stations might be translated to impacts in their locations. Likewise, the flood-impacted community of Kerang in Victoria struggled to translate forecasted river levels into local inundation depths. Spatial modelling linked to visualization can aid communication and assist emergency responses by, for example, highlighting evacuation routes that could be cut. Other systems such as FloodRanger and CoastRanger enable stakeholders to explore longer-term outcomes of adaptation options within a virtual gaming environment (Pontee and Morris, 2011).

Role-play exercises such as Operation Trident (2004) and Exercise Watermark (2011) are periodically used to test contingency planning and systems set up by central government departments to deal with real flooding and infrastructure emergencies (Cabinet Office, 2010; Environment Agency, 2005). Key sectors under scrutiny include food, energy, water, transport, communications, emergency services, health care, financial services and government. But there is also a need to improve the capability of communities and households to help themselves because even high-income countries have limited resources for dealing with major flood emergencies. Publicity campaigns can raise awareness of appropriate actions to take before, during and after a flood, including evacuation routes. The National Disaster Management Days held in Japan are credited with saving lives during the 2011 earthquake and tsunami. In Bangladesh, the Union Disaster Management Committee has Standing Orders to ensure that locals are kept informed of practical measures to take in the event of a flood, and to arrange rehearsals for dissemination of warnings, evacuation, rescue and relief operations.

V Implementing measures to manage flood risk

The previous section discussed some of the institutional structures and processes that enable (or impede) adaptation. Many are relevant to adaptation actions to limit impacts on water quality, the built environment, human health and transport systems because floods affect many sectors. We now consider the steps that can be taken to defend against, live with or withdraw from increasing flood risk (Table 3). These are not mutually exclusive strategies: as before, we are striving to identify portfolios of measures that are robust to the uncertainty in climate-driven future flood frequency, yet reach beyond conventional flood management practices. We are also seeking to draw out generic approaches since an inventory of specific adaptation options would be populated by many items that are culturally specific. For example, floating gardens may offer greater food security in the wake of devastating floods in Bangladesh, but would not be viable in other social and physical landscapes (see Irfanullah et al., 2011).

1 Defending against floods

Traditional approaches to flood defence involved the construction of levees, sluices, impoundments, channels and diversions. Hard

Table 3. Implementing measures to reduce vulnerability to flood risk

Defend against the risk	Direct engineering work to remove hazard (e.g. lake drainage)
	Climate change safety margin for new construction
	New infrastructure to achieve level of service
	Repair, retro-fit, upgrade public/private infrastructure ('build back better')
	Adaptively managing (reservoir) control rules
	Higher specification for vulnerable equipment/networks
	Restore natural coastal defences (mangroves, salt marsh, dunes)
Live with the risk	Make space for water
	• Land management for flood attenuation (headwaters)
	• Re-zoning land use (floodplain)
	• City-scale planning, incorporation of green spaces (built areas)
	• Managed realignment (coastal zone)
	Integrated flood forecasting, warning systems, and public information
	Safe havens, rest centres and shelters
	Flood-resilient construction and networks
	Temporary and demountable defences
	Revise maintenance regime
	Accept flood damages
Withdraw from the risk	Strategic planning control and set-aside
	Physical relocation of people and critical assets

defences of this kind are designed to achieve a level of service (such as protect a settlement from a 100-year flood) given available hydrological information and accumulated local knowledge. In the case of a nuclear power station, the safety case may require protection against a 1 in 10,000-year event. Confidence in such extreme water levels is always low even under stationary climate conditions because of the brevity of data sets and methods of extrapolation, but can be improved using historical and pooled flood frequency analysis (Macdonald et al., 2006). These techniques are not sufficient for long-lived infrastructure under a changing climate, unless a declining standard of protection is accepted (Mailhot and Duchesne, 2010). The only option for the engineer is to apply a climate change safety margin or factor. This, in turn, prompts the questions: what evidence should be used to define the safety margin, and at what point in the design process should it be applied?

Denmark (Arnbjerg-Nielsen, 2008), Germany (Ihringer, 2004) and the UK (DCLG, 2006) are already applying climate change allowances for floods, and guidance in the *Rainfall-Runoff Engineers Australia Publication* is under review. The *Queensland Inland Flooding Study* (State of Queensland, 2010) recommends a 5% increase in rainfall intensity per degree of global warming (assumed to be 2°C by 2050, 3°C by 2070 and 4°C by 2100). The climate change factors are applied to rainfall amounts while historic flood levels with probability 0.5% and 0.2% are scaled to 1% and 0.5%, respectively, by the 2050s. This differs from other approaches which base their climate change factors on model projections for heavy precipitation over the region of interest. In Germany, different factors are used depending on the flood return period. The UK allowance used to assume a 20% increase to all peak flows (Reynard et al., 2004), but this has been refined (Defra, 2011a; Prudhomme et al., 2010). In New South Wales, the recommended sensitivity analysis is based on increases in extreme rainfall and flood volumes of 10–30% (NSW DECC, 2007).

Differences also exist in their legal status. Although there is no legislation in Denmark, The Water Pollution Committee of the Society of Danish engineers regards their factors as the industry standard. The New South Wales guidelines clearly state that *the information does not constitute legal advice*. The UK allowances (for sea level, intense rainfall, wave heights, wind speeds and river discharge) are all enshrined in planning regulation (DCLG, 2006) and guidance for engineers (Defra, 2006). The Canadian Standards Association (CSA, 2010) offers general guidance on the implications of climate change for rainfall intensity-duration and frequency, but design standards appear to be at the experimental stage (He et al., 2006, 2011; Kije Sipi Ltd, 2001). One suggestion is that climate factors should be on a sliding scale anchored to a reference year (Infrastructure Canada, 2006).

Some infrastructure life-cycles extend well beyond the 21st century and/or require exceptionally large safety margins. The Netherlands Delta Committee undertook a scientific assessment of high-end climate change scenarios for sea level up to 2200 (Vellinga et al., 2009). Likewise, the UK nuclear industry is developing extreme water level scenarios for the next generation of power stations which are all located on the coast (Wilby et al., 2011). Similarly, the Thames Estuary 2100 study used a 'High-plus-plus' scenario to test flood defence options for London to the end of the 21st century (see EA, 2009; Lowe et al., 2009). The stakes, in terms of financial or social impacts, are enormous in all these cases so the scenarios were formed from plausible high-end scenarios of indeterminate probability that give a worst case for sensitivity testing of defences. For example, a global mean warming of 6°C, with high climate sensitivity, increased ice discharge from Antarctica, accelerated melt from Greenland, and possible thermohaline collapse in the North Atlantic, combined with local gravitational effects and subsidence, could increase mean sea levels by 4 m along the coast of the Netherlands by 2200 (Vellinga et al., 2009). Extreme water levels are even higher when combined with scenarios for tidal surge and waves.

Based on these scenarios, the Delta Commission (2008) proposed strengthening flood protection by intensifying beach nourishment at an annual cost of €1.2–1.8 billion. The principle is to work with natural processes such as dune formation to extend the Netherlands' coastline seaward. Mangroves and coastal wetlands provide flood protection services in other regions. For example, when a supercyclone struck Orissa in 1999, villages with wider mangroves between them and the coast experienced significantly fewer deaths (Das and Vincent, 2009). Similarly, coastal wetlands in the USA provide an estimated US$23 billion per year in hurricane protection services (Costanza et al., 2008). It is further recognized that ecosystem-based solutions for flood defence yield many other benefits, not least conservation value (Euliss et al., 2011). While protection and restoration of salt marsh, coastal wetlands and mangroves are clearly beneficial to flood defence, long-term conservation efforts need to secure space for inland migration of coastal habitats as sea levels rise (e.g. McLeod and Salm, 2006). Similarly, the potential for inland wetland and floodplain restoration to improve natural capacities for floodwater retention has long been recognized (e.g. Hey and Philippi, 1995) and is now being realized in river systems such as the Danube (Ebert et al., 2009).

Existing flood defence and urban drainage infrastructure will need to be gradually upgraded during scheduled maintenance. This is to protect present assets and maintain levels of performance in the future (Auld, 2008b; Stevens, 2008). Arnbjerg-Nielsen (2011) observes that elements of the drainage system with short technical lifetimes ($\sim$10 years for pumps, telecommunication devices and detention ponds) can be optimized with less attention to performance and resilience than long-lived assets ($\sim$80 years for concrete sewer and pipe replacement). Post-disaster reconstruction or routine replacement may also provide opportunities to 'build back better' (i.e. incorporate higher-specification designs or materials for vulnerable assets). In all cases, the economic benefits of such adaptations must be demonstrated. For example, Ranger et al. (2011) calculated that an improved urban drainage system for Mumbai could reduce direct and indirect losses (e.g. due to disruption) from the 100-year flood by 70%. Karamouz et al. (2011) considered a broader range of performance metrics for the drainage system of Tehran, including effectiveness at transporting solid wastes and sediment under different scenarios. Semadeni-Davies et al. (2008) assert that renovation of existing networks and installation of SUDS in Helsingborg, Sweden, have the potential to allay adverse impacts arising from both climate change and urban growth. Incorporation of rainwater-harvesting tanks was found to improve downstream sewer system performance in Star City, South Korea, at the same time as improving water supply (Han and Mun, 2011).

An alternative strategy is to defend against floods by operating existing infrastructure in different ways. This involves adjusting control rules to achieve the same standards of protection, or even entirely new objectives, for given scenarios of climate variability and change. Modelling studies in North America indicate that adaptive reservoir management can maintain levels of performance for water supply, energy production and environmental flows even under future droughts (Georgakakos et al., 2011; Li et al., 2010; Watts et al., 2011). However, depending on the climate change scenario, increasing reservoir storage for flood control may require trade-offs against other allocations for hydropower production, irrigation and instream flow targets in multipurpose systems (Gosh et al., 2010; Payne et al., 2004; Raje and Mujumdar, 2010). The planning pathway and optimal rule curves also depend on decision-maker attitudes to risk and weight attached to different climate scenarios (Brekke et al., 2009), as well as the system structure in the case of multi-reservoir configurations (Eum and Simonovic, 2010). The Thames Estuary strategy (EA, 2009) is a further example of an adaptive management approach that links different combinations of hard and soft flood defence options depending on changing risks (from sea level rise) and societal attitudes (Figure 3).

2 Living with floods

Guaranteed defence against flooding is an impossible goal even for a nuclear power station; living with floods means accepting some damage is inevitable but these harms can be reduced when appropriate policy and technical instruments are applied. Such adaptations are occurring over a range of scales: spanning river basin planning and city land management, through to actions taken by local communities and householders to improve flood resistance and resilience.

As indicated before, development control is the first line of defence when limiting flood risk exposure. However, spatial planning and land management can also make space for water by adopting a whole landscape approach to flood risk management (Defra, 2005a; Roggema, 2009). In headwaters, runoff attenuation features (e.g. terraces, small ponds on farmland) can delay flood peaks and thereby extend warning times (Li et al., 2007; Parrott et al., 2009; Wilkinson et al., 2010). Tree planting and other forms of catchment rehabilitation can stabilize hillslopes and reduce flood peaks at the watershed scale (Jackson et al., 2008; Lin et al., 2011) but the benefits when aggregated to whole catchments are unclear (Defra, 2005b) and there is considerable debate about the extent to which deforestation in catchments exacerbates flood risks and impacts at larger scales (Bradshaw et al., 2007, 2009; Van Dijk et al., 2008). Furthermore, forest protection and impoundment schemes to improve flood regulation downstream may reduce the adaptive capacity of mountain communities that rely on forest products (e.g. Beckman, 2011).

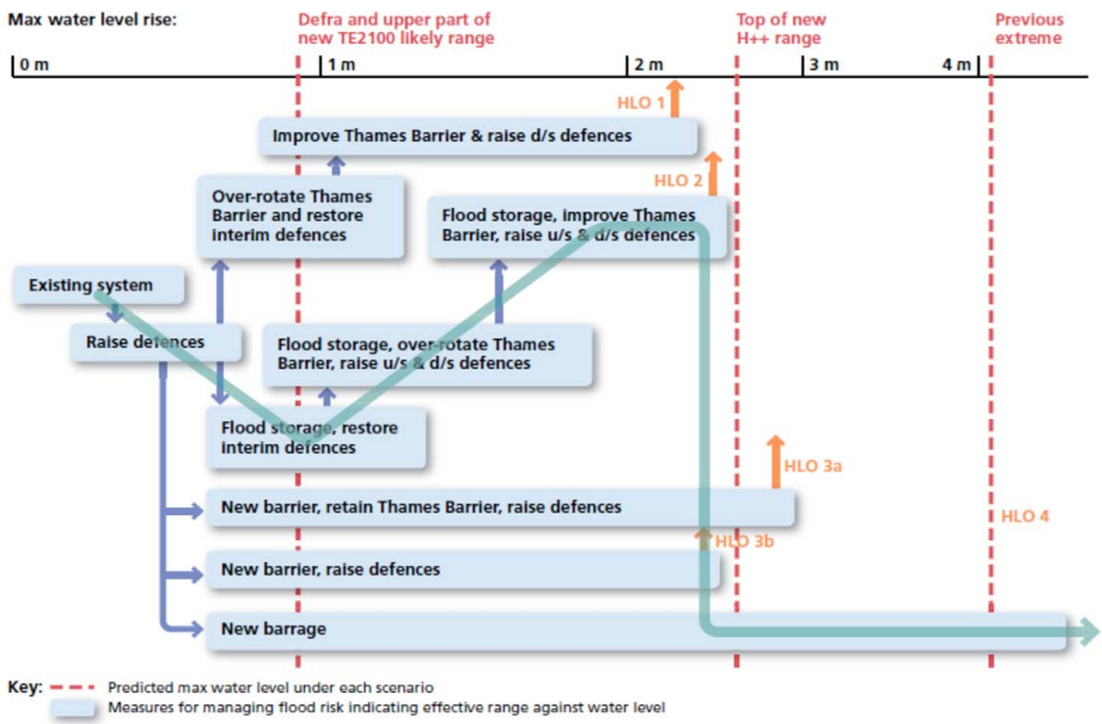

Figure 3. Conceptual diagram showing alternative adaptation pathways to provide flood defence for London despite uncertainty about sea level rise
Source: Lowe et al. (2009)

Within the floodplain and coastal margin, re-zoning of land use, compulsory purchases and voluntary land swaps may improve flood control and biodiversity, but clearly have profound social and economic consequences (see Barnett et al., 2011). Planners are also looking at the potential for green spaces, gardens and wetlands to deliver multiple adaptation benefits within city landscapes (e.g. GLA, 2005; Morimoto, 2011). However, specific guidance is still needed on the design and management of flood retention features and SUDS (Scholz and Yang, 2010), especially when taking into account the combined impact on flooding of climate change *with* urban growth (Jung et al., 2011). Planners and building designers also have to reduce flood hazards alongside other drivers of morbidity and mortality such as thermal stress, water- and vector-borne diseases, air pollution, and fire linked to climate change (Bambrick et al., 2011; Mourshed, 2011; Wilby, 2007).

It is appreciated that new structures of water and energy service provision are needed to improve resistance and resilience (i.e. recovery) to flooding (Duit et al., 2010). One way is to develop community- and household-scale water and energy systems – that incorporate smart technologies – to reduce or eliminate reliance on vulnerable mains supplies carried from remote sources (Biggs et al., 2011). Alternatively, conventional, large-scale infrastructure networks (for energy, water, communication and transport) are designed to be more resilient to present and future natural hazards (Defra, 2011b). This is achieved by periodic review of critical nodes and connections in the system, then defending these to higher standards, or by incorporating backup systems, in cost-effective ways. For example, some UK water companies are already modelling the outcome of protecting individual assets (via embankments, walls, flood-proof building) and improving system resilience (via new pipelines, sources of supply, demand management, duplicating infrastructure) to improve security of supplies to customers (e.g. Henriques and Spraggs, 2011).

Surveys of households in Germany and the Netherlands reveal willingness to undertake measures to reduce flood damage, especially if there is a financial incentive through lower home insurance (Botzen et al., 2009a; Kreibich, 2011). Other incentives include the avoidance of uninsured and non-monetary losses (such as distress) or higher property values. Temporary flood resistance measures (e.g. demountable defences such as sand bags, covers for airbricks) are generally more cost-effective than flood resilience measures (e.g. water-resistant flooring and plaster, rewiring, relocation of heaters) except in areas where there is very high annual risk of flooding (Defra, 2008). Unfortunately, insurance companies will not always pay for 'betterment' to provide for improvements in flood-damaged properties with more resilient materials. (Local governments tend to be reluctant to pay higher costs for upgrading damaged public infrastructure too.) In Bangladesh, the *Char Livelihoods Programme* has been progressively flood-proofing individual homesteads by raising them onto earth platforms to protect against the highest recorded monsoon floods. In Dhaka, physical protection of slum dwellings or compounds is almost non-existent but occupants use other coping strategies for living with floods, such as storing food and building materials, or drawing on social capital (Braun and Assheuer, 2011; Jabeen et al., 2010).

Integrated real-time hazard-forecasts have become an accepted part of living with floods and will continue to be so regardless of climate change (Chang, 2011). For maximum affect, such systems must be 'people-centred' (Basher, 2006; Parker et al., 2009). This presupposes that four elements are in place: (1) knowledge of the flood hazard in relation to distributions of human vulnerability; (2) technical capacity to monitor flood precursors, observe their evolution and issue warnings; (3) preparedness of populations to act on intelligible warnings; and (4) capability to take timely and appropriate actions. Other factors may also be important. For example, a sober assessment of the actual value of forecasts in reducing food insecurity in southern Africa (in part due to flood shocks) showed that they are ineffective if divorced from the complex social context (Vogel and O'Brien, 2006). Mozambique's flood warning system relies on multi-agency cooperation facilitated by the Southern African Regional Outlook Forum (SARCOF) (Hellmuth et al., 2007). Collecting and sharing data for flood forecasting in mountainous terrain is always problematic but remotely sensed snow cover and precipitation can be used to forecast floods in transboundary river systems such as the Brahmaputra (Immerzeel et al., 2009; Kamal-Heikman et al., 2007). Other technical innovations include the auto-control of pumping operations in sewerage systems used to discharge excess rainwater, as in Taipei City (Chiang et al., 2011).

3 Withdrawing from floods

Evacuation procedures figure prominently in flood emergency plans but these depend on the safety of escape routes and security of shelter points. Extreme flood conditions may test both assumptions. For example, Haynes et al. (2009) evaluate the relative merits of 'shelter-in-place' versus evacuation during flash floods based on an analysis of Australian fatalities and injuries. Their results show that over 75% of fatalities arise when people enter floodwaters in a vehicle or on foot; similar statistics are reported for the USA (Ashley and Ashley, 2008). Although evacuation is generally the preferred option, shelter-in-place may take precedence during flash floods when limited warning times do not allow safe exit. Since climate change is expected to cause more heavy rainfall and flash flooding, emergency protocols will need to be kept under review, and guidance to the public updated accordingly.

Over longer timescales, adverse environmental conditions can force migration, but this involves complex social and behavioural factors and is seldom in response to a single driver (McLeman and Smit, 2006). Hence, mass migration can be framed in many ways, including as a failure of in situ adaptation, as a challenge to migration policy (from 'climate refugees') or as a rational human response to land degradation, conflict and climate change (Bardsley and Hugo, 2010). Others see catastrophes in large river basins as triggers for policy innovation and adaptation (Krysanova et al., 2010), or even institutional change (McSweeney and Coomes, 2011). In extreme circumstances, migration of people and businesses from perpetually hazardous areas may be the only option. For example, it has been speculated that cumulative environmental deterioration by cycles of drought and flooding in the Sahel could trigger mass displacement (Tschakert et al., 2010). In Southeast Asia, low-lying mega-deltas and flood-prone cities such as Bangkok could experience significant out-migration along established corridors in response to rising sea levels, increased cyclone intensity and tidal surge (Bardsley and Hugo, 2010). Vietnam's 'Living With The Flood' programme has already resettled one million people residing within the Mekong Delta (Danh and Mushtaq, 2011).

Some governments are pursuing policies of strategic retreat from floodplains and the coastal zone. For example, the Victorian State Government is buying land from flood-impacted farmers and restoring it to natural floodplain functions. Likewise, following deadly flash flooding in 2011, the State Government of Queensland enabled the town of Grantham to bypass normal planning regulations and rebuild or relocate housing to higher ground through voluntary swaps for landholders. However, state-sponsored resettlement and re-zoning as an adaptation response to flooding is highly contentious. There are obvious concerns about equity and justice when public and private benefits, costs, liabilities, risks and uncertainties are redistributed (Thomas and Twyman, 2005). However, the 'sense of place' and the values that individuals attach to landscapes influence their levels of risk perception. Because of psychological bias, an individual's physical vulnerability explains only a small amount of variance in risk perception (Brody et al., 2008). A study of public perceptions in the Southern Fleurieu Peninsula, Australia, found that high landscape values (for recreation) were correlated with low perceived risk of riparian flooding, sea level rise, and wave action. Such findings can assist with the rational allocation of resources: areas of low landscape value and high perceived climate risks might be sacrificed, whereas high-value landscapes with high risks (e.g. floodplain communities) might attract more agency resources (Raymond and Brown, 2011).

In the coastal zone, planned retreat could occur behind natural defences such as beaches, dunes, wetlands and salt marshes. However, this presupposes that policy and planning instruments are in place to reserve land for protective habitats as sea levels advance landwards. One assessment of the scope for planned retreat in South East Queensland found that this adaptation option is becoming less feasible because of policies promoting population growth and prioritization of homes over conservation of coastal ecosystems (Abel et al., 2011). Furthermore, liability laws favour development and new construction leads to path-dependency with lock-in of assets which, in turn, strengthens the political case for hard defences as the value of assets increase. According to Abel et al. (2011) these obstacles could be overcome by amending development rules, improving incentives for relocation, and by using catastrophes as an opportunity to change approach rather than rebuilding as before. Furthermore, they recommended that if building occurs in low-lying flood-prone areas any costs resulting from local decisions should not be transferred to other administrative levels or to society as a whole. The principle that present and future costs (for managing flood risk) are met by the beneficiaries of the development is also found in European planning (e.g. DCLG, 2006; Delta Commission, 2008).

Figure 4. Evidence of the extraordinary steps taken by the community to flood-proof the electricity substation serving Kerang, Northern Victoria

VI Floods of September 2010 to February 2011 in Victoria, Australia

While the large-scale flooding across Queensland, and in the city of Brisbane in particular, was the focus of most media attention in Australia, the 2010/11 floods in Victoria had a profound impact. About one-third of the State experienced storm and/or flood damage, 4000 homes were inundated, costs to primary industries and tourism were estimated at A$269 million and A$176 million, respectively, over 500 km of roads were affected, and more than 10,000 personal hardship grants were issued (Comrie, 2011). The valiant actions of the citizens of Kerang to protect their electricity substation attracted international media attention (Figure 4). But many unseen individuals and flood-affected communities are still enduring hardships; others are inconvenienced by damaged infrastructure or are still in recovery phase.

The terms of reference for the State inquiry did not mention climate change (Victorian Floods Review, 2011). Nonetheless, the mission is clear: irrespective of the causal factors, this Review focused on ensuring that Victoria is better able to manage such events in the future (Comrie, 2011: 10). Meanwhile, water companies are thinking about more intense storms, sewer overflows and flooding in the context of longer-term planning for increased water scarcity (e.g. Melbourne Water, 2005), and complex negotiations surround future water management in the Murray-Darling basin. Universities are also actively researching use of climate model scenarios for impacts and adaptation in the sector (e.g. Wiseman et al., 2011). The Victorian Review identified two related opportunities for enhancing adaptive capacity.

First, more research is needed into the underlying physical drivers of extreme flood events. Jones (2011) submitted a critique to the Northern Victorian Flood Review that explained the local causes and consequences of flooding by the Loddon River. From his personal account it is clear that the flooding was a consequence of several factors. La Niña brought wet conditions in August and September 2010, replenishing wetlands that were parched by drought since the late 1990s. By the end of 2010 northern catchments were saturated, then in January 2011 large parts of central and northern Victoria received the highest rainfalls on record. However, Jones (2011) believes that the impact of the flood was exacerbated by changing patterns of land use, the poor condition of some levees, and by modifications to drainage lines. Limited technical capabilities for translating estimated

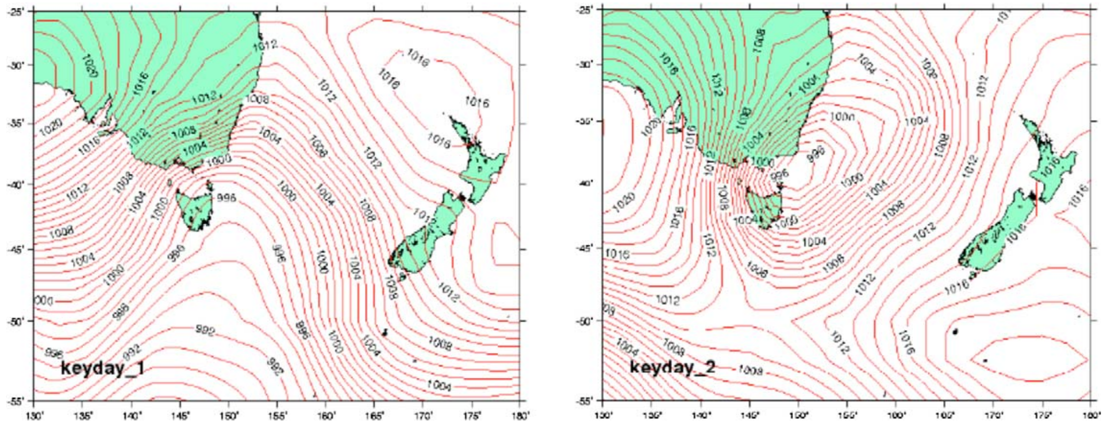

Figure 5. Surface pressure patterns with coincident severe rainfall and surge at Melbourne. Historically, keyday 1 has yielded 37% of severe rainfall and 84% of severe surge events of which around 10% and 7%, respectively, coincide.
Source: Abbs and McInnes (2010)

rainfall-runoff into water depths across the floodplain meant that communities and emergency services were struggling to predict, then allocate resources to critical locations. The interim review noted that the Victoria State Emergency Services (VICSES) was simply overwhelmed by the size and protracted nature of the floods (Comrie, 2011: 4).

Climate projections point to greater flood risk due to: higher atmospheric humidity, more intense subdaily rainfalls, poleward migration of mid-latitude storm tracks, more intense tropical cyclones, sea level rise (and to a lesser extent storm surge) (Westra, 2011). But there is also growing appreciation of the role played by antecedent soil moisture in modulating fluvial responses to heavy rainfall. Since the phase of the Interdecadal Pacific Oscillation (IPO) strongly determines catchment wetness, under certain phases the likelihood of major flooding can be much greater for the same design storm (Pui et al., 2011). Furthermore, in Victoria there is the possibility of joint occurrence of an intense rainfall-derived flood event in the coastal zone coinciding with storm surge under the same weather patterns. Some climate model projections suggest increases in the likelihood of coincident events in southwestern Australia (Abbs and McInnes, 2010). For Melbourne the most problematic synoptic conditions occur when there are frontal troughs associated with low pressure to the south of the continent and winds from the southwest (Figure 5). Systematic monitoring and review should determine how the space-time occurrence of such extremes is evolving.

Second, a two-tiered framework is needed for reducing risks and managing consequences of low-likelihood but high-impact floods (as distinct from ‘normal’ flooding). Extraordinary executive powers are needed in the case of ‘super’ floods. These would enable more integrated management and control arrangements across emergency services and other state government agencies such as the Country Fire Authority, Victoria Police and local authorities, the immediate release of resources and call-up of voluntary personnel, even from neighbouring jurisdictions. Role-play exercises could provide valuable opportunities for combined services to practise their joint response, learn from system failings, and thereby provide a better response to actual catastrophes. Previous exercises conducted in the UK identified a number of weaknesses in operational capabilities (see EA, 2005). For example, when responding to an imagined 1-in-1000-year flood, roles and responsibilities were not always clear. This scale of event stretched capabilities of forecasting systems, and more clarity was needed on when and where to evacuate people. The exercise showed that a national review of dedicated emergency support equipment (e.g. pumps, generators, boats) was needed as well as ways of sharing them between organizations. The onus is then on national government to ensure that the recommendations of the role-play exercise are properly resourced and implemented. Local authorities also need clear plans that identify key assets at risk for different flood levels and agreed priority response arrangements, so that resources are directed to protecting the most critical infrastructure.

The emphasis of both the Victorian Floods Review and of the Parliamentary inquiry was very much on improving flood forecasting capabilities and emergency responses (Victorian Floods Review, 2011). Comrie (2011) further recognized that planning controls are an effective means of minimizing flood damage, and that local planning schemes need to be reconsidered. This is consistent with the National Strategy for Disaster Resilience (COAG, 2009) which highlights the role of government at all levels in strengthening resilience through planning arrangements. The Victorian Review noted the inadequate protection of critical community infrastructure (such as the power substation at Kerang). This raises important questions about the obligations of remote global corporations to safeguard mains supplies for vulnerable communities in terms of their accountability and ability to react quickly and effectively in emergencies. Local councils also want greater clarity on procedures and financing for ‘betterment’ when undertaking repairs to public assets.

VII Conclusions

This study supports the view that flood risks and benefits are very unevenly distributed. By and large, the public sector, households and small businesses bear most of the risk; some elements of the private sector benefit from land development and flood reconstruction (Handmer, 2008). In other words, floods are not bad for everyone and such tensions reduce the overall incentive for adaptation. Nonetheless, interest in adaptation (as measured by volume of literature) is growing exponentially. In the case of flood risk management, much of what is labelled ‘adaptation’ could just be described as ‘good practice’. All of the measures that enable adaptation – access to information, institutional flexibility and openness, and improved preparedness – are low regret. They are not free, so carry some opportunity cost, but would continue to reduce flood damages regardless of the extent of future climate change.

The same cannot be said of the implementing actions for defending against, living with or withdrawing from flood risk. Such actions require boldness on the part of politicians to accept what are generally precautionary measures. In an era of austerity, when budgets are being cut for new build and maintenance of existing flood defences, wider economic forces may shape the composition of national adaptation portfolios. For example, the UK Government’s 2010 Comprehensive Spending Review reduced budgets for construction and maintenance by 8% over the following four years. On the other hand, the same Government is legally bound to ‘lay programmes before Parliament setting out . . . the time-scales for introducing those proposals and policies, addressing the risks identified in the most recent report [that is, responses to expected growth in flood hazards identified by the national Climate Change Risk Assessment of 2011]’ (Climate Change Act 2008).

However, whether it is retrofitting existing housing stock, new defences, or setting aside land to buffer coastal and floodplain communities, economic appraisals of costs and benefits can help optimize the *timing* of such investments.

Likewise, climate change safety margins for new construction are inherently defensive because they originate from uncertain climate model projections. In this case, periodic review of the scenarios and supporting guidance helps evolving scientific understanding inform (but not dictate) building codes. Targeted research could further improve knowledge of the physical controls of severe floods – particularly those arising from coincident extremes of catchment wetness, heavy rainfall and tidal surge – recognizing that a holistic view of flood risk requires as much attention to the socio-economic drivers. This would require a shift of emphasis away from climate modelling alone. Our structured survey found several other themes for policy reflection and research.

First, improved management of transboundary flood risk is a matter of urgency. (Here, ‘transboundary’ applies in both a geographical and a sectoral sense). Multinational frameworks are in place to share information but accountabilities are less clear. Whatever the direction of climate change, rapid economic and population growth in mega-deltas and floodplains is increasing flood risk exposure and has to be managed with the full cooperation of all riparian interests. Discordant monitoring systems and inconsistent planning approaches reveal boundary constraints *within* nations. Institutional boundaries and limited capacities may hinder adaptation at local scales. More generally, policies for improving food and energy security could work in tension with policies designed to manage land use in ways that reduce flood risk. Such conflicts are likely to have complex, multiscale dimensions that merit further research to help bridging organizations integrate adaptation responses across different tiers of governance.

Second, there is the immense challenge of improving resistance and resilience for present assets and housing stocks. This can be achieved at different scales: from individual households to neighbourhoods, whole cities and regions. Insurance-based mechanisms may incentivize risk-reduction measures at household level, but a more radical review of the relative merits of centralized versus distributed infrastructure networks is needed. The challenge is to design dwellings and cityscapes that reduce vulnerability to multiple hazards including heatwave, flood, fire and poor air quality (Hardoy and Lankao, 2011). Where possible, adaptations to flooding should also harmonize with natural processes to deliver other benefits including habitat creation, river restoration and lower carbon emissions. These can be implemented in a progressive way in response to changing information on future flood risks.

Third, solutions should yield equitable outcomes in terms of risk reduction for all members of society. The Dutch Delta Commission (2008: 16) expresses this vision very succinctly: ‘A human life is worth the same everywhere and the probability of a fatality due to a disastrous flood must therefore be assessed on a common basis, to be agreed throughout society.’ In the Netherlands, that probability is set at one in a million. However, recent inquiries recognize that the public must also take responsibility for managing some of the risk through improved readiness and timely response to flood warnings.

Finally, the principle of adaptive management of climate risks is gaining traction in many circumstances, particularly where stakeholders can articulate a clear set of options and outcomes (e.g. Great Lakes, Thames Estuary, Dutch coast and hinterland). However, this management framework depends on systematic monitoring with periodic review of evolving risks and vulnerabilities. Although the recurrent costs to the public and private sector should not be underestimated, adaptive management currently offers the best hope of reducing flood risk in an uncertain social and physical climate.

Acknowledgements

RW is grateful to all the consultees who provided valuable insight to flood management issues.

We thank the two anonymous referees for their constructive remarks.

Funding

RW thanks the Victorian Centre for Climate Change Adaptation Research (VCCCAR) for sponsoring his research fellowship at the University of Melbourne.

References

Aakre S, Banaszak I, Mechler R, et al. (2010) Financial adaptation to disaster risk in the European Union: Identifying roles for the public sector. *Mitigation and Adaptation Strategies for Global Change* 15: 721 736.

Abbs D and McInnes K (2010) *Coincident Extreme Rainfall and Storm Surge Events in Southern Australia*. Aspendale: CSIRO.

Abel N, Gorddard R, Harman B, et al. (2011) Sea level rise, coastal development and planned retreat: Analytical framework, governance principles and an Australian case study. *Environmental Science and Policy* 14: 279 288.

Adaptation Sub Committee (ASC) (2010) *How Well Pre pared is the UK for Climate Change?* London: Climate Change Committee.

Adaptation Sub Committee (ASC) (2011) *Adapting to Cli mate Change in the UK: Measuring Progress*. London: Climate Change Committee.

Adger WN, Agrawala S, Mirza MMQ, et al. (2007) Assessment of adaptation practices, options, con straints and capacity. In: Parry ML, Canziani OF, Palutikof JP, et al. (eds) *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, 717 743.

Adger WN, Dessai S, Goulden M, et al. (2009) Are there social limits to adaptation to climate change? *Climatic Change* 93: 335 354.

Adger WN, Huq S, Brown K, et al. (2003) Adaptation to climate change in the developing world. *Progress in Development Studies* 3: 179 195.

Ahmad QK and Ahmed AU (2003) Regional cooperation in flood management in the Ganges Brahmaputra Meghna region: Bangladesh perspective. *Natural Hazards* 28: 181 198.

Arnbjerg Nielsen K (2008) *Forventede Ændringer i Ekstremregn Som Følge Af Klimaændringer (Antici pated Changes in Extreme Rainfall Due To Climate Change)*. Recommendation 29. Copenhagen: The Water Pollution Committee of the Society of Danish Engineers.

Arnbjerg Nielsen K (2011) Past, present, and future design of urban drainage systems with focus on Danish experi ences. *Water Science and Technology* 63: 527 535.

Ashley ST and Ashley WS (2008) Flood fatalities in the United States. *Journal of Applied Meteorology and Climatology* 47: 805 818.

Auld HE (2008a) Disaster risk reduction under current and changing climate conditions. *World Meteorological Organization Bulletin* 57: 118 125.

Auld HE (2008b) Adaptation by design: The impact of changing climate on infrastructure. *Journal of Public Works and Infrastructure* 3: 276 288.

Auld HE, MacIver D, and Klassen J (2004) Heavy rainfall and waterborne disease outbreaks: The Walkerton example. *Journal of Toxicology and Environmental Health Part A* 67: 1879 1887.

Bambrick HJ, Capon AG, Barniett GB, et al. (2011) Cli mate change and health in the urban environment: Adaptation opportunities in Australian cities. *Asia Pacific Journal of Public Health* 23: 67S 79S.

Bardsley DK and Hugo GJ (2010) Migration and climate change: Examining thresholds of change to guide effective adaptation decision making. *Population and Environment* 32: 238 262.

Barnett J and O'Neill S (2010) Maladaptation. *Global Environmental Change* 20: 211 213.

Barnett J, Fincher R, Hurlimann A, et al. (2011) *Equitable Outcomes in Adaptation to Sea Level Rise*. Melbourne: University of Melbourne.

Basher R (2006) Global early warning systems for natural hazards: Systematic and people centred. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering* 364: 2167 2282.

Beckman M (2011) Converging and conflicting interests in adaptation to environmental change in central Vietnam. *Climate and Development* 3: 32 41.

Berry HL, Hogan A, Owen J, et al. (2011) Climate change and farmers' mental health: Risks and responses. *Asia Pacific Journal of Public Health* 23: 119S 132S.

Biesbroek GR, Swart RJ, Carter TR, et al. (2010) Europe adapts to climate change: Comparing national adapta tion strategies. *Global Environmental Change* 20: 440 450.

Biggs C, Arcari P, Strengers Y, et al. (2011) *Assessing Resilient Urban Systems to Support Long Term*

Adaptation to Climate Change. Melbourne: Victorian Centre for Climate Change Adaptation Research.

Botzen WJW and van den Bergh JCJM (2008) Insurance against climate change and flooding in the Netherlands: Present, future and comparison with other countries. *Risk Analysis* 28: 413 426.

Botzen WJW, Aerts JCJH, and van den Bergh JCJM (2009a) Willingness of homeowners to mitigate cli mate risk through insurance. *Ecological Economics* 68: 2265 2277.

Botzen WJW, Aerts JCJH, and van den Bergh JCJM (2009b) Dependence of flood risk perceptions on socio economic and objective risk factors. *Water Resources Research* 45: W10440.

Botzen WJW, van den Bergh JCJM, and Bouwer LM (2010) Climate change and increased risk for the insurance sector: A global perspective and an assessment for the Netherlands. *Natural Hazards* 52: 577 598.

Bouwer LM (2011) Have disaster losses increased due to anthropogenic climate change? *Bulletin of the Amer ican Meteorological Society* 92: 39 46.

Bradshaw CJA, Brook BW, Peh KSH, et al. (2009) Flooding policy makers with evidence to save forests. *Ambio* 38: 125 126.

Bradshaw CJA, Sodhi NS, Peh KSH, et al. (2007) Global evidence that deforestation amplifies flood risk and severity in the developing world. *Global Change Biology* 13: 2379 2395.

Braun B and Assheuer T (2011) Floods in megacity environments: Vulnerability and coping strategies of slum dwellers in Dhaka/Bangladesh. *Natural Hazards* 58: 771 787.

Brekke LD, Maurer EP, Anderson JD, et al. (2009) Assessing reservoir operations risk under climate change. *Water Resources Research* 45: W04411.

Brody SD, Zahran S, Vedlitz A, et al. (2008) Examining the relationship between physical vulnerability and public perceptions of global climate change in the United States. *Environment and Behavior* 40: 72 95.

Brown C, Werick W, Leger W, et al. (2011) A decision analytic approach to managing climate risks: Applica tion to the Upper Great Lakes. *Journal of the American Water Resources Association* 47: 524 534.

Burby RJ (2001) Flood insurance and floodplain man agement: The US experience. *Global Environmental Change* 3: 111 122.

Burton I (1996) The growth of adaptation capacity: Prac tice and policy. In: Smith J, Bhatti N, and Menzhulin G (eds) *Adapting to Climate Change: An International Perspective*. New York: Springer, 55 67.

Burton I (2006) Adapt and thrive: Options for reducing the climate change adaptation deficit. *Policy Options* 33 38.

Cabinet Office (2010) *Sector Resilience Plan for Critical Infrastructure 2010*. London: Civil Contingencies Secretariat.

Canadian Standards Association (CSA) (2010) *PLUS 4013 Technical Guide: Development, Interpretation and Use of Rainfall Intensity Duration Frequency (IDF) Information: Guideline for Canadian Water Resources Practitioners*. Mississauga, Canada: CSA.

Cardenas V, Hochrainer S, Pflug G, et al. (2007) Sovereign financial disaster risk management: The case of Mex ico. *Environmental Hazards* 7: 40 53.

Chang CH (2011) Preparedness and storm hazards in a global warming world: Lessons from Southeast Asia. *Natural Hazards* 56: 667 679.

Cheong SM (2011) Policy solutions in the USA. *Climatic Change* 106: 57 70.

Chiang YM, Chang LC, Tsai MJ, et al. (2011) Auto control of pumping operations in sewerage systems by rule based fuzzy neural networks. *Hydrology and Earth System Sciences* 15: 185 196.

Chowdhury MR and Ward MN (2007) Seasonal flooding in Bangladesh variability and predictability. *Hydro logical Processes* 21: 335 347.

Comrie N (2011) *Review of the 2010 11 Flood Warnings and Response*. Melbourne: Victorian Government.

Costanza R, Perez Maqueo O, Martinez ML, et al. (2008) The value of coastal wetlands for hurricane protection. *Ambio* 37: 241 248.

Council of Australian Governments (COAG) (2009) *National Strategy for Disaster Resilience*. Canberra: National Emergency Management Committee of the Australian Government.

Danh VT and Mushtaq S (2011) Living with floods: An evaluation of the resettlement program of the Mekong Delta of Vietnam. In: Stewart MA and Coclanis PA (eds) *Environmental Change and Agricultural Sus tainability in the Mekong Delta*, Advances in Global Change Research Series 45. Dordrecht: Springer, 181 204.

Dankers R and Feyen L (2008) Climate change impact on flood hazard in Europe: An assessment based on high resolution climate simulations. *Journal of Geophysical Research* 113: D19105.

Das S and Vincent JR (2009) Mangroves protected villages and reduced death toll during Indian super cyclone. *Proceedings of the National Academy of Sciences of the United States of America* 106: 7357 7360.

Dawson RJ, Ball T, Werritty J, et al. (2011) Assessing the effectiveness of non structural flood management measures in the Thames Estuary under conditions of socio economic and environmental change. *Global Environmental Change* 21(2): 628 646.

De Bruin K, Delink RB, Ruijs A, et al. (2009) Adapting to climate change in the Netherlands: An inventory of climate adaptation options and ranking of alternatives. *Climatic Change* 95: 23 45.

Defra (2005a) *Making Space for Water: Taking Forward a New Government Strategy for Flood and Coastal Erosion Risk Management in England*. London: Department for Environment, Food and Rural Affairs.

Defra (2005b) *Review of Impacts of Rural Land Use and Management on Flood Generation: Impact Study Report*. London: Department for Environment, Food and Rural Affairs.

Defra (2006) *Flood and Coastal Defence Appraisal Gui dance (FCDPAG3) Economic Appraisal Supplemen tary Note to Operating Authorities Climate Change Impacts*. London: Department for Environment, Food and Rural Affairs.

Defra (2008) *Developing the Evidence Base for Flood Resilience: Technical Summary*. London: Department for Environment, Food and Rural Affairs.

Defra (2011a) *Adapting to Climate Change: Advice for Flood and Coastal Erosion Risk Management Author ities*. London: Department for Environment, Food and Rural Affairs.

Defra (2011b) *Climate Resilient Infrastructure: Preparing for a Changing Climate*. London: Department for Environment, Food and Rural Affairs.

Delta Commission (2008) *Working Together with Water: A Living Land Builds for its Future*. The Hague: Delta Commission.

Department of Communities and Local Government (DCLG) (2006) *Planning Policy Statement 25: Development and Flood Risk Annex B: Climate Change*. London: The Stationery Office.

Department of Communities and Local Government (DCLG) (2007) *Planning Policy Statement 1: Planning and Climate Change Supplement*. London: The Sta tionery Office.

Duit A, Galaz V, Eckerberg K, et al. (2010) Governance, complexity and resilience. *Global Environmental Change* 20: 363 368.

Eakin H, Eriksen S, Eikeland PO, et al. (2011) Public sector reform and governance for adaptation: Implica tions of new public management for adaptive capacity in Mexico and Norway. *Environmental Management* 47: 338 351.

Ebert S, Hulea O, and Strobel (2009) Floodplain restora tion along the lower Danube: A climate change adap tation case study. *Climate and Development* 1: 212 219.

Environment Agency (EA) (2005) *Exercise Triton 04*. Bristol: Rio House.

Environment Agency (EA) (2009) *TE2100 Plan Con sultation Document*. London: Thames Barrier.

Euliss NH, Smith LM, Liu SG, et al. (2011) Integrating estimates of ecosystem services from conservation programs and practices into models for decision mak ers. *Ecological Applications* 21: S128 S134.

Eum HI and Simonovic SP (2010) Integrated reservoir management system for adaptation to climate change: The Nakdong River basin in Korea. *Water Resources Management* 24: 3397 3417.

European Commission (EC) (2009) *River Basin Management in a Changing Climate: Guiding Prin ciples to Assist Adaptation*. Brussels: European Commission.

European Environment Agency (EEA) (2009) *Report on Good Practice Measures for Climate Change Adapta tion in River Basin Management Plans*. Copenhagen: European Topic Centre on Water.

Ford JD, Berrang Ford L, and Paterson J (2011) A sys tematic review of observed climate change adaptation in developed nations: A letter. *Climatic Change* 106: 327 336.

Garrelts H and Lange H (2011) Path dependencies and path change in complex fields of action: Climate adaptation policies in Germany in the realm of flood risk man agement. *Ambio* 40: 200 209.

Georgakakos AP, Yao H, Kistenmacher M, et al. (2011) Value of adaptive water resources management in Northern California under climatic variability and change: Reservoir management. *Journal of Hydrology* 412 413: 34 46.

Gosh S, Raje D, and Mujumdar PP (2010) Mahanadi streamflow: Climate change impact assessment and adaptive strategies. *Current Science* 98: 1084 1091.

Greater London Authority (GLA) (2005) *Adapting to Climate Change: A Checklist for Development*. London: London Climate Change Partnership.

Hallegatte S (2009) Strategies to adapt to an uncertain climate change. *Global Environmental Change* 19: 240 247.

Hallegatte S, Ranger N, Mestre O, et al. (2011) Assessing climate change impacts, sea level rise and storm surge risk in port cities: A case study on Copenhagen. *Climatic Change* 104: 113 137.

Han MY and Mun JS (2011) Operational data of the Star City rainwater harvesting system and its role as climate change adaptation and a social influence. *Water Science and Technology* 63: 2796 2801.

Handmer J (2008) Risk creation, bearing and sharing on Australian floodplains. *International Journal of Water Resources Development* 24: 527 540.

Hansen HS (2010) Modelling the future coastal zone urban development as implied by the IPCC SRES and assessing the impact from sea level rise. *Landscape and Urban Planning* 98: 141 149.

Hanson S, Nicholls R, Ranger N, et al. (2011) A global ranking of port cities with high exposure to climate extremes. *Climatic Change* 104: 89 111.

Hardoy J and Lankao PR (2011) Latin American cities and climate change: Challenges and options to mitigation and adaptation responses. *Current Opinion in Environmental Sustainability* 3: 158 163.

Haynes K, Coates L, Leigh R, et al. (2009). 'Shelter in place' vs. evacuation in flash floods. *Environmental Hazards Human and Policy Dimensions* 8: 291 303.

He J, Valeo C, and Bouchart FJC (2006) Enhancing urban infrastructure investment planning practices for a changing climate. *Water Science and Technology* 53: 13 20.

He JX, Valeo C, Chu A, et al. (2011) Stormwater quantity and quality response to climate change using artificial neural networks. *Hydrological Processes* 25: 1298 1312.

Hedger MM, Connell R, and Bramwell P (2006) Bridging the gap: Empowering decision making for adaptation through the UK Climate Impacts Programme. *Climate Policy* 6: 201 215.

Hellmuth ME, Moorhead A, Thomson MC, et al. (2007) (eds) *Climate Risk Management in Africa: Learning from Practice*. New York: International Research Institute for Climate and Society.

Henriques C and Spraggs G (2011) Alleviating the flood risk of critical water supply sites: Asset and system resilience. *Journal of Water Supply Research and Technology Aqua* 60: 61 68.

Hey DL and Philippi NS (1995) Flood reduction through wetland restoration: The Upper Mississippi River Basin as a case study. *Restoration Ecology* 3: 4 17.

Hinkel J, Nicholls RJ, Vafeidis AT, et al. (2010) Assessing risk of and adaptation to sea level rise in the European Union: An application of DIVA. *Mitigation and Adaptation Strategies for Global Change* 15: 703 719.

Hirabayashi Y and Kanae S (2009) First estimate of the future global population at risk of flooding. *Hydrological Research Letters* 3: 6 9.

Hochrainer S, Linnerooth Bayer J, and Mechler R (2010) Adaptation and risk financing. The European Solidarity Fund. Its legitimacy, viability and efficiency. *Mitigation and Adaptation Strategies for Global Change* 15: 797 810.

Howe PD (2011) Hurricane preparedness as anticipatory adaptation: A case study of community businesses. *Global Environmental Change Human and Policy Dimensions* 21: 711 720.

Hulme M (2009) *Why We Disagree About Climate Change: Understanding Controversy, Inaction and Opportunity*. Cambridge: Cambridge University Press.

Hulme M and Dessai S (2008) Negotiating future climates for public policy: A critical assessment of the development of climate scenarios for the UK. *Environmental Science and Policy* 11: 54 70.

Huntjens P, Pahl Wostl C, and Grin J (2010) Climate change adaptation in European river basins. *Regional Environmental Change* 10: 263 284.

Ihringer J (2004) Ergebnisse von Klimaszenarien und Hochwasserstatistik. In: *KLIWA Bericht 4*. München: KLIWA Symposium, S.153 168.

Immerzeel WW, Droogers P, de Jong SM, et al. (2009) Large scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing. *Remote Sensing and Environment* 113: 40 49.

Infrastructure Canada (2006) *Adapting Infrastructure to Climate Change in Canada's Cities and Communities: A Literature Review*. Quebec: Environment Canada.

Intergovernmental Panel on Climate Change (2012) *Special Report on Extremes (SREX)*, forthcoming.

Irfanullah HM, Azad MAK, Kamruzzaman M, et al. (2011) Floating gardening in Bangladesh: A means to rebuild lives after devastating flood. *Indian Journal of Traditional Knowledge* 10: 31 38.

Jabeen H, Johnson C, and Allen A (2010) Built in resilience: Learning from grassroots coping strategies for climate variability. *Environment and Urbanization* 22: 415 431.

Jackson BM, Wheater HS, Mcintyre NR, et al. (2008) The impact of upland land management on flooding: Insights from a multiscale experimental and modelling pro gramme. *Journal of Flood Risk Management* 1: 71 80.

Jones R (2011) *Northern Victoria Flood Review: Reflec tions and Analysis*. Melbourne: Centre for Strategic Economic Analysis at the University of Melbourne.

Jung IW, Chang H, and Moradkhani H (2011) Quantifying uncertainty in urban flooding analysis considering hydro climatic projection and urban development effects. *Hydrology and Earth System Sciences* 15: 617 633.

Kamal Heikman S, Derry LA, Stedinger JR, et al. (2007) A simple predictive tool for the lower Brahmaputra River basin monsoon flooding. *Earth Interactions* 11: 1 11.

Karamouz M, Hosseinpour A, and Nazif S (2011) Improvement of urban drainage system performance under climate change impact: Case study. *Journal of Hydrologic Engineering* 16: 395 412.

Kay AL, Crooks SM, Pall P, et al. (2011) Attribution of autumn/winter 2000 flood risk in England to anthro pogenic climate change: A catchment based study. Journal of Hydrology 406: 97 112.

Keim ME (2008) Building human resilience: The role of public health preparedness and response as an adapta tion to climate change. *American Journal of Preventive Medicine* 35: 508 516.

Kije Sipi Ltd (2001) *Impacts and Adaptation of Drainage Systems, Design Methods and Politics*. Ottawa: Natural Resources, Canada Climate Change Action Fund.

Kreibich H (2011) Do perceptions of climate change influence precautionary measures? *International Jour nal of Climate Change Strategies and Management* 3: 189 199.

Kreibich H, Christenberger S, and Schwarze R (2011) Economic motivation of households to undertake pre cautionary measures against floods. *Natural Hazards and Earth System Sciences* 11: 309 321.

Krysanova V, Dickens C, Timmerman J, et al. (2010) Cross comparison of climate change adaptation strate gies across large river basins in Europe, Africa and Asia. *Water Resource Management* 24: 4121 4160.

Kundzewicz ZW and Stakhiv EZ (2010) Are climate models 'ready for prime time' in water resources management applications, or is more research needed? *Hydrological Sciences Journal* 55: 1085 1089.

Kundzewicz ZW, Lugeri N, Dankers R, et al. (2010) Assessing river flood risk and adaptation review of projections for the future. *Mitigation and Adaptation Strategies for Global Change* 15: 641 656.

Kunreuther H and Michel Kerjan E (2009) *Encouraging Adaptation to Climate Change: Long Term Flood Insurance*. Washington, DC: Resources for the Future.

Lau CL, Smythe LD, Craig SB, et al. (2010) Climate change, flooding, urbanisation and leptospirosis: Fuelling the fire? *Transactions of the Royal Society of Tropical Medicine and Hygiene* 104: 631 638.

Lebel L, Manuta JB, and Garden P (2010a) Institutional traps and vulnerability to changes in climate and flood regimes in Thailand. *Regional Environmental Change* 11: 45 58.

Lebel L, Xu JC, Bastakoti RC, et al. (2010b) Pursuits of adaptiveness in the shared rivers of Monsoon Asia. *International Environmental Agreements Politics, Law and Economics* 10: 355 375.

Lemmen DS, Warren FJ, Lacroix J, et al. (2008) *From Impacts to Adaptation: Canada in a Changing Climate 2007*. Ottawa: Government of Canada.

Li LH, Xu HG, Chen X, et al. (2010) Streamflow forecast and reservoir operation performance assessment under climate change. *Water Resources Management* 24: 83 104.

Li LJ, Zhang L, Wang H, et al. (2007) Assessing the impact of climate variability and human activities on stream flow from the Wuding River basin in China. *Hydro logical Processes* 21: 3485 3491.

Lin YJ, Chang YH, Tan YC, et al. (2011) National policy of watershed management and flood mitigation after the 921 Chi Chi earthquake in Taiwan. *Natural Hazards* 56: 709 731.

Llosa S and Zodrow I (2011) *Disaster Risk Reduction Legislation as a Basis for Effective Adaptation*. Gen eva: United Nations.

London Climate Change Partnership (LCCP) (2002) *London's Warming: The Impacts of Climate Change on London*. London: Greater London Authority.

Lowe JA, Howard T, Pardaens A, et al. (2009) *UK Climate Projections Science Report: Marine and Coastal Pro jections*. Exeter: Met Office Hadley Centre.

Macdonald N, Werritty A, Black AR, et al. (2006) Historical and pooled flood frequency analysis for the River Tay at Perth, Scotland. *Area* 38: 34 46.

McEvoy D, Mtaczak P, Banaszak I, et al. (2010) Framing adaptation to climate related extreme events. *Mitigation*

and Adaptation Strategies for Global Change 15: 779 795.
McGray H, Hammill A, and Bradley R (2007) *Weathering the Storm: Options for Framing Adaptation and Devel opment*. Washington, DC: World Resources Institute.
McLeman R and Smit B (2006) Migration as an adaptation to climate change. *Climatic Change* 76: 31 53.
McLeod E and Salm RV (2006) *Managing Mangroves for Resilience to Climate Change*. Gland: The World Conservation Union (IUCN).
McNie EC (2007) Reconciling the supply of scientific information with user demands: An analysis of the problem and review of the literature. *Environmental Science Policy* 10: 17 38.
McSweeney K and Coomes OT (2011) Climate related disaster opens a window of opportunity for rural poor in northeastern Honduras. *Proceedings of the National Academy of Sciences of the United States of America* 108: 5203 5208.
Mailhot A and Duchesne S (2010) Design criteria of urban drainage infrastructure under climate change. *Journal of Water Resources Planning and Management ASCE* 136: 201 208.
Mechler R, Hochrainer S, Aaheim A, et al. (2010) Mod elling economic impacts and adaptation to extreme events: Insights from European case studies. *Mitigation and Adaptation Strategies for Global Change* 15: 737 762.
Meenawat H and Sovacool BK (2011) Improving adaptive capacity and resilience in Bhutan. *Mitigation and Adaptation Strategies for Global Change* 16: 515 533.
Melbourne Water (2005) *Implications of Potential Climate Change for Melbourne's Water Resources*. Melbourne: CSIRO Urban Water and Climate Impacts Groups.
Milly PCD, Betancourt J, Falkenmark M, et al. (2008) Stationarity is dead: Whither water management? *Sci ence* 319: 573 574.
Mirza MMQ, Dixit A, and Nishat A (2003) Special issue on flood problems and management in South Asia: Preface. *Natural Hazards* 28: vii ix.
Morimoto Y (2011) Biodiversity and ecosystem services in urban areas for smart adaptation to climate change: 'Do you Kyoto'? *Landscape and Ecological Engi neering* 7: 9 16.
Mourshed M (2011) The impact of the projected change in temperature in heating and cooling requirements in buildings in Dhaka, Bangladesh. *Applied Energy* 88: 3737 3746.
Naess LO, Bang G, Eriksen S, et al. (2005) Institutional adaptation to climate change: Flood responses at the municipal level in Norway. *Global Environmental Change* 15: 125 138.
New South Wales Department of Environment and Climate Change (NSW DECC) (2007) *Floodplain Risk Man agement Guideline Practical Consideration of Climate Change*. Sydney: New South Wales Government.
Pall P, Aina T, Stone DA, et al. (2011) Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature* 470: 382 386.
Parker DJ, Priest SJ, and Tapsell SM (2009) Understand ing and enhancing the public's behavioural response to flood warning information. *Meteorological Applica tions* 16: 103 114.
Parrott A, Brooks W, Harmar O, et al. (2009) Role of rural land use management in flood and coastal risk management. *Journal of Flood Risk Management* 2: 272 284.
Payne JT, Wood AW, Hamlet AF, et al. (2004) Mitigating the effects of climate change on the water resources of the Columbia River basin. *Climatic Change* 62: 233 256.
Pitt M (2007) *Learning Lessons From the 2007 Floods: An Independent Review by Sir Michael Pitt*. London: Cabinet Office.
Pontee NI and Morris L (2011) CoastRanger MS: A tool for improving public engagement. *Journal of Coastal Research* 27: 18 25.
Prudhomme C, Wilby RL, Crooks S, et al. (2010) Scenario neutral approach to climate change impact studies: Application to flood risk. *Journal of Hydrology* 390: 198 209.
Pui A, Lall A, and Sharma A (2011) How does the Inter decadal Pacific Oscillation affect design floods in Australia? *Water Resources Research* 47: W05554.
Queensland Floods Commission of Inquiry (QFCI) (2011) *Interim Report August 2011*. Brisbane: Queensland Floods Commission of Inquiry.
Quincey DJ, Richardson SD, Luckman A, et al. (2007) Early recognition of glacial lake hazards in the Hima laya using remote sensing datasets. *Global and Pla netary Change* 56: 137 152.
Raje D and Mujumdar PP (2010) Reservoir performance under uncertainty in hydrologic impacts of climate change. *Advances in Water Resources* 33: 312 326.
Ranger N, Hallegatte S, Bhattacharya S, et al. (2011) An assessment of the potential impact of climate change risk in Mumbai. *Climatic Change* 104: 139 167.

Raymond CM and Brown G (2011) Assessing spatial associations between perceptions of landscape value and climate change risk for use in climate change planning. *Climatic Change* 104: 653 678.

Reynard NS, Crooks SM, and Kay AL (2004) *Impact of Climate Change on Flood Flows in River Catchments*. Wallingford: Centre for Ecology and Hydrology.

Roggema R (2009) *Adaptation to Climate Change: A Spatial Challenge*. Dordrecht: Springer.

Rosenzweig C, Solecki WD, Blake R, et al. (2011) Developing coastal adaptation to climate change in the New York City infrastructure shed: Process, approach, tools and strategies. *Climatic Change* 106: 93 127.

Royal Commission on Environmental Pollution (RCEP) (2010) *Adapting Institutions to Climate Change*. London: The Stationery Office.

Scholz M and Yang QL (2010) Guidance on variables characterising water bodies including sustainable flood retention basins. *Landscape and Urban Planning* 98: 190 199.

Schwarze R and Wagner GG (2004) In the aftermath of Dresden: New directions in German flood insurance. *Geneva Papers on Risk and Insurance* 29: 154 168.

Semadeni Davies A, Hernebring C, Svensson G, et al. (2008) The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: Combined sewer system. *Journal of Hydrology* 350: 100 113.

Shukla J, Palmer TN, Hagedorn R, et al. (2010) Toward a new generation of world climate research and computing facilities. *Bulletin of the American Meteorological Society* 91: 1407 1412.

Shultz JM, Russell J, and Espinel Z (2005) Epidemiology of tropical cyclones: The dynamics of disaster, disease and development. *Epidemiologic Reviews* 27: 21 35.

Smit B, Burton I, Klein RJT, et al. (2000) An anatomy of adaptation to climate change and variability. *Climatic Change* 45: 223 251.

Smith MS, Horrocks L, Harvey A, et al. (2011) Rethinking adaptation for a 4 degrees C world. *Philosophical Transactions of the Royal Society A* 369: 196 216.

Smith TF, Daffara P, O'Toole K, et al. (2011) A method for building community resilience to climate change in emerging coastal cities. Futures 43: 673 679.

State of Queensland (2010) *Increasing Queensland's Resilience to Inland Flooding in a Changing Climate: Final Report of the Inland Flooding Study*. Brisbane: Queensland Government.

Stevens L (2008) *Assessment of Impacts of Climate Change on Australia's Physical Infrastructure*. Parksville: Academy of Technological Sciences and Engineering (ATSE).

Storbjork S and Hedren J (2011) Institutional capacity building for targeting sea level rise in the climate adaptation of Swedish coastal zone management. Lessons from Coastby. *Ocean and Coastal Management* 54: 265 273.

Thomas DSG and Twyman C (2005) Equity and justice in climate change adaptation amongst natural resource dependent societies. *Global Environmental Change* 15: 115 124.

Tompkins EL, Adger WN, Boyd E, et al. (2010) Observed adaptation to climate change: UK evidence of transition to a well adapting society. *Global and Environmental Change* 20: 627 635.

Tompkins EL, Lemos MC, and Boyd E (2008) A less disastrous disaster: Managing response to climate driven hazards in the Cayman Islands and NE Brazil. *Global Environmental Change* 18: 736 745.

Tribbia J and Moser SC (2008) More than information: What coastal managers need to plan for climate change. *Environmental Science Policy* 11: 315 328.

Tschakert P, Sagoe R, Ofori Darko G, et al. (2010) Floods in the Sahel: An analysis of anomalies, memory and anticipatory learning. *Climatic Change* 103: 471 502.

Tu TT and Nitivattananon V (2011) Adaptation to flood risks in Ho Chi Minh City, Vietnam. *International Journal of Climate Change Strategies and Management* 3: 61 73.

United Nations Development Programme (UNDP) (2007) *Human Development Report 2007/2008*. New York: United Nations.

United Nations International Strategy for Disaster Reduction (UNISDR) (2005) *Hyogo Framework for Action 2005 2015: Building the Resilience of Nations and Communities to Disasters*. Geneva: United Nations.

United Nations International Strategy for Disaster Reduction (UNISDR) (2011) *Global Assessment Report on Disaster Risk Reduction: Revealing Risk, Redefining Development*. Geneva: United Nations.

United States Climate Change Science Program (US CCSP) (2009) *Coastal Sensitivity to Sea Level Rise: A Focus on the Mid Atlantic Region*. Washington, DC: US Environmental Protection Agency.

Urwin K and Jordan A (2008) Does public policy support or undermine climate change adaptation? Exploring policy interplay across different scales of governance. *Global Environmental Change* 18: 180 191.

Van Dijk AIJM, Van Noordwijk M, Bruijnzeel SLA, et al. (2008) Forest flood relation still tenuous comment on 'Global evidence that deforestation amplifies flood risk and severity in the developing world' by Bradshaw CJA, Sodi, NS, Peh KS H et al. *Global Change Biology* 15: 110 115.

Vellinga P, Katsman C, Sterl A, et al. (2009) *Exploring High End Climate Change Scenarios for Flood Protec tion of the Netherlands*. De Bilt: KNMI.

Victoria State (2007) *State Flood Response Plan*. Mel bourne: Victoria State Emergency Service.

Victorian Floods Review (2011) Terms of reference. Available at: http://www.floodsreview.vic.gov.au/ about the review/terms of reference.html.

Vogel C and O'Brien K (2006) Who can eat information? Examining the effectiveness of seasonal climate fore casts and regional climate risk management strategies. *Climate Research* 33: 111 122.

Walker G and Burningham K (2011) Flood risk, vulner ability and environmental justice: Evidence and eva luation of inequality in a UK context. *Critical Social Policy* 31: 216 240.

Wamsler C and Lawson N (2011) The role of formal and informal insurance mechanisms for reducing urban disaster risk: A south north comparison. *Housing Stud ies* 26: 197 223.

Ward PJ, Marfai MA, Yulianto F, et al. (2011) Coastal inundation and damage exposure estimation: A case study for Jakarta. *Natural Hazards* 56: 899 916.

Warraich H, Zaidi AKM, and Patel K (2011) Floods in Pakistan: A public health crisis. *Bulletin of the World Health Organization* 89: 236 237.

Watts RJ, Richter BD, Opperman JJ, et al. (2011) Dam reoperation in an era of climate change. *Marine and Freshwater Research* 62: 321 327.

Webster TL, Forbes DL, Dickie S, et al. (2004) Using topographic LiDAR to map flood risk from storm surge events for Charlottetown, Prince Edward Island, Canada. *Canadian Journal of Remote Sensing* 30: 64 76.

Wegerich K (2008) Hydro hegemony in the Amu Darya Basin. *Water Policy* 10: 71 88.

Westra S (2011) *Adapting to Climate Change Revising our Approach to Estimating Future Floods*. Sydney: University of New South Wales.

White AB, Colman B, Carter GM, et al. (2012) NOAA's rapid response to the Howard A. Hanson Dam flood risk management crisis. *Bulletin of the American Meteorological Society* 93: 189 207.

Wilby RL (2007) A review of climate change impacts on the built environment. *Built Environment Journal* 33: 31 45.

Wilby RL (2009) *Climate for Development in South Asia (ClimDev SAsia): An Inventory of Cooperative Pro grammes and Sources of Climate Risk Information to Support Robust Adaptation*. Loughborough: Lough borough University.

Wilby RL and Vaughan K (2011) The hallmarks of orga nisations that are adapting to climate change. *Water and Environment Journal* 25: 271 281.

Wilby RL, Nicholls RJ, Warren R, et al. (2011) New nuclear build sites: Adaptation options over their full life cycle. *Proceedings of the Institution of Civil Engineers: Civil Engineering* 164: 129 136.

Wilby RL, Orr HG, Hedger M, et al. (2006) Risks posed by climate change to delivery of Water Framework Directive objectives. *Environment International* 32: 1043 1055.

Wilby RL, Troni J, Biot Y, et al. (2009) A review of cli mate risk information for adaptation and development planning. *International Journal of Climatology* 29: 1193 1215.

Wilkinson ME, Quinn PF, and Welton P (2010). Runoff management during the September 2008 floods in the Bleford catchment, Northumberland. *Journal of Flood Risk Management* 3: 285 295.

Wiseman J, Biggs C, Rickards L, et al. (2011) *Scenarios for Climate Adaptation Report*. Melbourne: Victorian Centre for Climate Change Adaptation Research (VCCCAR).

World Bank/United Nations (2010) *Natural Hazards, UnNatural Disasters. The Economics of Effective Prevention*. Washington, DC: World Bank.