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Adapting to flood risk under climate change

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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

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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);

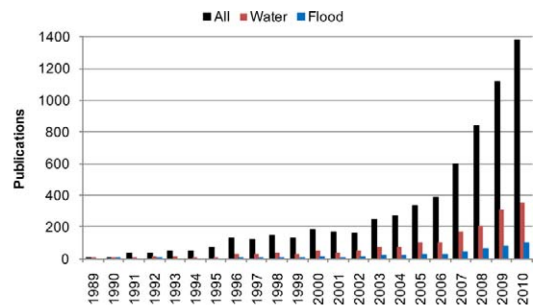

Figure 1. Annual number of peer-reviewed publications addressing all aspects of adaptation to climate change, water-sector issues (including flooding), and flooding (only)

- 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

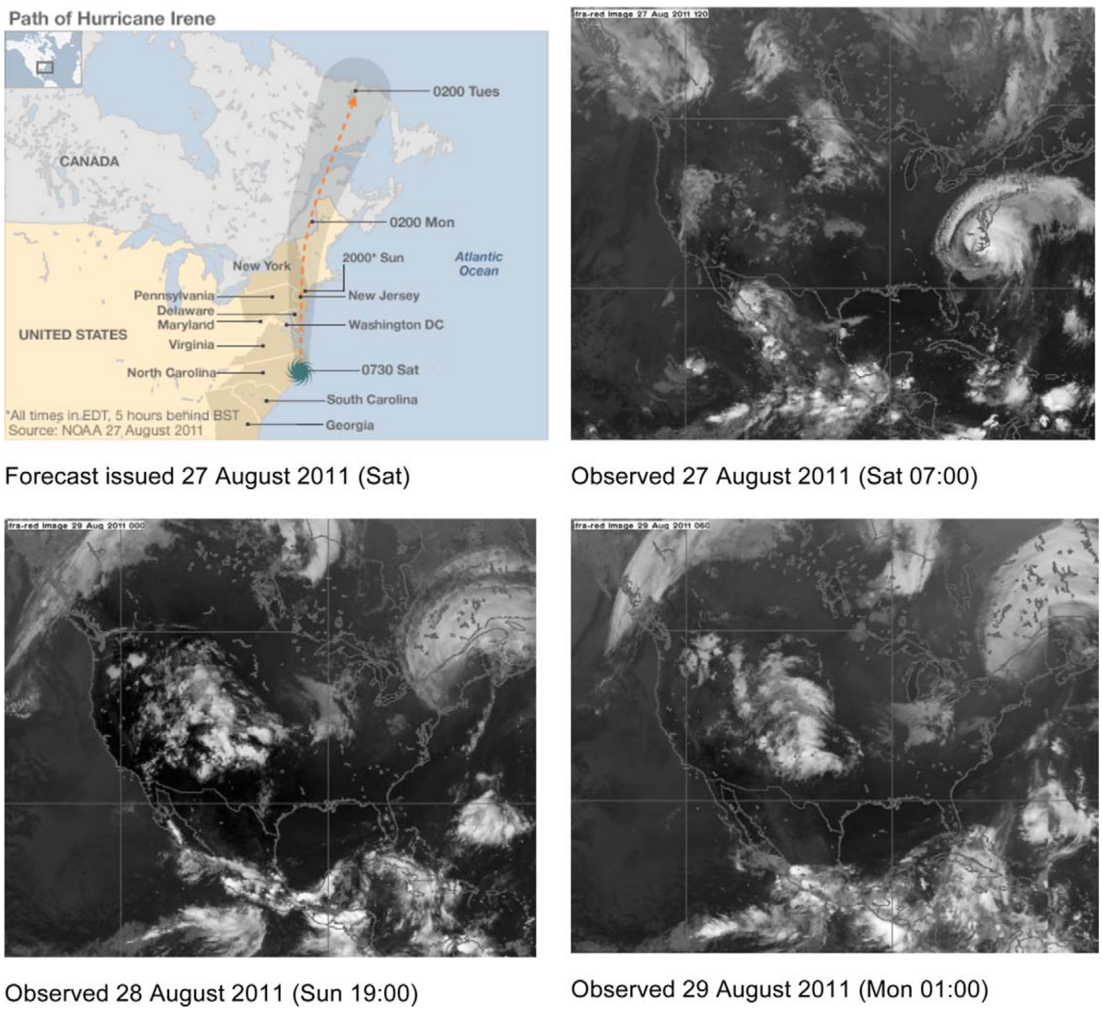

Figure 2. The widely acclaimed forecast (National Weather Service) and actual path of hurricane Irene, 27–29 August 2011 (all times in EDT)
Source of satellite imagery: http://www.metoffice.gov.uk/weather/satellite

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).

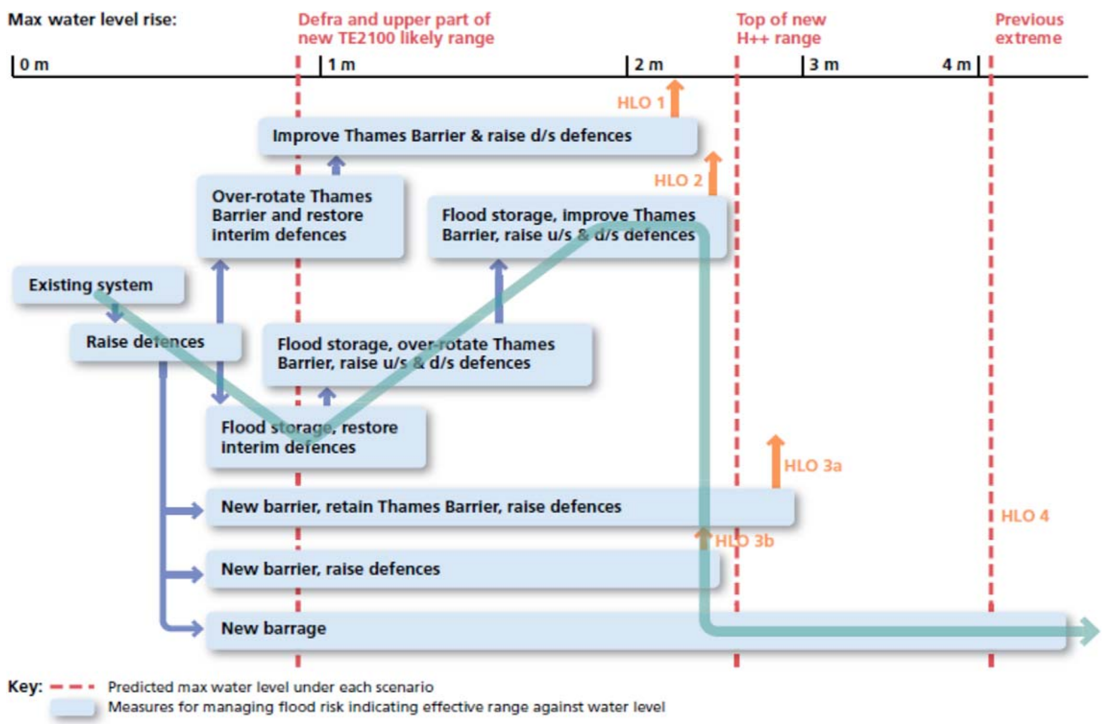

Figure 3. Conceptual diagram showing alternative adaptation pathways to provide flood defence for London despite uncertainty about sea level rise
Source: Lowe et al. (2009)

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

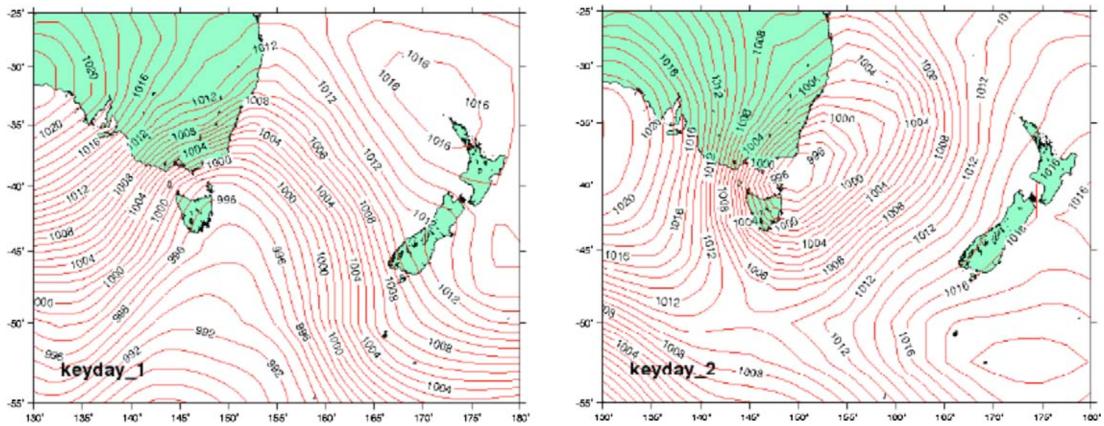

Figure 5. Surface pressure patterns with coincident severe rainfall and surge at Melbourne. Historically, keyday_1 has yielded 37% of severe rainfall and 84% of severe surge events of which around 10% and 7%, respectively, coincide.
Source: Abbs and McInnes (2010)

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.

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