Resilience to extreme weather

THE ROYAL SOCIETY

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Cover image
Waves crashing against a breakwater, Aberdeen harbour.

Contents

Foreword

People around the world today are being severely impacted by extreme weather: news reports of devastating events are an almost daily occurrence. In the future, the growing global population and changing climate are likely to exacerbate the current challenges. People's quality of life and prospects depend on their ability to cope, adapt and develop in the face of these challenges.

In 2015 there is a unique opportunity to protect people and their livelihoods for decades to come through the international agreements due to be reached on disaster risk reduction, sustainable development and climate change. By presenting evidence of trends in extreme weather and the different ways resilience can be built to it, we hope this report will galvanise action by local and national governments, the international community, scientific bodies, the private sector, and affected communities.

I would like to thank Professor Georgina Mace CBE FRS, the Working Group, and the Society's staff for their analysis of such a broad range of topics. I would also like to thank the many people who contributed throughout the project, including the Review Panel, who have helped focus this report on the most pressing issues.

Paul Nurse

Paul Nurse
President of the Royal Society

Resilience to extreme weather

Extreme weather can have devastating impacts. Images and reports from events such as Typhoon Haiyan and Hurricane Sandy, broadcast around the world, serve as reminders of the huge damage caused to societies and the suffering of individuals when extreme weather strikes.

This report considers the latest scientific evidence concerning the impact of extreme weather on people throughout the world. With maps and models it indicates where high densities of vulnerable people are more likely to be exposed to floods, droughts and heatwaves in coming decades and assesses actions that can help prevent disasters. It shows how, with forethought and planning, societies can do more than simply cope with extreme weather, and can instead adapt, progress and develop: how they can build resilience.

Globally, the risks from extreme weather are significant and increasing, mainly because larger numbers of people and their assets are being exposed to extreme weather. Many people are already highly vulnerable to the impacts. In the future, climate change will affect the frequency and severity of extreme events. Exactly how and where extremes will occur is not known but past trends can no longer be used to predict future extreme weather patterns.

Societies are not resilient to extreme weather today. To reduce this resilience deficit action needs to be taken by the international community, governments, local policymakers, the private sector and non-governmental organisations. Lessons can be learnt from past events. There are ways of protecting communities from the direct impact of extreme weather, including innovative approaches based on a growing understanding of the role of the natural environment in reducing hazards, and recognition of the importance of mobilising community support.

However, resilience requires much more than protection from specific hazards. Despite uncertainties about the nature and extent of future extreme weather, investing in systematic planning and prevention is necessary to reduce the costs – human and financial – of future disasters and responses to them. Agreeing and using measures of resilience would help to stimulate action and track progress, highlighting where effort is most needed.

In 2015 important international agreements will be reached about disaster risk reduction, sustainable development and climate change. The purpose, design and implementation of these agreements should be aligned and informed by robust evidence. These agreements and their implementation present an opportunity to develop a coherent strategy to build resilience to extreme weather locally, nationally and internationally, and to shape plans, responses and outcomes for decades to come.

Left
In 2011, unusually heavy rains combined with high sea tides triggered massive flooding in Thailand. Approximately one third of all provinces were affected.

Recommendations

PLANNING AND PREPARING

RECOMMENDATION 1

Governments have a responsibility to develop and resource resilience strategies, and will be most effective when they:

- focus on minimising the consequences of infrastructure failure rather than avoiding failure completely – for example by prioritising the resilience of critical infrastructure and having plans to minimise impacts when non-critical infrastructure fails;
- incorporate resilience-building into other relevant policies such as poverty alleviation and land-use planning;
- consider all the factors – the whole system – likely to be impacted by extreme weather, including geographical areas beyond those directly affected, and effects over decades;
- use a range of expertise from disciplines such as environmental management, climate change adaptation, disaster risk reduction and sustainable development, and from sources including the private sector, non-governmental organisations and local communities; and
- support and enable local action that is consistent with national resilience strategies.

RECOMMENDATION 2

At the international level, governments will be more effective when they act together to build resilience; sharing expertise, co-ordinating policy and pooling resources to confront common risks. To limit the need for costly disaster responses, more national and international funds will need to be directed to measures that build resilience to extreme weather.

PROTECTING PEOPLE AND THEIR ASSETS

RECOMMENDATION 3

It is important that the purpose, design and implementation of policy frameworks covering climate change, disaster risk reduction and development are aligned and consistent regarding extreme weather. There is an opportunity to do this in 2015 at the international level. In particular, efforts should be made to:

- emphasise the importance of the natural environment in the successor to the Hyogo Framework for Action, Sustainable Development Goals and future climate agreement – for example by highlighting its role in building resilience rather than just its role in driving risk;
- develop and use identical or comparable metrics in these policy frameworks to incentivise co-ordinated action and allow the effectiveness of different resilience-building measures to be compared;
- measure progress in implementing resilience-building strategies ('input' metrics) as well as the impacts of extreme weather ('outcome' metrics);
- align the timeframes and reporting protocols for the successor to the Hyogo Framework for Action and Sustainable Development Goals; and
- ensure international oversight to strengthen national and local monitoring capacity, particularly in the developing world, and to co-ordinate data collection.

RECOMMENDATION 4

Extreme weather events are hard to anticipate and their impacts can affect societies in unexpected ways. Those who make and implement policies need to take practical measures to protect people and their assets from extreme weather. These will be most effective when they:

- address multiple hazards and use a portfolio of defensive options;
- consider defensive options beyond traditional engineering approaches – for example, ecosystem-based and hybrid approaches that offer additional benefits to people – and consider the value of conserving existing natural ecosystems that are difficult or impossible to restore; and
- monitor and evaluate the effectiveness of interventions, in particular of more novel approaches such as ecosystem-based ones, and apply the results to improve future decision-making.

MAKING DECISIONS BASED ON EVIDENCE

RECOMMENDATION 5

The re/insurance sector has made considerable progress in evaluating the risks posed by extreme weather. These risks now need to be better accounted for in the wider financial system, in order to inform valuations and investment decisions and to incentivise organisations to reduce their exposure. This could be done through a requirement for public and private sector organisations to report their financial exposure to extreme weather at a minimum of 1 in 100 (1%) per year risk levels.

RECOMMENDATION 6

Information about extreme weather should be suitable for users' needs. Involving those who make and implement policy in research is an important way of ensuring the usefulness of information produced. Funders should encourage collaborations and ongoing dialogue between producers and users of knowledge.

RECOMMENDATION 7

Research to improve the understanding of risks from current weather and to model accurately future climate change impacts should be increased to provide relevant information for decision-makers, particularly at regional and local levels. In particular, efforts should be increased to:

- improve systematic observations and analyses in all regions of the world for trends in extreme weather and its impacts;
- expand interdisciplinary research to understand fully how people are affected by extremes;
- improve international collaborations between climate research institutes, which would allow optimum use of resources to overcome modelling limitations and improve regional and local models and forecasts; and
- produce appropriate data, models and knowledge that can be shared to inform more complete risk assessments for extreme weather.

Chapter one
Introduction

Left
Hurricane over Cuba, approaching Florida, USA.

Introduction

1.1 Aims and rationale

1.1.1 What does the report do?

This report is about enhancing people's resilience to extreme weather events such as floods, droughts and heatwaves. It addresses questions such as:

- How and for what reasons might the occurrence and impact of extreme weather events change in the future?
- What are the most effective ways of protecting people and building resilience?
- How can different sectors – locally, nationally and internationally – help build resilience?
- What should policymakers consider when making decisions about resilience-building?
- What does a 'resilience' approach to planning and management look like?

There is already a great deal of excellent work in this area, in fields as diverse as disaster risk management, international development, urban and landscape planning, climate change adaptation, and public health. We have not attempted to synthesise this information. Instead, we critically review the available evidence to highlight common issues in these diverse fields, and clarify the key processes and principles associated with successfully enhancing resilience.

The report considers what influences the trends in extreme weather events and the damage they cause. It aims to help policymakers take steps to effectively reduce the impact of, and build resilience to, extreme weather. It also suggests how the scientific community can develop better evidence to support this process. The emphasis of the report is on preventative measures rather than emergency planning. Post-disaster recovery is not covered.

1.1.2 Why extreme weather?

People need to be resilient to a range of events, from economic shocks to natural hazards such as earthquakes. This report covers resilience to extreme weather because of its increasing impact across the world and its relationship with climate change.

Extreme weather can cause significant damage; not only immediate loss of lives and assets, but also longer-term damage to livelihoods and economies. Despite difficulties in identifying changes in long-term trends, there is growing scientific consensus that anthropogenic climate change is likely to change the location, frequency, timing, duration and intensity of extreme weather[1]. It could also generate unprecedented extremes (section 2.3.1).

Climate change and its effect on extreme weather events will be strongly dependent on future greenhouse gas emissions. Therefore, an effective way to reduce the risks posed by such events is to mitigate climate change (Box 3). However, regardless of future emissions, events such as floods, droughts and heatwaves will continue to occur.

1. IPCC 2012 *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* (ed. Field, C B, Barros, V, Stocker, T F, Qin, D, Dokken, D J, Ebi, K L, Mastrandrea, M D, Mach, K J, Plattner, G-K, Allen, S K, Tignor, M & Midgley P M). Cambridge and New York: Cambridge University Press.

Over recent decades there has been progress in reducing the mortality risk worldwide due to extreme weather, although the number of lives lost is still increasing in some countries[2]. Evidence from past events (particularly similar events that have occurred in the same place but at different points in time – Box 1) suggests that lessons can be learnt from disasters and steps taken to build resilience to future extreme events.

However, the global economic cost of disasters has increased in recent decades[3]. It is estimated that between 1980 and 2004 the total cost[4] of extreme weather came to US$1.4 trillion (of which just one quarter was insured). Looking to the future, it is estimated that large coastal cities alone could face combined annual losses of US$1 trillion from flooding by mid-century (see Surat demonstration)[5]. Escalating observed and projected losses demonstrate the need to build resilience to extreme weather now.

1.1.3 Why now?

In 2015 major international agreements will be made on disaster risk reduction, climate change and sustainable development: a successor to the current Hyogo Framework for Action will be agreed at the World Conference on Disaster Risk Reduction in March 2015; a new set of global Sustainable Development Goals will be agreed in September 2015 when the Millennium Development Goals expire; and a new agreement on climate change, including adaptation, will be adopted in December 2015 (Box 4). These agreements and their implementation present a unique opportunity for a coherent strategy to enhance resilience to extreme weather locally, nationally and internationally and to shape plans, responses and outcomes for decades to come.

It is important that the purpose, design and implementation of these international processes are aligned (section 4.1.3). We hope that those involved in negotiating and implementing these agreements will consider scientific evidence and tools to support their decisions, and will act upon the recommendations offered in this report.

Recent scientific and technological advances also provide a significant opportunity to enhance resilience to extreme weather. Large scale, high resolution data and models are being further enhanced by new high bandwidth communications. Alongside the open data revolution, such tools provide policymakers with unprecedented access to reliable data with which to inform their decisions.

Escalating observed and projected losses demonstrate the need to build resilience to extreme weather now.

2. UNISDR 2011 *Global Assessment Report on Disaster Risk Reduction: Revealing Risk, Redefining Development.* Geneva: United Nations International Strategy for Disaster Risk Reduction.
3. This is disputed by some; different normalising approaches can lead to different results. As yet no perfect approach has been developed. See for example Neumayer, E & Barthel, F 2010 *Normalising economic loss from natural disasters: A global analysis.* Global Environmental Change **21**(1), 13-24, Centre for Climate Change Economics.
4. This is a inevitably a modest estimate of 'costs' since it does not take into account losses of things that are difficult to monetise (eg life, cultural heritage, psychological wellbeing, sense of place and ecosystem services) or impacts on the informal or undocumented economy.
5. These results assume socio-economic growth, climate change and subsidence, and no additional adaptation Hallegatte, S, Green, C, Nicholls, R J & Corfee-Morlot, J 2013 *Future flood losses in major coastal cities.* Nature Climate Change **3**, 802-806.

Above
Cyclone shelter in India. Photo by ADRA India via Flickr, used under CC BY ND 2.0.

BOX 1

Learning from past events

The two examples below illustrate how the impact of similar extreme events can be different if action is taken to build resilience.

Odisha cyclones:
1999 versus 2013

Odisha (formerly Orissa) is one of the most disaster-affected states in India. Two comparable events are the 'Super Cyclone' 05B in October 1999 with wind speeds up to 260 km/hr and Cyclone Phailin in October 2013 with wind speeds up to 220 km/hr[6]. In 1999 there were almost 9,000 people killed across 14 of Odisha's 30 districts[7]. By contrast, 21 lives were lost from the 2013 cyclone and 23 more from related flash flooding. Thanks to a range of disaster management systems, over 1.2 million people were evacuated nationally, including 850,000 in Odisha, constituting the largest evacuation in India for 23 years[8]. The difference in impacts in 1999 and 2013 demonstrates the effectiveness of building resilience through preparedness, early warnings, political commitment and technology.

In December 1999, Odisha was the first Indian state to create a State Disaster Management Agency. In collaboration with the World Bank-supported National Cyclone Risk Mitigation Project, Odisha has spent US$255 million on disaster preparedness, including early warning systems, yearly drills, infrastructure improvements, and evacuation planning[9]. Over 203 multipurpose cyclone shelters have been built and are managed by community-based Cyclone Shelter Management and Maintenance Committees[10]. In 2013, 75 Indian Red Cross shelters[11] provided safety to over 100,000 people, compared to 23 shelters for 42,000 people in 1999. Nationally, the Indian Meteorological Department has improved forecasting capabilities to provide effective early warnings such as those given four days before Phailin. In addition, satellite phones were distributed to the 14 most vulnerable districts in Odisha to ensure continued communication during the cyclone. Public awareness has also grown since 1999, and the anniversary of the 'Super Cyclone' on

6. Harriman, L 2013 *Cyclone Phailin in India: Early warning and timely actions saved lives.* Nairobi: UNEP Global Environmental Alert Service. (See http://na.unep.net/geas/archive/pdfs/GEAS_Nov2013_Phailin.pdf, accessed 26 August 2014).
7. Orissa State Disaster Management Authority 2013 *Orissa Disaster Rapid Action Force.* (See http://www.osdma.org/ViewDetails.aspx?vchglinkid=GL011&vchplinkid=PL034, accessed 26 August 2014).
8. International Federation of Red Cross and Red Crescent Societies 2013 *Disaster Relief Emergency Fund (DREF), India: Cyclone Phailin.* (See http://www.ifrc.org/docs/Appeals/13/MDRIN0013dref.pdf, accessed 26 August 2014).
9. World Bank 2013 *Cyclone Devastation Averted: India Weathers Phailin.* (See http://www.worldbank.org/en/news/feature/2013/10/17/india-cyclone-phailin-destruction-preparation, accessed 26 August 2014).
10. Odisha State Disaster Management Authority 2013 *Multipurpose Cyclone Shelters.* (See http://www.osdma.org/ViewDetails.aspx?vchglinkid=GL007&vchplinkid=PL040&vchslinkid=SL013#, accessed 26 August 2014).
11. *Op. cit.*, note 8.

29 October is now the designated Odisha Disaster Preparedness Day and the National Day for Disaster Reduction[12].

UK storm surge and floods:
1953 versus 2013

After the North Sea storm surge in December 2013, the UK Environment Agency estimated that around 2,600 homes had been flooded. However, 800,000 homes had been protected from flooding and there were no attributed deaths[13]. By comparison, a similar surge in 1953 led to the loss of 307 lives, with 30,000 people evacuated from their homes and 24,000 properties seriously damaged. Sub-standard post-war prefabricated homes, neglected coastal defences, unlimited coastal development, the absence of forecasting, lack of clear responsibility for embankment upkeep by authorities, and ineffective warnings exacerbated the devastation in 1953[14]. Since then, the UK has taken deliberate steps to safeguard lives, livelihoods and property. Learning from the 1953 storm has paid large dividends in terms of avoiding losses.

After the 1953 surge, the report of the Viscount Waverley Departmental Committee on Coastal Flooding[15] became the foundation of comprehensive coastal management policy in the UK. The keys to success since 1953 have been improvements in forecasting and warning systems, and enhanced co-operation via emergency response committees such as the Government's 'COBRA' Committee which brings together representatives of relevant departments and agencies in times of emergency. In addition, substantial investments in physical defences such as the Thames Barrier (completed in 1982), flood walls, beach nourishment and better water-level estimation techniques have also safeguarded lives, livelihoods and property. Since the upgrade in defences and the improvement to warning systems, no subsequent flood event has come close to the damage levels seen in 1953, even though subsequent events – such as January 1976, January 1978 and November 2007 – have approached or even exceeded 1953 sea levels.

Above
The Thames Barrier, River Thames, London.

12. Odisha State Disaster Management Authority (2009) *Orissa Disaster Preparedness Day. 29th October.* (See http://www.odisha.gov.in/portal/LIWPL/event_archive/Events_Archives/Orissa_Disaster_Peparedness_Day.pdf, accessed 26 August 2014).

13. Environment Agency 2014 *Board Meeting Floods Briefing, 6th February.* (See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/296059/Floods_briefing_for_6_February_2014_board_meeting.pdf, accessed 26 August 2014).

14. Baxter, P 2005 *The East Coast Big Flood, 31 January – 1 February 1953: a summary of the human disaster.* Philosophical Transactions of the Royal Society **363** (1831), 1293-1312.

15. Home Office, Scottish Office, Ministry of Housing and Local Government and Ministry of Agriculture and Fisheries 1954 *Report of the Departmental Committee on coastal flooding.* London: HMSO.

> ‘The capacity of individuals, communities and systems to survive, adapt, and grow in the face of stress and shocks, and even transform when conditions require it.’
>
> Definition of resilience, Rockefeller Foundation 2009[16].

1.2 Terminology and scope

1.2.1 Resilience

In this report we have chosen to look at ways of building resilience to extreme weather. This encompasses more than merely coping with these events. It also includes adapting and progressing in the face of extreme weather, and covers risks and solutions across the areas of climate change, disasters, environment and sustainable development.

Throughout the report we use the term resilience in a broad sense, in a similar manner to the Rockefeller report[16], defining resilience as ‘the capacity of individuals, communities and systems to survive, adapt, and grow in the face of stress and shocks, and even transform when conditions require it’. We take ‘systems’ to mean the combination of people with their environment and way of life, and generally use ‘people’ to refer to all of these. There are a number of alternative definitions of resilience in general use[17]. However, many of these are more complex and/or more specific.

Resilience can act as an umbrella term linking established concepts of risk and sustainability in a dynamic way[18], as it relates to the capacity of a system to deal with change. It encompasses but is broader than disaster risk reduction. Disaster risk reduction focuses on minimising the risk that a hazard leads to a disaster, and is therefore a more static concept. Resilience is not simply about minimising the risk of parts of the system failing but also about ensuring ‘safe’ failure so that the failure of any part of the system does not have catastrophic consequences.

Resilience can be specific or general. Specific resilience is the resilience of a particular group or part of a system to an individual stress, at a particular time, or in a particular place. General resilience is the capacity of social-ecological systems to adapt or transform in response to unfamiliar, unexpected and extreme events[19]. General resilience needs to be considered alongside specific resilience because being highly resilient to one stress or shock can increase vulnerability more generally[20].

16. Rockefeller Foundation 2009 *Building Climate Change Resilience.* (See http://www.rockefellerfoundation.org/uploads/files/c9725eb2-b76e-42eb-82db-c5672a43a097-climate.pdf, accessed 10 October 2014).

17. For example, UNISDR (UNISDR 2009 *Terminology on DRR*. Geneva: UNISDR (See http://www.unisdr.org/we/inform/terminology)) defines resilience as ‘the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions.’ The Intergovernmental Panel on Climate Change (IPCC 2014 *Summary for policymakers*. In: *Climate Change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of working group II to the fifth assessment report of the Intergovernmental Panel on Climate Change* (ed. Field, C B, Barros V R, Dokken D J, Mach K J, Mastrandrea M D, Bilir, T E, Chatterjee, M, Ebi, K L, Estrada, Y O, Genova, R C, Girma, B, Kissel, E S, Levy, A N, MacCracken, S, Mastrandrea, P R & White L). Cambridge and New York: Cambridge University Press.) defines resilience as ‘the capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.’

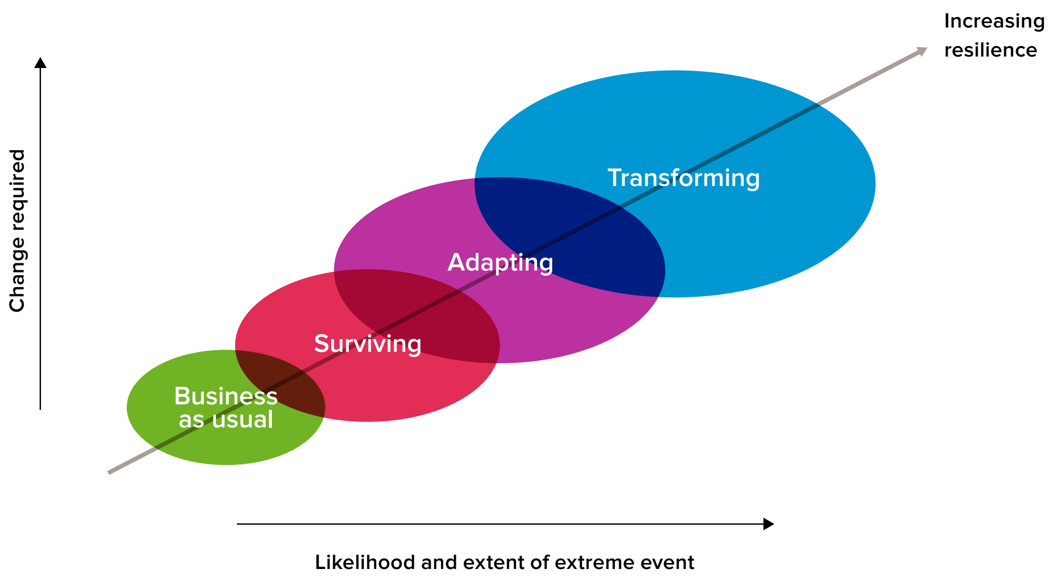
18. Weichselgartner, J, & Kelman, I 2014 *Geographies of resilience: challenges and opportunities of a descriptive concept.* Progress in Human Geography, 1-19 (DOI: 10.1177/0309132513518834).

19. Carpenter, S,Arrow,K J, Barrett, S, Biggs, R, Brock, W A, Crépin, A, Engström, G, Folke, C, Hughes, T P,Kautsky, N, Li, C, McCarney, G, Meng, K, Mäler, K, Polasky, S, Scheffer, M, Shogren, J, Sterner, T, Vincent, J R, Walke, B, Xepapadeas, A & de Zeeuw, A 2012 *General resilience to cope with extreme events.* Sustainability **4**, 3248-3259.

20. Folke, C, Carpenter, S R, Walker, B, Scheffer, M, Chapin, T & Rockstrom, J 2010 *Resilience Thinking: Integrating resilience, adaptability and transformation.* Ecology and Society **15**(4), 20.

FIGURE 1

Surviving, adapting and transforming as components of resilience



There are different components of resilience, any of which is likely to be better than simply suffering the consequences of stresses and shocks. Resilient responses start with surviving (sometimes referred to as ‘absorbing’), which involves coping with stresses and shocks but possibly living a reduced quality of life as a result. Much disaster risk reduction effort is focused on this as it is a prerequisite to any more positive response. A more active response, adapting, involves making changes to structures, lifestyles or livelihoods in response to the stresses and shocks, leading to an altered and potentially improved quality of life. Transforming goes one step further and involves making fundamental (as opposed to marginal) changes to the system. Transformation can entail a long-term shift or can happen rapidly in response to a trigger event. Like adaptation, transformation can be negative (unintended) as well as positive (proactive). Our focus is on positive adaptation and transformation.

These three responses – surviving, adapting and transforming – are processes rather than outcomes. They are overlapping rather than discrete, and are often pursued simultaneously (Figure 1).

In this report, chapter 3 covers interventions aimed at defending people from individual hazards. The interventions can therefore be classified as helping build specific resilience: if implemented without other measures they would mainly contribute to the ‘surviving’ component of resilience. The processes and principles necessary to build more general resilience are considered in chapter 4.

'A process of iteratively planning, implementing, and modifying strategies for managing resources in the face of uncertainty and change.'

Adaptive management, IPCC 2014[23].

1.2.2 Systems theory and adaptive management

The concept of resilience and systems theory both acknowledge the complex dynamics between different components of a system, as well as the ability of systems to change in response to disturbance[21]. In line with systems theory, resilient systems should comprise a diversity of complementary but independent components, with built-in redundancy to reduce the risk of catastrophic failure (section 4.1.1). Systems exist at all levels and the resilience of each level depends on the resilience of the larger system it is part of – ultimately global resilience. An understanding of the complex and unpredictable connections and interdependencies that exist in and between systems is a prerequisite for managing them in a way that fosters resilience[22].

'Adaptive management' is another important concept for understanding resilience and how to build it. The Intergovernmental Panel on Climate Change defines adaptive management as 'A process of iteratively planning, implementing, and modifying strategies for managing resources in the face of uncertainty and change. Adaptive management involves adjusting approaches in response to observations of their effect and changes in the system brought on by resulting feedback effects and other variables'[23].

Resilience-building is an ongoing process involving the use of new information and evaluation of existing measures to regularly update resilience planning and decision-making (Figure 2). An adaptive management process for building resilience to extreme weather would involve identifying and prioritising the risks and opportunities associated with extreme weather, implementing measures to address them, establishing monitoring arrangements, regularly assessing the effectiveness of interventions, evaluating progress and readjusting measures as a result[24].

21. Biggs, R, Schluter, M & Schoon M L 2014 *Principles for Building Resilience: Sustaining ecosystem services in social-ecological systems.* Cambridge: Cambridge University Press. In Press.

22. Walker, B H, Anderies, J M, Kinzig, A P & Ryan, P 2006 *Exploring Resilience in Social-Ecological Systems Through Comparative Studies and Theory Development: Guest Editorial, part of a Special Feature on Exploring Resilience in Social-Ecological Systems*. Ecology and Society, **11**(1), 12.

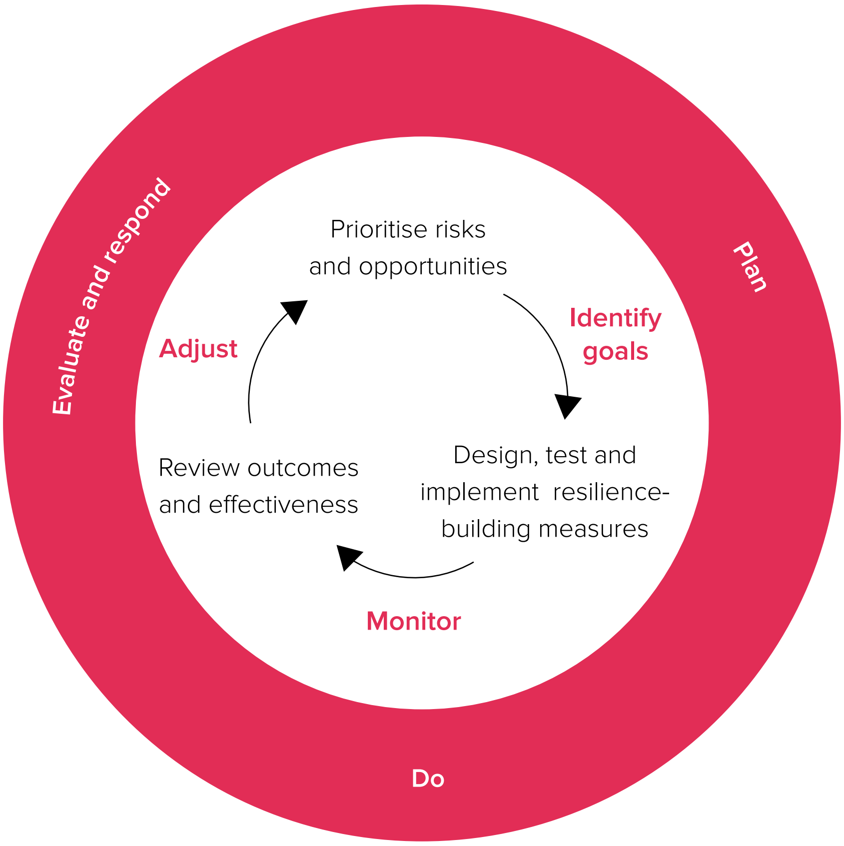
23. IPCC 2014 *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. Barros, V R, Field, C B, Dokken, D J, Mastrandrea, M D, Mach, K J, Bilir, T E, Chatterjee, M, Ebi, K L, Estrada, Y O, Genova, R C, Girma, B, Kissel, E S, Levy, A N, MacCracken, S, Mastrandrea, P R & White, L L). Cambridge and New York: Cambridge University Press.

24. National Research Council 2010 *America's climate choices. Informing an effective response to climate change.* Washington, DC: National Academies Press.

Knowledge of a system is often partial and incomplete[25]. For example, it is usually impossible to predict future extreme events with precision and accuracy. By recognising this uncertainty an adaptive management approach allows decisions to be made and actions taken in the absence of complete information, and results in policies with built-in flexibility[26]. Acting under uncertainty and accepting some risk of failure is often necessary to pursue opportunities for enhancing resilience (see Surat demonstration). In some cases the risk of inaction can be the greatest risk of all[27].

FIGURE 2

Adaptive management



25. Biggs, R, Schlüter, M, Biggs, D, Bohensky, E L, BurnSilver, S, Cundill, G, Dakos, V, Daw, T M, Evans, L S, Kotschy, K, Leitch, A M, Meek, C, Quinlan, A, Raudsepp-Hearne, C, Robards, M D, Schoon, M L, Schultz, L & West, P C 2012 *Towards principles for enhancing the resilience of ecosystem services.* Annual Review of Environment and Resources **37**, 421-448.

26. *Op. cit.*, note 21

27. The World Bank 2014 *World Development Report 2014: Risk and opportunity. Managing risk for development.* Washington DC: The World Bank (See http://siteresources.worldbank.org/EXTNWDR2013/Resources/8258024-1352909193861/8936935-1356011448215/8986901-1380046989056/WDR-2014_Complete_Report.pdf, accessed 10 October 2014).

1.2.3 Risk

The Intergovernmental Panel on Climate Change defines risk as 'The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur'[28]. A common way to estimate risk is to measure the exposure ('presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected'[29]) and vulnerability ('propensity or predisposition to be adversely affected… including sensitivity or susceptibility to harm and lack of capacity to cope and adapt'[30]) of people, and combine this with the severity and likelihood of a hazard. By 'hazard' we mean a physical event that may cause 'loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources'[31].

We consider reducing risk (the combination of hazard, exposure and vulnerability) as a core component of enhancing resilience. However, this on its own does not necessarily provide assurance about longer-term improvements in security or quality of life, or the ongoing capacity to adapt or transform in a dynamic manner.

28. IPCC 2014 *Summary for policymakers.* In: *Climate Change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of working group II to the fifth assessment report of the Intergovernmental Panel on Climate Change* (ed. Field, C B, Barros V R, Dokken D J, Mach K J, Mastrandrea M D, Bilir, T E, Chatterjee, M, Ebi, K L, Estrada, Y O, Genova, R C, Girma, B, Kissel, E S, Levy, A N, MacCracken, S, Mastrandrea, P R & White L). Cambridge and New York: Cambridge University Press.

29. *Op. cit.*, note 28.

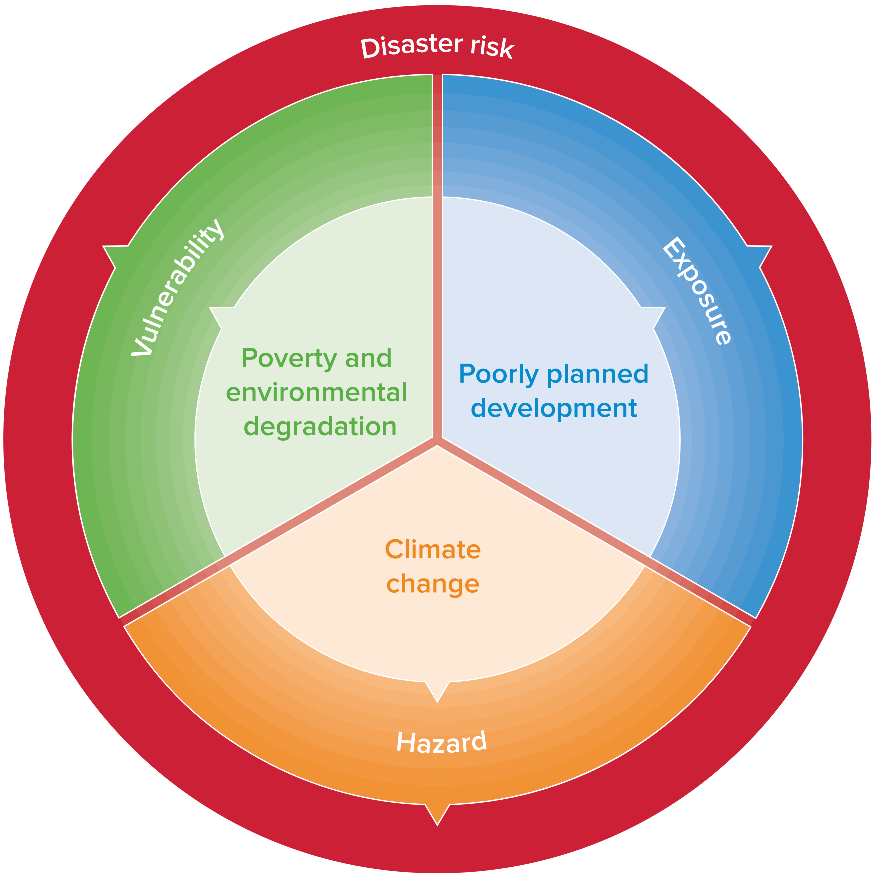
30. *Op. cit.*, note 28.

31. *Op. cit.*, note 28.

FIGURE 3

How risk results from the interaction of exposure, vulnerability and the hazard.

Disaster risk is determined by the occurrence of a hazard (eg a cyclone), which may impact exposed populations and assets (eg houses located in the cyclone path). Vulnerability is the characteristic of the population or asset making it particularly susceptible to damaging effects (eg fragility of housing construction). Poorly planned development, poverty, environmental degradation and climate change are all drivers that can increase the magnitude of this interaction, leading to larger disasters.



We consider floods (both coastal and river), droughts and heatwaves, since these are among the most frequent and damaging extreme events.

1.2.4 Which extreme events do we consider?

We adopt the Intergovernmental Panel on Climate Change's definition of extreme weather as 'The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable'[32], and the United Nations Office for Disaster Risk Reduction's definition of disaster as 'A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources'[33].

We consider floods (both coastal and river), droughts and heatwaves, since these are among the most frequent and damaging extreme events[34]. Chapter 2 focuses on the impact of these events and how that might change in the future as a result of demographic and climate change. We also consider sea level rise as it affects and can exacerbate coastal flooding. Extreme cold events are not covered. Storms feature in some of our examples, but are not considered in detail since they are highly complex compound events comprising multiple hazards (high winds[35], precipitation and often lightning) and are harder to analyse than the hazards considered. However the report's recommendations are relevant to all extreme weather and many are relevant to other types of natural hazard too.

The distinction between weather and climate, and similarly between extreme weather events and extreme climate events, is the length of time being considered. An extreme weather event (eg a flood) is associated with changing weather patterns within timeframes of less than a day to a few weeks. An extreme climate event (eg a drought) is associated with longer timeframes, and can be the accumulation of several weather events[36]. For simplicity, we use 'extreme weather' to refer to both weather and climate-related extreme events.

32. *Op. cit.*, note 1.

33. UNISDR 2009 *Terminology on DRR*. Geneva: UNISDR (See http://www.unisdr.org/we/inform/terminology).

34. World Meteorological Organisation 2014 *Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes (1970 – 2012).* Geneva: WMO. 'Storms, droughts, floods and extreme temperatures all figure on both lists of the worst disasters. Storms and floods accounted for 79 per cent of the total number of disasters due to weather, water and climate extremes and caused 54 per cent of deaths and 84 per cent of economic losses. Droughts caused 35 per cent of deaths, mainly due to the severe African droughts of 1975, 1983 and 1984.' pp.6.

35. Windstorms are not considered in detail.

36. *Op. cit.*, note 1.

1.2.5 Which solutions do we consider?

There is a huge range of options, applicable at different levels, which can reduce risk and enhance resilience to extreme weather. These have different strengths and weaknesses in different contexts, and the strength of the evidence regarding their cost-effectiveness varies.

In chapter 3 we consider options that can reduce the direct impact of floods, droughts and heatwaves. We focus on hazard specific ecosystem-based approaches, engineering-based approaches, and hybrids of the two, as well as briefly considering social approaches which can be effective against multiple hazards. In reality social and physical options should be considered together as they can be mutually reinforcing.

Chapter 4 explores some of the principles and processes for building general resilience to extreme weather. These include the roles and responsibilities of international, national and local institutions including governments and the private sector, the role of planning, and ways of measuring resilience.

Hypothetical examples are used to illustrate the issues raised in chapters 2, 3 and 4. In addition, chapter 5 is devoted to four practical demonstrations of how different communities are building resilience.

Chapter two
Extreme weather: impacts, trends and drivers

- Extreme weather can have a huge impact on people's lives and livelihoods. Over recent decades global mortality associated with weather-related extremes has declined, but global economic costs have risen. Societies are not well adapted to the extreme weather that is being experienced today.
- Future anthropogenic climate change and demographic change are likely to increase exposure of people and their assets to extreme weather. The risks from climate change can be underestimated if no account is taken of people's exposure and vulnerability.
- Decision-makers need local climate information to inform resilience planning.
- Uncertainty needs to be better integrated into decision-making processes to allow decisions to be taken with imperfect knowledge.
- Mitigation of and adaptation to climate change are both elements of a resilience approach to dealing with extreme weather.

Left
During a late season monsoon the village of Ko Tao, Thailand, was flooded by a sudden rainfall. Stores and homes were destroyed and people were left without shelter.

Hypothetical city 1 of 3

Hazards, exposure and vulnerability

City X is an urban agglomeration of 15 million people in a low lying coastal zone at the convergence of two large rivers. City X is exposed to multiple hazards. There are wet and dry seasons, meaning the city experiences flash floods as well as droughts and heatwaves. In addition, over-extraction of water increases groundwater salinity and land subsidence. Climate change is already contributing to more extreme weather and rising sea levels. The city has a resilience deficit now. Migration and urbanisation due to dwindling rural livelihoods leads to vulnerability as many young families move to the city with their elderly grandparents. Climate change will further harm local crop yields, forcing more migration to City X and creating food insecurity.

This year, City X experienced the most extreme weather on record, including heavy rainfall which caused landslides and extensive loss of life in hillside slums. Flooding in the business district produced high economic losses. Heatwaves have decreased outdoor labour productivity meaning construction has not kept pace with rapid urbanisation. Productivity in factories declined and deaths increased due to high temperatures indoors. Three cyclones hit City X within two years, one of which caused a 6 metre storm surge, destroying the largest coastal slum and leading to a cholera outbreak. The wetlands and mangroves that previously protected the city have been removed for fishing purposes (City X is the largest regional fish exporter). Storms damage the many fish farms, affecting the whole region. Coastal hotels on the beach have also been destroyed, harming the city's reputation as an idyllic holiday resort.

Extreme weather: impacts, trends and drivers

Extreme weather events can have a huge impact on people's lives and livelihoods. They are a significant barrier to sustainable development and can often prevent people from escaping poverty or pull people back into it[37]. Climate and demographic changes are key factors that will affect disaster risk in the future. Both must be considered when developing and implementing plans to build resilience to extreme weather.

2.1 Why are extreme events important?

Extreme events can affect people's lives in a variety of ways. The most obvious are immediate impacts such as loss of life, injury, loss of livelihoods and assets, and loss of cultural heritage and ecosystem services. Extreme events can also have long-term, indirect impacts on lives and economies, such as declines in school attendance, nutrition, health and productivity, and increases in inequality and unemployment. They can also have huge impacts on people's emotional and psychological wellbeing[38].

Over recent decades much progress has been made in reducing the mortality rates associated with extreme weather (Box 1). Rates are declining globally but are still increasing in countries with low Gross Domestic Product and weak governance[39]. Despite this generally positive trend, over the same period global economic losses from extreme weather have increased. Figure 4 shows the trend of increasing losses as a percentage of global GDP.

In addition, the Intergovernmental Panel on Climate Change has estimated that between 1980 and 2004 (a slightly shorter time period than shown in Figure 4), the total cost of extreme weather events came to US$1.4 trillion (of which just one-quarter was insured)[40]. This is likely to be an underestimate due to constraints and data gaps associated with assessing the impacts of extremes. Often direct effects are the only impacts that are recorded. In addition, impacts such as loss of cultural heritage and ecosystems services, and impacts on the informal or undocumented economy, are particularly difficult to measure (section 4.4). Global data about the impacts of extremes are also largely only available for insured losses and major disasters. The trend shown in Figure 4 is dominated by a small number of high impact disasters, notably North American and Asian storms and Asian and European floods[41].

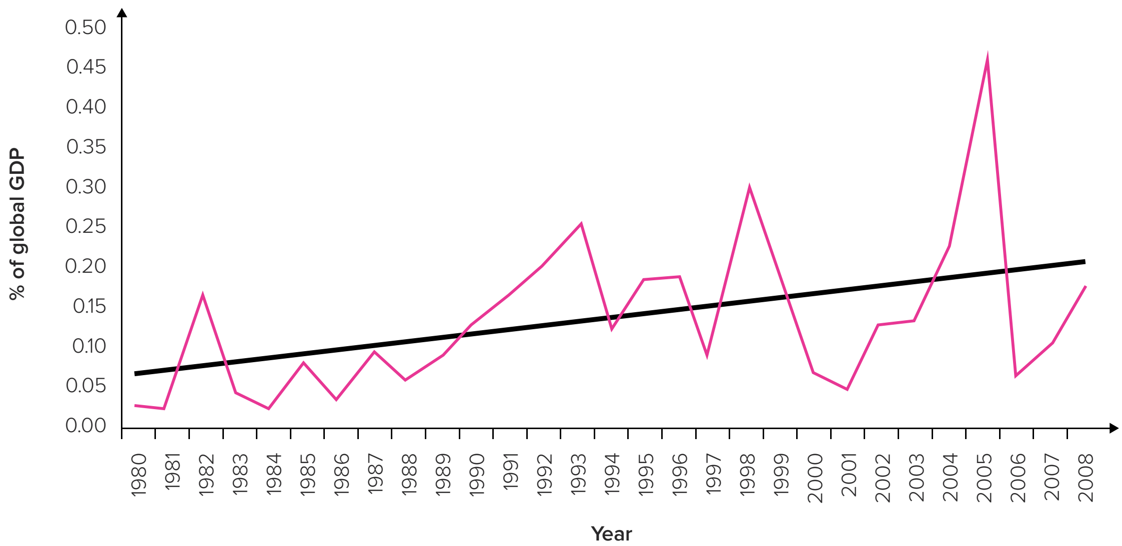
There is a growing number of national disaster databases which record smaller events. For example, the United Nations International Strategy for Disaster Reduction has developed a method for constructing small-scale disaster databases which is now being used in several countries[42] (section 4.4). However, lower intensity events remain an important gap in the understanding of extreme weather.

37. Mitchell, T, Guha-Sapir, D, Hall, J, Lovell, E, Muir-Wood, R, Norris, A, Scott, L & Wallemacq P 2014 *Setting, measuring and monitoring targets for reducing disaster risk: Recommendations for post-2015 international policy frameworks.* London: Overseas Development Institute (ODI).
38. *Op. cit.*, note 1.
39. *Op. cit.*, note 2.
40. *Op. cit.*, note 1.
41. Mohleji, S & Pielke, R Jr. 2014 *Reconciliation of Trends in Global and Regional Economic Losses from Weather Events: 1980–2008. Natural Hazards Review.* **15**(4), 04014009 (See http://dx.doi.org/10.1061/(ASCE)NH.1527-6996.0000141).
42. *Op. cit.*, note 2.

FIGURE 4

Global economic losses from extreme weather as % of global GDP

The global insured and uninsured economic losses from the two biggest categories of weather-related extreme events (category 6 'great natural catastrophes' and category 5 'devastating catastrophes'[43]) over the last 30 years from the Munich Re NatCatSERVICE database. A fitted line suggests that the percentage of GDP (adjusted for differences in national inflation) lost to major disasters is increasing over time[44].



43. Events fall into the 'great' category 'if the affected region's ability to help themselves is clearly overstretched and supra-regional or international assistance is required. Generally this involves thousands of fatalities, hundreds of thousands of people made homeless, or when the overall losses – depending on the economic circumstances of the country concerned – and/or insured losses reach exceptional orders of magnitude'. Events are categorised as 'devastating' if the number of fatalities exceeds 500 and/or the overall loss exceeds US$ 650 million (2010 US$). Munich Re 2011 *Catastrophe categories.* Münchener Rückversicherungs-Gesellschaft, Geo Risks Research, NatCatSERVICE, free registration at the following website is required to access the document: http://www.munichre.com/natcatservice

44. Figure taken from: Mohleji, S & Pielke, R Jr. 2014 *Reconciliation of Trends in Global and Regional Economic Losses from Weather Events: 1980–2008.* Natural Hazards Review **15**(4), 04014009 and reproduced with permission from ASCE.

If more countries recorded smaller impact events and maintained loss databases, these data could be used for better resilience planning. Consistency and comparability between events is also important; standardised metrics to assess the impact of extremes should be developed and used across the full range of events (section 4.4). Assessing the full impact of extreme weather will require expertise and interdisciplinary research across a broad range of disciplines; from engineering to behavioural science.

2.2 What is causing the current trend in economic losses?

Chapter 1 outlined how the risk presented by extreme weather can be estimated by combining the exposure and vulnerability of people and their assets with the severity and likelihood of the hazard. However, it is difficult to assess the relative contribution of exposure, vulnerability and hazard. Impacts could increase if extremes become more frequent or intense, if people and assets move to or grow in exposed areas, or if those exposed become more vulnerable.

Despite the difficulty of assessing why economic losses are growing, this is widely attributed to increasing exposure of people and assets. Exposure increases when populations grow or move to vulnerable areas. Economic growth can also result in greater exposure of assets and can therefore increase economic losses[45]. However, if economic growth is used to build resilience this can reduce the exposure and vulnerability of people and assets to extreme weather[46].

The vulnerability of people and assets varies across and within countries and this plays a significant role in current patterns of disaster loss. The impact of extreme weather is not uniform globally; although financial losses are far higher in absolute terms in developed countries, loss of life and economic loss as a percentage of GDP are higher in developing countries[47]. Populations in countries with a low Human Development Index make up only 11% of those exposed to hazards but account for 53% of disaster mortality[48].

The extent of current impacts and losses highlights that societies are not sufficiently well adapted to extreme weather being experienced today. This ‘resilience deficit’ can particularly be seen in developing countries but, even in developed countries, the impacts of extreme events are still harshly felt. In Europe, over the last 30 years, there has been a 50% rise in the economic costs of damage from extreme weather events in real terms[49] (see Europe demonstration). Dramatic impacts such as those caused by Hurricane Sandy in the US also illustrate this deficit.

Discussions of adaptation often focus on future risks but, because of the current resilience deficit, measures that aim to increase resilience can also have significant benefits today[50]. However to be effective in the long-term measures put in place to reduce the impact of today’s extreme weather need to be implemented with possible future changes in mind.

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45. *Op. cit.*, note 1.
46. *Op. cit.*, note 1.
47. *Op. cit.*, note 1.
48. UNDP 2010 *Reducing disaster risk: A challenge for development.* New York: UNDP.
49. Hov, Ø, Cubasch, U, Fischer, E, Höppe, P, Iversen, T, Kvamstø, N G, Kundzewicz, Z W, Rezacova, D, Rios, D, Santos, F D, Schädler, B, Veisz, O, Zerefos, C, Benestad, R, Murlis, J, Donat, M, Leckebusch, G C & Ulbrich, U 2012 *Extreme weather events in Europe: preparing for climate change adaptation*. Oslo: The Norwegian Academy of Science and Letters, Norwegian Meteorological Institute and EASAC (See www.easac.eu/home/reports-and-statements/detail-view/article/extreme-weat.html).
50. *Op. cit.*, note 28.

TABLE 1

Observed changes in weather-related extremes since 1950 (adapted from IPCC 2012[51])

Weather-related extremes	Observed changes (since 1950)	Attribution of observed changes
Temperature	Decrease in number of unusually cold days and nights at the global scale. Increase in number of unusually warm days and nights at the global scale. Increase in length or number of warm spells or heatwaves in many (but not all) regions.	Likely anthropogenic influence on trends in warm/cold days/nights at the global scale.
Precipitation	Statistically significant increases in the number of heavy precipitation events in more regions than those with decreases, but strong regional and sub-regional variations in the trends.	Medium confidence that anthropogenic influences have contributed to intensification of extreme precipitation at a global scale.
Droughts	Some regions of the world have experienced more intense and longer droughts, in particular in Southern Europe and West Africa, but opposite trends also exist, for example, in Central-North America and North-Western Australia.	Medium confidence that anthropogenic influence has contributed to some observed changes in drought patterns. Low confidence in attribution of changes in drought at the level of single regions due to inconsistent or insufficient evidence.
Floods	Limited to medium evidence available to assess climate-driven observed changes in the magnitude and frequency of floods at regional scale. There is a trend toward earlier occurrence of spring peak river flows in snowmelt and glacier-fed rivers.	Low confidence that anthropogenic warming has affected the magnitude or frequency of floods at a global scale. Medium to high confidence in anthropogenic influence on changes in some components of the water cycle (precipitation, snowmelt) affecting floods.
Extreme sea level and coastal impacts (caused by severe weather events)	Increase in extreme coastal high water worldwide related to increases in mean sea level in the late 20th century.	It is likely that there is an anthropogenic contribution to extreme high water via mean sea level rise.

51. *Op. cit.*, note 1.

2.3 How might impacts from extreme weather change in the future?

The impacts from extreme weather are dependent on the exposure and vulnerability of people and their assets as well as event likelihood and severity. How are each of these aspects expected to change in the future? Demographic changes and anthropogenic climate change will be key drivers of changes in these core elements and here we address what effect they may have.

2.3.1 Trends in extremes: the role of anthropogenic climate change

Weather-related extremes naturally vary over years and decades, meaning periods with more extremes and periods with fewer are expected. These variations are in part due to the intrinsic randomness of extreme weather and in part a response to changes in atmospheric, ocean and land surface processes over these time scales. In addition to this natural variability, anthropogenic climate change will also affect the location, frequency, timing, duration, and intensity of extreme weather events in the future. It could also generate unprecedented extremes, meaning that the past may not remain a good analogue for the future[52,53].

The quality and quantity of observations available for different extremes, and the number of studies assessing them, vary across different regions and timeframes. The amount of data available can be limited, particularly for the most infrequent extreme events, which can prevent the identification of statistically significant changes over time. For rare events (those with an annual probability of 0.01 or smaller), often those that people are most concerned about, there may be either no or very few observations of them[54].

An underlying challenge with projecting how extremes will change in the future because of anthropogenic climate change is that, because of limited data and analyses, it is not fully understood how extreme weather varies naturally. Climate change adds to the uncertainty, perhaps significantly, but does not change the fundamental management problem.

Despite these difficulties, there is evidence from observations that there have been changes in some extremes since 1950. Table 1 indicates the changes which have been observed to date, along with associated limitations in current understanding. Although changes have been observed, the influence of these changes on economic losses cannot be attributed nor excluded due to the short timescale of loss data[55].

Anthropogenic climate change will also affect the location, frequency, timing, duration, and intensity of extreme weather events in the future.

52. *Op. cit.*, note 1.
53. Milly, P C D, Betancourt, J, Falkenmark, M, Hirsch, R M, Kundzewicz, Z W, Lettenmaier, D P, & Stouffer, R J 2008 *Stationarity Is Dead: Whither Water Management?* Science **319**(5863), 573–574.
54. *Op. cit.*, note 1.
55. *Op. cit.*, note 41.

As well as incomplete knowledge of the earth system, an additional challenge for projecting how extremes might change is that the models used to do so have limitations. Particularly, the spatial resolution of global climate models (typically around 100 km) is insufficient to indicate where extreme events are likely to occur and who will be affected, due in part to computational limitations.

Climate models are much more reliable over long time periods and large spatial areas, for example over several decades and on global scales. They are also more reliable for temperature than for precipitation and wind. For weather extremes, which often occur at a more local level over shorter time scales, the ability to project changes due to either natural or anthropogenic climate change is more limited. Models also underestimate the high intensity, low probability events; the category into which weather extremes fall.

The degree of change will increase in the longer term (to 2100) and with higher concentrations of atmospheric greenhouse gases. Models do indicate that climate change could cause the following changes in extreme weather:

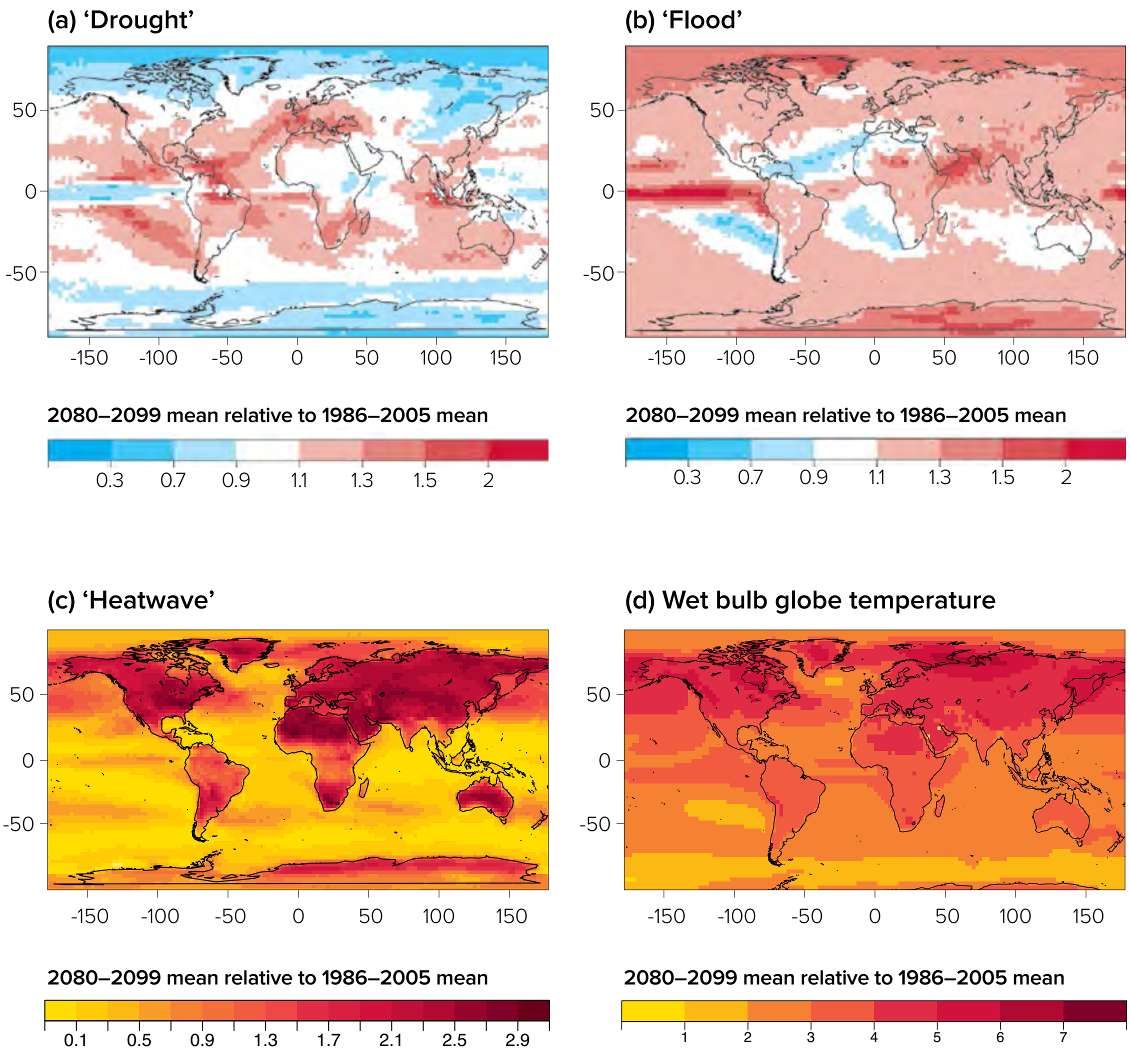
- increases in surface temperature, especially over land and in the high northern latitudes;
- increases in the incidence of high-temperature extremes (in absolute terms) and heatwaves;
- decreases in the incidence of low-temperature extremes (in absolute terms);
- increases in the frequency and intensity of heavy precipitation events;
- higher extreme sea levels and increased risks of coastal flooding due to sea level rise, more intense tropical storms and storm surges;
- a weaker but wider Hadley cell[56], which results in a spreading of subtropical dry zones towards the poles.

56. The Hadley cell is an atmospheric circulation between the equator and a latitude of approximately 30°. Warm, humid air rises at the equator and moves towards the poles in the upper troposphere, this air mass having lost most of its water vapour sinks in the subtropics and moves back towards the equator. Subtropical dry zones, trade winds and storms are all influenced by the Hadley cell.

FIGURE 5

The effect of climate change on extreme weather

Estimated fractional changes, shown as ratios for the period 2080–2099 relative to the period 1986–2005, in (a) 'Drought' intensity, defined as the annual-mean longest dry period , where a dry day is any day with < 1 mm of precipitation; (b) 'Flood' frequency, where a flood event is defined as a 5-day precipitation total exceeding the 10 year return level in the historical period (1986–2005); (c) 'Heatwave' frequency, where a heatwave is defined as more than 5 consecutive days where the summer mean daily minimum temperature exceeds that in the historical period (1986-2005) by more than 5 °C; and (d) Change in summer mean (Northern Hemisphere June-July-August, Southern Hemisphere December-January-February) wet bulb globe temperature (see Dunne et al., 2012[57], for the definition of the wet bulb globe temperature) under the RCP 8.5 emissions scenario.



57. Dunne, J P, Stouffer, R J & John, J G 2012 *Reductions in labour capacity from heat stress under climate warming,* Nature Climate Change, **3**, 563–566 (DOI:10.1038/nclimate1827).

BOX 2

River floods, droughts and heatwaves

Floods and droughts are extreme events that are difficult to project based solely on climate data. They are both 'compound events', as a combination of extreme events and underlying conditions come together to amplify the impact.

River floods, though related to precipitation extremes, are also affected by other atmospheric and surface conditions. For example, whether a flood occurs depends on whether the ground is already saturated when a heavy rainfall event occurs and can be made more likely through land use changes that reduce how much water can be absorbed into the ground. In addition, different regions of the world vary naturally in terms of tendency for flooding, for example, due to natural variations in soil permeability. The choice of a 5 day total is also somewhat arbitrary as the appropriate time window will vary with basin scale. Here the maps show 5-day precipitation totals exceeding the 10 year return level in the historical period (1986–2005) as an indicator for future flood events.

The 2012 Intergovernmental Panel on Climate Change report describes drought as generally 'a period of abnormally dry weather long enough to cause serious hydrological imbalance'. Drought can be defined in three different ways; it can be considered as meteorological, agricultural or hydrological. For this mapping, meteorological drought is considered, which is related to rainfall, rather than agricultural (related to soil moisture) and hydrological (related to stream flow). The metric used for drought is the mean annual maximum number of consecutive dry days, where a dry day is any day with <1 mm of precipitation.

In Figure 5 a heatwave is classified as five consecutive days 5 °C above the mean current night-time summer temperature. This metric is often used to estimate the impacts of heatwaves on human-health and mortality[58].

Figure 5d shows predicted future changes in wet bulb globe temperature, the indicator most relevant to outdoor labour productivity[59]. The wet bulb globe temperature is currently used to define occupational thresholds for environmental heat stress risks in industrial and United States military labour standards[60].

58. *Op. cit.*, note 1.

59. Kjellstrom, T, Lemke, B & Otto, M 2013 *Mapping occupational heat exposure and effects in South-East Asia: ongoing time trends 1980-2011 and future estimates to 2050.* Industrial Health **51**(1), 56–67 (DOI: 10.2486/indhealth.2012-0174).

60. US Department of the Army and Air Force 2003 *Heat Stress Control and Heat Casualty Management.* Washington DC: US Department of the Army and Air Force (See http://armypubs.army.mil/med/dr_pubs/dr_a/pdf/tbmed507.pdf., accessed 10 October 2014)

Figure 5 shows the spatial variations in future changes in (a) 'drought', (b) 'floods', (c) 'heatwaves' and (d) wet bulb globe temperature[61], the latter being used as an indicator for loss of outdoor labour productivity. The different metrics used for these four aspects of the climate are discussed in Box 2. The maps show the change between the present and 2100 under a high emissions scenario (one of the Representative Concentration Pathways – RCP 8.5 – used by the Intergovernmental Panel on Climate Change (see climate and exposure mapping methodology available at royalsociety.org/resilience). The RCP 8.5 emissions trajectory is used throughout the report. The RCP 8.5 pathway is projected to lead to an increase in global mean surface temperatures of 2.6 °C to 4.8 °C for 2081–2100 relative to 1986–2005[62]. Although RCP 8.5 is the highest emission scenario considered in the Intergovernmental Panel on Climate Change Fifth Assessment Report, current emissions trends are closest to this scenario[63]. In addition, using this pathway allows consideration of the upper bounds of risk. Figure 6 also shows projections of sea level rise, which is relevant to storm surges and coastal flooding.

As can be seen (Figure 5c), the likelihood of heatwaves increases in almost all regions around the world, particularly in the higher latitudes. So too does the wet bulb globe temperature (Figure 5d). The picture for droughts and floods is more nuanced (Figures 5a and 5b). In general, wet regions are likely to get wetter under climate change whilst dry regions become dryer. This means that areas currently struggling with floods and droughts might expect these challenges to become increasingly severe.

Sea level rise exacerbates the impact of extreme weather such as storm surges and coastal flooding. In addition, it increases gradual processes such as coastal erosion and saline intrusion into freshwater aquifers, which can have large impacts on people's lives. Figure 6 shows global mean sea level rise estimates for a high (RCP 8.5) and a low (RCP 2.6[64]) emissions trajectory. Under the higher emissions scenario, and therefore higher sea level rise trajectory, global mean sea level rise is projected to be around 0.75 metres by 2100. Under the lower emissions trajectory, and therefore low sea level rise, the global mean sea level rise is projected be 0.45 metres by 2100. The shaded sections of the figure show the uncertainty range, although higher rises are possible. The extent to which global temperatures rise as a result of greenhouse gas emissions, is the dominant factor influencing future sea level rise.

61. Wet bulb globe temperature is a combination of both actual air temperature and humidity. Increases in wet bulb globe temperature are used to determine losses in outdoor labour productivity; 26 °C is the upper wet bulb globe temperature at which physical labour can be conducted at full productivity. Increases in wet bulb globe temperature above this level result in lower outdoor labour productivity. Here we use this as an indicator for future constraints on development (see Kjellstrom, T, Lemke, B & Otto, M 2013 *Mapping occupational heat exposure and effects in South-East Asia: ongoing time trends 1980-2011 and future estimates to 2050.* Industrial health **51**(1), 56–67). The wet bulb globe temperature used here is based on the mean of the changes projected by the models in the coupled model intercomparison project, phase 5 archive.

62. IPCC, 2013 *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. Stocker, T F, Qin, D, Plattner, G-K, Tignor, M, Allen, S K, Boschung, J, Nauels, A, Xia, Y, Bex, V & Midgley, P M). Cambridge, UK and New York, USA: Cambridge University Press.

63. Friedlingstein, P, Houghton, R A, Marland, G, Hackler T A, Boden, T J, Conway, J G, Canadell, M R, Raupach, P & Le Quéré, C 2010 *Update on CO_2 emissions*, Nature Geoscience, **3**, 811–812 (doi:10.1038/ngeo1022)

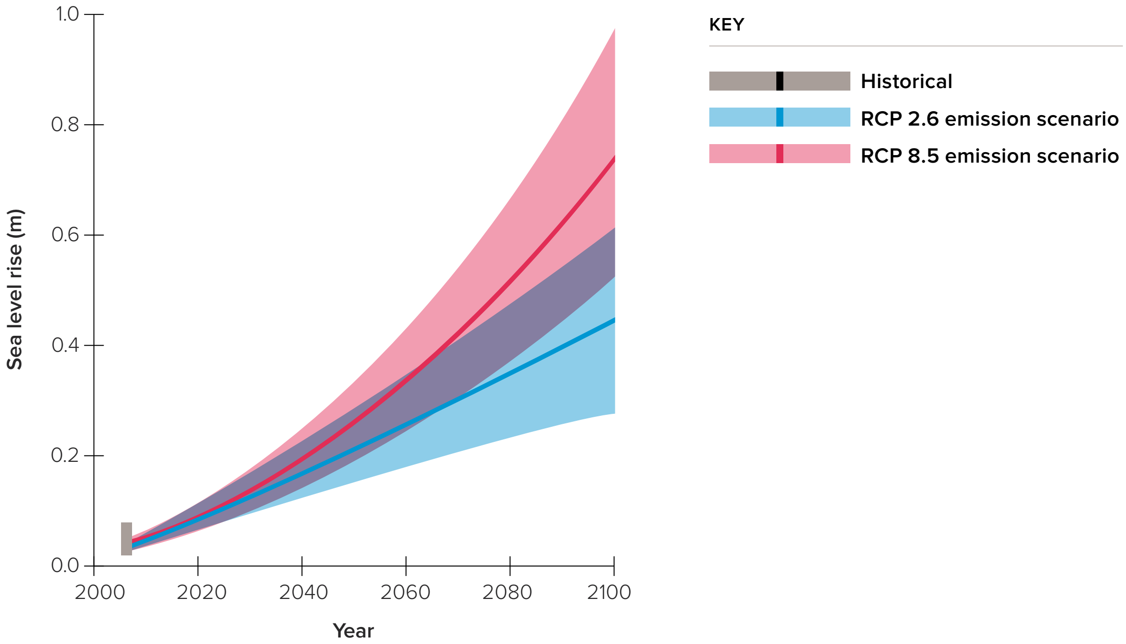
64. RCP 2.6 is the lowest emissions trajectory used by the Intergovernmental Panel on Climate Change.

The global figure does not convey the evidence that the most extreme changes will occur where people live – on land.

FIGURE 6

Global mean sea level rise

Projections of global mean sea level rise over the 21st century relative to 1986 – 2005 for a low (RCP 2.6) and high (RCP 8.5) emission scenario[65].



Although global mean metrics are often used, it is the local and regional variations that will be important for societies. Particularly for mean surface temperature, the global figure does not convey the evidence that the most extreme changes will occur where people live – on land (Figures 8, 9 and 10). For example, for a rise in global average temperature of 4 °C above pre-industrial levels, the higher rate at which land heats up when compared to the oceans means that the average land temperature increase would be 5.5 °C[66].

The current ability to project how climate and extreme weather might change in the future also presents a problem for resilience planning. At the moment climate modelling is not sophisticated enough to produce reliable climate impact predictions for the local scales and short time periods needed by decision-makers.

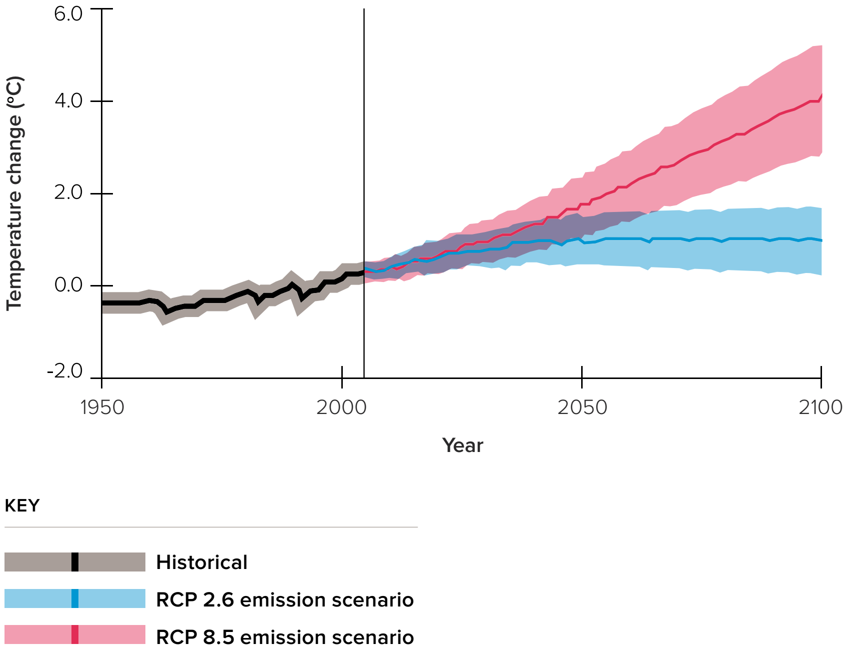
65. *Op. cit.*, note 62.

66. Met Office 2013 *The impact of four degree temperature rise.* (See http://www.metoffice.gov.uk/climate-guide/climate-change/impacts/four-degree-rise, accessed 31 July 2014).

FIGURE 7

Global average surface temperature change

Global average surface temperature change projected from the RCP 8.5 (the highest emissions pathway) and RCP 2.6 (the pathway with the most aggressive emissions reductions) over the 21st century relative to 1986 – 2005[67].



It is important to produce information that is most useful to decision-makers for risk assessments and risk management. In particular, regional and even local forecasts of climate change are needed. More comprehensive data collection and analyses of extremes, as well as improvements in modelling capability would result in better understanding of future changes in extreme weather. Efforts should be made to overcome computational limitations and international collaborations could allow limited resources to be invested efficiently. Improved understanding of extremes and projections can be used to inform decision-makers about what they may need to adapt to and allow them to make better informed decisions. Data, models and knowledge should be open and transparent to maximise access and research potential. The information produced, including from new technological opportunities, needs to be accessible, assessable, intelligible and useable to ensure that full use it made of it[68].

67. *Op. cit.*, note 62.

68. Royal Society 2012 *Science as an Open Enterprise.* London: Royal Society. (See https://royalsociety.org/~/media/Royal_Society_Content/policy/projects/sape/2012-06-20-SAOE.pdf, accessed 10 October 2014).

BOX 3

Climate change mitigation

This chapter highlights that the climate and extreme weather experienced in 2100 will be heavily dependent upon the emissions pathway that the world follows. Mitigation is the best way to minimise changes in extreme weather in the long term.

Mitigation is defined as 'a human intervention to reduce the sources or enhance the sinks of greenhouse gases'. For around the last 20 years international negotiations under the United Nations Framework Convention on Climate Change have been underway with the aim of achieving 'stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner'[69].

Despite international, national and local level efforts, global greenhouse gas emissions from human activities continue to grow. Total anthropogenic greenhouse gas emissions were the highest in human history from 2000 to 2010 and reached 49 (±4.5) gigatonnes of carbon dioxide equivalent per year in 2010. If emissions continue on the current trajectory, without additional steps to reduce them, the global mean surface temperature increase in 2100 will be between 3.7 and 4.8 °C compared to pre-industrial levels[70].

There are a large variety of mitigation options available, across a wide range of sectors from buildings and urban areas to agriculture and other land uses. So this upper end of future climate change is not unalterable. However, reaching the lower end and the much discussed target of 'a global average temperature increase of less than 2 °C relative to pre-industrial levels' will require much more rapid implementation of these options than seen today.

Regardless of the future emissions pathway, at least some level of climate change is already certain because of current and past greenhouse gas emissions. This change will need to be factored into decisions being made now about infrastructure, planning and investment. Measures will need to be put in place to ensure that societies are resilient to these future changes.

69. United Nations 1992, *United Nations Framework Convention on Climate Change*. (See http://unfccc.int/essential_background/convention/items/6036.php, accessed 10 October 2014)

70. IPCC 2014 *Summary for Policymakers*, In: *Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. Edenhofer, O, Pichs-Madruga, R, Sokona, Y, Farahani, E, Kadner, S, Seyboth, K, Adler, A, Baum, I, Brunner, S, Eickemeier, P, Kriemann, B, Savolainen, J, Schlömer, S, von Stechow, C, Zwickel, T & Minx, J C). Cambridge and New York: Cambridge University Press.

Although there will be improvements in ability to model extremes over time, it will be a slow process and uncertainty will remain. Better quantification of residual uncertainties will be needed. Scientists need to ensure that their communication of uncertainty is effective and understandable. Methods of dealing with uncertainty need to be integrated into the decision-making process so that decisions can be taken with imperfect knowledge. Strong communication and knowledge co-production are needed between scientists and decision-makers to ensure information generated is used (see Pickering demonstration). This model of knowledge generation should be supported by funders of research.

The extent of climate change in the future depends heavily on the amount of greenhouse gases released into the atmosphere in the future (Figure 7). This adds an additional layer of uncertainty onto estimating future changes. In 2100, although the magnitude of climate change will be larger under all feasible emissions scenarios, the severity of the change will be strongly dependent on the amount of greenhouse gases emitted during the 21st century. Although this report focuses on adapting to change, the best way to reduce the most severe changes in extreme weather is to mitigate climate change by limiting greenhouse gas emissions (Box 3). However, adaptation will still be needed to increase resilience to current extreme weather and those changes we are committed to because of current and past emissions of greenhouse gases.

2.3.2 Demographic trends and increasing exposure to extreme weather

The exposure of people and assets to extreme weather must be taken into account when considering how future risks might change. Climate change will not happen in an otherwise stationary system: the global population will continue to grow, demographic patterns will alter and people will continue to move within and between countries. The risks from climate change can be underestimated if no account is taken of people's exposure and vulnerability.

Demographic trends such as population growth and urbanisation have greatly influenced the observed patterns of loss from extreme weather. During the 19th and 20th centuries the global population has grown from around 1 billion (in 1825) to 7 billion in 2011. One of the major population migration trends of the 20th and 21st centuries has been urbanisation; today, around 50% of the global population live in urban areas. The age composition has also shifted; in 2000 the number of people aged 60 years and over outnumbered those less than 4 years of age for the first time[71].

Socioeconomic conditions also play a big role in vulnerability, as demonstrated by the uneven patterns of mortality and economic losses within developed and developing countries. Whilst economic growth can help to increase resilience, if poorly managed, it can lead to greater exposure of assets to extremes and therefore greater economic losses[72].

The risks from climate change can be underestimated if no account is taken of people's exposure and vulnerability.

71. Royal Society 2012 *People and the Planet,* London: Royal Society. (See https://royalsociety.org/~/media/Royal_Society_Content/policy/projects/people-planet/2012-04-25-PeoplePlanet.pdf, accessed 10 October 2014).

72. UNISDR 2013 *Global Assessment Report on Disaster Risk Reduction. From shared risk to shared value: the business case for disaster risk reduction.* Geneva: UNISDR (See http://www.preventionweb.net/english/hyogo/gar/2013/en/home/GAR_2013/GAR_2013_2.html, accessed 6 October 2014).

Urbanisation leads to a concentration of people and economic assets; when this happens in areas that experience extreme weather it can lead to big increases in exposure. Many of today's cities are located in extreme weather prone areas. Coastal settlements and those in mountainous areas can be particularly at risk[73]. Urbanisation can also exacerbate extreme weather; raising flood risk by increasing run off concentration, making land and mud slides more likely through deforestation, and worsening heatwaves through the urban heat island effect.

Rapid urbanisation presents a challenge to governments, particularly if they lack effective governance and planning, financial resources or the political will to invest in developing services and infrastructure for growing urban areas[74]. Highly vulnerable urban populations have grown as a result. Often the most vulnerable, those who are poor and marginalised, are those who live in the most exposed areas. In many places around the world people have moved into flood-prone areas or onto land that is at risk of slope failure in mountainous areas[75]. Around one billion people world-wide live in informal settlements which are likely to be at higher risk due to poor infrastructure, lack of services and low-quality housing. They are also typically the parts of settlements most likely to be located in areas of higher exposure[76].

People migrate within and between countries for economic, political, social and environmental reasons. Urbanisation is often driven by rural poverty. A possible increase in risk could be seen as an acceptable trade off in the face of a perceived opportunity for a better life. Or there may be limited choices involved[77]. Research suggests that migrations take place, in most parts of the world, away from areas that are degraded to areas that are generally better, so do not necessarily lead to increased exposure or vulnerability. However, the exception is migration to coasts and coastal cities that may be prone to floods and cyclones (see Surat demonstration)[78].

Mobility is often used as an adaptation response to environmental (and social) changes. Increased migration may be a response to future climate change and environmental degradation. However, increased losses from extreme events may reduce the resources that people depend upon to migrate. This means that people with high vulnerability may be unable to move away from areas of high exposure[79].

73. Da Silva, J 2012 9th Brunel international lecture shifting agendas: Response to resilience – The role of the engineer in disaster risk reduction. (See http://www.ice.org.uk/Events-conferences/Recorded-lectures/Lectures/9th-Brunel-International-Lecture-Shifting-Agendas-, accessed 10 October 2014)

74. *Op. cit*., note 73.

75. *Op. cit*., note 1.

76. *Op. cit*., note 1.

77. *Op. cit*., note 1.

78. De Sherbinin, A, Levy, M, Adamo, S, MacManus, K, Yetman, G, Mara, V, Razafindrazay, L, Goodrich, B, Srebotnjak, T & Aichele C 2012 *Migration and risk: net migration in marginal ecosystems and hazardous areas.* Environmental Research Letters **7**(4) 045602 (DOI: 10.1088/1748-9326/7/4/045602).

79. The Government Office for Science 2011 *Foresight: Migration and Global Environmental Change.* London: The Government Office for Science.

It is expected that the global population will continue to grow, become increasingly urban and societies will continue to age over the next century. According to the 2010 medium projection of the United Nations, by 2050 the world will have 9.3 billion people[80]. Urbanisation trends are also projected to continue; it's estimated that by 2050 around 75% of the global populations will live in urban areas. Most of this growth will occur in developing nations (around 95%)[81].

Projections of future population growth, urbanisation patterns and aging indicate that exposure to extreme weather will continue to increase[82]. It has been estimated that in Africa and Asia there could be between 114 and 192 million more people living in floodplains in urban areas in 2060 than in 2000[83].

2.3.3 Bringing climate and demographic change together

This section of the report looks at how projected demographic changes and projected changes in extremes might interact, up to 2100, to affect the level of exposure to different extremes: floods, droughts and heatwaves. We also look at how global mean sea level rise will affect the average person in 2100. The projections of population are based on a continuation of current trends; of urbanisation, other migration and poverty reduction with population peaking in 2070 and falling to 9 billion by 2100. The second Shared Socioeconomic Pathway (SSP2) is used for these projections[84]. The projection of climate change and its effect on extreme events is that used for Figure 5. The full methodology for the analysis below can be found online at royal society.org/resilience.

80. These projections are based upon a series of assumptions about how fertility rates will change in different countries, so are associated with some uncertainty, as with all projections.

81. Godrey, N & Savage, R 2012 *Future Proofing Cities: Risks and opportunities for inclusive urban growth in developing countries.* Epsom: Atkins. (See http://r4d.dfid.gov.uk/pdf/outputs/urbanisation/FPC_Report_FINAL.pdf, accessed 26 August 2014).

82. *Op. cit*., note 28.

83. *Op. cit*., note 79.

84. The SSPs are a set of five scenarios, or storylines for the main characteristics of future development path. The demographic trends used in this report are based on the SSP – 'Middle of the Road or Current Trends Continue'. More information on the SSPs can be found online at royalsociety.org/resilience.

Flood and drought

Climate change will drive wet regions to get wetter whilst dry regions become dryer. Figure 8 shows the increase in the number of 'exposure events'[85] to droughts and floods in 2090 under a high emissions pathway. Climate change will cause the number of flood and drought exposure events to increase, regardless of future population growth (Figure 8a). However, when population growth is taken into account, an additional billion flood exposure events[86] and an additional 600 million drought exposure events are expected per year by 2090.

The increase in the exposure to flood and drought risk is unlikely to be evenly distributed. The trends in population growth act to exacerbate the increasing exposure in many regions, particularly East, West and Central Africa, India and South East Asia. In China, the population is projected to be lower in 2090 than today. The exposure is therefore lower with a 2090 population than a 2010 population. Despite this, the number of people at risk from flood and drought is still likely to increase in China due to climate change under a high emissions scenario.

FIGURE 8

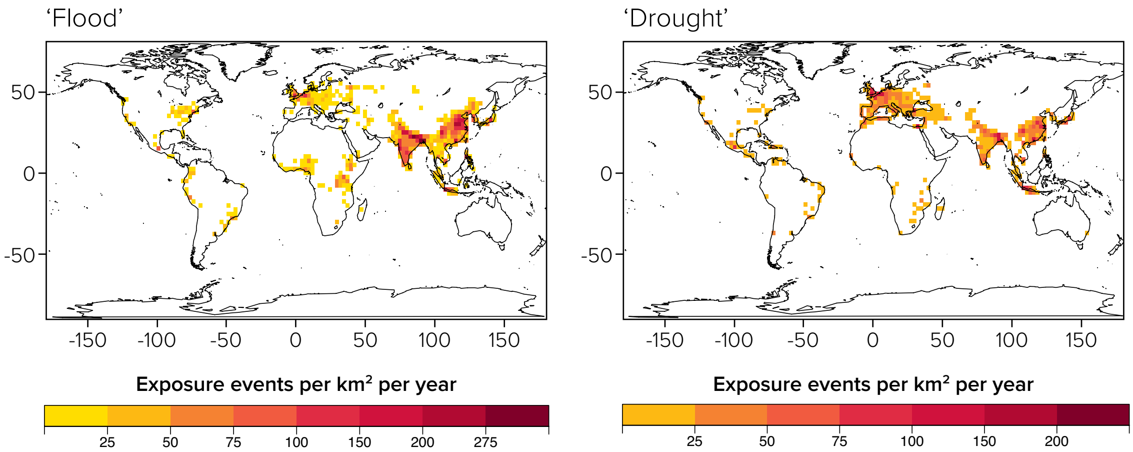
Estimated change in exposure to 'floods' and 'droughts' resulting from projections of 21st century climate and demographic change.

(a) Estimates of changes in the mean number of 'flood' (left) and 'drought' (right) (see Box 2 for definitions) exposure events per year and per km^2 as a result of changes to climate in 2100 under RCP 8.5 emissions scenario and assuming the 2010 population; (b) as for (a) but for the 2090 population under the SSP2 population scenario; (c) time-series of the estimated change in the number of 'flood' (left) and 'drought' (right) exposure events with population change under SSP2 (red-line) and without population change (black-line).

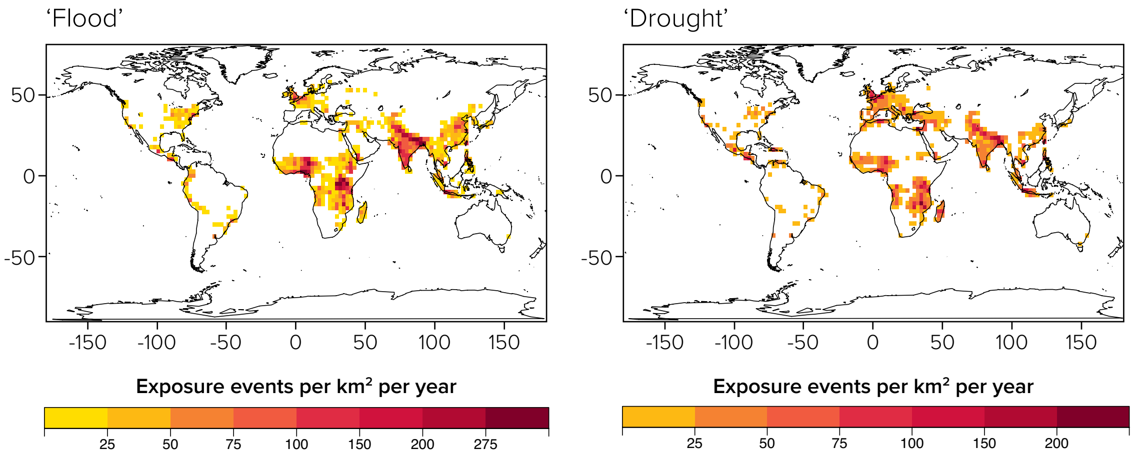
85. Where the number of exposure events = size of the vulnerable population x frequency of climate extreme.

86. Where a flood exposure event = number of those exposed to floods x frequency of floods.

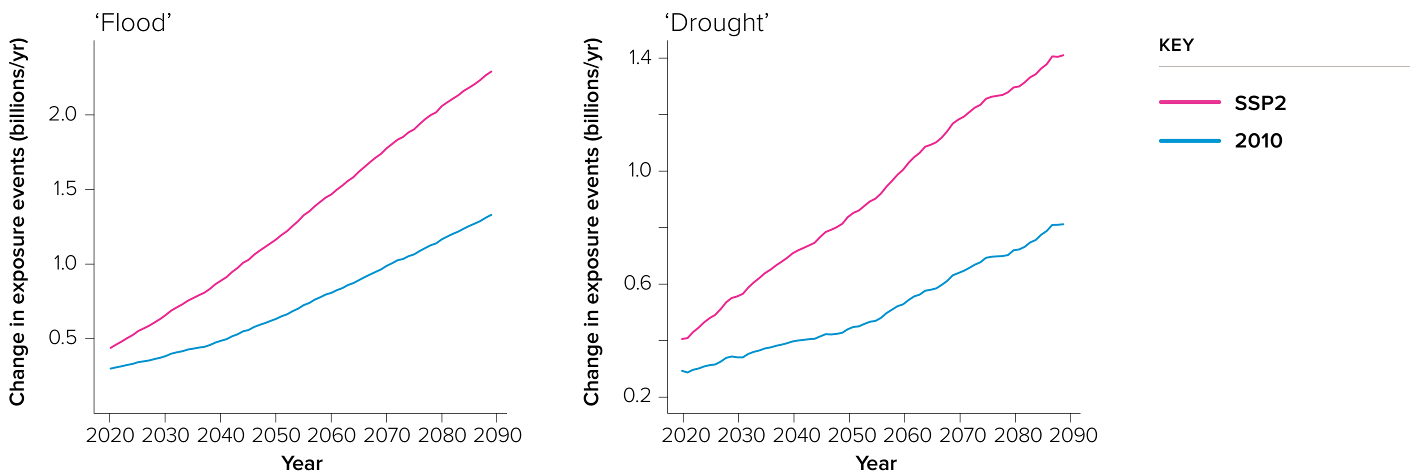
(a) Change in exposure (2010 population)



(b) Change in exposure (2090 population)



(c) Time-series of exposure



Temperature rise

Rising temperatures and heatwave extremes could have potentially large impacts on human well-being (see Europe demonstration). Certain sections of the population can be particularly vulnerable to different extremes. Changes in the proportion of vulnerable groups of people need to be taken account of when assessing future risk. For heatwaves the elderly population are particularly vulnerable, as are children and those whose livelihoods are heavily dependent upon natural resources.

A section of the population that is often overlooked when vulnerabilities to heatwaves and rising temperatures are discussed is the working population; people who work outdoors or in indoor environments without air conditioning can suffer from health-related effects, such as heat stress, and overall decreases in well-being in addition to negative impacts on their livelihoods. Rising temperatures affect the productivity of those conducting physical labour, which could have wider impacts on economic productivity and food production. People naturally acclimatise to modest temperature change, for example through physiological changes and through behaviour change, such as changing the hours worked in summer months. However, there are limits to both. Here we look at how increasing temperatures will affect the number of heatwave exposure events the elderly population experience and the impact of increasing temperatures on outdoor labour productivity.

Heatwaves

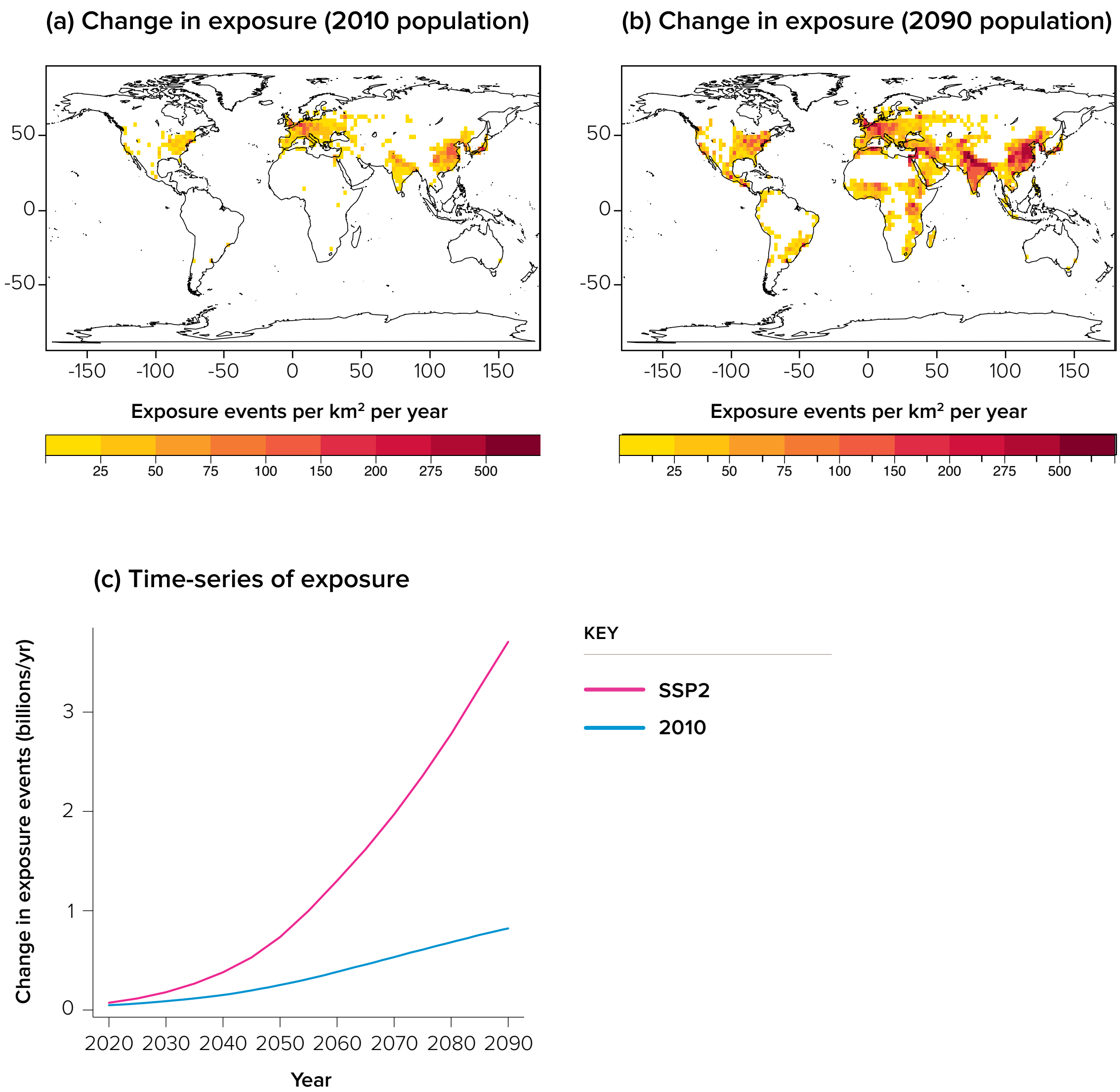
Section 2.3.1 showed that the likelihood of heatwaves is increasing in almost all regions around the world, particularly in the higher latitudes. In many countries, climate change is projected to lead to an increase in the number of heatwave exposure events for people over 65, even without possible future changes in demography being taken into account.

Demographic changes are likely to dramatically increase the number of over-65s exposed to heatwaves. The SSP2 scenario projects a large increase in the global elderly population. Without demographic change, the number of heatwave exposure events per year could increase from around 0.1 billion to almost 1 billion in 2090 as a result of climate change. When demographic change is taken into account the number of heatwave exposure events for over 65s could increase to 4 billion per year in 2090.

FIGURE 9

Estimated change in exposure to 'heatwaves' resulting from projections of 21st century climate and demographic change.

(a) Estimated change in the mean number of heatwave exposure events for people over 65 per year and per km^2 as a result of the climate change in 2090 under the RCP 8.5 emissions scenario and assuming the 2010 demography; (b) as for (a) but for the 2090 demography under the SSP2 population scenario; (c) time-series of the estimated change in the number of heatwave exposure events for people over 65 with demographic change as in SSP2 (red-line) and without demographic change (black-line).



An increasing loss of outdoor labour productivity over the next few decades, would present a growing challenge to countries' productivity and economic development.

Outdoor labour productivity

There are well-described physiological limits to physical work productivity due to high heat exposure[87]. It has been shown that heat stress reduces a person's work capacity, leading to lower labour productivity and economic output. In many regions of the world heat stress levels are already high enough to cause major loss of hourly work capacity[88]. The climate metric most relevant to outdoor labour productivity is the wet bulb globe temperature, which is used in this report.

In section 2.3.1 it was shown that the summer mean wet bulb globe temperature is projected to increase in all regions around the world, particularly in the higher latitudes, under a high emissions pathway. In Figure 10 the rural population is multiplied by the wet bulb temperature indicator (methodology available online at royalsociety.org/resilience), under the assumption that most outdoor jobs are in rural areas, to determine the total labour capacity lost. Workers in the agriculture sector will be some of the most exposed. However, other sectors do involve significant outdoor labour, for example construction. Rapidly growing urban areas may experience significant impacts if construction productivity is reduced. There are also jobs in indoor but non-air-conditioned environments in urban areas that will be affected by rising wet bulb globe temperature, for example in the manufacturing sector.

Rising wet bulb globe temperature will be particularly important in areas where warm seasons combine with high wet bulb globe temperature increases to create long periods of time (from weeks to months) when the wet bulb globe temperature is high enough to significantly reduce outdoor labour productivity. In these situations large changes to working practices may be required and some areas may become unsuitable for outdoor work[89].

Without demographic change, Figure 10a indicates that increasing wet bulb globe temperature could result in significant loss of labour across much of Africa, Asia and parts of North, South and Central America. Unlike for floods, droughts and heatwaves, the SSP2 population scenario results in a lower number of people affected by reduced ability to work outdoors. In SSP2 the effects of urbanisation mean that there is a much smaller rural population compared with today. Under slower rates of urbanisation, larger losses of outdoor labour productivity would be projected for 2090. An increasing loss of outdoor labour productivity over the next few decades, such as that depicted in Figure 10c, would present a growing challenge to countries' productivity and economic development. It would also have a large effect on people's lives, health and livelihoods.

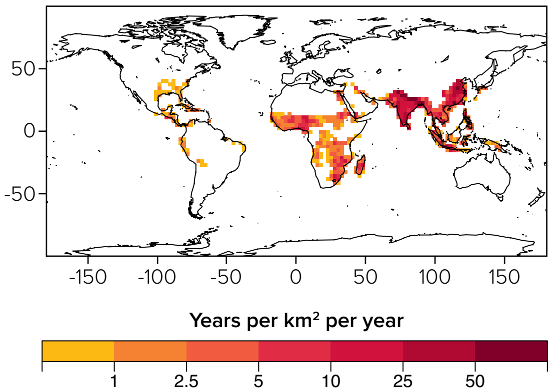
87. *Op. cit.*, note 59.
88. *Op. cit.*, note 59.
89. *Op. cit.*, note 28.

FIGURE 10

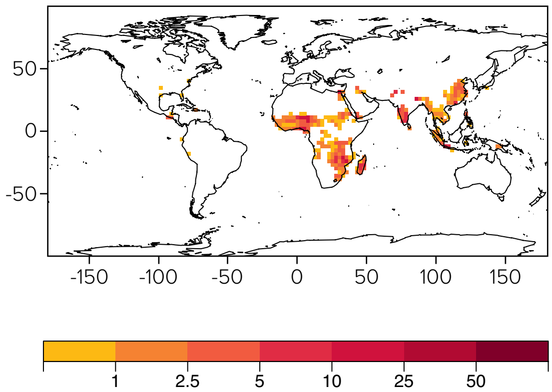
Estimated change in outdoor labour productivity resulting from projections of 21st century climate and rural population change.

(a) Estimated annual loss of outdoor labour productivity in years per km^2 as a result of the climate change in 2090 under a RCP 8.5 emissions scenario and assuming the 2010 rural population; (b) as for (a) but for the 2090 rural population under the SSP2 population scenario; (c) time-series of the estimated annual loss of outdoor labour (in millions of years) with rural population change under SSP2 (red-line) and without rural population change (black-line). Note that the loss of one year of labour, for example, could arise from 100 people each losing a 1/100th of a year, or from one person losing one year, or any other combinations that multiplies to give one.

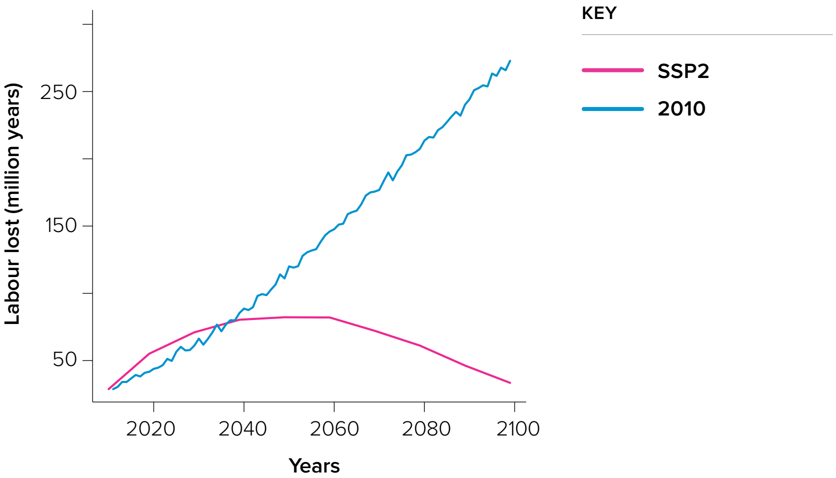
(a) Loss of labour (2010 population)



(b) Loss of labour (2090 population)



(c) Time-series of global lost labour



Sea level rise

Figure 6 showed that global mean sea level rise is projected to be around 0.75 metres by 2100 under a high emissions scenario and around 0.45 metres under a low emissions scenario. Whilst regional sea level rise projections are more uncertain, the global scenarios do not reflect the sea level that the average person, or even length of coastline will experience. Figure 11 shows global mean sea level rise estimates for an RCP 8.5 sea level pattern (high sea level rise) weighted by coastal length (red lines), expected number of people flooded per year (blue lines) and by the total population in the low elevation coastal zone below 10 m (green lines). This is done following the DIVA data model, which divides the world's coasts into about 12,000 linear segments[90]. As the latter two factors are scaled by relative population, the figure shows the average sea level rise experienced by an average person in each group (ie people flooded per year and total population in low elevation coastal zones). The plots highlight that the average person in both categories above will experience higher sea level rise than the average length of coastline. Sea level rise will not be uniform around the world and people are concentrated in coastal areas where sea level rise is predicted to be greater than the average.

In addition to sea level rise caused by anthropogenic global warming, many parts of the coastline are changing due to both natural subsidence (for example, New York City) and subsidence caused by human activity, such as drainage and withdrawal of groundwater. The latter can be rapid and is a particular problem for coastal cities built on deltas. For example, over the past century, parts of Tokyo, Shanghai and Bangkok have subsided up to 5 metres, 3 metres and 2 metres, respectively, and this issue continues in other cities such as Jakarta and Manila[91].

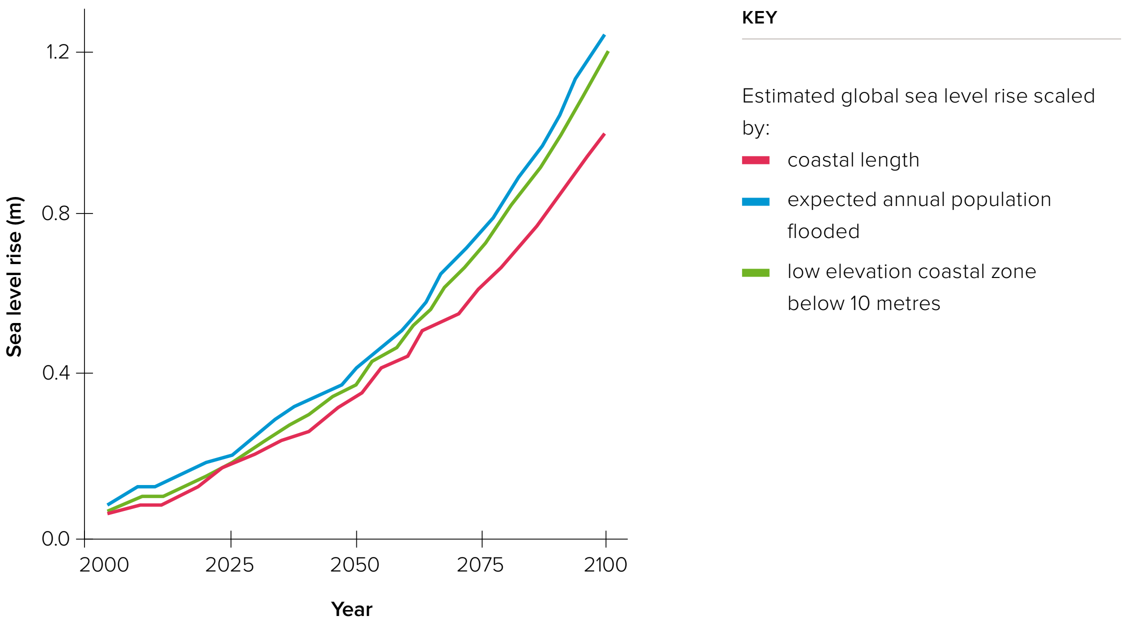
90. Hinkel, J, Lincke, D, Vafeidis, A T, Perrette, M, Nicholls, R J, Tol, R S J, Marzeion, B, Fettweis, X, Ionescu, C & Levermann, A 2014 *Coastal flood damage and adaptation costs under 21st century sea-level rise.* Proceedings of the National Academy of Sciences **111**(9), 3292-3297 (doi:10.1073/pnas.1222469111).

91. Nicholls, R J 2011 *Planning for the impacts of sea level rise.* Oceanography **24**(2), 144–157 (http://dx.doi.org/10.5670/oceanog.2011.34).

FIGURE 11

Estimated sea level rise

Estimated global sea level rise scaled by coastal length (red line), and two population estimates: the expected annual population flooded (blue line) and the total population in low elevation coastal zone below 10 m (green line). Data from Hinkel *et al.* (2014)[92].



92. *Op. cit.*, note 90.

In the absence of counteracting policy measures, human populations are likely to be growing, ageing and migrating towards urban areas leading to greater exposure to extreme weather.

2.4 Risk hotspots

Climate change under a high emissions trajectory is expected to result in changes in extreme weather that will pose increasing risks to societies around the world. Projected changes in demography will act to significantly increase the number of people exposed to such extremes. In the absence of counteracting policy measures, human populations are likely to be growing, ageing and migrating towards urban areas leading to greater exposure to extreme weather.

People rarely have to deal with a single type of extreme event in isolation: they will need solutions that can effectively reduce risks of multiple extremes. The analysis presented here has assessed some different climate-related extremes individually. However, this is not an accurate representation of how people experience extremes. Many areas will be affected by multiple different extremes, in addition to rapid demographic change.

Coastal cities are experiencing increasing flood exposure that is likely to continue as a result of growing populations and assets, changing extreme events, sea level rise and subsidence[93]. As exposure increases, it is likely that economic costs will also increase. Average global flood losses could increase in the worst case to US$1 trillion or more per year by 2050, up from US$6 billion per year in 2005[94].

In the face of these compound challenges, it will be difficult for societies to reverse the trend of increasing economic losses from disasters. In addition, the trend of generally decreasing disaster mortality needs to be maintained and accelerated. Interventions will be needed to build resilience to these increasing risks.

93. Hallegatte, S, Green, C, Nicholls, R J & Corfee-Morlot, J 2013. *Future flood losses in major coastal cities.* Nature Climate Change **3**(9), 802–806 (DOI:10.1038/nclimate1979).

94. *Op. cit.*, note 93.

RECOMMENDATION 6

Information about extreme weather should be suitable for users' needs. Involving those who make and implement policy in research is an important way of ensuring the usefulness of information produced. Funders should encourage collaborations and ongoing dialogue between producers and users of knowledge.

RECOMMENDATION 7

Research to improve the understanding of risks from current weather and to model accurately future climate change impacts should be increased to provide relevant information for decision-makers, particularly at regional and local levels. In particular, efforts should be increased to:

- improve systematic observations and analyses in all regions of the world for trends in extreme weather and its impacts;
- expand interdisciplinary research to understand fully how people are affected by extremes;
- improve international collaborations between climate research institutes, which would allow optimum use of resources to overcome modelling limitations and improve regional and local models and forecasts; and
- produce appropriate data, models and knowledge that can be shared to inform more complete risk assessments for extreme weather.

Chapter three
Defensive measures

- There is a range of physical and biophysical defensive measures which can reduce the direct impact of extreme weather on people.
- Engineering options tend to be effective in offering protection, but can have other negative impacts. Ecosystem-based approaches tend to offer more additional benefits, including protection against multiple hazards, but evidence regarding their effectiveness varies. Hybrid approaches can combine the advantages of both types of option.
- Social or behavioural measures can build resilience to a range of extreme events and can enhance the effectiveness of other resilience-building options.

Left
Water well in the Oman desert.

Hypothetical city 2 of 3

Defensive measures

In the immediate aftermath of the most recent storm in City X, rebuilding plans focused on returning the city to its former state. A lack of investment in resilience planning led to a city that was merely coping, rather than adapting and progressing. However, realising this lack of progress, the national government and city administration have started to take responsibility for resilience, incorporating it into other policies and generating a 'Resilience Strategy'.

As part of this, hybrid approaches that combine natural ecosystems with harder structures are being implemented to defend the city from extreme weather. Local communities are being supported to replant mangroves, restore wetlands and maintain coastal vegetation using indigenous knowledge. They are also being given rights to the mangrove forests to encourage sustainable use. The project includes fish and crab farming inland, protected by the mangroves, which provides economic security. The high population density and demand for houses and amenities means there is insufficient land for ecosystem-based approaches to be used to protect against the most extreme events. Therefore protective dykes are being built behind the vegetated areas. Because of their use in conjunction with ecosystem-based approaches, the dykes are smaller and more affordable, both in terms of construction and maintenance, than if used in isolation. Interventions to reduce river flooding include installing levees, planting trees in upper catchments and re-establishing floodplains.

A Sustainable Urban Drainage System (SUDS) (see Appendix 3) supports sustainable land-use planning, water management, recycling and storage in ponds and parks. This part of a 'greening the urban landscape' initiative to increase resilience to several hazards (wind storms, flooding and high temperatures) and reduce air pollution. Public-private partnerships are re-building migrant housing, incorporating green roofs and walls and natural cooling systems. The ecosystem-based approaches and 'greening the urban landscape' initiative are collectively contributing to climate change mitigation, as well as reductions in drought and heat impacts.

Defensive measures

This chapter considers the types of measures that can be used to protect people from specific hazards and makes recommendations that should be applied to future decision-making and planning. The extreme events covered (coastal flooding, river flooding, drought and heatwaves) are major hazards that can have significant impacts on people in terms of mortality, assets and well-being (section 1.2.4). Options are categorised as engineering (using manufactured structures); ecosystem-based (using natural infrastructure and processes); or hybrid (using manufactured and natural elements).

General resilience (section 1.2.1) requires more than just providing protection against specific hazards. As discussed in section 2.4 extreme weather events often occur simultaneously or in a cascade[95] and are the result of complex interactions. Because of the risk of multiple hazards (including ones which are not weather-related) and the difficulty in predicting which hazards may occur in a particular area (section 2.3), it is best to build general resilience so that people can survive, adapt and grow in the face of a range of adverse events. Chapter 4 examines some of the principles and processes that underpin a wide range of approaches to enhancing resilience[96].

3.1 EbA: ecosystem-based adaptation or approaches

EbA is an acronym used to refer to either 'ecosystem-based adaptation' or 'ecosystem-based approaches (to adaptation and/or disaster risk reduction)'. In 2009 the United Nations Convention on Biological Diversity defined ecosystem-based adaptation as 'the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change[97].

Since then the term has been used in a number of policy arenas including climate change, disaster risk reduction, conservation and development[98] to cover a very broad range of actions. While ecosystems have long been used to reduce the impact of and vulnerability to extreme weather[99], many actions have not been formally classified as an ecosystem-based approach[100] and may have been taken primarily with a view to delivering other benefits.

Because of the risk of multiple hazards and the difficulty in predicting which hazards may occur in a particular area, it is best to build general resilience.

95. Budimir, M E A, Atkinson, P M & Lewis, H G 2014 *Earthquake-and-landslide events are associated with more fatalities than earthquakes alone.* Natural Hazards **72**, 895–914 (DOI:10.1007/s11069-014-1044-4).

96. NB: The division of proposed 'solutions' between Chapters 3 and 4 – ranging from the specific to the general – is for the purpose of clarity only. In reality, different interventions at different scales act simultaneously and are often overlapping rather than discrete.

97. Secretariat of the Convention on *Biological Diversity 2009 Biodiversity and Climate-Change Adaptation. In: Connecting Biodiversity and Climate Change Mitigation and Adaptation: Report of the Second Ad Hoc Technical Expert Group on Biodiversity and Climate Change.* Montreal: Secretariat of the Convention on Biological Diversity. (See http://www.cbd.int/doc/publications/cbd-ts-41-en.pdf, accessed on 10 October 2014).

98. Conservation International 2013 *Inclusion of Ecosystem-Based Approaches for Adaptation/Ecosystem-Based Adaptation (EbA) to Climate Change in International and National Policy.* Virginia: Conservation International.

99. *Op. cit.*, note 1.

100. Doswald, N, Munroe, R, Roe, D, Giuliani, A, Castelli, I, Stephens, J, Möller, I, Spencer, T, Vira, T & Reid, H 2014 *Effectiveness of ecosystem-based approaches for adaptation: review of the evidence-base.* Climate and Development, **6**(2), 185-201 (DOI: 10.1080/17565529.2013.867247).

Right
Volunteers plant vegetation on the sand dunes of Seaside Park, New Jersey following Hurricane Sandy.

There is considerable evidence about the contribution that healthy, natural or modified ecosystems make to reducing the risks of climate extremes and disasters.

'Ecosystem-based adaptation / approach' is sometimes used interchangeably with terms such as 'soft engineering', 'eco-disaster risk reduction', 'nature-based defences' and 'green infrastructure'; and is occasionally defined in opposition to 'hard' or 'grey' engineering approaches. This is an artificial dichotomy. In reality there is a spectrum of approaches some of which cannot be classified as either purely engineering or ecosystem-based – these are often referred to as hybrid approaches.

Regardless of the terminology, there is considerable evidence about the contribution that healthy, natural or modified ecosystems make to reducing the risks of climate extremes and disasters[101]. Large-scale ecosystems such as tropical forests are vital for climate regulation and global resilience. They influence climate forcing and feedbacks, for example through carbon sequestration.

At a more local scale they can contribute to resilience by acting as a physical defence, by sustaining livelihoods and providing basic needs, and by contributing to post-disaster recovery[102, 103]. However the scientific evidence about their role in reducing vulnerabilities to many disasters is still developing.

There can be drawbacks to ecosystem-based approaches such as the amount of land they require, uncertainty regarding costs, and the long time needed before they become established and effective. Despite these, in the face of uncertainty regarding both risks and the effectiveness of different options, ecosystem-based approaches are often advocated as being 'low regret' or 'no regret' options, providing multiple benefits (in addition to their hazard reduction function) which justify the expenditure[104] (section 3.2.4).

101. *Op. cit.*, note 1.

102. Munang, R, Thiaw, I, Alverson, K, Liu, J, & Han, Z 2009 *The Role of ecosystem services in climate change adaptation and disaster risk reduction.* UNEP Copenhagen Discussion Series, Paper 2. (See http://www.unep.org/climatechange/Portals/5/documents/UNEP-DiscussionSeries_2.pdf, accessed 26 August 2014).

103. Renaud, F G, Sudmeier-Rieux, K & Estrella M. (ed.) 2013 *The role of ecosystems in disaster risk reduction.* Tokyo: United Nations University Press.

104. The Government Office for Science 2012 *Reducing Risks of Future Disasters: Priorities for Decision Makers.* London: The Government Office for Science.

In this report the term 'ecosystem-based approaches' refers to specific physical interventions which directly reduce the impact of extreme weather on people through the use of natural ecosystems and processes. The scope of this report does not include detailed examination of the vital role ecosystems and natural processes play in building broader human resilience both before and after a disaster.

3.2 Analysis of defensive options

3.2.1 Option comparison

(Appendix 3. In addition, a sample of the literature reviewed for chapter 3 is available to download at royalsociety.org/resilience.)

While there is a lot of information available about different options designed to reduce the impact of extreme events and prevent disasters, much of it is not directly comparable[105]. To enable some broad comparisons, the plots below, including the choice of option, have been developed based on a combination of relevant research literature and expert scores and opinion. Options were scored in relation to one type of extreme event. Those which are used to protect against a range of hazards are not included in the plots.

The plots compare the effectiveness of each option (encompassing both the magnitude of the event against which the intervention can be effective and the spatial scale over which it is effective) versus the affordability (based on a combination of both the initial and long-term (to 2050) costs of the intervention).

They also show an assessment of the strength of the evidence regarding the cost-effectiveness of each option and an assessment of the additional consequences of that intervention on some key factors beyond the impact on the hazard being considered (section 3.2.4). These factors are: access to food, access to water, access to livelihoods, biodiversity, climate change mitigation and protection against other hazards. Scores were sought as to whether the impact of the intervention would be positive, neutral or negative on each factor.

Guidance on the baseline against which options should be assessed was not given unless experts specifically asked for it. If asked, it was suggested that the baseline should be the current trajectory of change. Globally, this includes a trend of degradation of natural ecosystems[106]. For this reason, and because of the difference in affordability, maintenance of vegetation is included in the analysis as a separate option, in addition to options covering the creation / planting of habitats (this is discussed further in section 3.2.4).

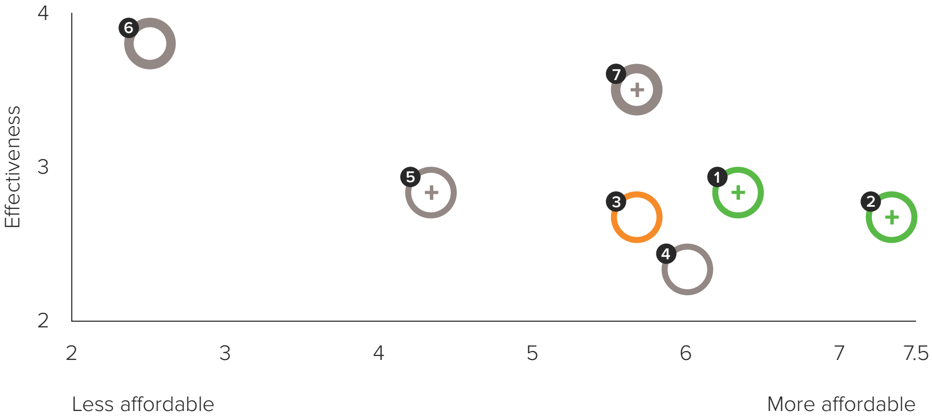
105. The Principles for Sustainable Insurance Global Resilience 2014 *Building disaster resilient communities and economies.* Geneva: UNEP Finance Initiative. (See http://www.unepfi.org/fileadmin/documents/building_disaster-resilient_communities_economies_01.pdf, accessed 26 August 2014).

106. UNEP 2005 *Millennium Ecosystem Assessment* (See http://www.unep.org/maweb/en/index.aspx, accessed 26 August 2014).

FIGURE 12

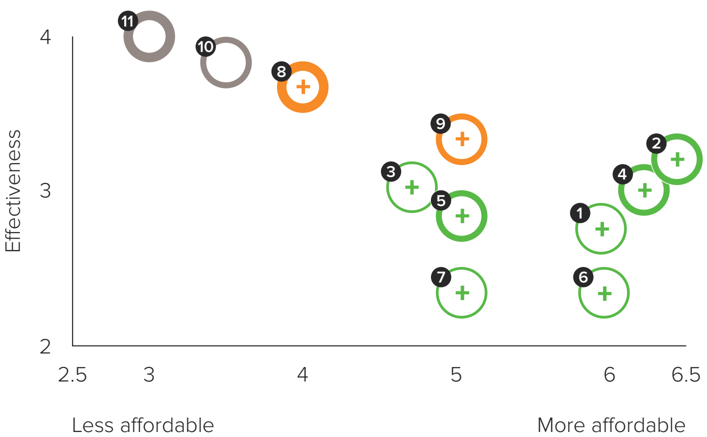
The effectiveness, affordability, strength of evidence and additional consequences of different options designed to reduce the impact of four types of extreme event.

Heatwaves

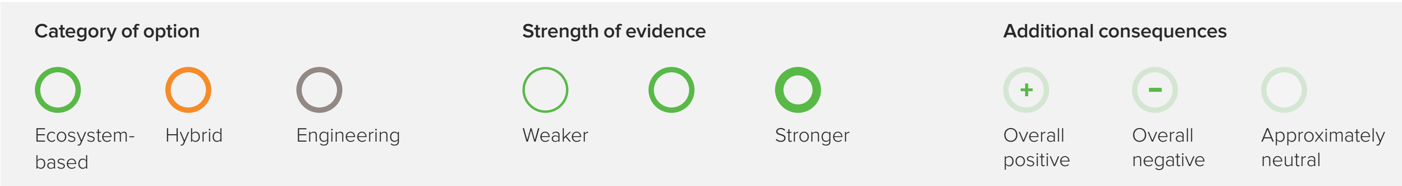


1 Afforestation
2 Maintenance of existing vegetation
3 Green roofs, vertical greening systems
4 White roofs
5 Urban planning, grid design etc.
6 Air conditioning
7 Insulation

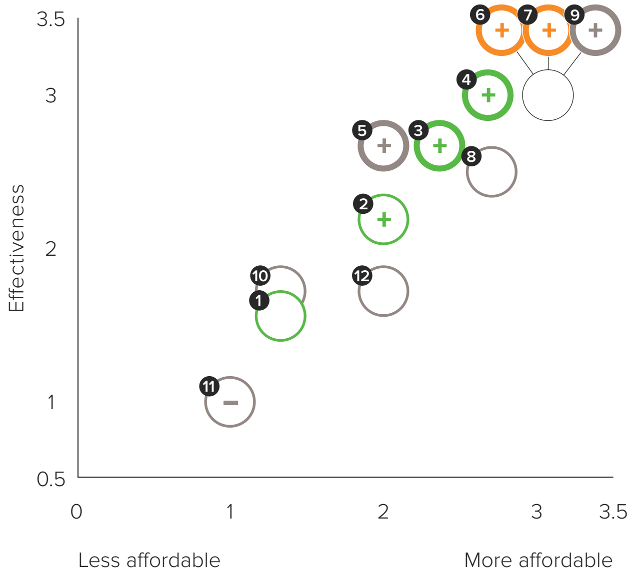
Coastal flooding



1 Maintenance of natural reefs (coral/oyster)
2 Maintenance of mangroves
3 Mangrove planting and re-establishment
4 Maintenance of saltmarsh, wetlands, inter-tidal ecosystems
5 Creation of saltmarsh, wetlands, inter-tidal ecosystems
6 Maintenance of other coastal vegetation, forest and ecosystems
7 Coastal re-vegetation/afforestation (above inter-tidal zone)
8 Beach and dune nourishment
9 Artificial reefs (and/or substrates for reef replenishment)
10 Dykes, levees
11 Coastal barrages

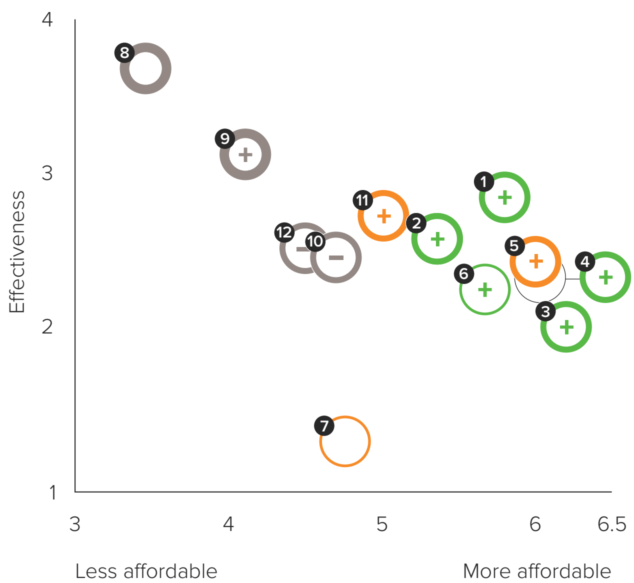


Drought



1 Removal of 'thirsty' invasive plant species
2 Reforestation
3 Forest conservation
4 Agroforestry
5 Breeding drought resilient crops and livestock
6 Sustainable agroecosystem management practices
7 Soil and water conservation
8 Reservoirs, ponds and other water storage
9 Wells
10 Irrigation
11 Interbasin water transfer
12 Waste water recycling

River flooding



1 Re-establishment of floodplains, 'green rivers'
2 Catchment afforestation, increased vegetation cover
3 Maintenance of existing catchment vegetation
4 Planting of riparian 'buffers'
5 Changes to catchment agricultural land management
6 'Natural' flood management
7 Stream habitat restoration
8 Dams
9 Drains, dykes, levees, sluices, pumps
10 Dredging
11 Sustainable urban drainage systems (SUDS)
12 Canalisation of urban streams

Above
Locals employed through an Oxfam cash-for-work program digging rain water traps in Gobro, Niger. Photo by Fatoumata Diabate/Oxfam via Flickr, CC BY NC ND 2.0.

The purpose of this analysis is to draw out broad recommendations regarding what to consider when making plans to protect people from extreme weather. The plots are indicative and cannot be used to decide between individual options. This is because the plots consider individual events in isolation; a single score is used to assess options which vary depending upon the context, or can be implemented in a variety of ways; possible impacts of poor implementation are not considered; all possible options are not included[107] and nor are all possible additional consequences. Decisions about which options to use need to take into account the specific context as well as the affordability and effectiveness.

The drought plot has a different pattern from the other three, with a more mixed picture of the affordability and effectiveness of options – some engineering options being less effective than some ecosystem-based and hybrid ones. Drought is different from many other hazards because it involves a wide range of processes and operates over a long period of time. The problem is one of a scarce resource, so engineering options only help where they are accessing water that is otherwise unavailable (eg wells) or unuseable (eg waste water recycling). Catching and making best use of what rain does fall is a key response. Techniques that do this, such as the soil and water conservation options, tend to be small-scale and ecosystem-based or hybrid.

These plots suggest that:

- Engineering options are often the most effective in reducing the impact of the hazard. However, they generally have low affordability and few additional benefits. The evidence base for these options is strong.

- Ecosystem-based options are the most affordable and have positive additional consequences, but are often not as effective as other options at reducing the impact of the hazard. The evidence-base to support these options tends to be weaker so there is uncertainty regarding their effectiveness.

- Hybrid options tend to be in the middle in terms of effectiveness and affordability but often have positive additional consequences. The strength of evidence to support these options varies but is generally stronger than that for ecosystem-based options.

107. This is particularly true in the case of the heatwaves plot where options such as building design have not been included and where options which cool only indoor areas, such as air conditioning, insulation and modified roofs, are compared with options which cool outdoor areas, such as vegetation.

3.2.2 Strength of the evidence

There is strong evidence for engineering options that are long established and have an easily measureable impact upon the hazard, such as dykes, dams, air conditioning and wells. In contrast, the role of ecosystems in reducing the impact of extreme weather has only relatively recently been appreciated and begun to be measured[108]; as a result the evidence for these options is weaker. Some hybrid options are supported by stronger evidence than the ecosystem-based ones because of the well-evidenced engineering components they include.

Much work is currently being done to test ecosystem-based and hybrid approaches[109]. However, data collection and scientific monitoring is not always planned when practical projects are designed, and there are currently no standards to ensure that monitoring will be effective and allow comparison with other options. Much evaluation is anecdotal, and has not been peer-reviewed and tends to focus on success[110].

The need for improved monitoring and evaluation of defensive interventions, while challenging[111], is supported by other recent literature reviews[112] and reports[113] and applies not only to the assessment of specific options but also to broader disaster risk reduction and climate change adaptation plans[114]. The increased international oversight mentioned in section 4.4.2 could also help in standardising monitoring and evaluation information and ensuring such information is collated, to make accurate comparisons between options more feasible.

3.2.3 Effectiveness and affordability of options

While improvements in assessing the effectiveness of resilience options are needed, uncertainties will always remain. This should not slow or prevent action to protect people from, and build people's resilience to, extreme weather. There are many options which, if implemented based on the best scientific knowledge and evidence, can offer protection. However, for all types of event considered here, there is no one single cost-effective option which is backed up by strong evidence and has positive additional consequences.

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108. IPCC 2014 Cross Chapter Box CC-EA. *Ecosystem-based approaches to adaptation- emerging opportunities. In: Climate Change 2014: Impacts, adaptation, and vulnerability.* Part A: Global and sectoral aspects. Contribution of working group II to the fifth assessment report of the Intergovernmental Panel on Climate Change (ed. Field, C B, Barros V R, Dokken D J, Mach K J, Mastrandrea M D, Bilir, T E, Chatterjee, M, Ebi, K L, Estrada, Y O, Genova, R C, Girma, B, Kissel, E S, Levy, A N, MacCracken, S, Mastrandrea, P R & White L). Cambridge and New York: Cambridge University Press.

109. See examples in Spalding, M D, McIvor, A L, Beck, M W, Koch, E W, Möller, I, Reed, D J, Rubinoff, P, Spencer, T, Tolhurst, T J, Warmsley, Ty V, van Wesenbeek, B K, Wolanski, E & Woodroffe, C D 2014 *Coastal Ecosystems: A Critical Element of Risk Reduction*. Conservation Letters, **7**(3), 293–301. (DOI:10.1111/conl.12074).

110. Munroe, R, Roe, D, Doswald, N, Spencer, T, Möller, I, Vira, B, Reid, H, Kontoleon, A, Giuliani, A, Castelli, I & Stephens J 2012 *Review of the evidence base for ecosystem-based approaches for adaptation to climate change*. Environmental Evidence, **1**, 1-13 (DOI:10.1186/2047-2382-1-13).

111. *Op. cit.*, note 103.

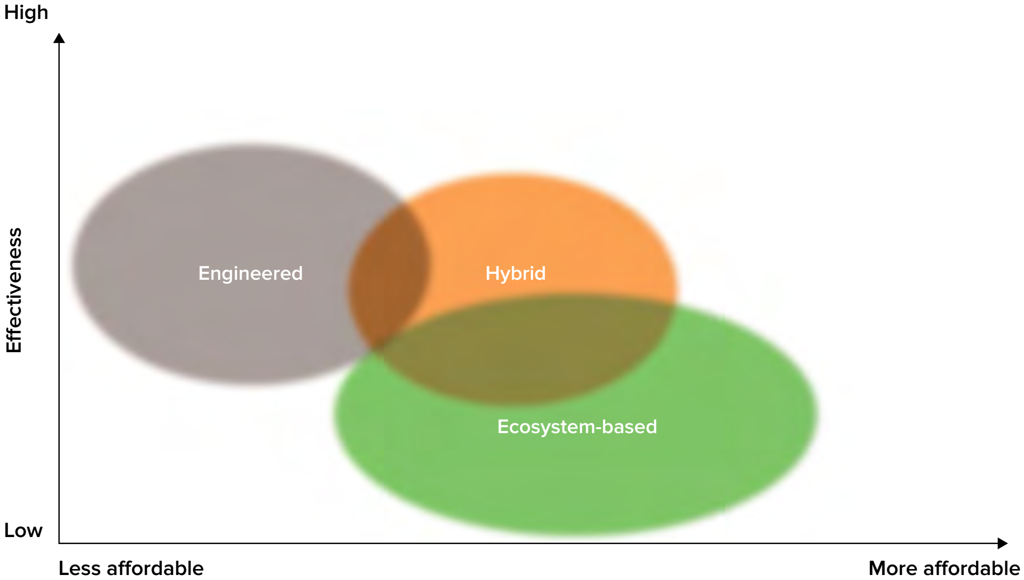
112. *Op. cit.*, note 100.

113. *Op. cit.*, note 105.

114. Bours, D, McGill, C & Pringle, P 2014 *International and donor agency portfolio evaluations: Trends in monitoring and evaluation of climate change adaptation programmes.* Oxford: Sea Change & UKCIP.

FIGURE 13

A schematic chart summarising the results from the hazard-specific analysis above, showing the approximate effectiveness and affordability of the different categories of option



Different types of extreme weather may require different options and interventions of different scales[115]. There is also variation in the scale at which options operate most effectively and in the extent to which options can be scaled up. There is some evidence to suggest that ecosystem-based options are more effective against events that are smaller, slower onset and/or more extensive[116]. The results above support this: ecosystem-based approaches rarely score highest for effectiveness, which according to the guidance that was given to experts (Appendix 3) should be given to options effective 'against extreme events – 1 in 200 years'. However, there is some emerging evidence which contradicts this, at least for certain hazards (storm surges) and suggests that some ecosystem-based techniques may be effective against even the most extreme events[117].

115. *Op. cit.*, note 1.

116. *Op. cit.*, note 103.

117. Möller, I, Kudella, M, Rupprecht, F, Spencer, T, Paul, M, van Wesenbeeck, B K, Wolters, G, Jensen, K, Bouma T J, Miranda-Lange, M & Schimmels S 2014 *Wave attenuation over coastal salt marshes under storm surge conditions.* Nature Geoscience **7**(10), 727–731. (DOI:10.1038/ngeo2251).

The variation in the effectiveness and affordability of options suggests that a range of options should be used, each of which can be effective against different scales and intensities of extreme weather[118]. This range, or 'portfolio', should include options not covered in the plots above, such as social and behavioural options, which can be effective against a range of hazards. In addition to the general rule that deploying a greater array of resilience options leads to a greater array of benefits[119], some options necessarily overlap with and can be prerequisites for others. Social approaches are often vital to building resilience and frequently increase the effectiveness of other options[120]. For instance, many of the drought options work better where local people have recognised rights to manage land and water – both on an individual family basis and as a collective group. If the interventions are mutually supportive, the combined impact can be even greater. The Demonstrations in Chapter 5 illustrate these points.

It is particularly effective to deploy a range of options as part of a comprehensive strategy to build general resilience to extreme weather. Section 4.2 covers this in more detail.

3.2.4 Additional consequences

Any action taken to reduce the impact of a hazard will have additional consequences. These can be positive or negative and can range from improved well-being to depleted biodiversity. Several terms are used to describe these additional consequences, including 'indirect' or 'spill-over effects'. The term 'co-benefits' is often used where the impacts are positive.

Some protective options have different effects on different people. For example, air conditioning can reduce the impact of heat for those with access to it, but can increase the hazard for others by raising the outdoor temperature. Implementation of measures can also create feedback loops resulting in additional impacts on the hazard, as in the example above, or the hazard reduction function. In addition, any choice of intervention will generate opportunity costs. While engineering options can be expensive, many ecosystem-based options require significant areas of land and therefore can also have high opportunity costs[121].

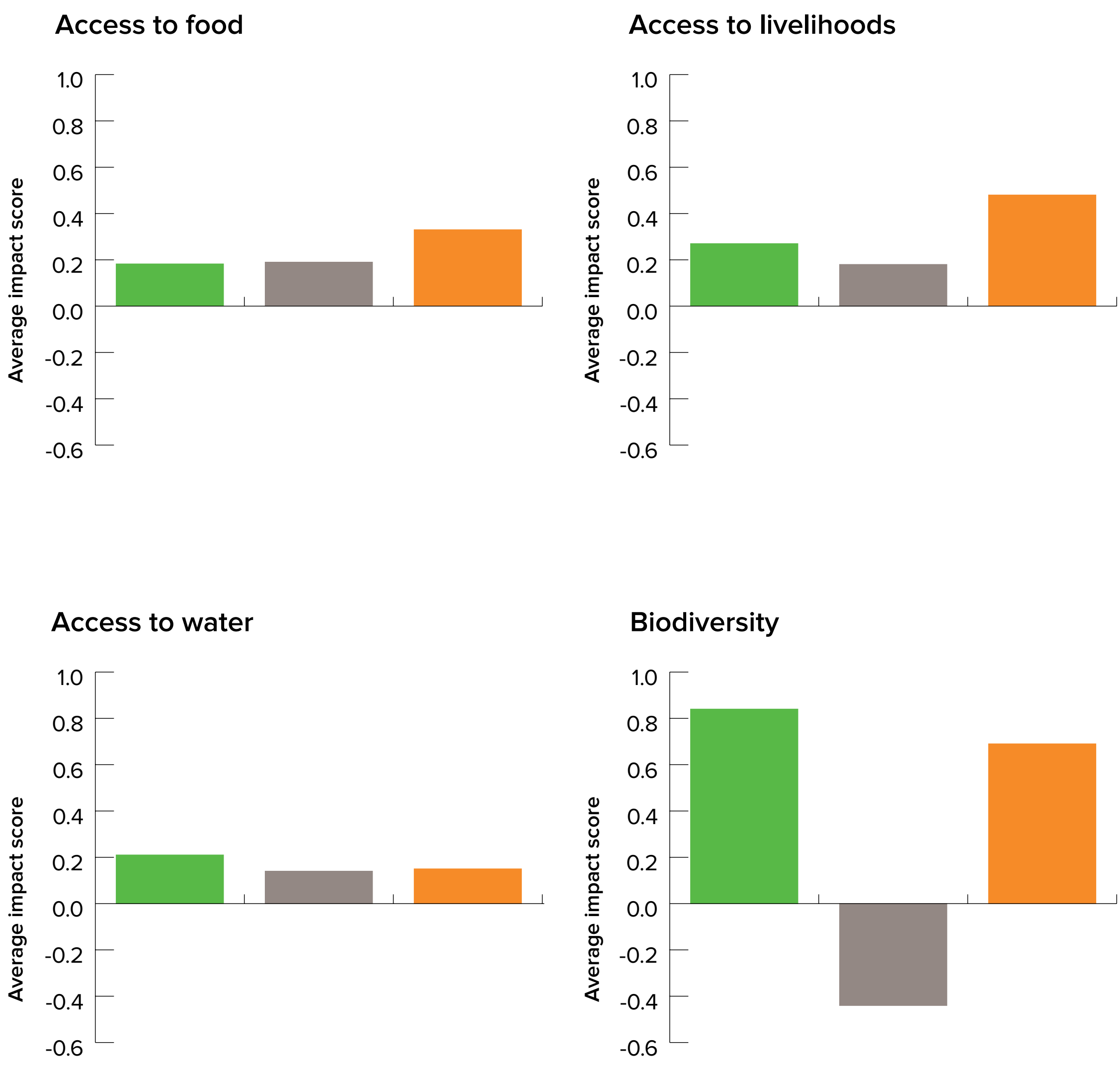
Social approaches are often vital to building resilience and frequently increase the effectiveness of other options.

118. *Op. cit.*, note 105.
119. US Army Corps of Engineers 2013 *Coastal Risk Reduction and Resilience: Using the Full Array of Measures.* Washington, DC: Directorate of Civil Works, US Army Corps of Engineers. (See http://www.corpsclimate.us/ccacrrr.cfm, accessed 27 August 2014).
120. *Op. cit.*, note 28.
121. *Op. cit.*, note 103.

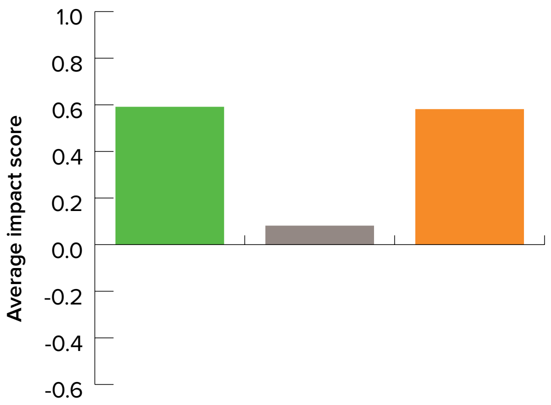
FIGURE 14

Additional consequences of ecosystem-based, engineering and hybrid options

The average impact score of the different categories of defensive options, across all types of extreme event considered, on each additional consequence assessed.



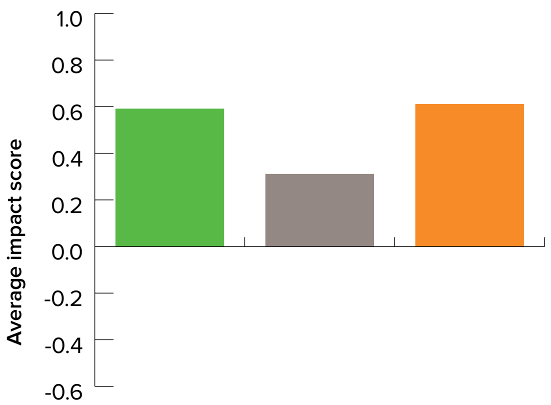
Climate change mitigation



KEY

- Ecosystem-based
- Engineering
- Hybrid

Protection against multiple hazards



The exercise carried out for this report sought views on six factors, in addition to the particular hazard impact, that the intervention could affect. The plots in Figure 12 show whether the options' impact across all these factors combined was positive, negative or neutral. The charts in Figure 14 show the impact of each category of intervention – engineering, ecosystem-based or hybrid – on each of the factors covered.

The score given is dependent on the baseline against which it is being judged. This can particularly affect the scores regarding access to food and water for the ecosystem-based options. The maintenance of existing, or creation of new, vegetation can impact either positively or negatively on livelihoods and access to food and water depending upon what the alternative land use would be. There is also some double counting of impacts which are linked such as access to food and water and to food and livelihoods and, in some cases, between the hazard impact reduction effect and the additional consequences. This is particularly the case for drought resilience options which all scored positively for their impact on access to water.

Many of the categories of additional consequences – access to food, livelihoods, water and biodiversity – are delivered consistently over a period of time and not just when the hazard strikes.

Overall, options classified as ecosystem-based have more positive consequences than those that are engineering-based. Hybrid approaches appear to have the most positive consequences overall – almost the same as or marginally higher than ecosystem-based approaches for all the factors considered.

Offering protection against multiple hazards is an important additional benefit given that hazards seldom occur in isolation but can take place simultaneously or in a cascade (section 2.4 and Surat demonstration). All the categories of intervention score positively overall for this factor. Engineering approaches, which are usually designed to reduce the impact of a specific hazard, achieve the lowest overall score. Ecosystem-based approaches, some of which are less hazard specific – for example, coastal forests can offer protection against coastal flooding, inland flooding, high winds, and high temperatures – score more highly for protection against multiple hazards.

The scores for access to food and water are low for all categories of approaches reflecting the high degree of variability depending upon the previous land-use as mentioned above.

Additional consequences and costs should be identified and included in the decision-making process as far as possible. Engaging widely, with experts and local communities, makes it more likely that additional consequences are identified (section 4.1.2).

Left
Deforested slope near Kabale, Uganda increases the risk of flooding in the valleys below.

3.2.5 The use of ecosystem-based and hybrid approaches

The results of the comparative analysis suggest that ecosystem-based options can be effective in reducing the impact of the events considered. Although quantitative comparison of options is not possible, there are numerous studies demonstrating the effectiveness of a variety of ecosystem-based approaches[122].

Recently there have been significant advances in the understanding of how vegetation and ecosystems can reduce the impact of extreme weather. This is leading to improvements in the ability to predict the impact of, and effectively plan, some ecosystem-based options, in particular coastal options[123]. This needs to be continued and expanded to other areas and hazards. More evidence is needed, including the translation from biophysical measurement studies to options trialled at large scale, as in the Pickering 'Slowing the Flow' project (see Pickering demonstration), to work towards some generalizable rules for application (which exist for engineering options).

122. See for example, see Costanza, R, Pérez-Maqueo, O, Luisa, M, Sutton, P, Anderson, S J & Mulder, K 2008 *The value of coastal wetlands for hurricane protection.* Ambio, **37**(4), 241-248; Ferrario, F, Beck, M W, Storlazzi, C D, Micheli, F, Shepard, C C & Airoldi, L 2014 *The effectiveness of coral reefs for coastal hazard risk reduction and adaption.* Nature Communications, **5** (DOI: 10.1038/ncomms4794); Renaud, F G (ed.), Sudmeier-Rieux, K & Estrella, M 2013 *The role of ecosystems in disaster risk reduction.* Tokyo, Japan: United Nations Press; and Spalding, M. D, Ruffo, S, Lacambra, C, Meliane, I, Hale, L Z, Shepard, C C & Beck, M W 2014 *The role of ecosystems in coastal protection: adapting to climate change and coastal hazards.* Ocean and Coastal Management, **90**, 50-57.

123. See for example the work of IH Cantabria (http://www.ihcantabria.com/en/); Deltares (http://www.deltares.nl/en); TNC work (www.coastalresilience.org); and the tool at www.lis.coastalresilience.org.

Across all the types of extreme event, maintaining existing vegetation is one of the most affordable options.

Across all the types of extreme event, maintaining existing vegetation is one of the most affordable options because it has few initial costs and on-going costs tend to be low. Creation of new habitat and vegetation is less affordable than merely maintaining existing vegetation due to the initial costs of planting or establishing the new habitat. However, the plots suggest it can be more effective – this may be because of the opportunity it offers to design the habitat to maximise the protective function.

Options which have a relatively high likelihood of failure should still be used if the consequences of that failure are low. This is often the case for ecosystem-based options, while large-scale engineering options can have low likelihood of failure but catastrophic consequences when failure occurs, for example when overtopped dykes in New Orleans trapped flood water in the city. This is a form of maladaptation (Box 5).

There is evidence which suggests that ecosystem-based options have benefits in addition to those considered in this analysis, which are delivered consistently, rather than just when a hazard strikes. While they support a full range of ecosystem services, there is also some evidence that they involve local people more and, if managed by the community, are more enduring[124]; they tend to be more adaptive to new conditions than manufactured structures[125, 126] and are less likely to create a false sense of security than static engineered structures[127]; However these options can also take a long time to be fully effective[128], are vulnerable to climate change themselves[129] and take up large land areas necessitating trade-offs.

124. UNFCCC Subsidiary Body for Scientific and Technological Advice 2013 *Report on the technical workshop on ecosystem-based approaches for adaptation to climate change.* Bonn: UNFCCC. (See http://unfccc.int/resource/docs/2013/sbsta/eng/02.pdf, accessed 27 August 2014).

125. McIvor, A L, Spencer, T, Möller, I & Spalding M 2013 *The response of mangrove soil surface elevation to sea level rise.* Cambridge: The Nature Conservancy and Wetlands International. (See http://coastalresilience.org/science/mangroves/surface-elevation-and-sea-level-rise, accessed 27 August 2014).

126. Borsje, B W, van Wesenbeeck, B K, Dekker, F, Paalvast, P, Bouma, T J, van Katwijk, M M & de Vries M B 2011 *How ecological engineering can serve in coastal protection.* Ecological Engineering **37**(2), 113–122 (DOI: 10.1016/j.ecoleng.2010.11.027)

127. Porter, J and Demeritt, D 2012 *Flood risk management, mapping and planning: The institutional politics of decision-support in England.* Environment and Planning A, **44**(10), 2359-2378.

128. *Op. cit.*, note 124.

129. Jones, H P, Hole, D G & Zavaleta, E S 2012 *Harnessing nature to help people adapt to climate change.* Nature Climate Change **2**, 504-509 (DOI:10.1038/nclimate1463).

Hybrid options can be effective in addressing these shortcomings[130, 131, 132]. The key constraints in implementing defensive options are often the availability of land and funds. This analysis shows that hybrid options can be both effective and affordable and have positive additional benefits. For example, two of the most affordable and effective options on the drought plot are the hybrid options of 'sustainable agro-ecosystem management practices' and 'soil and water conservation'. These are bundles of separate, mutually reinforcing, small interventions, involving some ecosystem-based elements, some changes to agricultural practices and some low-tech engineering, which can be tailored to local contexts (Sahel demonstration).

Although they are not effective in all circumstances, ecosystem-based approaches to hazard impact reduction, if implemented correctly, based on good evidence, are low regret options in terms of the additional positive consequences they can offer, their lower cost in comparison to other options and their reduced potential for mal-adaptation. Hybrid approaches can combine some of the positive aspects of both engineered and ecosystem-based approaches and warrant further research and development.

RECOMMENDATION 4

Extreme weather events are hard to anticipate and their impacts can affect societies in unexpected ways. Those who make and implement policies need to take practical measures to protect people and their assets from extreme weather. These will be most effective when they:

- address multiple hazards and use a portfolio of defensive options;
- consider defensive options beyond traditional engineering approaches – for example, ecosystem-based and hybrid approaches that offer additional benefits to people – and consider the value of conserving existing natural ecosystems that are difficult or impossible to restore; and
- monitor and evaluate the effectiveness of interventions, in particular of more novel approaches such as ecosystem-based ones, and apply the results to improve future decision-making.

130. The Nature Conservancy 2013 *The Case for Green Infrastructure*. (See http://www.nature.org/about-us/the-case-for-green-infrastructure.pdf, accessed 27 August 2014).

131. Rijkswaterstaad and Deltares 2013 *Eco-engineering in the Netherlands, soft interventions with a solid impact.* Netherlands: Rijkswaterstaad and Deltares

132. Spalding, M D, McIvor, A L, Beck, M W, Koch, E W, Möller, I, Reed, D J, Rubinoff, P, Spencer, T, Tolhurst, T J, Warmsley, Ty V, van Wesenbeek, B K, Wolanski, E & Woodroffe, C D 2014 *Coastal Ecosystems: A Critical Element of Risk Reduction.* Conservation Letters, **7**(3), 293–301. (DOI:10.1111/conl.12074).


食爲天

Chapter four
Building resilience

- Building resilience requires joint action and responsibility at local, national and international levels, by the public and private sectors, local communities and non-governmental organisations.
- Governments have a responsibility to develop and resource strategies to support the resilience of their populations and infrastructure. These strategies should bring together multiple sectors and types of knowledge, involve long-term and systems thinking, and reconcile national and local priorities.
- At the international level, policy frameworks on disasters, climate change, sustainable development and the environment should be complementary and mutually reinforcing, with identical or comparable metrics.
- Directing more national and international funds to resilience-building measures would reduce the funds needed for disaster responses, which are more costly. Resilience metrics based on 'inputs' could highlight where more expenditure is needed.
- Integrating resilience into the global financial system would inform valuations and investment decisions and incentivise organisations to reduce their exposure. This could be done through a requirement for organisations to consistently report their financial exposure to extreme weather.

Left
Buildings raised to avoid river flooding, Feng Huang, China. Photo by Trey Ratcliff via Flickr, used under CC BY NC SA 2.0.

Hypothetical city 3 of 3

Resilience and governance

In the immediate aftermath of the most recent storm, rebuilding plans focused on returning the city to its former state. Water shortages led to class tensions, both within the city and in surrounding rural areas, as corrupt political leaders allowed unsustainable water use by the rich but not the poor. A lack of investment in resilience planning led to a city that was merely coping, rather than adapting and progressing. A few individuals were making poorly-informed, short-sighted decisions, with limited expert input or consultation with residents and businesses.

However, recently the national government and city administration have started to take responsibility for the resilience of City X. The city has joined an international 'Resilient Cities' forum for sharing experiences and knowledge. This has generated a 'Resilience Strategy' for the next 30 years which, as well as the defensive measures outlined in the previous box, includes ongoing data collection, participatory appraisals, adaptive management, awareness-raising campaigns (tailored to the city's low literacy rates), city targets aligned with the global Sustainable Development Goals, and a multi-stakeholder 'Resilience Group' linking local communities, businesses, the city administration and national government. The Strategy integrates utilities, land-use, biodiversity, transport, housing and economic development, and has a clear lead agency reporting directly to the city mayor. Private companies compete for contracts for resilient low-cost housing for migrants and slum dwellers. Legal frameworks for land tenure and formalisation of the fish farm industry through certification are supporting more risk-conscious practices. A city fund has also been established, backed by an international disaster risk reduction fund, the city budget, the national climate change plan, and private sector corporate social responsibility requirements.

Building resilience

Building resilience to extreme weather requires more than just protecting people and assets from particular hazards. Further actions are needed to empower people to progress and develop rather than merely cope. This chapter examines some of the principles, processes and institutions involved in building resilience at local, national and international levels.

4.1 Building resilience at multiple levels

Building resilience requires shared action and responsibility at multiple levels, from the individual or household to the international community[133, 134] (see Surat demonstration). Different institutions can work together to complement, and if necessary substitute for, each other's actions. Local government and the private sector are increasingly recognised as critical components given their respective roles in scaling up the resilience of communities, households, and civil society, and in managing risk information and financing[135]. New 'communities of interest' are being formed by businesses and local governments, which have the potential to play an important role in building resilience[136].

4.1.1 The responsibility of national governments

National governments play a crucial role in laying the foundations for resilience and empowering others to take action. They have the primary responsibility to protect their people and infrastructure (including the most vulnerable) by providing information, public policy and goods, legal frameworks, and financial support[137, 138, 139]. This protection is considered a basic right by the Office of the United Nations High Commissioner for Human Rights, which states that 'A failure (by governments and others) to take reasonable preventive action to reduce exposure and vulnerability and to enhance resilience, as well as to provide effective mitigation, is therefore a human rights question'[140]. While national governments have a central role in building resilience, their ability to successfully fulfil this role varies from country to country[141], depending on resources and the balance of power between the state and the individual[142].

133. The World Bank 2014 *Building resilience: integrating climate and disaster risk into development.* Washington DC: The World Bank (See http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2013/11/14/000456286_20131114153130/Rendered/PDF/826480WP0v10Bu0130Box37986200OUO090.pdf, accessed 6 October 2014)

134. UNISDR 2013 *Chair's summary: fourth session of the Global Platform for Disaster Risk Reduction. Resilient People, Resilient Planet.* Geneva: UNISDR (See https://www.ifrc.org/docs/IDRL/33306_finalchairssummaryoffourthsessionof.pdf, accessed 27 August 2014).

135. *Op. cit.*, note 28.

136. *Op. cit.*, note 72.

137. *Op. cit.*, note 28.

138. *Op. cit.*, note 27.

139. UNISDR 2005 *Hyogo Framework for Action 2005-2015:* Building the resilience of nations and communities to disasters. Washington, DC: World Bank.(See http://www.unisdr.org/files/1037_hyogoframeworkforactionenglish.pdf, accessed 6 October 2014).

140. Office of the United Nations High Commissioner for Human Rights (OHCHR) 2013 *Organization profile: Policies and Programmes in DRR.* (See http://www.preventionweb.net/english/professional/contacts/profile.php?id=1370, accessed 27 August 2014).

141. Bussell, J (ed.) 2014 *Institutional capacity for natural disasters: case studies in Africa. Climate Change and African Political Stability. Student Working Paper No.6.* Austin: The Strauss Center for International Security and Law, University of Texas. (See http://reliefweb.int/sites/reliefweb.int/files/resources/studentworkingpaper6-ccaps_strs_f-for%20web.pdf, accessed 27 August 2014).

142. Pelling, M & Dill, K 2010 *Disaster Politics: Tipping Points for Change in the Adaptation of Socio-political Regimes*, Progress in Human Geography **34**(1), 21–37.

National governments play a crucial role in laying the foundations for resilience and empowering others to take action.

National governments also have a responsibility to develop and resource resilience strategies. These should include, but also go beyond, emergency plans which can be put into effect when extreme weather is forecast. They should consider all the factors – the whole system – likely to be affected by extreme weather, including areas not directly impacted and effects over decades (section 4.2). They should also integrate multiple sectors (water, energy, climate change, land-use, biodiversity, transport, housing, economic development etc) and should attempt to arbitrate among competing local interests (section 4.1.2). Bringing competing agendas under a coherent strategy is preferable to a piecemeal project-by-project approach to building resilience[143]. The UK's National Risk Register of Civil Emergencies[144], which considers risks collectively at a national scale, is an example of how risks can be identified and prioritised as a starting point for building resilience in a strategic way.

Strategic resilience planning should draw on expertise from a range of sources, including the private sector, non-governmental organisations and local communities, and a range of disciplines[145]. The concept of resilience can be helpful in bringing traditionally discrete disciplines (such as environmental management, climate change adaptation, disaster risk reduction and development) under a single conceptual umbrella[146, 147]. A 'resilience' approach to national public policy, investment and development planning should be informed by an understanding of climate and disaster risk, as the United Nations Office for Disaster Risk Reduction is trialling in 20 countries[148]. Although resilience should be incorporated into all relevant policies, this is particularly important for land-use and urban planning policies given their direct impact on people's exposure to extreme events[149].

In reality, however, many countries' governance systems are structured along sectorial lines, with limited capacity for understanding and managing the interactions between sectors[150]. Extreme weather affects numerous sectors and so presents a challenge to this governance model. It creates a need for ministries of environment (which typically oversee adaptation and climate resilience) to be better co-ordinated with civil protection agencies (which typically

143. National Research Council of the National Academies 2014 *Reducing Coastal Risk on the East and Gulf Coasts.* Washington, DC: The National Academies Press. (See http://www.nap.edu/catalog.php?record_id=18811&utm_expid=4418042-5.krRTDpXJQISoXLpdo-1Ynw.0&utm_referrer=http%3A%2F%2Fwww8.nationalacademies.org%2Fonpinews%2Fnewsitem.aspx%3FRecordID%3D18811, accessed 6 October 2014).

144. Cabinet Office and National security and intelligence 2013 *Collection: National Risk Register (NRR) of civil emergencies.* See https://www.gov.uk/government/collections/national-risk-register-of-civil-emergencies, accessed 6 October 2014.

145. UK National Ecosystem Assessment 2014 *The UK National Ecosystem Assessment: synthesis of the key findings.* UK: UNEP-WCMC, LWEC, UK (See http://uknea.unep-wcmc.org/Resources/tabid/82/Default.aspx, accessed 27 August 2014).

146. *Op. cit.*, note 133.

147. Levine, S 2014 *Assessing resilience: why quantification misses the point.* London: Humanitarian Policy Group, Overseas Development Institute. (See http://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/9049.pdf, accessed 6 October 2014).

148. See, for example, UNISDR 2014 *Risk-Sensitive Business Investment.* Geneva: UNISDR (See http://www.unisdr.org/files/37968_finalwp5.pdf, accessed 27 August 2014).

149. UNISDR 2014 *Development of the Post-2015 Framework for Disaster Risk Reduction: Co-Chair's pre-zero draft.* Geneva: UNISDR (See http://www.wcdrr.org/preparatory/post2015, accessed 6 October 2014).

150. *Op. cit.*, note 28.

oversee disaster management, often under ministries of interior). Poorly co-ordinated sectors can not only fail to build resilience, but can also undermine each other's objectives, potentially increasing vulnerability and leading to maladaptation (Box 5).

Opinions differ regarding the most effective governance model for building resilience. Some evidence suggests that a diversity of institutions with shared, decentralised responsibilities represents the most effective way of managing environmental challenges[151]. Others have argued in favour of a lead national agency for resilience which convenes decision-makers from multiple agencies and levels of government, as well as from the private sector and civil society. Emerging evidence suggests that in order to effectively convene these diverse groups, this agency should be located at the highest possible level of government. While models vary, countries including Kiribati, Mexico, Mozambique, Morocco, Samoa and Zambia have established co-ordinating agencies under finance and planning ministries, or offices of the President or Prime Minister[152].

Infrastructure

Like the resilience of populations, the resilience of infrastructure is a primary concern of governments[153], and one where strategic planning rather than piecemeal interventions is important.

Long-term climate change (eg sea level rise) and extreme weather present a challenge to infrastructure – including transport, energy, water, buildings (and their occupants), and communications – and can cause major disruption to societies and economies. Yet they also present an opportunity to develop innovative infrastructure systems (see Surat demonstration)[154]. This applies in developing countries, where rapid urbanisation (section 2.3.2) allows resilience to be embedded into the planning, design and construction of new infrastructure (subject to sufficient institutional capacity and funds[155]). It also applies in developed countries when existing infrastructure is replaced.

Building resilient infrastructure requires taking a long-term view and planning ahead for future extreme events. Initiatives following Hurricane Sandy provide examples of this, including the US President's 'Rebuild By Design' competition which promotes resilience through innovative planning and design[156], and the US Green

Above
High angle view of traffic on a complex series of roads and intersections in Auckland, New Zealand.

151. Cash, D W, Adger, W N, Berkes, F, Garden, P, Lebel, L, Olsson, P, Pritchard, L & Young, O 2006 *Scale and Cross-Scale Dynamics: Governance and Information in a Multilevel World, Ecology and Society* **11**(2), 8. (See http://www.ecologyandsociety.org/vol11/iss2/art8/, accessed 6 October 2014).

152. *Op. cit.*, note 133.

153. However, resilience infrastructure also requires collaboration between numerous sectors and actors. For example, see the UK Government's vision for Adapting National Infrastructure, 2011 and National Adaptation Programme, 2013, chapter 3, which outline responsibilities for the public and private sectors, and professional sectors such as engineers. http://archive.defra.gov.uk/environment/climate/programme/infrastructure.htm & https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/209866/pb13942-nap-20130701.pdf, accessed 27 August 2014).

154. The Royal Academy of Engineering, on behalf of Engineering the Future 2011 *Infrastructure, Engineering and Climate Change Adaptation: ensuring services in an uncertain future.* London: RAEng. (See www.raeng.org.uk/adaptation, accessed 27 August 2014).

155. While building resilient infrastructure is cost-effective in the long term, safer physical structures require design changes that typically cost 10-50% more to build. See GFDRR 2010 *Damage, Loss and Needs Assessment: Guidance Notes. Volume 2*. Washington, DC: The World Bank.

156. US Department of Housing and Urban Development 2013 *The Hurricane Sandy Task Force: Rebuild by design.* See http://portal.hud.gov/hudportal/HUD?src=/sandyrebuilding/rebuildbydesign, accessed 27 August 2014.

The most critical components of an infrastructure system should be prioritised when building resilience.

Building Council's 33 proposals for making New York City's buildings more resilient to future events[157]. Other cities around the world are also taking a long-term view. For instance, Dar Es Salaam, Tanzania's largest city, has drawn up a city-wide plan looking ahead to 2036. It proposes establishing a Metropolitan Development Authority to oversee planning and infrastructure development, and aims to embed resilience (particularly to flooding) into all urban development policies.

Systems thinking is also central to the planning, design and maintenance of resilient infrastructure. It involves taking a holistic approach and recognising that vulnerabilities or failure in one sector can affect the whole system, potentially leading to a cascade of failures. These knock-on effects are due to interdependencies in the system, which can be exposed by stresses and shocks such as extreme events. For example, the failure of flood defences could lead to flooded power stations, causing power cuts and telecommunications failures.

The most critical components of an infrastructure system should be prioritised when building resilience. For example, a critical rail network comprising routes of national economic importance might be maintained more regularly or re-designed to a higher standard than a non-critical network. That way, the critical functions that the system performs are more likely to remain intact even if the system's structure or non-critical components do not. The goal should not be to completely avoid failure (which would be very difficult and prohibitively expensive) but rather to minimise its consequences[158 159]. In doing so, it should be accepted that resilient systems exhibit redundancy, or spare capacity (section 1.2.1), so are not necessarily the most economically efficient systems. This idea is widely accepted when it comes to replicating software and backing up files[160], but is an important trade-off in all infrastructure systems.

4.1.2 Local engagement

Extreme events have specific local characteristics and managing them requires local communities and administrators to help plan and implement locally-relevant policies. Community participation and the appropriation of local knowledge in planning is often cited as a central hallmark of resilient systems[161]. Moreover, the integration of local, traditional and indigenous knowledge into climate change adaptation has been shown to increase its effectiveness[162], leading to the co-design of practical, innovative solutions (see Pickering and Sahel demonstrations).

157. US Green *Building Council 2013 Building Resiliency Task Force: Report to mayor Michael R. Bloomberg and speaker Christine C. Quinn.* New York: Urban Green Council. (See http://urbangreencouncil.org/content/projects/building-resiliency-task-force, accessed 27 August 2014).

158. UK Department for Transport 2014 *Transport Resilience Review: a review of the resilience of the transport network to extreme weather events.* London: UK Department for Transport (See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/335265/transport-resilience-review-print.pdf , accessed 6 October 2014).

159. Institution of Civil Engineers 2014 *The State of the Nation: Infrastructure 2014*. London: Institution of Civil Engineers. (See http://www.ice.org.uk/getattachment/8185ef54-ca0d-457d-8a1f-d0e2212e1fb3/State-of-the-Nation--Infrastructure-2014.aspx, accessed 6 October 2014).

160. Mitchell, W & Townsend, A 2005 *Cyborg Agonists: Disaster and reconstruction in the digital electronic era.* In The Resilient City (ed. Vale, L & Campanella, T). New York: Oxford University Press.

161. Bahadur, A V, Ibrahim, M & Tanner, T 2010 *The Resilience Renaissance? Unpacking of resilience for tackling climate change and disasters. Strengthening Climate Resilience Discussion Paper 1.* Brighton: Institute of Development Studies.

162. *Op. cit.*, note 28.

Left
Residents undertake a community resource mapping exercise near Kabale, Uganda.

The integration of local, traditional and indigenous knowledge into climate change adaptation has been shown to increase its effectiveness.

Resilience planning often involves using appraisal tools to evaluate the relative merits of different resilience-building options. Tools include cost-benefit analyses, cost-effectiveness analyses and multi-criteria analyses, among others[163]. There are inherent value judgements in these sorts of appraisals which should be acknowledged in a transparent way[164]. For instance, cost-benefit and cost-effectiveness analyses are affected by the choice of metric to maximise, the timeframe, the spatial scale, the discount rate[165], and the inclusion of non-monetary outcomes (eg loss of life or natural capital). In order to develop locally-relevant policies, the information generated by appraisals should feed into deliberative decision-making processes involving local participants and considering local impacts. These can take the form of focus groups, citizen juries or stakeholder forums, and can draw on techniques to elucidate people's willingness to pay or to be compensated. Although appraisals and decision-making are distinct processes, they should act in a complementary way so that those affected by decisions can contribute to the appraisals that inform them[166].

163. Frontier Economics 2013 *The Economics of Climate Resilience: Appraising flood management initiatives; a case study CA0401*. London: DEFRA. (See http://randd.defra.gov.uk/Default.aspx?Module=More&Location=None&ProjectID=18016, accessed 27 August 2014).

164. Kelman, I 2014 *Disaster Mitigation is Cost Effective. Background Note: World Development Report.* Norway: CICERO. (See http://siteresources.worldbank.org/EXTNWDR2013/Resources/8258024-1352909193861/8936935-1356011448215/8986901-1380568255405/WDR14_bp_Disaster_Mitigation_is_Cost_Effective_Kelman.pdf, accessed 27 August 2014).

165. Discounting is a technique for comparing costs and benefits that occur at different times. The discount rate is used to convert all costs and benefits to 'present values', so that they can be compared. The discount rate reflects the relative value of the present versus the future (with high rates indicating a low value placed on the future). Discount rates that change over time are commonly used in developing countries and by the World Bank.

166. Turner, K & Welters, R 2014 *New tools to improve the management of the coastal environment: How can new approaches help national decision makers improve management of coastlines for people and wildlife?* Swindon: Living With Environmental Change. (See http://www.lwec.org.uk/sites/default/files/attachments_biblio/LWEC10_WEB_No_10.pdf, accessed 6 October 2014).

There is a growing realisation that climate change, disasters, environment and development are inextricably linked.

Local communities should also be involved in implementing policies to build resilience. This is done in the UK via Local Resilience Forums comprising representatives from local public services, which plan and prepare for local events[167]. Adaptive management, which allows policies to be adapted when new information becomes available, was introduced in section 1.2.2. The concept of 'adaptive co-management' reflects this need for flexible, iterative policies. However, it goes a step further by focusing explicitly on knowledge sharing and collaborative learning between different actors, scales and institutions – often communities and policymakers (see Pickering demonstration). It also emphasises the importance of feedback loops and information flows between central decision-makers and affected communities, so that national strategies and competing local interests can be reconciled.

4.1.3 The international context

The challenges of building resilience to extreme weather often exceed national capacities and boundaries, and so require international action. This can take the form of providing expertise, co-ordinating policy (global, regional and bilateral) and pooling resources to confront common risks.

There are several international frameworks that relate to building resilience. Foremost among them are the Hyogo Framework for Action and its successor, the United Nations Framework Convention on Climate Change, the Sustainable Development Goals, and the United Nations Convention on Biological Diversity (Box 4). Agreements that will be reached under these frameworks in 2015 provide a unique opportunity to enhance resilience to extreme weather worldwide; shaping plans, responses and outcomes for years to come.

There is a growing realisation that climate change, disasters, environment and development are inextricably linked, with climate change, disasters and environmental degradation often undermining hard-won development gains. In recognition of this, the World Bank is integrating climate and disaster risk into its development programmes, including supporting 18 countries under the Pilot Program for Climate Resilience[168]. Yet despite clear overlaps, international frameworks are not as joined up as they could be[169, 170]. More closely aligned policies on disasters, climate change, sustainable development and the environment would reinforce global efforts to build resilience to extreme weather. It would also avoid duplication of efforts and confusion over the roles and mandates of each framework[171], and could reduce monitoring and reporting demands at national and sub-national levels.

167. UK Cabinet Office 2013 *The role of Local Resilience Forums: a reference document.* London: UK Cabinet Office (See https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/62277/The_role_of_Local_Resilience_Forums-_A_reference_document_v2_July_2013.pdf, accessed 6 October 2014).

168. *Op. cit.*, note 133.

169. *Op. cit.*, note 1.

170. UNISDR 2013 *Disaster Risk Reduction at COP19: Briefing Note.* Geneva: UNISDR (See http://www.unisdr.org/files/35351_cop19warsawunisdrbriefingpaperforsu.pdf, accessed 27 August 2014).

171. Kellett, J, Mitchell, T, Bahadur, A, Jones, L, Kirbyshire, A, Lovell, E, Le Masson, V, Peters, K & Wilkinson, E 2014 *The future framework for decision-makers*, London: Overseas Development Institute (See http://www.odi.org/publications/8473-disaster-risk-reduction-drr-climate-change-vulnerability-conflict, accessed 31 October 2014).

Adequate references to the Hyogo Framework for Action's successor in the Sustainable Development Goals and future climate agreement would be a pragmatic way of aligning the frameworks and allowing disaster risk reduction to inform sustainable development and climate change considerations. In turn, the successor to the Hyogo Framework for Action should draw on evidence from the climate change convention's Cancun Adaptation Framework and Warsaw International Mechanism for Loss and Damage so as not to under-represent climate-related disasters (Box 4). The importance of the natural environment should also be emphasised in all three frameworks, for example by highlighting its role in building resilience rather than just its role in driving risk (section 3.1). Another practical step would be to fully align the timeframe and reporting protocols for the successor to the Hyogo Framework for Action and Sustainable Development Goals[172], and to use consistent targets and indicators for both frameworks (section 4.4).

While efforts to build resilience are often joined up at the local level, many institutions fail to co-ordinate action at national and international levels. Overcoming this, some have argued, represents the single most important (yet most difficult) part of building resilience[173]. As the Royal Society explored in its 'People and the planet' report[174], collaboration rather than competition between institutions is essential for people and the planet to flourish. New institutional arrangements will be essential for delivering co-ordinated, complementary international policies for building resilience.

172. *Op. cit.*, note 37.

173. *Op. cit.*, note 133.

174. *Op. cit.*, note 71.

BOX 4

International policy frameworks

Hyogo Framework for Action

The Hyogo Framework for Action details the work required by all sectors and actors to reduce disaster risk. It runs from 2005 to 2015 and negotiations are underway to agree its successor. This will be endorsed at the World Conference on Disaster Risk Reduction in March 2015.

Negotiations to date indicate that the new framework will highlight the value of science in the disaster risk reduction cycle: from prevention, prediction and early detection of disasters, to response and recovery. The role of science in informing which measures should be implemented (as opposed to just facilitating their implementation) is also being recognised. A Scientific and Technical Advisory Group is already established, with a vision for making science useful, useable and used in disaster risk reduction by 2015[175]. In addition, the development of an international science and technology partnership, with oversight of disaster risk reduction, is gaining traction.

United Nations Framework Convention on Climate Change

There has been a growing focus on adaptation under this convention in recent years, with several institutions being established: the Cancun Adaptation Framework (2010), the Adaptation Committee (2011), and the Warsaw International Mechanism on Loss and Damage (2013). In addition, the Nairobi Work Programme[176] aims to improve Parties' understanding and assessment of climate change adaptation, and help them to make informed decisions about practical adaptation action. The convention also funds adaptation, including through the Green Climate Fund which is emerging as a hub of adaptation finance.

Since 2011 a process has been underway to agree 'a protocol, another legal instrument or an agreed outcome with legal force'[177], to be adopted no later than 2015. The new climate agreement will cover a range of issues, including adaptation.

Sustainable Development Goals

A set of global Sustainable Development Goals will be agreed in September 2015 when the Millennium Development Goals expire. Although not legally binding, the new goals will define the direction of international development for at least the next decade. The Sustainable Development Solutions Network was established to feed scientific and technical expertise into the development of the goals. A High-Level Panel reported in 2013, criticising the Millennium Development Goals for not integrating the economic, social and

175. Southgate R J, Roth C, Schneider J, Shi P, Onishi T, Wenger D, Amman W, Ogallo L, Beddington J, Murray V 2013 *Using Sciencefor Disaster Risk Reduction*.Geneva: UNISDR. (See www.preventionweb.net/go/scitech, accessed 27 August 2014).

176. UNFCCC 2005 *Nairobi work programme on impacts, vulnerability and adaptation to climate change* (NWP) (See http://unfccc.int/adaptation/workstreams/nairobi_work_programme/items/3633.php).

177. UNFCCC 2011 *Establishment of an Ad Hoc Working Group on the Durban Platform for Enhanced Action. Decision* 1/CP.17. Bonn: UNFCCC (See http://unfccc.int/resource/docs/2011/cop17/eng/09a01.pdf#page=2, accessed 27 August 2014).

environmental aspects of sustainable development, and reaffirming the enormous challenge to development posed by climate change[178]. An Open Working Group was also established, which in June 2014 proposed a set of goals and targets. The following refer explicitly to resilience[179]:

Goal 1: End poverty in all its forms everywhere.
Target 1.5: 'by 2030 build the resilience of the poor and those in vulnerable situations, and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters'.

Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable.
Target 11.4: 'by 2030 halve the number of deaths and decrease by 50% the economic losses relative to GDP caused by natural disasters'.
Target 11.b: 'by 2020, increase by x% the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resilience, mitigation and adaptation to climate change and natural disasters'.

Goal 13: Take urgent action to combat climate change and its impacts.
Target 13.1: 'strengthen resilience and adaptive capacity to climate related hazards and natural disasters in all countries'.

United Nations Convention on Biological Diversity

The Convention on Biological Diversity aims to conserve biodiversity, use it sustainably, and fairly and equitably share its benefits. The convention is responsible for coining the term 'ecosystem-based adaptation' in 2009 (section 3.1).

In 2010 an updated Strategic Plan for Biodiversity for 2011-2020 was adopted. This includes 20 targets to reduce and eventually reverse biodiversity loss. Target 15 focuses on ecosystem resilience and states that 'By 2020, ecosystem resilience and the contribution of biodiversity to carbon stocks has been enhanced, through conservation and restoration, including restoration of at least 15 per cent of degraded ecosystems, thereby contributing to climate change mitigation and adaptation and to combating desertification'[180]. The convention also holds relevant negotiations under its 'biodiversity and climate change and disaster risk reduction', 'biodiversity for sustainable development' and 'ecosystem conservation and restoration' themes.

Above
Flags at the Conference of the Parties to the United Nations Convention on Biological Diversity, Hyderabad, India in 2012.

178. High-Level Panel of Eminent Persons on the Post-2015 Development Agenda 2013 *A new global partnership: eradicate poverty and transform economies through sustainable development.* New York: United Nations. (See http://www.un.org/sg/management/pdf/HLP_P2015_Report.pdf, accessed 27 August 2014).

179. UN Department of Economic and Social Affairs. *Introduction to the Proposal of the Open Working Group for Sustainable Development Goals.* (See http://sustainabledevelopment.un.org/focussdgs.html, accessed 27 August 2014).

180. Convention on Biological Diversity 2010 *Strategic Plan 2011-2010: Aichi Biodiversity Targets. COP10 Decision X/2*. (See http://www.cbd.int/sp/targets/, accessed 27 August 2014).

4.2 Comprehensive forward planning

As well as involving multiple sectors and actors locally, nationally and internationally, building resilience also requires large geographical areas and long timescales to be considered.

Experience from past events suggests that building resilience at one level (eg neighbourhood) can risk undermining it at another (eg regional or national)[181]. Extreme weather does not respect administrative boundaries, and intervening in one area (eg upstream, or in a rural area) can have knock-on effects for people and property elsewhere (eg downstream, or in an urban area). Resilience planning should therefore reflect the extent of the system affected, directly and indirectly, by extreme weather. It should take account of risks that are not immediately visible at the local level, and should prevent local actions that compromise larger-scale resilience. Failure to do this can result in maladaptation (Box 5).

BOX 5

Maladaptation

Maladaptation is defined by the Intergovernmental Panel on Climate Change as 'Any changes in natural or human systems that inadvertently increase vulnerability to climatic stimuli; an adaptation that does not succeed in reducing vulnerability but increases it instead'[182]. Maladaptation can result from actions at any level, from the individual or household to the international community.

Example:
Since 1982 national water management policies have been implemented along the Inkomati River in Mozambique and its tributaries in South Africa. These include dam-building, irrigation and water redistribution. However, policies developed without considering their indirect and long-term consequences have exacerbated water management challenges and have amplified the impacts of local stresses such as unpredictable weather, disease and fishery decline. High water use and dam-building in South Africa have caused low river flow rates into Mozambique, along with salt water intrusion and floods from upstream dam releases. The downstream impacts on poor communities have compounded local vulnerabilities, limited livelihood options and undermined coping abilities[183, 184].

181. Moser, S & Boykoff, M 2013 *Climate change and adaptation successes: the scope of the challenge, In Successful adaptation to climate change: linking science and policy in a rapidly changing world* (ed. Moser, S & Boykoff, M). Oxford: Routledge.

182. *Op. cit.*, note 28.

183. Bunce, M, Brown, K & Rosendo, S 2010 *Policy Misfits, Climate Change and Cross-scale Vulnerability in Coastal Africa: How Development Projects Undermine Resilience*. Environmental Science & Policy **13**(6). 485-497.

184. Drieschova, A, Giordano, M, & Fischhendler, I 2008 *Governance mechanisms to address flow variability in water treaties.* Global Environmental Change **18**(2), 285–295.

Resilience planning also requires long timescales that far exceed those associated with funding and political cycles. As the Royal Society argued in its 'People and the planet' report[185], farsighted political leadership focused on long-term goals is needed to ensure that people and the planet flourish rather than merely survive. Anticipatory (as opposed to reactive) investment in resilience-building measures is required to 'get ahead of the disaster curve', but this can challenge the status quo.

4.2.1 The need for early planning and investment

There is often a window of opportunity for building resilience following a major disaster [186, 187]. For example, all school infrastructure standards in the Philippines were upgraded as part of the 'Safe Schools Initiative' following Typhoon Haiyan in 2013[188, 189, 190]. A disaster risk reduction item was also included in the 2014 Philippines national budget just weeks after Haiyan struck[191, 192]. However, actions taken in the immediate aftermath of a disaster tend to be instinctive[193], and the need for rapid recovery and rebuilding can outweigh the need for well-considered policies. Some have argued that this was the case in New Jersey and New York following Hurricane Sandy, when rebuilding permits were expedited, permit fees waived, and coastal engineering encouraged[194, 195] without considering the long-term impacts of rebuilding in risky environments[196]. The reliance on reactive rather

185. *Op. cit.*, note 71.

186. Birkmann, J, Buckle, P, Jaeger, J, Pelling, M, Setiadi, N, Garschagen, M, Fernando, N & Kropp, J 2010 *Extreme events and disasters: a window of opportunity for change? Analysis of organisational, institutional and political change, formal and informal responses after mega-disasters.* Natural Hazards **55**(3), 637-655.

187. Fan, L 2013 *Disaster as opportunity? Building back better in Aceh, Myanmar and Haiti. Humanitarian Policy Group Working Paper.* London: Overseas Development Institute (ODI) (See http://www.odi.org/publications/8007-resilience-build-back-better-bbb-aceh-tsunami-cyclone-myanmar-earthquake-haiti-disaster-recovery, accessed 27 August 2014).

188. UNISDR 2014 *Philippines Leads in UN Disaster-Safe Schools Initiative.* (See http://www.unisdr.org/archive/36661, accessed 27 August 2014).

189. UNISDR 2013 *Philippines Launches Safe Schools Campaign Post-Haiyan.* Geneva: UNISDR. (See http://www.preventionweb.net/files/35607_2013no31.pdf, accessed 27 August 2014).

190. Department of Education for the Philippines 2014 *DepEd Strengthens Commitment to School Safety.* (See http://www.deped.gov.ph/press-releases/deped-strengthens-commitment-school-safety, accessed 13 October 2014).

191. UNISDR 2013 *Annual Report: Final Report on 2012-2013 Biennium Work Programme.* Geneva: UNISDR.

192. McElroy, A 2013 *Philippines unveils dedicated disaster risk budget for 2014.* (See http://www.unisdr.org/archive/35997, accessed 27 August 2014).

193. Kahneman, D 2012 *Thinking, Fast and Slow.* London: Penguin.

194. Golstein, W, Peterson, A & Zarrilli, D 2014 *One City, Rebuilding Together. A Report on the City of New York's Response to Hurricane Sandy and the Path Forward.* (See http://www1.nyc.gov/assets/home/downloads/pdf/reports/2014/sandy_041714.pdf, accessed 27 August 2014).

195. State of New Jersey Department of Environmental Protection 2013 *Christie Administration adopts rules to expedite recovery and rebuilding projects for Sandy affected New Jerseyans.* New Jersey: New Jersey Department of Environmental Protection. (See http://www.nj.gov/dep/newsrel/2013/13_0065.htm, accessed 27 August 2014).

196. Walsh, B 2012 *After Sandy: Why we can't keep rebuilding on the water's edge.* New York: TIME. (See http://science.time.com/2012/11/20/after-sandy-why-we-cant-keep-rebuilding-on-the-waters-edge/, accessed 27 August 2014).

Although numerous estimates exist, it is often quoted that every dollar invested in disaster risk reduction returns four dollars in disaster recovery savings.

than proactive approaches to building resilience also contributes to an international humanitarian system that is stretched beyond its means[197].

Effective resilience planning should therefore involve early, pre-emptive investment in measures to reduce future damages, in addition to tested emergency plans. This has been shown to be cost-effective in many instances. Although numerous estimates exist, it is often quoted that every dollar invested in disaster risk reduction returns four dollars in disaster recovery savings[198]. Ranges are also commonly given, such as the estimate that every dollar invested returns between two and ten dollars[199]. However, all such estimates are inevitably over-simplistic. Although the principle that early investment pays off is correct, it is not necessarily correct in all circumstances: benefits depend on where and how money is spent[200].

The reasons behind the current lack of early planning and investment, despite the evidence for its cost-effectiveness, vary from case to case. Common reasons include a lack of resources, information and suitable governance arrangements; cognitive and behavioural biases; absent markets and public goods; high discount rates; and the infrequent nature of some disasters, and uncertainty about their severity, location and precise timing. Short political cycles and the fact that political capital is rarely gained from cost-effective risk reduction measures also compound this challenge[201]. These barriers need to be identified, prioritised and tackled through private and public action[202].

Although emergency preparedness is a core feature of most efforts to manage climate and disaster risks[203], investing in pre-emptive resilience-building still represents a major transformation. It requires the traditionally separate domains of humanitarian response and longer-term development to be brought together. This in turn requires transforming existing funding mechanisms, and better co-ordinating funds across the proactive-reactive continuum nationally and internationally[204]. In order to limit the need for costly disaster response and recovery, more national and international funds will need to be directed to pre-emptive measures that build resilience to extreme weather.

197. Kellett, J & Peters K 2014 *Dare to prepare: taking risk seriously.* London: Overseas Development Institute (ODI) (See http://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/8747.pdf, accessed 6 October 2014).

198. Mechler, R 2012 *Reviewing the economic efficiency of disaster risk management. Review commissioned by Foresight project: Reducing the risk of future disasters,* London: Government Office for Science.

199. *Op. cit.*, note 105.

200. Government Office for Science 2012 *Foresight: Reducing Risks of Future Disasters: Priorities for Decision Makers. Final Project Report.* London: The Government Office for Science.

201. *Op. cit.*, note 164.

202. *Op. cit.*, note 133.

203. The World Bank, GFDRR and the Government of Japan 2012 *Managing disaster risks for a resilient future: The Sendai report.* Washington DC: The World Bank. (See http://siteresources.worldbank.org/DEVCOMMINT/Documentation/23283830/DC2012-0013(E)DRM.pdf, accessed 27 August 2014).

204. *Op. cit.*, note 197.

Left
Flooding in Brisbane. Photo by Erik Veland via Flickr, used under CC BY NC 2.0.

4.3 Integrating resilience into the global financial system

Integrating resilience to extreme weather into the global financial system – through financial accounting and regulation – would be an important transformational shift. Reform to the financial system could create the conditions to save millions of lives, livelihoods and property in the decades ahead.

4.3.1 The need for financial reform

At present the financial system as a whole does not take adequate account of the risks posed by extreme weather. These risks are not systematically factored into investors' valuations or assessed by creditors. Business surveys, economic forecasts and country briefings that guide investment decisions and credit ratings are typically based on the availability of skilled labour, access to export markets, political and economic stability, and financial incentives, with little or no consideration of disaster risks[205.] In addition, real estate markets largely ignore the risks associated with highly exposed locations. For instance, if two otherwise identical companies have notably different exposures to extreme events, with implications for their potential solvency or profit (eg one is located on a flood plain), the company with the greater exposure should have a reduced value or share price and should be less desirable to investors. Yet at present this is rarely the case.

Given the increasing exposure of assets to extreme events[206], the disconnect between material risk and asset valuation (and hence the invisibility of this risk within the financial system) is cause for concern. Until these risks are accurately evaluated and reported, companies will have limited incentives to reduce them, and valuations and investment decisions will continue to be poorly informed. Although some disaster risk information is

At present the financial system as a whole does not take adequate account of the risks posed by extreme weather.

205. *Op. cit.*, note 72.

206. *Op. cit.*, note 1.

already disclosed and used by investors, the data and procedures for making assessments are not standardised, which can limit their usefulness[207]. Ultimately, without financial reform, people's resilience will be undermined in the future.

4.3.2 What could reform involve?

Any change to financial regulation, accounting and reporting should be simple and consistent. Placing a *value* on resilience to extreme events would incentivise all capital owners (from farmers, to homeowners, to the world's largest multinational corporations) to avoid unnecessary risk and build resilience. It would also shift corporate risk management towards disaster risks, rather than focusing principally on financial, economic, market and legal risks[208].

A basic set of metrics could achieve this. For example, organisations could be required to report their maximum probable annual losses linked to extreme weather (or disasters more generally) against their current assets and operations at the following levels:

- 1 in 100 (1%) risk per year (a stress test for an organisation's solvency in an extreme event scenario)
- 1 in 20 (5%) risk per year (a stress test for an organisation's annual earnings or profits)
- Annual Average Loss (AAL) (a standardised metric for an organisation's exposure to extreme events)

The 1% stress test, which is gaining interest and support from the financial community[209], is not as extreme as it might at first sound: it implies a 10% chance of an organisation being affected once a decade.

This 'triple stress test' would represent a step in the right direction. However, pilots would be needed in different sectors and different-sized organisations to test its effectiveness and feasibility. Clearly defined reporting requirements would also be needed to ensure consistent reporting.

Over the last 30 years, underwriting in the re/insurance sector has made considerable progress in evaluating the risks posed by extreme weather, reflecting the sector's responsibility to manage extreme risks to people. Although insurance premiums do not always dis-incentivise investment in hazard-exposed areas[210] the principles, techniques and institutions developed in the re/insurance sector could facilitate reform in the wider financial system. These include the financial principle that material risks should be appropriately assessed, reported and communicated; the existence of regulatory bodies at national, regional and global levels; and the convention that insurance contracts should deliver their commitments at a level of 1 in 200 (0.5%) risk per year. Progress in the re/insurance sector has also been enabled by the increased use of scientific techniques to develop advanced methodologies, data

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207. Ernst & Young 2014 *Tomorrow's investment rules: global survey of institutional investors on non-financial performance.* London: Ernst and Young (See http://www.ey.com/Publication/vwLUAssets/EY-Institutional-Investor-Survey/$FILE/EY-Institutional-Investor-Survey.pdf, accessed 27 August 2014).

208. *Op. cit.*, note 72.

209. Climate Summit 2014 *Integrating Risks into the Financial System: The 1-in-100 Initiative Action Statement* (See http://www.un.org/climatechange/summit/wp-content/uploads/sites/2/2014/09/RESILIENCE-1-in-100-initiative.pdf, accessed 6 October 2014).

210. *Op. cit.*, note 72.

standards, analytical frameworks and open access catastrophe risk modelling platforms.[211]

The metrics suggested above would need to be refined to reflect the characteristics of different sectors, and it could take time for them to become an integrated part of capital markets. However, the techniques for generating these metrics are well understood. Many organisations already collect relevant risk information; this now needs to be disclosed and applied more strategically. In addition, work is already underway to develop tools allowing metrics such as Annual Average Loss to be factored into business and country forecasts and analyses[212]. Using the foundations already in place, resilience accounting could be relatively easily achieved within the next five years, at a very low cost relative to the costs inflicted by extreme weather.

The rules governing capital are increasingly framed, developed and applied at a global level. Global financial regulation is largely driven by three institutions – the Bank of International Settlement, the International Association of Insurance Supervisors and the International Organization of Securities Commissions – which work with banks, insurers, asset managers, regulators and accounting organisations to develop rules and reporting standards which are implemented through local financial institutions. These three global bodies have an important role in integrating resilience to extreme weather into the global financial system. Ratings agencies could also facilitate a shift towards more resilient investments. Furthermore, a UN-led public-private alliance called the '1-in-100 Initiative' promises to drive progress in this area[213].

Left
Depth gauges at Thruscross Reservoir, UK. Photo by Tom Blackwell via Flickr, used under CC BY NC 2.0.

4.4 Measuring resilience

Measuring resilience is not a straightforward process. Numerous metrics exist but these vary considerably regarding the subject and object of measurement (resilience of what, to what?) and often measure only one or a few dimensions of resilience. However, measuring resilience (or proxies for resilience) is necessary in order to assess the effectiveness of resilience-building measures and amend policies as necessary (section 1.2.2). Measuring resilience also makes resilience-building agencies more accountable and can help justify resilience expenditure[214].

211. The Royal Society 2012 *Hidden Wealth: the contribution of science to service sector innovation.* London: The Royal Society. (see https://royalsociety.org/~/media/Royal_Society_Content/policy/publications/2009/7863.pdf, accessed 5 November 2014).

212. UNISDR 2014 *Risk-sensitive business investment.* Geneva: UNISDR (See http://www.unisdr.org/files/37968_finalwp5.pdf, accessed 6 October 2014).

213. *Op. cit.*, note 209.

214. Twigger-Ross, C, Kashefi, E, Weldon, S, Brooks, K, Deeming, H, Forrest, S, Fielding, J, Gomersall, A, Harries, T, McCarthy, S, Orr, P, Parker, D & Tapsell, S 2014 *Flood Resilience Community Pathfinder Evaluation: Rapid Evidence Assessment.* London: DEFRA (See http://randd.defra.gov.uk/Default. aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=18744#RelatedDocuments, accessed 27 August 2014).

4.4.1 The need for consistent metrics

Earlier in this chapter the need for complementary, mutually reinforcing international frameworks was discussed. One way of achieving this would be to establish consistent (identical or comparable) goals, targets and indicators for building resilience to extreme weather in the different frameworks[215]. This would clarify priorities and simplify monitoring and reporting. Consistent metrics in the successor to the Hyogo Framework for Action and Sustainable Development Goals would be particularly useful (although indicators would need to be more detailed under the former than the latter). Consistent monitoring of progress under the different frameworks would help drive action. For example, the information collected by regional, national and local 'HFA Monitors'[216] could help monitor progress against the new development goals and disaster risk reduction framework[217].

Consistent metrics are also needed so that the effectiveness of different resilience options (eg building a sea wall or maintaining a mangrove forest) can be compared (section 3.2.3). Accurate measurement of the effectiveness of ecosystem-based options could help ensure that the environment receives more attention in international frameworks – as not only an underlying risk factor but also a potential solution[218].

4.4.2 Developing and using different types of metrics

Resilience metrics can be grouped into two broad categories: 'input' metrics and 'outcome' metrics. Outcome metrics relate to losses (eg loss of lives or assets) and other impacts (eg economic impacts or the existence of disaster refugees). They can be absolute or relative to GDP or population size. These metrics are useful for measuring the long-term effectiveness of actions, and work by the United Nations Office for Disaster Risk Reduction to develop national loss databases for disasters of all scales[219] is contributing to this (section 1.1.2). However, changes in losses cannot be reliably measured over one or two decades: using scenarios to track the *risk* of losses every year or few years has been proposed as a more reliable approach[220].

215. *Op. cit.*, note 37.

216. Prevention web, *HFA Monitoring & Review.* See http://www.preventionweb.net/english/hyogo/hfa-monitoring/?pid:73&pil:1

217. *Op. cit.*, note 149.

218. *Op. cit.*, note 103.

219. UNISDR 2014 *Risk-informed Public Policy and Investment.* Geneva: UNISDR (See http://www.unisdr.org/we/inform/publications/37965, accessed 28 August 2014).

220. *Op. cit.*, note 37.

Input metrics measure the extent to which resilience-building policies and institutions have been established. At different levels these could include: the number of countries with national and local resilience strategies; a city's population with access to early warning and evacuation systems or social protection schemes; or the number of a village's schools and health facilities built to hazard-resilient building codes. Given the importance of ecosystems in building resilience to extreme weather, input metrics should also reflect the state of the environment. Such metrics could include the percentage of the coastal population and infrastructure protected by coastal and marine ecosystems, or the extent of urban green spaces to minimise the impacts of heatwaves and flooding. Input metrics are particularly important as a way of encouraging early action and investment in resilience-building measures (section 4.2.1), whereas outcome metrics are inherently retrospective.

Input and outcome metrics are not mutually exclusive. Given the complexity of building resilience to extreme weather, a combination of (ideally quantifiable) metrics is needed[221]. The most appropriate metrics will depend on the particular context, and local actors will need to be involved in determining these and acquiring the necessary data[222] (section 4.1.2). For this reason, attempting to identify a definitive, universal resilience metric or metrics is missing the point[223].

Scientific and technological advances present significant opportunities to develop reliable, locally-relevant metrics in a collaborative way to galvanise the measurement of resilience. However, despite the availability of high resolution data, modelling capabilities and communication technologies, there remains a lack of suitable institutions and procedures to develop and use resilience metrics. Under the Hyogo Framework for Action national governments typically assess and report their own performance against disaster risk reduction targets. Measuring progress through independent reviews of countries and cities, or through other stakeholders reporting alongside governments, would be more rigorous[224]. International oversight is also needed to strengthen national and local monitoring capacity, particularly in the developing world, and to co-ordinate data collection. Such oversight should involve interactions with national statistical offices and should draw on data from technical agencies, technology companies and the scientific community[225].

Left
Roadside 'EvacuSpot' signals one of seventeen evacuation pick-up points in New Orleans, Louisiana following Hurricanes Katrina and Rita.

Input metrics are particularly important as a way of encouraging early action and investment in resilience-building.

221. UNISDR 2013 *Towards the post-2015 framework for disaster risk reduction. Indicators of success: a new system of indicators to measure progress in disaster risk management.* Geneva: UNISDR (See http://www.unisdr.org/files/35716_newsystemofprogressindicatorsfordrr.pdf, accessed 28 August 2014).

222. *Op. cit.*, note 200.

223. *Op. cit.*, note 147.

224. *Op. cit.*, note 37.

225. *Op. cit.*, note 37.

RECOMMENDATION 1

Governments have a responsibility to develop and resource resilience strategies, and will be most effective when they:

- focus on minimising the consequences of infrastructure failure rather than avoiding failure completely – for example by prioritising the resilience of critical infrastructure and having plans to minimise impacts when non-critical infrastructure fails;
- incorporate resilience-building into other relevant policies such as poverty alleviation and land-use planning;
- consider all the factors – the whole system – likely to be impacted by extreme weather, including geographical areas beyond those directly affected, and effects over decades;
- use a range of expertise from disciplines such as environmental management, climate change adaptation, disaster risk reduction and sustainable development, and from sources including the private sector, non-governmental organisations and local communities; and
- support and enable local action that is consistent with national resilience strategies.

RECOMMENDATION 2

At the international level, governments will be more effective when they act together to build resilience; sharing expertise, co-ordinating policy and pooling resources to confront common risks. To limit the need for costly disaster responses, more national and international funds will need to be directed to measures that build resilience to extreme weather.

RECOMMENDATION 3

It is important that the purpose, design and implementation of policy frameworks covering climate change, disaster risk reduction and development are aligned and consistent regarding extreme weather. There is an opportunity to do this in 2015 at the international level. In particular, efforts should be made to:

- emphasise the importance of the natural environment in the successor to the Hyogo Framework for Action, Sustainable Development Goals and future climate agreement – for example by highlighting its role in building resilience rather than just its role in driving risk;
- develop and use identical or comparable metrics in these policy frameworks to incentivise co-ordinated action and allow the effectiveness of different resilience-building measures to be compared;
- measure progress in implementing resilience-building strategies (‘input’ metrics) as well as the impacts of extreme weather (‘outcome’ metrics);
- align the timeframes and reporting protocols for the successor to the Hyogo Framework for Action and Sustainable Development Goals; and
- ensure international oversight to strengthen national and local monitoring capacity, particularly in the developing world, and to co-ordinate data collection.

RECOMMENDATION 5

The re/insurance sector has made considerable progress in evaluating the risks posed by extreme weather. These risks now need to be better accounted for in the wider financial system, in order to inform valuations and investment decisions and to incentivise organisations to reduce their exposure. This could be done through a requirement for public and private sector organisations to report their financial exposure to extreme weather at a minimum of 1 in 100 (1%) per year risk levels.

Chapter five
Demonstrations

In this report a number of ways of building resilience at local, national and international levels have been discussed. Resilience-building is not a one-size-fits-all exercise: to be effective it needs to involve and be tailored to suit the communities facing the impacts of extreme weather. In this chapter we present four demonstrations to illustrate how different communities around the world are building their resilience to extreme weather. These demonstrations cover a range of approaches including social, engineering, ecosystem-based and hybrid options in high, middle and low income countries.

Not all of the resilience-building measures included in the demonstrations have yet been tested against extreme weather. In addition, particular measures may be uniquely valuable or applicable in the specific community discussed. Nonetheless, the principles of having a clear strategy and understanding of risk, and engaging a range of stakeholders, are common throughout.

Left
Mangroves.

Demonstrations

River and coastal flooding: Surat, India

Above
Surat, India. Photo by Setu Vakkil via Flickr, used under CC BY NC SA 2.0.

Main messages:

- Collaboration and shared learning among a range of different stakeholders at local, national and international levels can galvanise resilience-building.
- The different components of a resilience strategy – such as top-down engineered structures and community-led ecosystem-based approaches – need to complement and reinforce one another.

Surat in India is one of the most vulnerable cities to climate change globally. It is home to 4.5 million people[226] and is growing rapidly. It is an important centre of trade and industry[227], particularly for diamond-cutting and textile production[228]. Located on the River Tapi estuarial floodplain in Southern Gujarat, 90% of the city is affected by weather-related extremes, including cyclones and flooding from high tides. Rising sea levels are a particular threat since western Surat is less than 10 metres above the average sea level. The city flooded in 1998, 2004, 2006, 2010 and 2013, suggesting that it is already experiencing a resilience deficit.

The city manages competing water demands using the upstream Ukai dam. Reservoir storage is kept at maximum levels for water security, agriculture and power generation, but this reduces spare capacity for extreme rainfall events, resulting in emergency dam releases during heavy rainfall. In 2006, 75% of the city was inundated by six metres of floodwater due to an emergency release coinciding with high tide. This caused 150 deaths and damages of US$4.5 million. 43% of the population had no warning of the event[229]. Expansion of the city's boundaries in 2006 incorporated the under-privileged Dumas coastal area. 71,000 homes are now prone to Khadi (tidal creek) floods and 450,000 are at risk from emergency dam releases. Urbanisation is exacerbating this problem as increasingly built-up river banks mean water cannot discharge safely to the Tapi's narrow river mouth.

However, in the face of these threats, Surat is quickly becoming a centre for comprehensive, strategic resilience-building. International networks are helping to support specific resilience policies and practices. For example, Surat joined the Asian Cities Climate Change Resilience Network in 2008. This initiative encourages dialogue between government officials, non-governmental organisations and other Asian cities. A multi-stakeholder body, the Surat Climate Change Trust, and Surat's 2011 Resilience Strategy also support collaboration between energy companies, police services, commerce departments and research institutes.

226. Bhat, G K, Karanth, A, Dashora, L, and Rajasekar, I 2013 *Addressing Flooding in the City of Surat Beyond its Boundaries.* Environment and Urbanization **25**(2), 429-441 (DOI: 10.1177/0956247813495002).
227. Rockefeller Foundation 2013 100 *Resilient Cities: Surat's Resilience Challenge.* New York: Rockefeller Foundation. (See http://www.100resilientcities.org/cities/entry/surats-resilience-challenge, accessed 28 August 2014).
228. ACCCRN 2011 *Surat's Resilience Strategy.* Surat: TARU. (See http://acccrn.org/sites/default/files/documents/SuratCityResilienceStrategy_ACCCRN_01Apr2011_small_0.pdf, accessed 28 August 2014).
229. *Op. cit.*, note 225.

In 2013 Surat joined the Rockefeller Foundation's 100 Resilient Cities Centennial Challenge which provides financial and logistical guidance for establishing a municipal Chief Resilience Officer, access to resilience solutions in a range of sectors, and inclusion in a global network of cities for sharing learning[230].

These collaborations have enabled specific resilience-building projects. Through the Asian Cities Climate Change Resilience Network, Surat has implemented two projects: an urban health and climate resilience centre and an early warning system. The early warning system uses a 'safe failure' controlled dam release and alerts citizens 48 hours in advance via mobile phone messages. This system translates disaster management plans developed at the city ward level into community understanding through drills and education. For example, colour coded markings on service poles and buildings show projected flood levels and contribute to early warnings. An urban service monitoring system also disseminates reports and maps of vulnerable groups requiring special emergency care.

Collaborative strategies have produced a rich knowledge base for building resilience. By integrating existing flood models with rainfall predictions, real-time events and reservoir data, models that took into account climate change were created. These models informed land-use policies providing 22,000 permanent homes for relocated slum dwellers, pro-poor building regulations, and a community-managed asset bank to mitigate flood risk. Other practices included an Asian Cities Climate Change Resilience Network-led planning and design competition, 'Surat Safe Habitat', which designed low income flood resistant housing for flood-prone areas.

Gujarat Coastal Zone Management Authority launched a community-based public-private partnership model for mangrove restoration, conservation and management in 2001[231]. Subsequently, a community-based coastal area eco-restoration project was launched in the Hazira mangrove forest in the Tapi Estuary to regenerate 1100 hectares of mangroves, supported by the private sector Hazira Group of Companies and Forest Department[232]. This re-plantation has climate benefits, supports livelihood security for coastal villages, and protects Surat from tidal storm surges and cyclones. However, these coastal protection measures were not incorporated within the Resilience Strategy. Instead, state-level decisions resulted in a protective seawall in the Dumas Beach area. Surat is a front-runner in building urban resilience. However more partnerships are needed to ensure the top-down and traditional engineered approach to coastal management works to complement social collaborations and community-led mangrove regeneration.

230. *Op. cit.*, note 227.

231. Gujarat Ecological Commission, Government of Gujarat, *Eco-Restoration of the Mangrove wetlands.* See http://www.gec.gujarat.gov.in/showpage.aspx?contentid=71, accessed 28 August 2014.

232. Hazira LNG & Port, 2010 *Coastal area Eco-Restoration project in Hazira Peninsula, South Gujarat India.* See http://www.haziralngandport.com/pdf/coastal_area_eco_restoration_project_reviewed.pdf, accessed 28 August 2014.

Heatwaves: Europe

Above
Air conditioning compressors.

Main messages:

- Supra-national commitment and policies are required for extreme events that exceed national borders.
- Physical interventions have their limitations. They are more effective when supported by appropriate national infrastructure policies and active local community networks.

The European heatwave in 2003 was a period of abnormally hot weather that lasted for 20 days, causing over 52,000 deaths in Europe. Temperatures exceeded 40 °C. There were over 14,800 fatalities in France from 2 to 15 August (60% more than expected over this length of time). Cities were particularly affected, with excess mortality reaching over 78% in Paris, Dijon, Poitiers, Le Mans and Lyon[233]. In the UK, 616 of the 2091 fatalities occurred in London alone.

In Europe, following the heatwave of 2003, there has been a strong commitment to building resilience at city, regional and national levels. In 2005, the Systeme D'alert Canicule et Santé was implemented in the 14 largest cities in France[234]. Heat health warning systems use forecasts of high-risk weather conditions to trigger public warnings. Before 2001, only one heat health warning system was in place in Europe. However 16 systems were operational by 2006 and 28 by 2009[235]. These vary in scope and extent, but include awareness raising, communication plans, heat surveillance systems and long-term strategies for reducing heat risk. Public health measures include media announcements, telephone help-lines, cooling centres, special emergency service preparedness, home visits and evacuation, outreach to the homeless, and utilities companies stopping disconnection for non-payment. The implementation of heat health warning systems contributed to a reduction in fatalities during the 2006 heatwave[236].

233. Larsen, J 2006 *Setting the Record Straight: More than 52,000 Europeans Died from Heat in Summer 2003.* Washington DC: Earth Policy Institute. (See http://www.earth-policy.org/plan_b_updates/2006/update56, accessed 28 August 2014).

234. Kovats, R & Ebi, K 2006 *Heatwaves and Public Health in Europe.* European Journal of Public Health **16**(6), 592-599 (DOI: 10.1093/eurpub/ckl049).

235. Lass, W, Haas, A, Hinkel, J & Jaeger, C 2011 *Avoiding the Avoidable: Towards a European Heatwaves Risk Governance.* International Journal for Disaster Risk Science **2** (1), 1-14 (DOI 10.1007/978-3-642-31641-8_8).

236. Fouillet, A, Rey, G, Wagner, V, Laaidi, K, Empereur-Bissonnet, P, Le Tertre, A, Frayssinet, P, Bessemoulin, P, Laurent, F, De Crouy-Chanel, P, Jougla, E & Hémon, D 2008 *Has the impact of heatwaves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave.* International Journal of Epidemiology **37**(2), pp. 309-317 (DOI: 10.1093/ije/dym253).

Supranational information-gathering provided the foundations for heatwave policy formation and subsequently, hazard reduction approaches. Built Infrastructure for Older People's Care in Conditions of Climate Change is a three year project within the 'Adaptation and Resilience in a Changing Climate' research network which aims to research and map how infrastructure for the elderly can be sufficiently resilient to withstand climate change until 2050. Similarly, EuroHEAT is a project, coordinated by the World Health Organisation Regional Office for Europe, that researches heat health effects in European cities, preparedness and public health system responses[237]. EuroHEAT's report 'Improving Public Health Response to Extreme Weather', included long-term measures for urban planning, energy, transport and housing recommendations such as building materials, cooling devices, thermometer and heat detector installation, and manuals for DIY activities around the home. The report also called for legislation, reviewing and adapting building codes, establishing guidelines and creating appropriate portfolios of options for countries.

Resilience to heatwaves relies on research projects which generate community awareness and understanding of heatwave risk and lead to social networks and community activism. Health burdens fall disproportionately on urban residents who are physiologically susceptible, socio-economically disadvantaged and live in the most degraded environments[238]. Likewise, risk is often heightened by social factors. People at higher risk of dying during heatwaves are those living alone, or in top floor apartments, demonstrating that many deaths are preventable. Therefore, social networks can reduce risk through public health information, awareness and community activism and are needed to support physical interventions. This is particularly important as physical resilience options for reducing the impact of heatwaves are often constrained by old infrastructure and high retrofitting costs, whilst new building construction emphasises protection from cold weather and can therefore inadvertently increase vulnerability to heatwaves[239]. Overall, legislation, national plans and social capital-building can pay real dividends for subsequent heatwaves.

237. WHO Europe 2007 *Improving Public Health Responses to Extreme Weather/Heat-Waves. EuroHEAT Meeting Report.* Copenhagen: WHO Regional Office for Europe. (See http://www.euro.who.int/__data/assets/pdf_file/0018/112473/E91350.pdf, accessed 28 August 2014).

238. Harlan, S L & Ruddell, D M 2011 *Climate Change and Health in Cities: Impacts of Heat and Air Pollution and Potential Co-benefits from Mitigation and Adaptation.* Current Opinion in Environmental Sustainability **3**(3), 126-134 (DOI: 10.1016/j.cosust.2011.01.001).

239. Zaidi, Z & Pelling, M 2013 *Institutionally Configured Risk: Assessing Urban Resilience and Disaster Risk Reduction to Heat Wave Risk in London.* Urban Studies. (DOI:10.1177/0042098013510957) (See http://usj.sagepub.com/content/early/2013/11/14/0042098013510957.abstract, accessed 28 August 2014).

Droughts: Southern Niger in the Sahel

Main messages:

- Local resource ownership and farmers rights are vital enabling social interventions.
- Knowledge-sharing and a definition of expertise that includes indigenous knowledge and traditional resilience-building practices are central to the survival of the Sahelian people in a climatically uncertain environment.

Drylands represent 40% of the Earth's land surface[240], ranging from arid lands with less than 200 mm/year of rainfall to savannah lands with more than 900 mm/year[241], and provide a home to 2.3 billion people[242]. High levels of rainfall fluctuation from year to year and across the landscape make for highly variable production systems, in which risk sharing, mobility, and diversification of income sources are key elements of any livelihood strategy. The drylands have suffered from recurring and extensive droughts, notably the Sahelian drought from 1969 to 1977[243], resulting in livestock and tree loss, harvest failure, famine, and soil erosion. This degradation of dryland soils and vegetation has been termed 'desertification'[244], which has created a widespread perception that deserts are advancing into neighbouring drylands, despite the lack of evidence for this. In practice, desertification is better understood as a process of land degradation in dry areas which includes soil erosion, a decline in vegetation cover, and reduced biodiversity.

The drylands are often perceived as 'unproductive wastelands'. Policies and projects are consequently put in place which misunderstand the high ecological variability and risk spreading strategies of people living in these regions, and ignore local knowledge and rights. Governments have sought to 'modernise' these areas using top-down models that fail to pay attention to local livelihoods, knowledge and institutions[245]. However, indigenous and local populations have managed to survive and prosper in these drought-prone, high-risk ecosystems; across the Sahel the population has doubled since 1980, despite persistent drought and high rainfall variability[246].

240. IUCN 2011 The great green wall: A technical options brief. Gland, Switzerland: IUCN. See http://www.iucn.org/about/work/programmes/ecosystem_management/about_work_global_prog_ecos_dry/, accessed 13.10.2014
241. Sendzimir, J, Reij, C & Magnuszewski, P 2011 *Rebuilding Resilience in the Sahel: Regreening in the Maradi and Zinder Regions of Niger.* Ecology and Society **16**(3), 1.
242. Hesse, C, Anderson, S, Cotula, L, Skinner, J & Toulmin, C 2013 *Managing the boom and bust: Supporting climate resilient livelihoods in the Sahel.* London: IIED.
243. Mortimore, M 2009 *Dryland Opportunities: A new paradigm for people, ecosystems and development.* Gland, Switzerland: IUCN. See https://www.iucn.org/about/union/secretariat/offices/esaro/resources/publications/?uPubsID=3920, accessed 13.10.2014.
244. *Op. cit.*, note 243.
245. *Op. cit.*, note 242.
246. World Initiative for Sustainable Pastoralism 2008 *World initiative on sustainable pastoralism*. Gland: IUCN. See http://www.iucn.org/wisp/, accessed 13.10.2014

Left
Innovative farming practices in the Sahel. Photo by M. Tall (CCAFS West Africa) via Flickr, used under CC BY NC SA 2.0.

Since the 1980s, small-scale community interventions have led to a 're-greening' of land in some parts of the Sahel, contributing to resilience and sustainable livelihoods. In southern Niger, for example, reforestation now covers 250,000 hectares per year equivalent to the re-growth of over 200 million trees. This has been achieved by farmer-assisted natural regeneration combined with techniques such as traditional conservation 'pit planting'. Farmers dig planting pits or 'zai', filling the holes with organic matter, which attracts termites that aid rainfall infiltration. Trees and crops planted in the zai do well because the pits also collect runoff from rainwater[247]. Another technique involves encouraging the re-growth of trees and shrubs through selective pruning, reduced grazing, and a ban on tree cutting. The subsequent mosaic of crop-tree-grazing systems is helping to build more resilient drylands, and is now thought to cover as many as 5 million hectares, benefiting 4.5 million people. Trees promote livelihood security and diversification by providing access to forest resources. They also help conserve soil structure, fertility, and biodiversity, while regulating water flows within the soil. Co-benefits include carbon sequestration and climate regulation. 'Re-greening' techniques have been spread by a range of donor agencies and non-governmental organisations due to their feasibility, adaptability and affordability.

247. Reij, C & Steeds, D 2003 *Success stories in Africa's drylands: supporting advocates and answering sceptics.* Amsterdam: CIS/Centre for International Cooperation.

Social infrastructure can enable or hinder ecosystem-based interventions. Many projects in the Sahel and elsewhere take a top-down approach, and ignore local expertise[248]. By contrast, in Niger the re-greening has involved altering definitions of 'expertise' to include local ecological knowledge and social relationships. Re-greening has also been facilitated by shifts in forestry rights. Control of agro-forestry was released from paramilitary forest officers, and recognition given to local people's rights to land and water, through both Niger's Code Rural and the decentralisation process[249].

Support for Niger's re-greening has come in particular from the non-governmental organisation 'Serving in Mission', the International Fund for Agricultural Development project in Maradi[250], and collaboration with Niger's Ministry of Agriculture and Ministry of Environment[251]. This has enabled a range of interventions which include farmer-managed natural regeneration practices, and strengthening of social organisations to manage natural regeneration practices[252]. Other approaches which focus on building social capital include communicating the successes of farmers over the past 30 years in the Sahel, using mobile phone communication, 'citizen journalism', and regional radio stations to disseminate knowledge and experience[253]. Local autonomy, rights, resource ownership and communicating expertise underwrite resilience-building in the uncertain landscapes of the Sahel[254].

248. *Op. cit.*, note 241.

249. Reij, C 2014 *Food Security in the Sahel is Difficult, but Achievable.* Washington, DC: World Resources Institute. See http://www.wri.org/blog/2014/02/improving-food-security-sahel-difficult-achievable, accessed 13.10.2014.

250. Tougiani, A, Guero, C & Rinaudo, T 2008 *Community mobilization for improved livelihoods through tree crop management in Niger.* GeoJournal **74**(5), 377-389 (DOI: 10.1007/s10708-008-9228-7) and International Fund for Agricultural Development, (IFAD) 2009 Sahelian Areas Development Fund Programme. Rome: IFAD.

251. Pretty, J & Ward, H 2001 Social capital and the environment. World Development, **29**(2), 209-227 (DOI: 10.1016/S0305-750X(00)00098-X).

252. *Op. cit.*, note 241.

253. *Op. cit.*, note 249.

254. *Op. cit.*, note 241.

River flooding: Pickering, UK

Main messages:

- Local communities can play a valuable role in generating knowledge and developing locally-relevant approaches for building resilience.
- A portfolio of interventions, selected according to affordability and community acceptability, can enhance the effectiveness of flood management strategies.
- Ecosystem-based and hybrid interventions can make a significant contribution to reducing flood risk, as well as delivering wider environmental, economic and social benefits.

Pickering is a historic market town in North Yorkshire on the banks of Pickering Beck. The Beck drains a steep-sided valley that generates rapid runoff, enhanced by past woodland clearance, land drainage, overgrazing, inappropriate cultivation and moorland burning. The catchment comprises four main land uses: forestry, improved grassland, heather moorland and arable. Pickering has a long history of flooding, mainly caused by intense summer storms[255]. In recent years, there were significant floods in 1999, 2000, 2002 and 2007. The 2007 event was the largest, flooding 85 properties and causing over £7 million damage. Climate change is projected to lead to more extreme storm events and flooding in the town, increasing the vulnerability of people, businesses and infrastructure.

Feasibility studies in 2001 of installing traditional 'hard' engineered flood defences in the town, including embankments and channel widening, proved that these would be neither cost-effective nor acceptable to the local community (due to the visual impact). Lack of progress and poor community engagement in decision-making resulted in increased frustration and concern about the continuing flood threat. The severe flooding experienced across the Yorkshire and Humber Region and elsewhere in 2007 led to the Pitt review[256] and a call for a more sustainable approach to flood risk management, including a greater focus on natural processes.

The local community in Pickering had already started to 'self-adapt' by creating the Ryedale Flood Research Group in 2003[257]. People provided photos, documents and maps, and together with funded academic researchers (under the Rural Economy and Land-Use programme) collectively mapped flooding impacts and developed a hydrological routing model[258]. Knowledge was gained through 'collective competencies' across the group, reframing research questions through participatory science, and pooling scientific and

255. Natural England 2012 *National Character Area Profile: Vale of Pickering: NE374*. Sheffield: Natural England. (See http://publications.naturalengland.org.uk/publication/3688500, accessed 28 August 2014).

256. Pitt, M 2009 *The Pitt review – lessons learned from the 2007 summer floods*. London: UK Cabinet Office (See http://webarchive.nationalarchives.gov.uk/20100807034701/http:/archive.cabinetoffice.gov.uk/pittreview/_/media/assets/www.cabinetoffice.gov.uk/flooding_review/pitt_review_full%20pdf.pdf).

257. Ryedale Flood Research Group 2008 Making Space for People: *Involving local knowledge in flood risk research and management in Ryedale, Yorkshire*. Yorkshire: Ryedale Flood Research Group (See http://knowledge-controversies.ouce.ox.ac.uk/ryedaleexhibition/Making_Space_for_People.pdf, accessed 28 August 2014).

258. Odoni, N & Lane, S N 2010 *Knowledge Theoretic Models in Hydrology. Progress in Physical Geography* **34**, 151-171.

'local' expertise[259]. Attention focused on trying to hold more flood water within the upstream catchment through better land management, including by creating a series of small flood storage bunds along the floodplain. Local ownership of the proposed solutions supported by hydrological modelling strengthened the case for a change in approach.

Opportunities for improving land-use are often significantly hindered by factors such as land ownership, designations, land users and mindsets[260]. A partnership approach is vital to achieve and integrate targeted changes on the ground. This was aided at Pickering by the pre-existing Rural Economy and Land Use project, which had already pioneered community participation in flood risk management. Another important factor was that 36% of the catchment was publicly owned by the Forestry Commission and the National Park Authority, while the Duchy of Lancaster Estates owned a further 15%, so relatively few land owners needed to agree to the changes.

The 'Slowing the Flow' initiative was developed in 2008 in order to demonstrate how the integrated application of a range of land management measures at the catchment scale could help to reduce flood risk, as well as provide wider societal benefits. Funding was received from the UK Department for the Environment, Food and Rural Affairs for an initial two-year project, which started in 2009. A collaborative partnership was formed to steer the work, led by Forest Research and involving Forestry Commission England, the Environment Agency, North York Moors National Park Authority, Natural England, Local Authorities, Defra, Durham University and community groups, including the Ryedale Flood Research and Pickering Flood Defence Groups[261]. Seven measures were developed with the aim of retaining more flood water in the upper and middle parts of the catchment and reducing flood peaks in Pickering. These measures included constructing flood storage bunds and large woody debris dams, creating woodland, blocking forest and moorland drains, establishing no-burn buffer zones and improving runoff management on farmland and within forested areas.

Mapping and modelling were used to identify the best locations for placement of the measures, with a key finding being that slowing the flow in the wrong place can increase, rather than decrease flood risk due to synchronisation of peak flows. The number and mix of measures was based on affordability, community acceptability and the provision of multiple benefits. The overall objective was to increase the level of flood protection for Pickering from a 25% chance to a less than 4% chance of flooding in any one year.

259. *Op. cit.*, note 257.

260. Nisbet, T R & Thomas, H 2008 *Restoring Floodplain Woodland for Flood Alleviation. Final Report to DEFRA on Project SLD2316* (39). London: DEFRA.

261. Nisbet, T R, Marrington, S, Thomas, H, Broadmeadow, S & Valatin, G 2011 *Slowing the Flow at Pickering, Final Report. DEFRA FCERM Multi-Objective Flood Management Demonstration Project*. London: DEFRA. (See http://www.forestry.gov.uk/pdf/stfap_final_report_Apr2011.pdf/$FILE/stfap_final_report_Apr2011.pdf).

Left
Woody debris dam installed as part of the 'Slowing the Flow' initiative near Pickering, North Yorkshire.

By October 2014, the following measures were either in place or close to completion within the catchment of the Pickering Beck and neighbouring River Seven: a large flood storage bund (120.000 m^3), a trial of two timber mini-bunds (1,000-4,000 m^3), 175 large woody debris dams, over 130 heather bale dams, 42 hectares of woodland planted, no-burn buffers established along all moorland streams, forest plans revised and a number of farm-based measures installed. Modelling studies predict that these measures should be successful in achieving at least the target level of flood protection for the town[262].

A programme of monitoring and evaluation was established to assess the effectiveness of the measures, including an economic valuation of ecosystem services. A number of the measures have been observed to be working and the local community believes that these were successful in preventing a near-flood in November 2012. However, an analysis of the flow data in 2014 was unable to confirm this due to the limited length of recorded data. More flood peaks need to be captured and tested before any definitive conclusions can be drawn. The results of the ecosystem services assessment found that the value of public benefits delivered by the measures greatly outweighed their cost, although the opposite was the case for private landowners, who are likely to be resistant to change unless sufficiently incentivised for service provision. There are plans is to continue with the flow monitoring and seek to install additional management measures within the catchment to further reduce flood risk to Pickering[263].

262. Dr Tom Nisbet, personal communication, 4 November 2014.

263. Dr Tom Nisbet, personal communication, 4 November 2014.

Appendices

Left
Aerial view of the residential area of Milton, during the great Brisbane Flood of 2011, the worst flooding disaster in Australia's history.

Appendices

Appendix 1: Main contributors

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The members of the Working Group involved in producing this report are listed below. The Working Group members acted in an individual and not organisational capacity and declared any conflicts of interest. Members contributed on the basis of their own expertise and good judgement.

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Review Panel

This report has been reviewed by an independent panel of experts, before being approved by the Council of the Royal Society. The Review Panel members were not asked to endorse the conclusions or recommendations of the report, but to act as independent referees of its technical content and presentation. Panel members acted in a personal and not an organisational capacity and were asked to declare any potential conflicts of interest. The Royal Society gratefully acknowledges the contribution of the reviewers.

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Appendix 2: Evidence gathering and acknowledgements

Evidence was gathered during the project in the following ways:

- A formal call for evidence at the start of the project
- Events on specific themes that arose during the project
  - Resilience, demography and ecosystem-based adaptation (hosted by Woodrow Wilson Center)
  - Perspectives from the re/insurance sector (hosted by Willis Group)
  - Science for disaster risk reduction
  - International policy frameworks
  - Risk sharing and financing in the developing world
  - Economics and decision-making
- Site visits to see resilience-building in action
  - Kabale, Uganda (hosted by Nature Uganda and Birdlife International)
  - Seaside Park, New Jersey, USA (hosted by Surfrider Foundation)
  - Pickering and Kingston upon Hull, Yorkshire, UK (hosted by the UK Environment Agency)
  - New Orleans, Louisiana, USA (hosted by Darryl Malek-Wiley)
- Meetings with key stakeholders

Call for evidence

An open call for evidence was issued in September 2013, following the Working Group's first meeting, which resulted in 25 responses. All non-confidential respondents are listed below.

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Appendix 3: Analysis of defensive options methodology

To assess the cost-effectiveness and consequences of different physical and biophysical defensive measures, and the strength and quality of evidence regarding those options, a table was developed for each hazard for completion by experts. Each table contained a list of some of the key physical and biophysical options to reduce the impact of that hazard. The options included were decided upon based on the relevant literature and external and Working Group members' expertise. Social and behavioural options were not included because most are relevant to a broad range of hazards and are not directly comparable to physical and biophysical options. The total number of options listed was limited to those most widely used to ensure that the results could be displayed on a single plot.

Experts, who were identified through literature reviews and the knowledge of Working Group members, were asked their opinions of:

- the effectiveness of the options;
- the strength of available evidence supporting this assessment of effectiveness;
- the affordability of the options. The affordability of the capital costs and maintenance costs were recorded separately. Opportunity costs were covered in the assessment of the 'consequences' of the interventions; and
- additional consequences relating to the options (positive, negative, or neutral) in terms of access to food, access to water, access to livelihoods, biodiversity, climate change mitigation and protection against other hazards. While there are many other consequences from interventions, these were felt to be the most important.

These expert opinions were collated and average scores calculated to produce the plots. The plots were then checked following examination of relevant literature (a sample of the literature reviewed for Chapter 3 is available to download at royalsociety.org/resilience) and by Working Group members to ensure accuracy.

Initially tables were developed for a wide range of hazards. The results from the coastal flooding, river flooding, drought and heatwaves are included in the report as they represent a range of different types of hazard, affecting different areas and have easily defined interventions.

FIGURE 16

The key showing how experts were asked to express their opinions regarding defensive options:

Effectiveness of Intervention		Strength of Evidence			Affordability		Consequences		Confidence (1 – 4)	
Based on your own judgement, how effective is the intervention at reducing the impact of the hazard in terms of loss of life, immediate physical damage to property etc?		How strong is the evidence that this intervention is effective in reality? Consider: amount of evidence; temporal scale; spatial coverage (aggregate)			How affordable is the intervention to implement? Separated into capital affordability (initial) and maintenance affordability (ongoing).		Are there any additional consequences to implementing this intervention? Broadly speaking, are these positive, negative or neutral?		Confidence in submitted opinion	
1	**Very limited effectiveness**	**1**	**Weak**	**Little or no evidence as to effectiveness**	**1**	**Very Low**	**1**	**Positive**	**1**	**Low**
2	**Nominally effective (only with a small effect, at a small-scale or during low-magnitude events; major limitations)**	**2**	**Partial**	**Limited scale, limited time-frame etc**	**2**	**Low**	**0**	**Neutral**	**2**	**Medium**
3	**Effective against non-extreme events (but unlikely to be effective in extreme, 1 in 200yr events)**	**3**	**Strong**	**Long-term data, extensively tested etc**	**3**	**Medium**	**-1**	**Negative**	**3**	**High**
4	**Highly effective, including in extreme events (1 in 200yrs)**				**4**	**High**			**4**	**Very High**

The following experts were consulted in the production of the plots, in addition to Working Group members:

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Description of defensive options

HEATWAVES

Afforestation: increasing tree cover provides more shade and evapotranspirative cooling, lowering local temperatures.

Maintenance of existing vegetation: prevents loss of shade and evapotranspirative cooling.

Green roofs and vertical greening systems: the growing of vegetation on either the roof or walls of a building. This can have a cooling effect through increased evapotranspiration.

White roofs: reflect more solar energy leading to a reduction in temperatures.

Urban planning: planning new or redeveloped urban areas so heat is reflected and air flow is improved can lead to lower temperatures.

Air conditioning: lowers indoor temperature and humidity.

Insulation: can retain lower temperatures inside buildings by preventing heat transfer from the outside to the inside of buildings.

DROUGHT

Removal of 'thirsty' invasive plant species: the removal of invasive plants with a high uptake of groundwater decreases the competition for water.

Reforestation: greater forest cover increases the capture of rainwater and reduces soil erosion. Reforestation also increases shade, lowering local temperatures and therefore reducing water loss through evaporation.

Forest conservation: prevents the loss of drought protection provided by forests (see reforestation).

Agroforestry: increasing the agricultural use of trees for timber, fruit or fodder increases rainwater capture, reduces soil erosion and provides shade.

Breeding drought resistant crops and livestock: research into the development and distribution of crop and livestock varieties which are drought tolerant can decrease water loss increasing the ability of local communities to survive droughts.

Sustainable agro-ecosystem management practices: encouraging the use of sustainable agro-ecosystem management practices such as minimum tillage, crop-livestock integration and intercropping can increase the conservation of soil moisture, reduce soil erosion and spread the risk of climate shocks.

Soil and water conservation: low tech structures such as bunds, contours and planting pits can conserve soil and water.

Reservoirs, ponds and other water storage: can reduce loss through evaporation, provide water during periods of low rainfall and allows water use to be monitored.

Wells: allow ground water to be accessed in areas where suitable aquifers exist.

Irrigation: allows the water supply to be maintained to prevent crop failure due to drought.

Interbasin water transfer: is the transfer of water from one water basin to another via channels, tunnels, dams, aqueducts, etc.

Waste water recycling: is the treatment of waste water so that it may be re-used.

COASTAL FLOODING

Maintenance of natural reefs: natural reefs provide an offshore buffer, dissipating wave energy and reducing coastal erosion. Maintaining natural reefs can therefore limit the damage caused by storm surges.

Maintenance of mangroves: mangroves act as an offshore buffer, they provide a dense web of roots and branches which stabilises sediment and dissipates wave energy. The maintenance of mangroves can therefore act to reduce the impact of storm surges.

Mangrove planting and re-establishment: as well as maintaining mangrove forests action can be taken to re-establish forests. This can be via allowing natural regeneration or by actively planting trees. The mangroves then act as outlined under 'maintenance of mangroves' description.

Maintenance of saltmarsh, wetlands and inter-tidal ecosystems: wetlands provide an onshore buffer against coastal flooding, dissipating wave energy and binding sediment to reduce coastal erosion.

Creation of saltmarsh, wetlands and inter-tidal ecosystems: the creation of wetland may take place on a local or regional scale and provides an onshore buffer against coastal flooding, dissipating wave energy and binding sediment to reduce coastal erosion.

Maintenance of other coastal vegetation and forest ecosystems: vegetation dissipates wave energy and binds sediment so can reduce coastal erosion.

Coastal re-vegetation/afforestation (above inter-tidal zone): restoring coastal vegetation and forests via planting or allowing natural regeneration can reduce coastal erosion as plant roots bind sediment and vegetation can dissipate wave energy.

Beach and dune nourishment: is the artificial addition of sediment (usually sand) to beaches. This can provide an onshore buffer against coastal flooding and reduce coastal erosion.

Artificial reefs (and/or substrates for reef replenishment): are engineered approaches designed to replicate coral reefs. Reefs then provide an offshore buffer dissipating wave energy and therefore reducing erosion.

Dykes and levees: are engineered structures which provide a physical barrier against coastal flooding.

Coastal barrages: are engineered structures with a primary function of preventing coastal flooding and erosion. They are designed to prevent storm surges from entering low-lying estuarine areas.

RIVER FLOODING

Re-establishment of floodplains 'green rivers': aims to allow the controlled flooding of designated areas in order to reduce discharge in the main river channel and therefore protect areas downstream. Submerged vegetation increases the flow resistance of a river therefore reduces the conveyance capacity.

Catchment afforestation, increased vegetation cover: increases the hydraulic roughness of catchments and therefore slows the flow of water. Tree roots also increase soil permeability therefore reducing surface flow reducing the risk of flash flooding.

Maintenance of existing catchment vegetation: can reduce the risk of flash flooding as described in 'Catchment afforestation' above.

Planting of riparian 'buffers': planting vegetation close to a water course, for example small wooded areas, can decrease water flow.

Changes to catchment agricultural land management: changing agricultural land management by, for example, reducing soil compaction and upland drainage can reduce run off and increase water capture. This, in turn, reduces the risk flash flooding downstream.

'Natural' flood management: increasing natural in-stream obstructions (e.g. woody debris) slows water flow and can increase local flooding reducing the risk of downstream flooding.

Stream habitat 'restoration': modifying river channels to restore habitats can reduce peak flows and the risk of flooding downstream.

Dams: the construction of dams allows water to be retained in a reservoir reducing downstream discharge.

Drains, dykes, levees, sluices, and pumps: are engineered options which provide direct physical protection to an area either via rapidly removing water or by preventing escape from water courses.

Dredging: is the systematic removal of accumulated material from a river or other watercourse. This can increase the capacity of that watercourse, allowing increased discharge of water load.

Sustainable urban drainage: the use of green roofs, ponds, swales and permeable surfaces can reduce the volume of storm water entering the drainage system by delaying the downstream passage of flood flows, reducing the volume run off and promoting rainfall infiltration into the soil.

Canalisation of urban streams: aims to move flood water quickly away from an urban area to downstream systems.

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