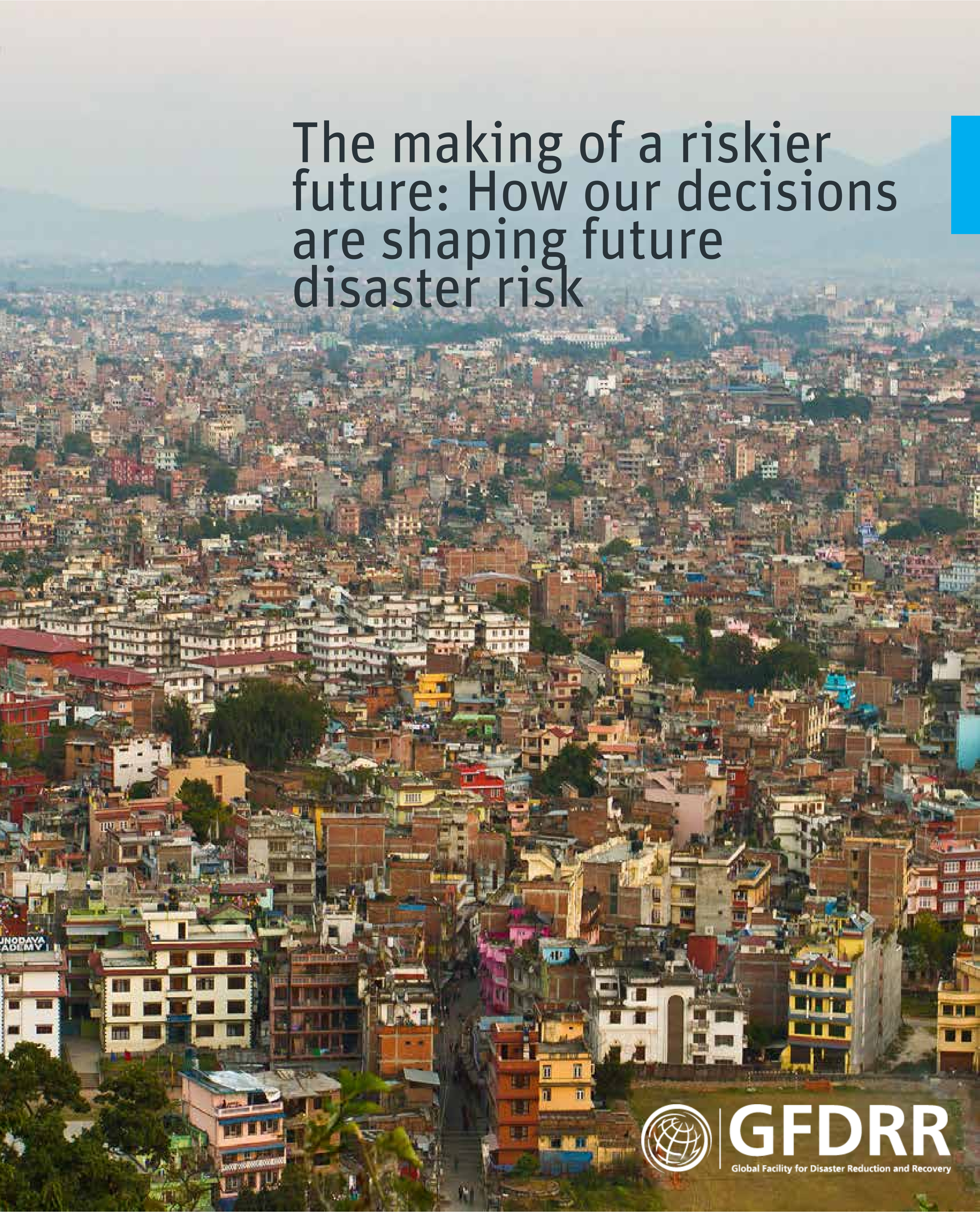
The making of a riskier future: How our decisions are shaping future disaster risk



GFDRR

Global Facility for Disaster Reduction and Recovery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The making of a riskier future: How our decisions are shaping future disaster risk

GFDRR
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Cover: Kathmandu cityscape, Nepal. Photo credit: sagarmanis/Thinkstock.com; Inside cover: Bhaktapur, Nepal – May 9, 2015: Woman outside her earthquake-ruined house in Bhaktapur, Nepal, located 30 km east of Kathmandu. The town was once rich with Buddhist and Hindu temples and a popular tourist spot for those visiting Kathmandu. Photo credit: Jules2013/Thinkstock.com

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Hello
Mamma

Foreword

Tomorrow's risk is being built today. We must therefore move away from risk assessments that show risk at a single point in the present and move instead towards risk assessments that can guide decision makers towards a resilient future.

Natural disasters can have truly global impacts. There is evidence that approximately 75,000 years ago, after the Toba volcano erupted in Sumatra, Indonesia, a global volcanic winter may have decimated the global human population to just several thousand. Since then, natural hazards have frequently affected communities on scales large and small, but civilization as a whole is more likely to survive a catastrophe today than ever before. That is the good news.

The disturbing news is that the impacts of natural disasters have been growing rapidly due to global population growth, urbanization and increased socioeconomic activity—with a tenfold increase in losses from disasters since the 1970s. Moreover, these numbers have yet to incorporate the real impact of climate change. By the end of the century, coastal areas will see more frequent and intense inundation due to sea level rise, and changes in rainfall patterns will trigger more frequent droughts and floods, putting many lives and livelihoods in jeopardy.

In 2015, world leaders made a commitment in Sendai, Japan to reduce the number of people affected, the direct economic loss, and the damage to critical infrastructure and basic services from disasters by 2030. To achieve this goal, we need to strengthen policies and actions that enable us to support larger populations, increased asset wealth, and more urbanized countries without increased disaster risk.

Tomorrow's risk is being built today. We must therefore move away from risk assessments that show risk at a single point in the present—which can quickly become outdated—and move instead towards risk assessments that can guide decision makers towards a resilient future. Only then will they be able to visualize the potential risk that results from their decisions taken today, and see the benefit of enacting policies to reduce climate change, halt the construction of unsafe buildings, enforce land use plans, reduce subsidence, and more.

We have more than 75,000 years of experience living with disasters, but today's challenges demand that we do things differently. We must continually learn, innovate, and push boundaries, so that we can build a safer world for ourselves and the generations to come.

Francis Ghesquiere
Head, Global Facility for Disaster Reduction and Recovery

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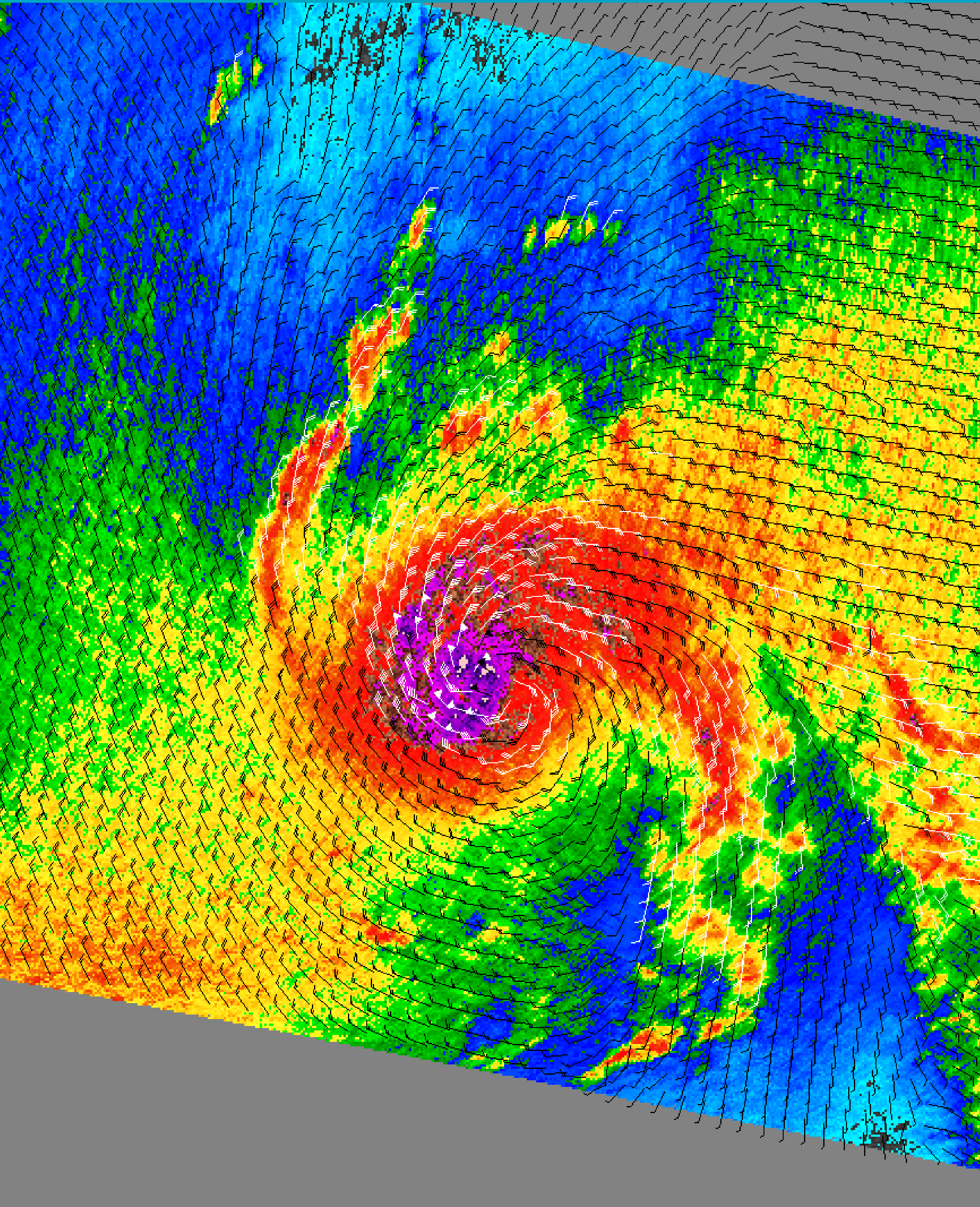
Neena Sasaki, 5, carries some of the family belongings from her home that was destroyed after the devastating earthquake and tsunami on March 15, 2011 in Rikuzentakata, Miyagi province, Japan. Photo credit: Paula Bronstein/Thinkstock.com



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Quickscat image showing the direction and intensity of surface winds across the Atlantic Ocean. Photo credit: Stocktrek Images

Abbreviations

AAL	average annual loss
AMO	Atlantic Multidecadal Oscillation
ARC	African Risk Capacity
AR5	Fifth Assessment Report
BRT	boosted regression tree
CMIP5	Coupled Model Intercomparison Project Phase 5
CCRIF	Caribbean Catastrophe Risk Insurance Facility
DEM	digital elevation model
DLR	German Aerospace Center
DMSP	Defense Meteorological Satellite Program
DPSIR	driving forces, pressures, state, impacts, and responses
DRM	disaster risk management
DRR	disaster risk reduction
ECA	Europe and Central Asia
ENSO	El Niño–Southern Oscillation
GCM	global climate model or general circulation model
GDP	gross domestic product
GEM	Global Earthquake Model
GFDRR	Global Facility for Disaster Reduction and Recovery
GHSL	Global Human Settlement Layer
GIS	geographical information system
GLOFRIS	Global Flood Risk with IMAGE Scenarios
GPS	Global Positioning System
G-R	Gutenberg-Richter
HDI	Human Development Index
HOT	Humanitarian OpenStreetMap Team
IDA	Incremental Dynamic Analysis
IMAGE	Integrated Model to Assess the Global Environment
InSAR	interferometric synthetic aperture radar
IPCC	Intergovernmental Panel on Climate Change
ISI-MIP	Inter-Sectoral Impact Model Intercomparison Project
LIDAR	Laser Imaging Detection and Ranging

MASDAP	Malawi Spatial Data Portal
MMI	Modified Mercalli Intensity
NAO	North Atlantic Oscillation
NGO	nongovernmental organization
OECD	Organisation for Economic Co-operation and Development
OLS	Operational Linescan System
OpenDRI	Open Data for Resilience Initiative
OSM	OpenStreetMap
PCRAFI	Pacific Catastrophe Risk Assessment and Financing Initiative
PGA	peak ground acceleration
RCM	regional climate model
RCP	Representative Concentration Pathway
RMA	Resource Management Act 1991
SAR	synthetic aperture radar
SRES	Special Report on Emissions Scenarios
SSP	Shared Socioeconomic Pathway
SuDS	sustainable drainage systems
STRM	Shuttle Radar Topography Mission
TCIP	Turkish Catastrophe Insurance Pool
VIIRS	Visible Infrared Imaging Radiometer Suite
URM	unreinforced masonry
WWA	World Weather Attribution


house
COLOR LAB PVT.

Executive Summary

Key messages from this report:

- **Most disaster risk assessment today is static, focusing only on understanding current risks. A paradigm shift is needed toward dynamic risk assessments, which reveal the drivers of risk and the effectiveness of policies focused on reducing risk.**
- **Global disaster risk is changing extremely fast, due to combined dynamics of hazard, exposure, and vulnerability.**
- **The drivers of disaster risk are in the control of policy makers, society, and individuals—but accurate assessment and continuous reevaluation of risk are required to enable effective risk reduction and prevent drastic increases in future losses.**

NEPAL

Partially collapsed house after the 7.8 earthquake hit Nepal on 25 April 2015.

Photo credit: © Thomas Dutour | Dreamstime.com

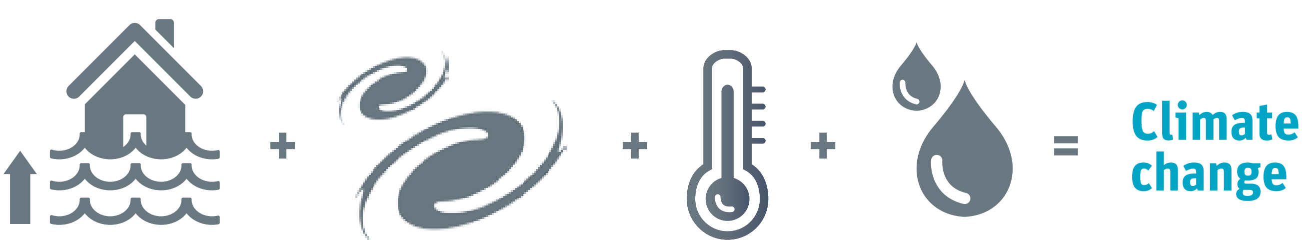
> There is variability in annual losses and deaths from disasters, but annual total damage (averaged over a 10-year period) has increased tenfold between 1976–1985 and 2005–2014, from US$14 billion to more than US$140 billion.

Disaster risks are rapidly increasing around the world: many regions are experiencing greater damage and higher losses than in the past. There is variability in annual losses and deaths from disasters, but annual total damage (averaged over a 10-year period) has increased tenfold between 1976–1985 and 2005–2014, from US$14 billion to more than US$140 billion. Average population affected each year has risen from around 60 million people (1976–1985) to over 170 million (2005–2014).[1] Disaster risk is influenced by the occurrence of potentially dangerous naturally occurring events, such as earthquakes or tropical cyclones (hazard); the population and economic assets located in hazard-prone areas (exposure); and the susceptibility of the exposed elements to the natural hazard (vulnerability). All three of these components are dynamic, and change over time under natural and human influences (figure ES.1). But most risk assessments do not account for these changes, so they provide a static view of risk. As a result, risk management policy decisions based on such assessments do not take into account the continuous and sometimes rapid changes in the drivers of risk and so may underestimate risk.

Changes in hazard are driven by climate change, which raises sea levels, changes the intensity of the strongest storms and the frequency with which they occur, increases extreme temperatures, and alters patterns of precipitation. Global sea-level rise of up to 0.6 m this century will increase disaster risk significantly in coastal areas. In addition, subsidence (sinking land) will increase the likelihood of flooding locally. In some coastal megacities subsidence has a greater influence on flood hazard than sea-level rise; the former occurs at a rate of up to 100 mm/year, in comparison with up to 10 mm/year for the latter (Erkens et al., case study C).

Exposure increases as population grows in hazardous areas, and as improved socioeconomic conditions raise the value of assets. Between 2010 and 2050, estimated global population exposed to river and coastal flood is expected to increase from 992 million to 1.3 billion (Jongman, Ward, and Aerts 2012). Average annual GDP at risk of earthquakes in Turkey is expected to increase by five times between 2010 and 2080 due to socioeconomic growth (Murnane et al., case study G). Urbanization—encompassing both the movement of people from rural to urban areas and population growth within cities—results in larger concentrations of exposure. In Indonesia, river flood risk may increase 166 percent over the next 30 years due to rapid expansion

[1] D. Guha-Sapir, R. Below, and Ph. Hoyois, EM-DAT: International Disaster Database, www.emdat.be, Université Catholique de Louvain, Brussels, Belgium, accessed July 2015.



of urban areas, and coastal flood risk may increase 445 percent over that same period (Muis et al. 2015). Population is expected to increase by at least 40 percent in 14 of the 20 most populated cities in the world between 2015 and 2030, with some cities growing by 10 million people in that period. Many of the largest cities are located in deltas and are highly prone to floods and other hazards (Hallegatte et al. 2013), and as these cities grow, an ever greater number of people and more assets are at risk of disaster. Another feature of urban expansion, the increase in impermeable surfaces, also directly affects flood hazard.

Vulnerability too changes with urban and socioeconomic development. Some people become less vulnerable because of improved construction and a more prosperous economic situation. But in many areas, structural vulnerability continues to increase because of unregulated building practices and unplanned development. For example, earthquake risk in Kathmandu (measured as the proportion of buildings that collapse in an earthquake) is expected to double to 50 percent by 2045 due to informal building expansion alone (Lallemant et al., case study D). Social vulnerability also changes over time, influenced by the occurrence of disasters, which disrupt lives and livelihoods, and by the effects of climate change, which could push over 100 million additional people back into poverty by 2030 (Hallegatte et al. 2015).

Increased exposure and changes in vulnerability have already affected disaster risk. A large proportion of recent increases in disaster losses are attributed to development occurring in hazardous areas (Bouwer et al. 2007). Concentrations of greenhouse gas in the atmosphere have risen in recent decades due to human activity, and recent years have seen extreme temperatures, and extremely damaging floods and cyclones. However, the changes observed so far are difficult to separate from natural variations in climate, and the greatest changes in climate extremes are projected to occur in the coming decades, meaning it may be several decades before the full effects of climate change are felt. Decisions being taken today are influencing future disaster risk—either reducing risk or increasing it. By promoting policies that reduce risk and avoiding maladaptive actions that increase risk, we can positively influence the risk environment of the future. The drivers of future risk are within the control of decision makers today: there is a huge opportunity today to manage the risks of tomorrow. Climate change mitigation by reduction of greenhouse gases remains key to preventing strong increases in climate-related hazard. In addition, a robust hazard protection strategy, one that includes ecosystem-based measures, can help to limit the harm caused by changes in frequency and intensity of hazard. Increases in exposure can be addressed by implementing and enforcing effective land-use policies that prevent urban expansion in hazard-prone areas. Finally, increases in vulnerability can be addressed by strengthening construction practices and improving disaster preparedness. All these policy measures rely on data and risk modeling: enhancements in data collection and risk assessment are therefore a crucial part of the policy-strengthening process.

Disaster risk assessment—vital for understanding risk in terms of expected population affected or losses incurred—underpins disaster risk management activities. In order to make policy and planning

Hazard
Natural phenomena

Exposure
Population and assets

Vulnerability
Structural and social

decisions that reduce future risk, present and future risk must be quantified. Thus risk assessments that inform disaster risk management must account for the dynamic nature of hazard, exposure, and vulnerability. By quantifying future risk with and without the effect of disaster risk management policies and comparing the results, risk management specialists can demonstrate how policy actions taken now and in the near future could affect the risk environment in the medium to long term.

Evolving hazard can be captured in disaster risk assessment through the implementation of climate change scenarios in global and regional climate models. This approach makes it possible to incorporate changes in intensity and frequency of extreme wind, temperature, and precipitation, along with sea-level rise, to project future flood, drought, cyclone, heat, and storm surge risk. Simulating the expansion of urban areas, projecting future population distribution, and implementing Shared Socioeconomic Pathways (SSPs) as scenarios of future socioeconomic conditions can be carried out to demonstrate the influence of changing exposure on disaster risk. Projection of future vulnerability has not been addressed extensively in risk assessments. It is possible to adjust estimates of structural vulnerability to reflect projected changes in construction, but the many interdependent factors that determine social vulnerability make it difficult to determine how social vulnerability will evolve into the future.

Despite the ability to quantify future risk (albeit with uncertainty), risk assessments typically fail to account for changing climate, population, urbanization, and environmental conditions. They thus reduce the opportunity to highlight long-term, cost-effective options for risk reduction. This is not due to an absence of appropriate methods; many risk assessment tools and methods exist, with differing complexity, and can be used to represent the evolution of risk if adequate data are available. Risk assessments most often fail to account for evolution of risk because they use information that represents risk factors at a single time point in the past, and do not include projections of those data into the future.

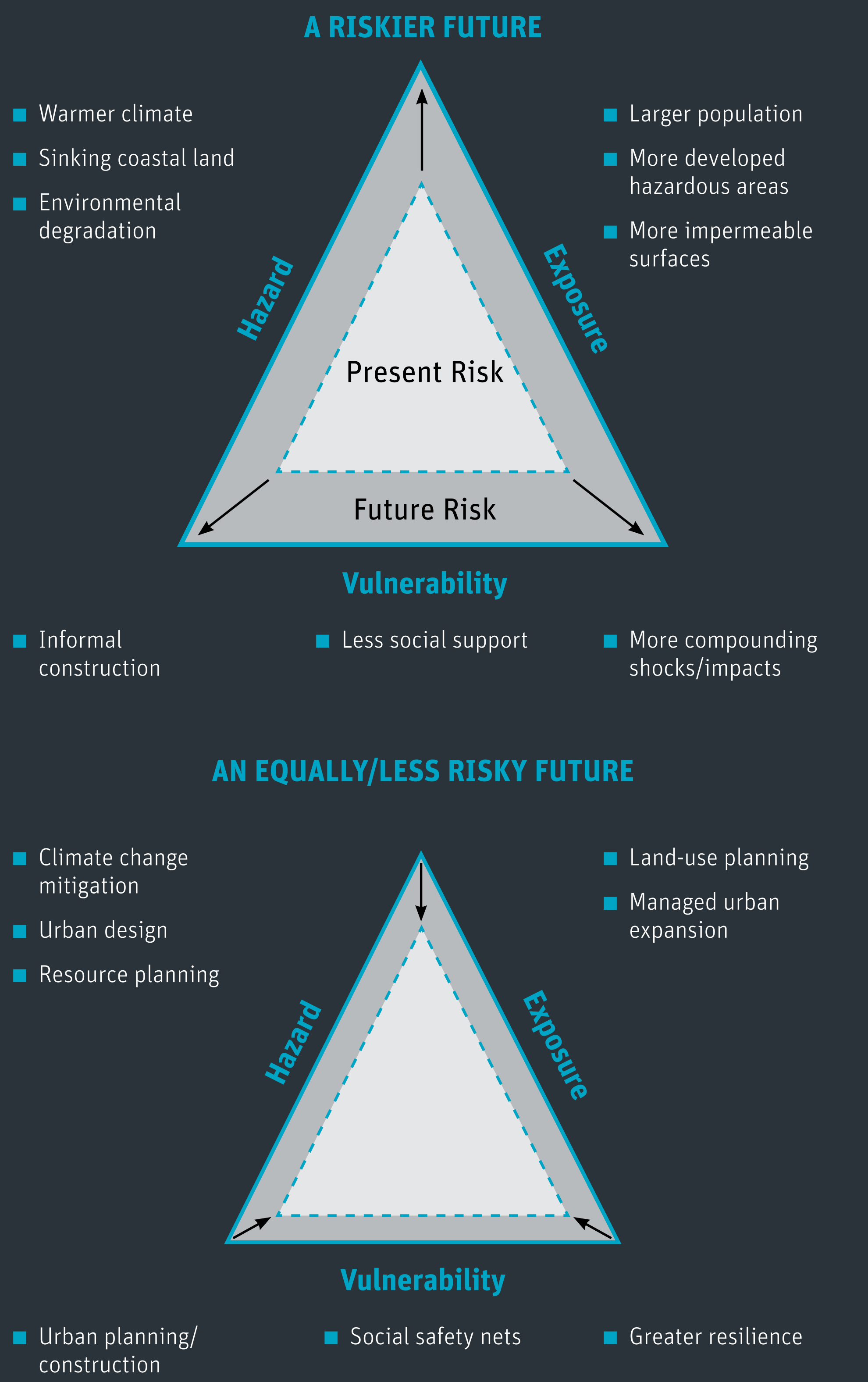
Advances in the risk management sector and relevant technologies mean that risk specialists are now better able than in the past to focus on assessing risk under future climate conditions. With improvements in data collection, we can obtain higher-resolution topographic and exposure data and can simulate trends in population movement and urbanization. At this stage, it is important both to review the range of efforts to quantify future risk, and to consider how to best apply this information in managing risk. This publication provides an introduction to the problem of evolving risk (chapter 1), a further background to disaster risk (chapter 2), and an overview of the factors driving the evolution of risk (chapters 3 to 5). Chapter 6 discusses some of the issues that complicate efforts to quantify evolving risk, and chapter 7 discusses a number of policy areas that can strongly affect future disaster risk. This chapter highlights steps that can be taken to mitigate the ongoing increase in risk and—like the publication as a whole—seeks to raise awareness among decision makers of the impacts planning and development decisions have on disaster risk. The report concludes with a series of studies that highlight, in more depth, some of the issues and approaches described in the earlier chapters.

Risk assessments need to account for...

Changing climate | **Population increase** | **Rapid urbanization** | **Future environmental conditions**

Figure ES.1. The result of our choices

Factors affecting the three components of disaster risk can increase future risk (top) or reduce (or mitigate increase in) future risk (bottom).




Raun Sumatra

Introduction

1

Following the adoption of the *Sendai Framework for Disaster Risk Reduction 2015–2030*, the disaster risk management (DRM) sector seeks to build on progress made under the Hyogo Framework for Action and to tackle the continued increase in annual disaster losses over the last decades. The goal of the framework is to

> *prevent new and reduce existing disaster risk through the implementation of integrated and inclusive economic, structural, legal, social, health, cultural, educational, environmental, technological, political and institutional measures that prevent and reduce hazard exposure and vulnerability to disaster, increase preparedness for response and recovery, and thus strengthen resilience* (United Nations 2015, 6, emphasis added).

Adaptation and risk management policies and practices will be more successful if they take the dynamic nature of vulnerability and exposure into account.

It is well known that disaster risk is subject to change in its underlying components: the *hazard* (the potentially dangerous naturally occurring event, such as an earthquake or tropical cyclone), *exposure* (the population and economic assets located in hazard-prone areas), and *vulnerability* (the susceptibility of the exposed elements to the natural hazard) (IPCC 2012). In an environment of rapid urbanization, population growth, unplanned development, unsafe building practices, and changing climate, investment in and design of disaster risk management activities must account for changes in the nature of hazard, exposure, and vulnerability. As the Intergovernmental Panel on Climate Change asserts, “adaptation and risk management policies and practices will be more successful if they take the dynamic nature of vulnerability and exposure into account” (IPCC 2012, 67).

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Bukittinggi, Sumatra, second largest city in West Sumatra. It is located near the Mount Singgalangand and Mount Marapi volcanoes. Photo credit: ElenaMirage/Thinkstock.com.

Information on future disaster risk is essential for improving resilience to extreme weather events (Royal Society 2014) and indeed to any natural hazard. The post-2015 Sendai Framework encourages DRM to take account of future risks:

> *It is urgent and critical to anticipate, plan for and act on risk scenarios over at least the next 50 years to protect more effectively human beings and their assets, and ecosystems* (United Nations 2015, 3).

Disaster risk assessment informs risk identification, risk reduction, preparedness, territorial planning, financial protection, and resilient reconstruction. Assessments provide the basis for disaster risk management and decision making in multiple sectors by quantifying the effects of disasters in terms of potential casualties and asset losses. The wide selection of tools, policies, and programs available to manage disaster risk all depend on the accurate assessment of current and future risk, over a range of time scales. Risk management policies and actions may be required to act over multi-decade time scales; risk transfer products (insurance) usually act on the time scale of a single year; and engineered solutions may act over a typical design lifetime of around 50 years. These long-term structural, infrastructural, and programmatic investments are inherently likely to be affected by changes in disaster risk that arise from future changes in environmental, social, and economic conditions.

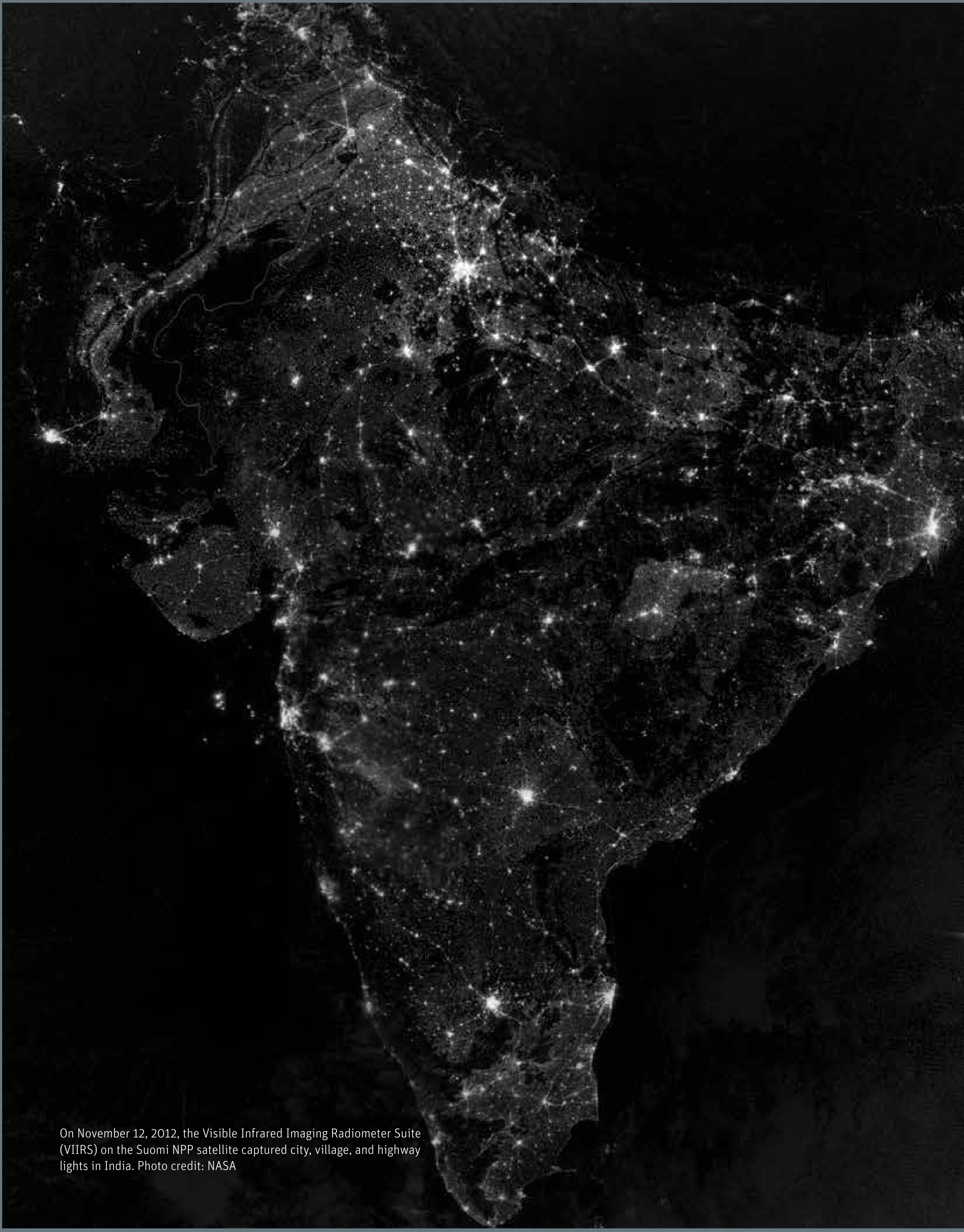
It should be said explicitly that in order to promote the utility of DRM programs into the future and to assess the benefits of current decisions on future risk, disaster risk assessments must be able to quantify future risk both with and without the effects of DRM policies. The ability to compare the two sets of results will allow risk management specialists to demonstrate **how policy actions taken now and in the near future could affect the risk environment of the mid- to long-term future**. By **promoting actions that reduce risk** and **avoiding maladaptive actions that increase risk,** we can positively influence the risk environment of the future (see box 1.1).

This publication focuses on the **incorporation of evolving risk into disaster risk assessments**. It first describes the nature of evolving hazard, exposure, and vulnerability, and then reviews the extent to which disaster risk assessments actually incorporate evolving risk. It highlights methodologies that have been used to include evolving risk in assessments—and in doing so highlights how the future riskscape looks for a range of perils. The report also points to current gaps in assessment of evolving disaster risk and makes recommendations on how to take risk evolution into account going forward. The second part of the publication presents case studies that highlight particular issues for evolving risk and showcase methodologies for assessing it.

Box 1.1 Keep Abreast of Evolving Risk

"Risk assessments need to account for temporal and spatial changes in hazard, exposure, and vulnerability, particularly in rapidly urbanizing areas or where climate change impacts will be felt the most. A risk assessment that provides an estimation of evolving or future risk is a way to engage stakeholders in carrying out actions now in order to avoid or mitigate the risk that is accumulating in their city or country. For example, risk analysis offers an opportunity to quantify the decrease in future risk that arises from better enforcement of building codes, and hence to demonstrate the benefit of spending additional funds on building code enforcement."

Source: GFDRR 2014, 29.



On November 12, 2012, the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi NPP satellite captured city, village, and highway lights in India. Photo credit: NASA

Disaster Risk

2

Disaster risk is a function of three interlinked components: hazard, exposure, and vulnerability.

Disaster risk is a function of three interlinked components: hazard, exposure, and vulnerability. Hazard refers to the likelihood and intensity of a potentially destructive natural phenomenon, such as ground shaking induced by an earthquake or extreme winds associated with a cyclone. Exposure refers to the location, attributes, and value of people and assets (such as buildings, agricultural land, and infrastructure) that are exposed to the hazard. Vulnerability is the potential extent to which physical, social, economic, and environmental assets may become damaged or disrupted when exposed to a hazard event. Vulnerability includes physical vulnerability, which refers to the level of damage sustained by built structures due to the physical load imparted by a hazard event. It also includes social vulnerability (also termed "socioeconomic vulnerability" or "socioeconomic resilience"), which refers to damage as it relates to livelihood, social connections, gender, and other factors that influence a community's ability to respond to, cope with, and recover from a disaster. Social vulnerability can affect the number of casualties, the loss or disruption sustained, and a community's subsequent recovery time.

Disaster risk evolves spatially and temporally in response to changes in one or more of these components, and to the inherent interactions between them—i.e., changes in one factor can influence the other factors. The influences on disaster risk include climate, development, and risk management (figure ES.1). Over time, disaster risk may increase or decrease, and it may evolve differently at the local, regional, national, and global scales. Indeed, risk rarely evolves uniformly in a community or region; it often increases

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Landslide and flood risk in Phong Nha, Vietnam. Photo credit: Simone Balog/World Bank

> Changes in hazard may arise from natural variability or human influences. The latter are particularly important for changes in hydrometeorological hazards, which are driven in large part climate change, changing land surface types, and altered ground elevation.

most with respect to particular types of assets, or for sectors of the population with greatest vulnerability. Thus poor residents living on unstable hillsides or in flood hazard zones are especially susceptible to increases in disaster risk arising from more frequent and intense rainfall in a future climate.

Changes in hazard may arise from natural variability or human influences. The latter are particularly important for changes in hydrometeorological hazards, which are driven in large part by climate change. As global temperature change influences the frequency, severity, and seasonal patterns of precipitation and monsoon events, regional changes occur in flood, drought, and heat wave hazards (see case study A). Climate change is likely to affect the frequency and severity of tropical cyclones, extratropical cyclones, river floods, and storm surges. Rising sea levels associated with ice-sheet melt and thermal expansion of ocean waters will contribute to increased coastal flooding and storm surge hazard. Changing land surface types (through urban development and deforestation) and ground elevation (through groundwater extraction) also affect hydrometeorological hazards.

Changes in exposure, on the other hand, are driven by socioeconomic development. Globally, exposure to natural hazards is increasing; economic progress is driving population growth and raising the value of physical assets. Thus more people and economic assets are now exposed to the potential impacts of disasters than in the past, and this trend is expected to continue.

Vulnerability evolves as a result of decisions made during the development process—or in the absence of effective policy making. Like changes in exposure, changes in vulnerability occur hand-in-hand with socioeconomic change. Appropriate investment of increased wealth can reduce vulnerability, while the absence of construction guidelines can increase it, for example by enabling informal construction of buildings that may be highly susceptible to damage from earthquakes. Disasters themselves can increase vulnerability, because they often leave communities with reduced access to resources or shelter.

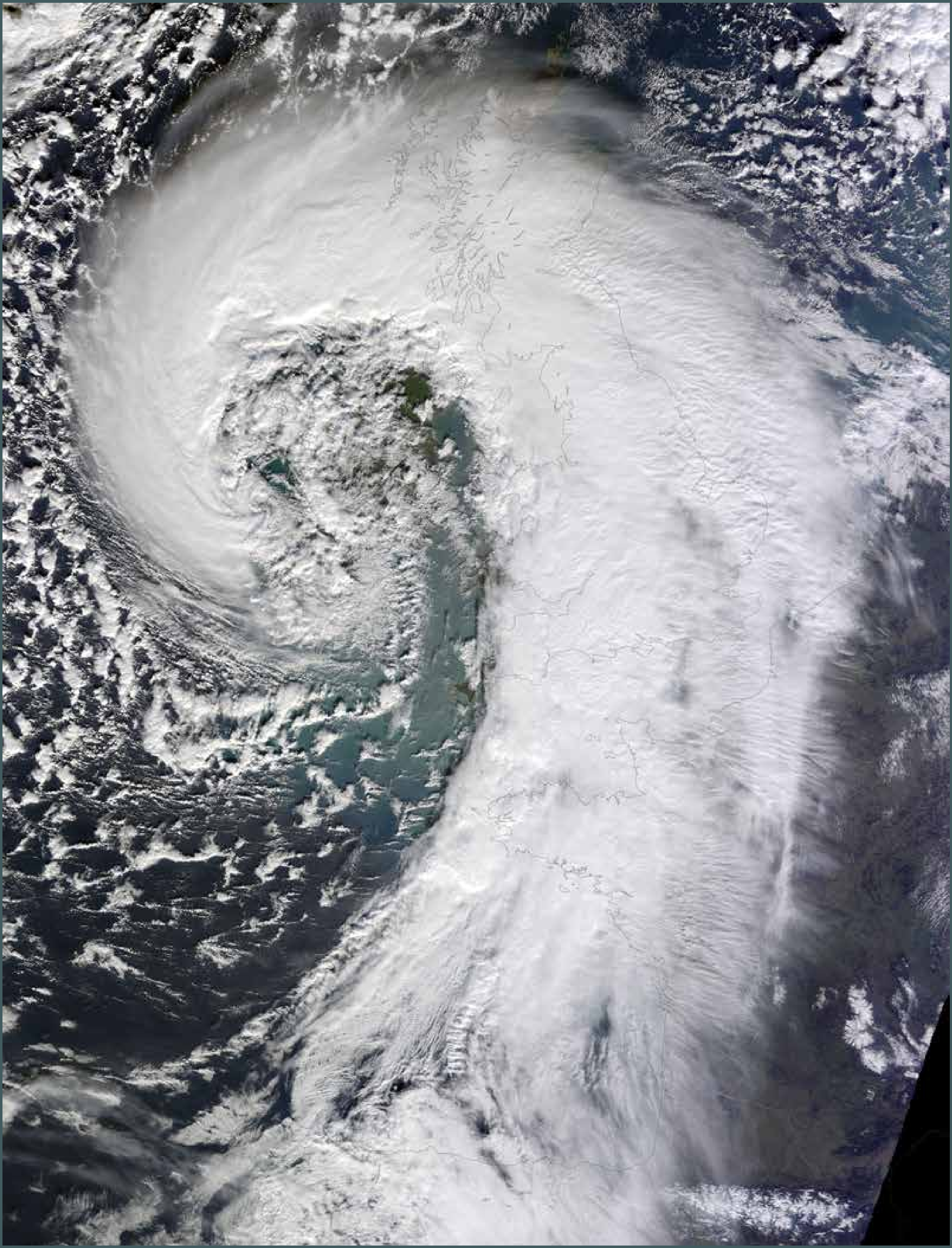
Disaster risk management operates by reducing one or more of the disaster risk components in order to reduce disaster risk overall.

Reducing the hazard involves reducing the frequency or intensity of the event. This is done by building protective systems (e.g., increasing river channel flood capacity so that a greater volume of water is contained before spilling over onto adjacent land), and by avoiding environmental degradation (e.g., deforestation) that can increase hazard. Reducing exposure (or preventing future increases in exposure) might involve changing land-use zoning to restrict new construction in hazardous areas or to manage the retreat of existing development to safer areas. Reducing vulnerability involves structurally strengthening existing buildings or complying with building codes to ensure that future construction can better withstand damage from extreme winds, water ingress, or ground shaking.

Disaster risk evolves in response to policy decisions (or their absence), and some policy decisions can inadvertently increase disaster risk by encouraging development in hazardous areas or allowing practices that increase vulnerability. Such decisions often result from neglecting to consider risks in planning or decision-making processes.

KIRIBATI

Building Seawalls. Photo credit: Lauren Day/World Bank



Drivers of Evolving Disaster Risk: Hazard

3

The evolution of hazard is felt through changes in the geographic distribution of potentially damaging events, as well as changes in the frequency and intensity of these events. The cause of these changes is hazard-dependent. Human activity influences hydrometeorological hazards by altering conditions in the oceanic and atmospheric systems, primarily through emission of greenhouse gases. The changes in these systems manifest as changes in global temperature, rainfall patterns, and mean sea level, which influence wind, flood, drought, heat, and wildfire hazards. The evolution of hazard also involves interactions between hazards. Changing rainfall patterns, for example, influence soil stability, whicj in turn influences landslide hazard and have a further impact on flood hazard.

The evolution of hazard is felt through changes in the geographic distribution of potentially damaging events, as well as changes in the frequency and intensity of these events.

Hydrometeorological hazards

The most commonly considered example of evolving hazard is the effect of climate change on hydrometeorological hazards. Globally, the climate is becoming warmer. Annual global temperature has shown an increasing trend over the last 130 years (figure 3.1), and all of the 10 warmest years on record since 1880 have occurred since 1998 (NOAA National Climatic Data Center 2014). Changing climate has been linked to changes in the characteristics of disasters: "A changing climate leads to changes in the frequency, intensity, spatial extent, duration and timing of extreme weather and climate events, and can result in unprecedented extremes" (IPCC 2012, 111). The various changes in risks resulting from those changes are described in box 3.1. Research into the mechanisms and risks of changing climate shows that disaster risk has been affected already.

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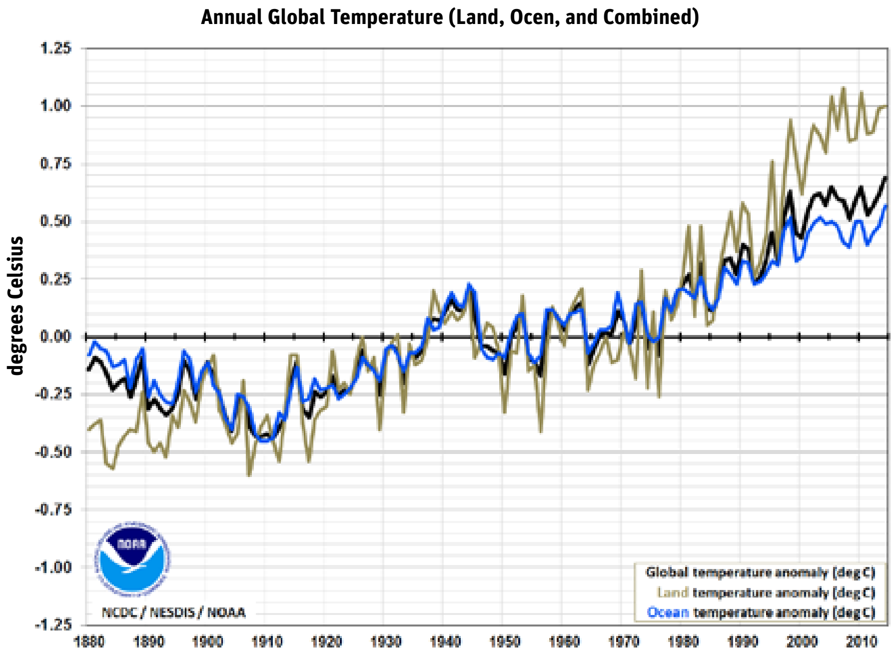
Extratropical cyclone over the United Kingdom. February 16, 2014.
Photo credit: NASA Earth Observatory image by Jesse Allen

Tropical cyclone

Tropical cyclones occur in several regions, and are known as typhoons in the western Pacific Ocean, hurricanes in the eastern Pacific and North Atlantic Oceans, and cyclones in the Indian and South Pacific Oceans (Figure 3.2). While there is very high confidence in short-term trends in tropical cyclone activity in some regions, long-term trends are more uncertain. Nonetheless, projected warming in the 21st century is expected to result in continued increase in frequency of the most intense storms (Stocker et al. 2013).

Tropical cyclones are known to occur in clusters of activity, characterized by the sea surface and wind conditions in their region of formation, trajectory of movement, and landfall intensity. As well as being spatially clustered, cyclones show strong seasonality and occur in temporal clusters when conditions are suitable for them to form and sustain their energy. Because of each cluster's varying characteristics and locations, cyclone activity in each cluster is related to different atmospheric and oceanic circulation patterns, or "oscillations." These circulation patterns vary naturally as well as in response to changes in climate conditions, meaning that they affect cyclone activity in each cluster in a different way. Year-to-year cyclone

Figure 3.1. Temperature time series for land only, ocean only, and combined land and ocean. Temperature scale is relative to the average global temperature across the duration of the time series.



Source: NOAA National Climatic Data Center 2014.

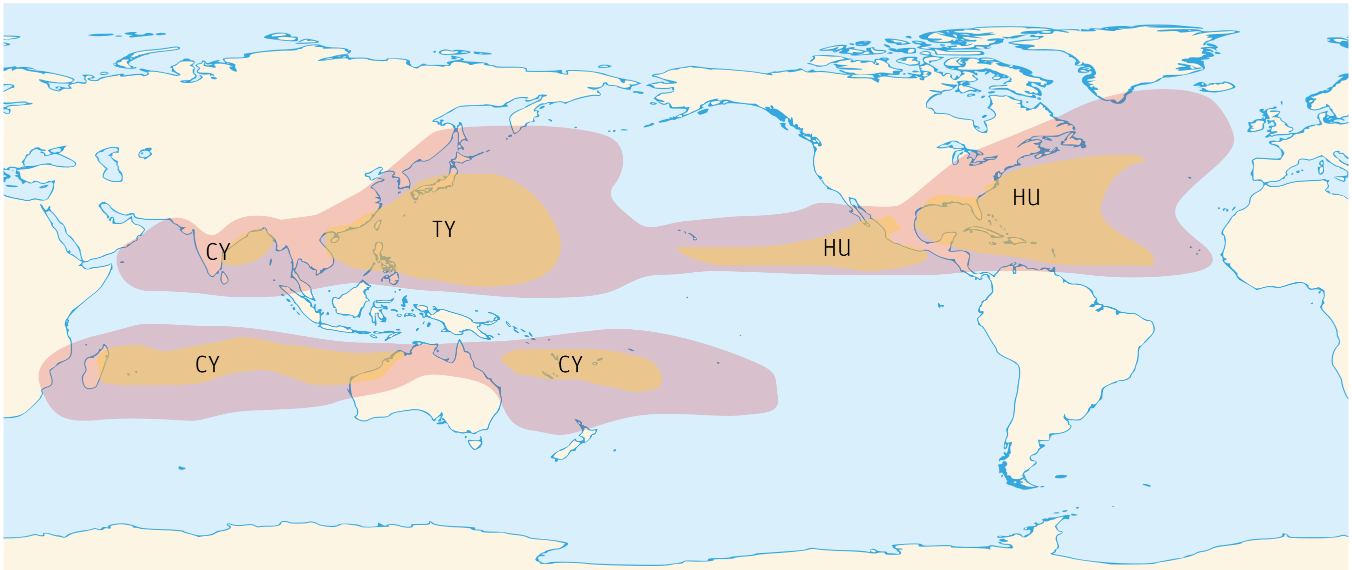
Box 3.1 Risks of Climate Change

The list below indicates how some of the risks associated with extreme weather and climate-related hazards will evolve as a result of climate change. The Intergovernmental Panel on Climate Change (IPCC) has "high confidence" in each of these risks, which arise due to warming, extreme temperatures, drying trends, and extreme precipitation.

- Negative impacts on average crop yields and increases in yield variability, leading to volatility in food security
- Urban risks associated with water supply systems, energy, and housing
- Displacement of people with increased climate extremes
- Declining work productivity, increasing morbidity (e.g., dehydration, heat stroke, and heat exhaustion), and mortality from exposure to heat waves
- Reduced access to water for rural and urban poor people due to water scarcity and increasing competition for water

Source: Field et al. 2014, table TS.4.

Figure 3.2 **Regional distribution of tropical cyclone occurrence and intensity. Regional terms are denoted as abbreviations: CY = cyclone; TY = typhoon; and HU = hurricane.**



Source: Based on earthobservatory.nasa.gov.

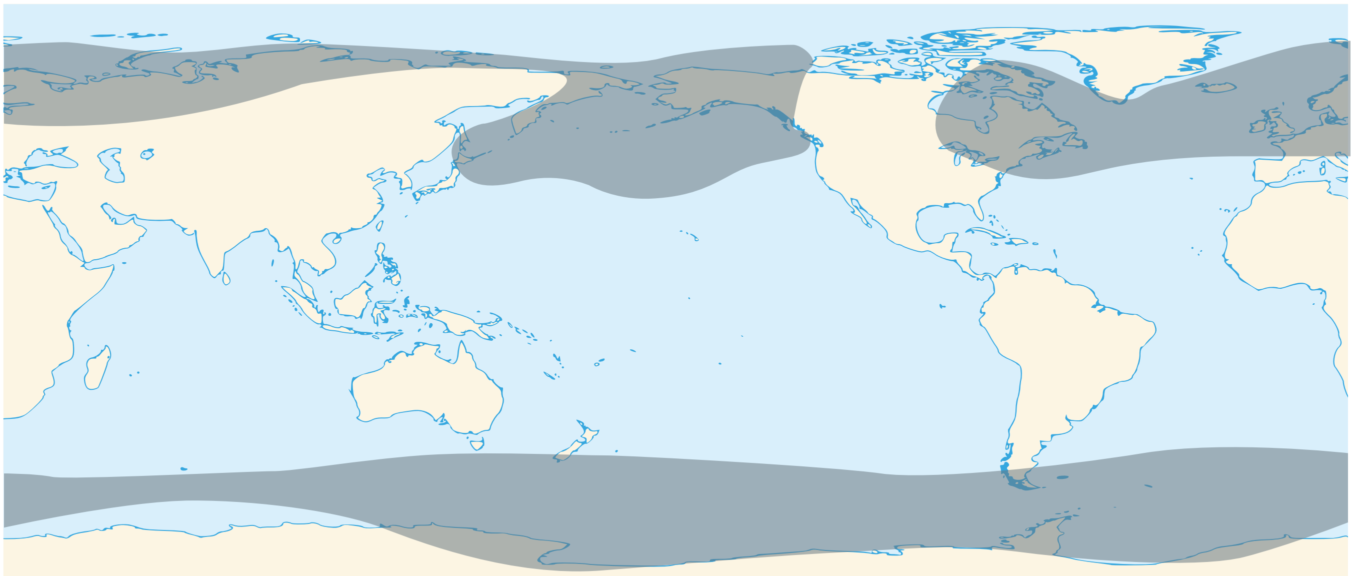
activity in the Pacific is strongly affected by fluctuations in sea surface temperature due to the El Niño Southern Oscillation (ENSO); and in the North Atlantic it is affected by the Atlantic Multidecadal Oscillation (AMO). Abrupt changes in such circulation patterns can cause rapid increase or decrease in hazard from year to year or across a period of several years. There is low confidence in projected changes to ENSO in the 21st century because the range in projection across climate models is wide (Stocker et al. 2013).

The intensity and frequency of the most extreme tropical cyclones have increased in the North Atlantic since 1980 (Kossin et al. 2007), and some data show the same trend for all basins globally—that is, an increase in the proportion of Category 4 and 5 cyclones and a decrease in the proportion of Category 1 and 2 cyclones (Holland and Bruyère 2014). The increase in the proportion of high-intensity cyclones is expected to impact losses significantly. Several studies suggest that, based on empirical relationships between wind speed and loss, future increase in losses will occur at a proportionally greater rate than changes in storm activity, independent of exposure change. Murnane and Elsner (2012) demonstrated an exponential relationship between cyclone wind speed at landfall and normalized economic loss, in which loss increases by 5 percent for every 1 m/s increase in wind speed. Based on the rate of increasing storm strength (0.1 m/s/y) (Elsner, Kossin, and Jagger 2008), this relationship points to a 5 percent increase in cyclone loss over 10 years, independent of exposure change. Based on a relationship between maximum landfall wind speed and normalized loss from U.S. hurricanes, Pielke (2007) estimated that an 18 percent increase in intensity would cause a 64 percent increase in damage. And using an existing catastrophe model framework, the Association of British Insurers (2005) estimated that average annual loss (AAL) might increase by 45–118 percent in the United States and 40–100 percent in Japan in response to just a 4–9 percent increase in hurricane wind speeds.

Evolution in cyclone hazard is not limited to an increase in intensity in areas already affected by cyclones. Changes in climate have caused spatial shifts in cyclone tracks, which effectively move the hazard into new areas. For example, such spatial shifts have resulted in increased landfall intensity of cyclones in East Asia (Park, Ho, and Kim 2014).

Cyclone-associated storm surge hazard is directly influenced by change in cyclone activity, but

Figure 3.3. Regional distribution of extratropical cyclone occurrence.



Source: Based on www.giss.nasa.gov.

also by sea-level rise. Mousavi et al. (2011) demonstrated that peak hurricane storm surge heights would rise by 0.3 m by the 2030s and by 0.8 m by the 2080s for a portion of the coastline of Texas; this analysis was based on sea-level rise, increased sea surface temperatures, and hurricane intensity (landfall pressure), all derived from climate modeling of three SRES scenarios,[1] as well as on local subsidence. An analysis of hurricane loss by Rhodium Group LLC (2014) used projected change in hurricane frequency and intensity plus the impact of sea-level rise to show that annual losses in the United States (East Coast and Gulf of Mexico only) could rise by as much as US$62 billion to US$91 billion by the end of the century compared to present day. This study demonstrated that as we look into the future, changes in hurricane frequency account for a greater proportion of loss (see case study B).

Extratropical cyclone

Extratropical cyclones are a type of storm system formed in regions of large horizontal temperature variations in middle or high latitudes. They stand in contrast to the more violent tropical cyclones, which form in regions of relatively uniform temperatures. Short-term evolution of extratropical cyclone risk occurs because extratropical cyclones are strongly seasonal; there is temporal clustering of multiple storms when large-scale atmospheric conditions are most suitable for storm formation and propagation. The North Atlantic Oscillation (NAO)—the difference in sea level pressure between northern and southern regions in the North Atlantic Ocean—has a strong influence on extratropical cyclone frequency, intensity, and track position, causing short-term evolution in hazard. Extratropical cyclones are most frequent and intense over northern Europe when there is a positive NAO, that is, a stronger than average pressure difference.

Clustering of European extratropical cyclones occurs due to a prevalence of suitable atmospheric conditions, some of them relatively poorly understood, in which multiple storm systems form and are directed into the same area by strong winds such as the jet stream. Short-term evolution in hazard is brought about by these varying conditions. The clustered windstorms can result in repeated damage in some areas, with the potential for very high losses during a single cyclone season.

The expected impact of climate change on extratropical cyclones appears to vary. There has been no clear upward trend in extratropical cyclone activity in the North Atlantic basin (Leckebusch et al. 2007), but

1 The SRES scenarios are those from the IPCC's *Special Report on Emissions Scenarios* (Nakićenović et al. 2000).

there have been increases in the South Atlantic–Indian Ocean basin and decreases in the South Pacific (Wang et al. 2013). To illustrate the impact that potential increases in extratropical cyclone intensity could have on insured losses in Europe, the Association of British Insurers (2005) determined that a 20 percent increase in wind speed for the top 5 percent of European extratropical cyclones could lead to a 35 percent increase in AAL. In a future climate, the tracks of Southern Hemisphere and North Pacific extratropical cyclones are expected to shift toward the poles, but such a shift is less likely in the North Atlantic (Stocker et al. 2013). The large natural variability in NAO means that any changes detected in the strength of the NAO have not been attributed to climate change, and there are no robust conclusions on how this circulation pattern (and resulting impact on extratropical cyclone) is likely to change in future due to climate change.

Flooding

Both coastal and river flood hazard are dynamic and evolve over time. Sea-level rise is a major source of evolving hazard, resulting in more frequent and severe **coastal flooding**. Between 1901 and 2010, the global average sea-level rise as recorded using tidal gauges totaled an estimated 19 cm (Church et al. 2013). Global mean sea-level rise at 2100 is likely to be 0.28–0.61 m above mean sea level in the period 1986–2005, even if climate policies are effective in reducing greenhouse gas emissions from 2020 (Church et al. 2013). Sea levels rise due to melting of ice sheets and glaciers, thermal expansion of seawater, and change in liquid water storage on land. Very few coastlines around the world will avoid the effects of sea-level rise; sea levels are expected to rise in more than 95 percent of the ocean area (although there will be regional and local variation in magnitude). The global increase in flood hazard, along with the coastal location of significant populations and assets, makes this evolving hazard an especially important one for disaster management and climate adaptation to address. In combination with increased tropical cyclone hazard, sea-level rise contributes to an increase in frequency and intensity of storm surge. Moreover, subsidence due to groundwater extraction and coastal erosion has a profound effect on the relative elevation of land and sea, and thus alters coastal flood hazard. In some locations, the rate of decrease in land elevation from subsidence is greater than the rate of increase in water levels from sea-level rise (Erkens et al., case study C). Increased sea levels may also contaminate agricultural land and water supplies with saline water, as seawater infiltrates into coastal aquifers.

River flooding is influenced by changes in rainfall patterns, which may be affected by natural cycles such as El Niño as well as long-term climate change. There is significant natural variability in patterns of river flooding, and low confidence in any global trend in flood magnitude and frequency in the historical record (Stocker et al. 2013). There are varying degrees of confidence in regional trends in timing, severity, and geographical distribution of extreme flood events (table 3.1). The steeply rising trend in global flood losses over the past decades, however, has primarily been driven by increasing exposure. Various analyses of historical loss databases have not yet been able to derive a clear signal of climate change in these increasing losses (Kundzewicz et al. 2014; Visser, Petersen, and Ligtvoet 2014). There is a strong relationship between river flooding and interannual climatic variability, such as that associated with El Niño and La Niña, which influences flooding in river basins covering almost half of the earth's surface (Ward et al. 2014).

> Sea-level rise is a major source of evolving hazard, resulting in more frequent and severe coastal flooding.

Individual studies do suggest meaningful changes in flood hazard, although the results from any one climate model may predict an increase or decrease (Hirabayashi et al. 2013). They suggest that flood frequency is likely to increase in much of South America, central Africa, and East and Southeast Asia in the period 2071–2100 compared to 1971–2000. Meanwhile, southern South America, southern and Eastern Europe, and Central Asia are likely to experience decreased flood frequency. Based on a fixed (2005) population distribution, an increase

Table 3.1. IPCC Summary of Observed Regional Changes in Flood Extremes

Region	Description (degree of confidence, contribution from climate change)
Africa	Reduced discharge in West African rivers (low confidence, major contribution from climate change)
Europe	Changed occurrence of extreme river discharges and floods (very low confidence, minor contribution from climate change)
Asia	Increased flow in several rivers due to shrinking glaciers (high confidence, major contribution from climate change)
	Earlier timing of maximum spring flood in Russian rivers (medium confidence, major contribution from climate change)
Australasia	Reduced inflow in river systems in southwestern Australia (since the mid-1970s) (high confidence, major contribution from climate change)
North America	Shift to earlier peak flow in snow-dominated rivers in western North America (high confidence, major contribution from climate change)
	Increased runoff in the western and northeastern United States (medium confidence, minor contribution from climate change)
Central/South America	Changes in extreme flows in Amazon River (medium confidence, major contribution from climate change)
	Changing discharge patterns in rivers in the western Andes (medium confidence, major contribution from climate change)
	Increased streamflow in subbasins of the La Plata River, beyond increase due to land-use change (high confidence, major contribution from climate change)

Source: Field et al. 2014, table TS. 1.

of between four and 14 times current flood-exposed population is projected.

Land-use change affecting hazard

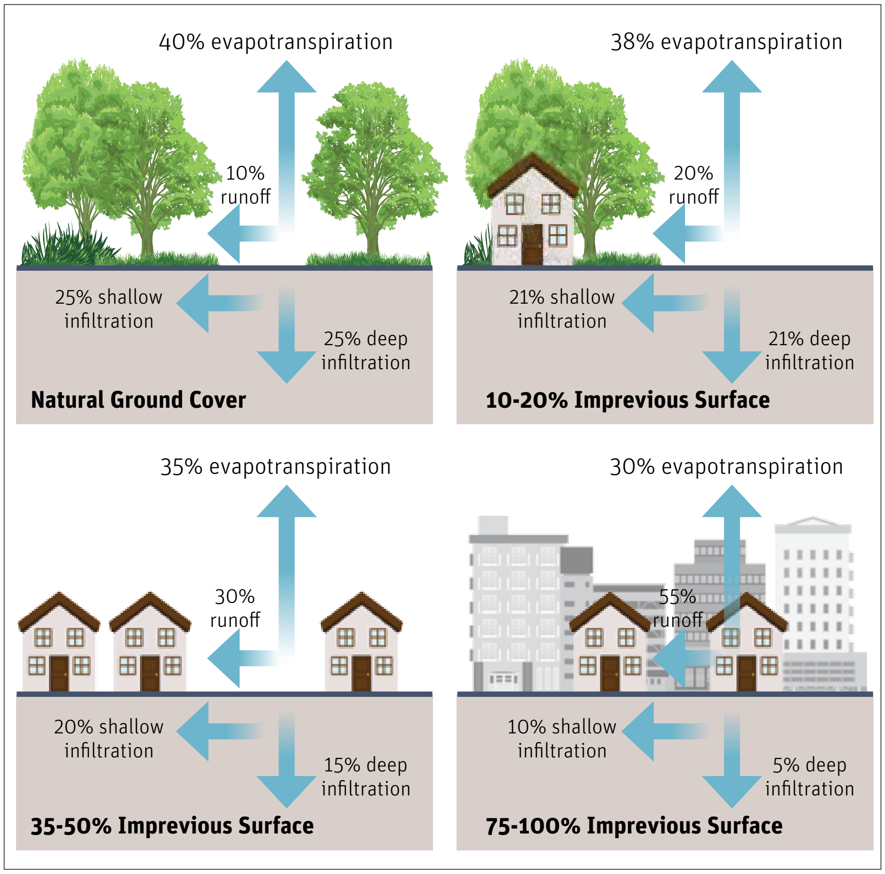
River and flash flood hazard in urban and rural environments is affected by environmental change resulting from socioeconomic development. The expansion of impermeable surfaces—which occurs as concrete or paved surfaces replace natural ground cover—decreases infiltration and increases runoff during precipitation events (Roesner 2014; see figure 3.4). In addition, the presence of urban drainage systems can reduce the time for precipitation to reach river channels: in urban areas, surface flow is directed into drainage systems that route the water to river channels much faster than in a natural catchment, where the water infiltrates and flows through the ground to reach the river channel. The large amount of flow reaching the channel at once makes it more likely that the channel will be overwhelmed and that flash flooding will occur. Deforestation also contributes to increased surface runoff (figure 3.4) by reducing the amount of moisture trees absorb from the soil, but also by removing the tree canopy, which intercepts precipitation; without the canopy, more rainwater reaches the ground, and reaches it more quickly (Savenije 2004). Deforestation also destabilizes the soil, contributing to increased sedimentation of river channels and drainage systems, which reduces their capacity and increases the likelihood of overflow.

Sinking ground/subsidence

Another important factor in evolving flood hazard is the reduction in ground elevation caused by subsidence. Subsidence may occur naturally, due to earthquakes or the settlement of sediment under its own weight, or as a result of anthropogenic effects such as groundwater extraction for water supply. Co-seismic uplift, or subsidence due to earthquake motion, modifies ground elevation rapidly and can result in temporary or permanent change in flood hazard (see box 3.2).

As a natural process, subsidence may occur within a balanced ecosystem but to a limited extent. The Mississippi delta in the United States had achieved a natural balance in which sediment carried by the river from its upper reaches

Figure 3.4. Relationship between ground cover and surface runoff.



Source: Adapted from Roesner 2014.

compensated for natural settlement, and the ground elevation of the delta remained constant or subsided slowly while the delta expanded. Disruption of sediment supply by the construction of flood levees and removal of sediment-stabilizing vegetation resulted in net subsidence and shrinking of the delta (Propublica 2014). The delta is expected to largely disappear in the next 50 years, as a combination of sea-level rise and subsidence causes accelerated land loss.

A major cause of subsidence is the extraction of groundwater from underground aquifers, for irrigation or for water supply to urban areas such as Jakarta (see box 3.3 and case study C). Groundwater extraction is closely linked to urban expansion; as urban populations grow and urban areas expand, the rate and spatial extent of extraction increases. Where aquifers are

Box 3.2 Effects of Co-seismic Subsidence in Recent Earthquake Events

In Christchurch, New Zealand, faulting and liquefaction from the 2011 earthquake caused subsidence of up to 1 m. Built on a floodplain, the city was at risk of flooding from tidal events and heavy precipitation even before the earthquake, and the Christchurch City Council had sought to account for projected sea-level rise by requiring new houses to be built with floor levels 3 m above sea level. As a result of the earthquake, however, flood risk from the Avon River has significantly increased, specifically because of subsidence, lateral spreading and heaving of the riverbed (which reduced river channel volume), and settling of riverbanks and levees. To mitigate the new level of risk, the city has had to dredge channels, construct emergency levees, and build a new storm water network (Giovinazzi et al. 2011), and there have been additional efforts to mitigate flooding of individual homes (Christchurch City Council 2014). While reconstruction of properties focuses on repairing earthquake damage, homes in the floodplain must be reconstructed with consideration for increased flood risk—that is, must be rebuilt with higher floor levels.

In subduction zone earthquakes, the area of co-seismic subsidence can be large, and primarily affects the near-shore or onshore side of the fault because of the fault structure and rupture mechanism. The Research Center for Prediction of Earthquakes and Volcanic Eruptions, at Tohoku University, found that subsidence due to the Great East Japan Earthquake lowered the ground level at the Oshiki Peninsula, close to the cities of Onagawa and Ishinomaki, by up to 5.3 m. As a result, the harbor areas of these cities now flood daily at high tide.

replenished (by rainfall) at slower rates than water is extracted, the water table is lowered and extraction must be conducted at sites further afield. This increases the area affected by extraction-induced subsidence.

The rate of subsidence can exceed that of sea-level rise, meaning that subsidence may be a greater influence on the increased coastal flood hazard than climate change. In Manila Bay, Philippines, extraction continues to lower the land, in some years by more than 10 cm (Rodolfo and Siringan 2006). The subsidence rate in Bangkok reached over 12 cm a year in the 1980s (Phien-wej, Giao, and Nutalaya 2006). And some parts of Jakarta, Indonesia, subside by as much as 20 cm per year due to groundwater extraction. Budiyono et al. (2015) analyzed future flood hazard in Jakarta with explicit consideration of future climate conditions and declining ground elevations due to subsidence. The results demonstrate the importance of incorporating subsidence in analysis of affected areas such as Jakarta. Taking change in precipitation, sea level, land use, and subsidence into account, annual damage in 2030 is expected to increase by 263 percent. Subsidence alone contributes an increase of 173 percent, while the contribution from increased precipitation intensity is highly uncertain (median 4 percent decrease in annual damage; -38 to +197 percent range in 5th to 95th percentiles).

Coastal erosion causes the coastal flood hazard to evolve by effectively moving the coastline inland, either gradually over time or in single periods of intense erosion during extreme storm events. Erosion reduces any buffer distance that exists between the shoreline and coastal populations or assets, allowing comparatively minor inundations (from storm surge or tsunami events) to affect coastal exposure. Erosion that occurs naturally because of long-term physical trends (e.g., cliff erosion or longshore drift) can be exacerbated by sea-level rise or more extreme coastal flooding. Additionally, the construction of coastal works, such as dams on rivers that discharge sediment at the coast, can disrupt the natural sediment refill and cause a sediment transport deficit that enhances erosion. For example, the development of a coastal highway in Alexandria, Egypt, has reduced the amount of sediment reaching coastal areas, contributing to "chronic long-term coastal erosion" of about 20 cm per year (World Bank 2011a, 37). This is a global issue, occurring from the coasts of Yorkshire, England (Winn, Young, and Edwards 2003), to Small Island Developing States such as Maldives (Yan and Kishore 2014). The degradation of coastal habitats (such as mangroves or coral reefs) through human activity can also increase risk, since these degraded habitats are less effective in protecting the coastline from storm waves, storm surge, and tsunami.

Sea-level rise

Sea-level rise is an extremely important influence on evolving hazard, contributing as much as or more than other associated factors to increased risk. For example, sea-level rise contributes more to increased extreme storm tide heights in Victoria, Australia, than higher wind speeds (McInnes et

Box 3.3 Effects of Subsidence in Jakarta, Indonesia

In rapidly urbanizing Jakarta, Indonesia, groundwater extraction has led to an estimated 2 m of subsidence between 1999 and 2013, with an additional 1.8 m expected between 2013 and 2025 (Deltares 2014).

The greatest subsidence is occurring in north Jakarta, where the rivers and canals that flow through the city discharge into Jakarta Bay. In conjunction with rising sea level and the occurrence of extreme weather events, subsidence is contributing to the increasing urban and tidal flood hazard. At current rates of subsidence and sea-level rise, and without coastal protection, residential and industrial areas of north Jakarta, major transport links (including the international airport), and ports could be submerged within 100 years (World Bank 2011b). Coastal protection in the form of the Jakarta Coastal Defence Strategy (a dike and polder system), along with land reclamation and improved pumping capacity, are proposed to tackle the problem. But the long-term solution lies in replacing groundwater extraction with piped water supply, thus reducing the rate of subsidence.

Example of chronic long-term coastal erosion in Alexandria, Egypt. Photo credit: krechet/Thinkstock.com

al. 2013). This suggests that storm surge risk is likely to increase under climate change, despite the remaining uncertainty around regional changes in cyclone frequency and intensity. To cite another example of the influence of sea-level, analysis shows that future peak hurricane storm surge heights in Texas, United States, are driven almost equally by sea-level rise and hurricane intensification (Mousavi et al. 2011), demonstrating the importance of including both factors in an analysis of evolving coastal flood hazard. Using projections of sea-level rise and global temperature change, Tebaldi, Strauss, and Zervas (2012) found a significant increase in frequency of storm surges on the U.S. coastline: surges with a current return period of around a century become decadal events by 2050.

Losses due to coastal flood are expected to occur at an increasingly rapid rate as sea levels rise. The relationship between sea-level rise and increase in loss (i.e., whether there is a proportional or nonlinear threshold response) is determined by local topography (McInnes et al. 2013). For example, given the same rise in sea level, the newly flooded area of a wide low-lying coastal plain will be proportionally greater than in a narrow steep-sided bay. Hallegatte et al. (2011) demonstrated an additional threshold effect in storm surge losses due to sea-level rise related to coastal protection in Copenhagen, Denmark. A 0.5 m sea-level rise is expected to result in a 60 percent increase in losses for 50-year and 100-year return periods, compared to losses due to surge at current mean sea level (even without the uncertain effect of change in storm frequency and change in exposure). A rise in sea level of 1 m, however, results in a 140 percent increase over present losses, because losses rapidly increase once a storm surge exceeds the current defense protection level.

Extreme heat

Rising temperatures have resulted in more severe, frequent, and widespread **extreme heat** events, which are already considered a significant issue for public health (Luber and McGeehin 2008). Increases are expected in both “highly unusual” events, such as those in Russia and Central Asia in 2010, the United States in 2012, and Australia in 2015, and “unprecedented” events, which do not occur under present-day climate conditions (World Bank 2014). Recent research suggests for example that the probability of extreme heat waves in eastern China has increased sixtyfold since the 1950s due to anthropogenic influences (Sun et al. 2014). Similarly, an analysis of the 2014–2015 heat wave in Europe shows that many of the extremes recorded during this event are at least twice as likely to happen today than they would have been in a world without climate change (case study A). The expected increase in number of hot days over a larger area of North America (Rhodium Group

Extreme heat events are very important from a humanitarian point of view, since they are a prime driver of mortality and since long-duration temperature extremes lead to drought, which may trigger climate-related human migration.

LLC 2014) means an increase in the spatial extent of regions affected by heat-related mortality, wildfire risk, and drought. One effect of the global trend of increasing urban population is a greater exposure to heat extremes; urban centers are susceptible to amplified heat extremes both because of waste heat emission from buildings and transport and the thermal properties of urban construction materials (McCarthy, Best, and Betts 2010; McCarthy et al. 2012). McCarthy, Best, and Betts (2010) showed that in a future with a doubling of CO_2, daily minimum and maximum temperatures would be expected to increase by at least 3°C in all world regions, and there would be a 30 percent increase in nocturnal heat in urban areas of South America and Southeast Asia.

Extreme heat events are very important from a humanitarian point of view, since they are a prime driver of mortality and since long-duration temperature extremes lead to drought, which may trigger climate-related human migration. Agricultural crop yield can be adversely affected by extreme heat, particularly if the heat stress occurs in key stages of the growing season. It is thus important to be able to quantify the risk to agricultural production in a changing climate. Deryng et al. (2014) showed a global average decrease in maize yield to 2080, and found that extreme heat stress occurring around the time of crop reproduction contributed to almost half of all maize yield loss and to a 50 percent decrease in yield gains for spring wheat. Soy, which has a higher critical temperature threshold, is less adversely affected by extreme heat and shows a 25 percent decrease in yield gains.

Drought

Drought hazard encompasses *meteorological* drought (a deficit of precipitation), *agricultural* or soil moisture drought (a deficit of soil moisture in the root zone), and *hydrological* drought (negative anomalies in groundwater, streamflow, or lake levels) (IPCC 2012). These natural drought phenomena are different from but linked to *water scarcity*, or *socioeconomic* drought, which may be partially or fully caused by human activities such as intensive agriculture or groundwater extraction (Dai, Trenberth, and Qian 2004). Drought hazard, in its various forms, is a complex hazard, driven by the interaction of climatic and socioeconomic factors over different time periods. To simulate these factors, modeling of drought risk under future climatic and socioeconomic conditions requires the use of climate models.

Some studies have found signals of increasing trends in drought occurrence under climate change (Briffa, van der Schrier, and Jones 2009; Dai, Trenberth, and Qian 2004). Such trends are not considered significant on a global scale, however (Sheffield, Wood, and Roderick 2012), and given the lack of direct observations there is a low degree of confidence concerning global drought trends (Stocker et al. 2013). There are distinct regional variations in the projected direction of change and the magnitude of factors contributing to drought (such as precipitation, runoff, soil moisture, and evapotranspiration). A reduction in precipitation is likely in the Mediterranean, southwest United States, and southern Africa; decreases in runoff and soil moisture are likely in southern Europe and the Middle East (Stocker et al. 2013); and wetter conditions are expected in the Horn of Africa (World Bank

2014). There is high confidence that heat and drought stress will reduce crop productivity, increase pest and disease damage, disrupt food system infrastructure through flooding, and generally be harmful to livelihoods and food security.

Analyses of the evolution of drought risk in the past and the future have been conducted at varying scales. On a global scale, the estimated share of the world population facing water scarcity increased from 20 percent in 1960 to 50 percent in 2000 (Veldkamp et al. 2015). In the short term (6 to 10 years), hydroclimatic variability is responsible for almost 80 percent of the yearly change in water scarcity, whereas socioeconomic development is the driving force behind long-term changes. The IPCC has high confidence that in drought-prone regions of Africa, drought stress will be exacerbated by current overexploitation and degradation and by future increases in demand for water resources. Global change in precipitation, evapotranspiration, and mean surface temperature to 2100 is expected to significantly increase the number of annual drought days[2] over North and South America, central and southern Africa, the Middle East, southern Asia, and central and western Australia (Hirabayashi et al. 2008).

Wildfire

The impacts of **wildfire** are substantial in many regions of the world. Both observed wildfire risk and the expected future evolution of wildfire risk are linked to long-term temperature and precipitation, among multiple other factors (Liu, Stanturf, and Goodrick 2010). Wildfire causes loss of lives and homes, damages ecosystem services, is harmful to human health, and entails substantial costs for fire suppression. Several high-profile wildfire events have occurred in the last several years (World Bank 2012), including devastating wildfires in southern Europe during a summer of record temperatures (2007); the worst Australian bushfires on record in the state of Victoria during a heat wave of record temperatures (2009); 500 wildfires around Moscow, Russia, during the hottest summer for 400 years, resulting in crop failure of about 25 percent, 55,000 deaths, and economic losses of US$15 billion (2010); and 3 million acres of burnt land in four southern U.S. states during a record heat wave and drought, resulting in US$6–8 billion in economic loss (2011). The February 2009 fires in Victoria, Australia, demonstrate how phenomena related to weather and climate—specifically a decade-long drought, record extreme heat, and record low humidity of 5 percent (Karoly 2010; Trewin and Vermont 2010)—interact with rapidly increasing exposure to drive the evolution of risk (IPCC 2012). Together the climate

Due to its tropical region, different physical effects of climate change—increased temperature and precipitation, increased salinity and extreme weather events such as floods, cyclones and drought—are felt in Sundarban, India. Photo credit: samrat35/Dreamstime.com

2 “Drought days” are days when daily discharge is lower than the 10th percentile of all river discharge data from the 20th-century simulation.

phenomena created the conditions for major uncontrollable wildfires (2009 Victorian Bushfires Royal Commission 2010).

Frequency and severity of large wildfires (in terms of area burned) are expected to increase in a warmer climate (Flannigan et al. 2009), in which hotter and drier conditions, more fuel, and more frequent lightning will lead to longer fire seasons. Climate change is expected to have a minor impact on wildfire risk in North America and South America, but a major impact in southern Europe and East Africa (Field et al. 2014). Under 4°C warming, some models project large increases in fire risk in southern Europe, Russia, and North America. A common trigger of natural wildfires, lightning, may increase in a warmer climate: annual mean lightning strike frequency has been shown to increase across the United States by 12 percent per 1°C of warming (Romps et al. 2014).

Geotechnical and geophysical hazards

Seismic and volcanic hazard

Seismic hazard can be affected by human activity. Mining, geothermal energy production, and the construction of reservoirs may induce seismicity—that is, locally increase the frequency of small-magnitude earthquakes (Simpson, Leith, and Scholz 1988; Majer et al. 2007). But there is no compelling evidence to suggest that human activity or changing climate affects the frequency or severity of large-magnitude earthquakes. Thus exposure and vulnerability are the main anthropogenic drivers of evolving earthquake risk. Regional earthquake hazard does evolve through time due to natural variation. An earthquake is the rupture at a fault when stress, caused by the movement of rock around the fault, builds to such a level that it exceeds the strength of that rock. The movement due to an earthquake increases stress in some parts of the surrounding rock and decreases stress in other parts. An increase in stress can increase the probability of (or decrease the time before) another earthquake in that area, because the fault is brought closer to its maximum capacity, i.e., closer to rupture. Likewise, a decrease in stress can lengthen the time before the next rupture occurs. As a result of this chain reaction effect, the occurrence of one large earthquake can increase regional earthquake hazard for months, several years, or even decades.

Although earthquakes themselves may not be influenced by climate change, the chance that earthquakes will trigger landslides in steep terrain can be increased as a result of changes in precipitation patterns, which can increase the amount of moisture in soil and decrease stability of slopes. In such cases, landslides can be triggered by a lower level of earthquake shaking than would otherwise have been required, or an earthquake may trigger larger landslides than it would otherwise have done (also see the section on landslide below).

As far as is known, **volcanic** activity is unaffected by human activity, and there is no evidence to suggest that trends in activity are affected by changing climate. As with earthquakes, the driving influences of evolving volcanic risk are changing exposure and vulnerability in areas affected by volcanoes. That is not to say that volcanic hazard is static. Levels of volcanic activity are time-varying in the short term and long term. An "active" volcano (one that has erupted in the last 10,000 years) will exhibit varying levels of volcanic activity (and therefore hazard) as it transitions between non-eruptive and eruptive states, perhaps over many years, decades, or centuries. Several volcanoes are known to erupt very frequently or almost constantly (e.g., Stromboli, Italy), but volcanoes can also exhibit different styles of eruption or different levels of activity that present a changing hazard level. Some eruptions can persist for months or years (e.g., Soufriere Hills, Monserrat); and within such a long-duration eruption, hazard can vary from day to day depending on short-term changes in eruptive activity or wind direction (affecting ash fall hazard).

Landslide

The IPCC (2012) expresses high confidence that climate change–driven increases in heavy precipitation will cause changes in slope instability and hence in **landslide** hazard. Landslides are a product of geological and, often, meteorological factors. Heavy rainfall is a significant contributor to slope instability because it can increase soil water pressure, while flooding or coastal erosion can increase the landslide hazard by undercutting the supporting toe of slopes or cliffs. These factors may not trigger a landslide independently in all cases, but they may provide the antecedent conditions that enhance slope susceptibility to other triggers, such as earthquakes. Landslide hazard may also evolve through destabilization of slopes by deforestation or urban development of hillsides. The majority of damaging landslides occur in remote areas in less developed countries. In most years, the major share of landslide fatalities is reported in China and South Asia during the Northern Hemisphere summer (Petley, Dunning, and Rosser 2005).

Before-and-after photographs of Nepal's Langtang Valley, following a massive landslide caused by the 2015 Gorkha earthquake. More than 350 people are estimated to have died as a result of the earthquake-induced landslide. Photos from 2012 (pre-quake) and 2015 (post-quake). Photo credit: David Breashears/GlacierWorks

Drivers of Evolving Disaster Risk: Exposure

4

Increasing exposure of people and economic assets has been the major cause of long-term increases in economic losses from weather- and climate-related disasters.

The rise in disaster losses over the past decades is due mainly to changes in socioeconomic factors, specifically population and wealth (for regional and global trends see figure 4.1 and figure 4.2). There is evidence of this for several hazards and regions, including hurricanes in the United States, and river floods and extratropical cyclones in Europe (e.g., Barredo 2009, 2010; Bouwer et al. 2007; Mohleji and Pielke 2014; Visser, Petersen, and Ligtvoet 2014). The effect of exposure on increasing disaster losses has been established with much more confidence than the effect of hazard and vulnerability, in part because of the relatively short time series of losses and the lack of well-developed methodologies for quantifying hazard and vulnerability (Visser, Petersen, and Ligtvoet 2014). The IPCC (2012, 9) has high confidence that "increasing exposure of people and economic assets has been the major cause of long-term increases in economic losses from weather- and climate-related disasters." According to Freire and Aubrecht (2012), moreover, "for many hazard occurrences, especially those above a certain magnitude or intensity, population exposure is arguably the greatest determinant of vulnerability and resulting losses and impacts." While the general trend is one of increasing exposure, of course decline in population and gross domestic product (GDP) can lead to a reduction in risk, as shown for earthquake risk in case study D.

FACING PAGE

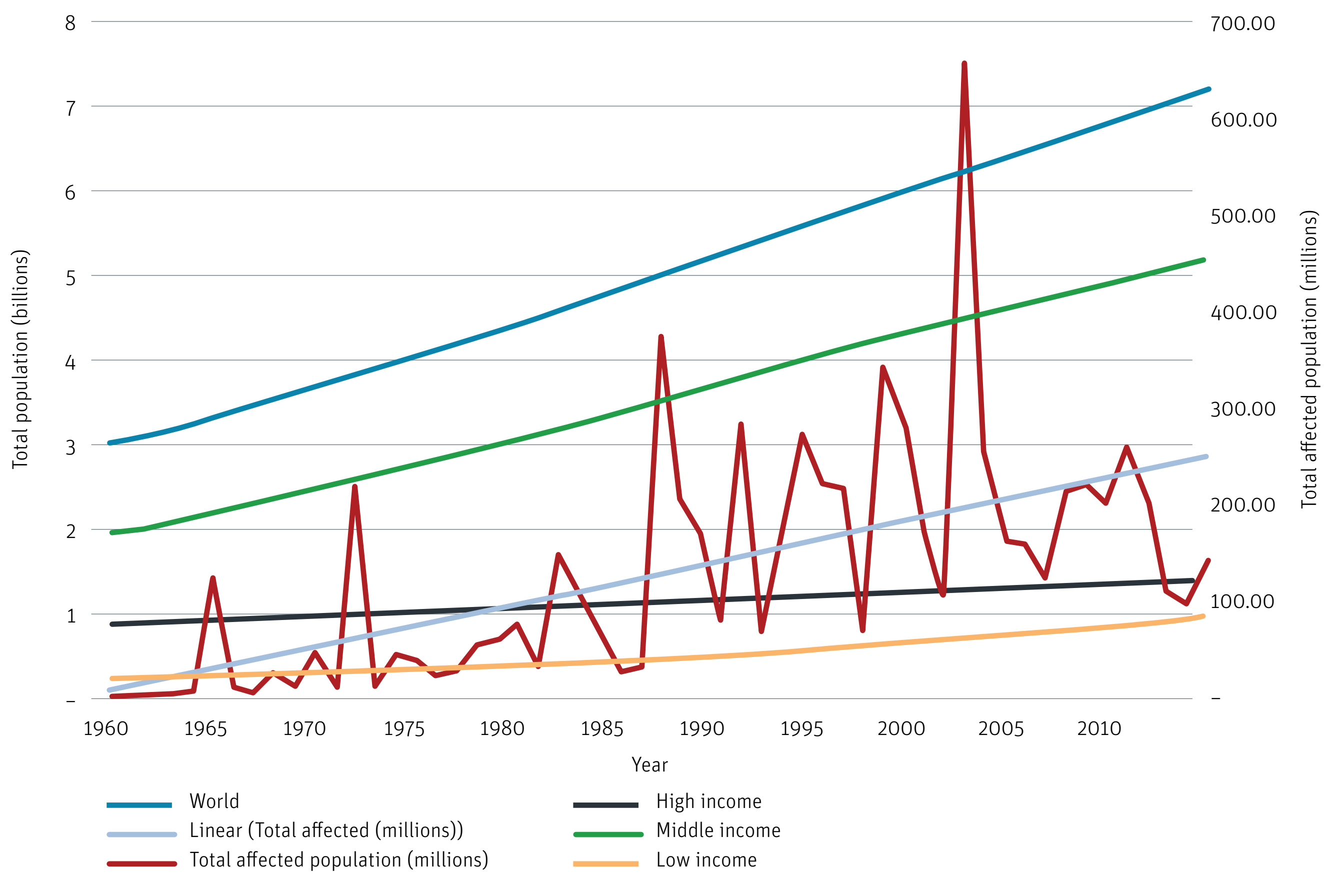
Taipei commuters. Photo credit: fazon1/Thinkstock.com

Population growth

Increased global exposure to natural hazards has largely been driven by population growth and the trend of an increased proportion of that population living in cities rather than rural areas (urbanization). All regions of the world experienced a vast increase in total population between 1960 and 2013 as well as an increase in the proportion of urban population (figure 4.1 and figure 4.3). The global population exposed to river and coastal flooding, to choose one hazard, doubled—increasing from around 520 million in 1970 to almost 1 billion in 2010 (Jongman, Ward, and Aerts 2012). Population growth is expected to continue this trend into the future. There is a 95 percent probability that world population will increase from 7.2 billion people in 2014 to between 9.0 and 13.2 billion people by 2100 (Gerland et al. 2014). Regional contributions to growth are variable, with South Asia, East Asia, and Africa showing the largest regional population increases (Gerland et al. 2014) and contributing the majority of the annual growth in individual cities (table 4.1).

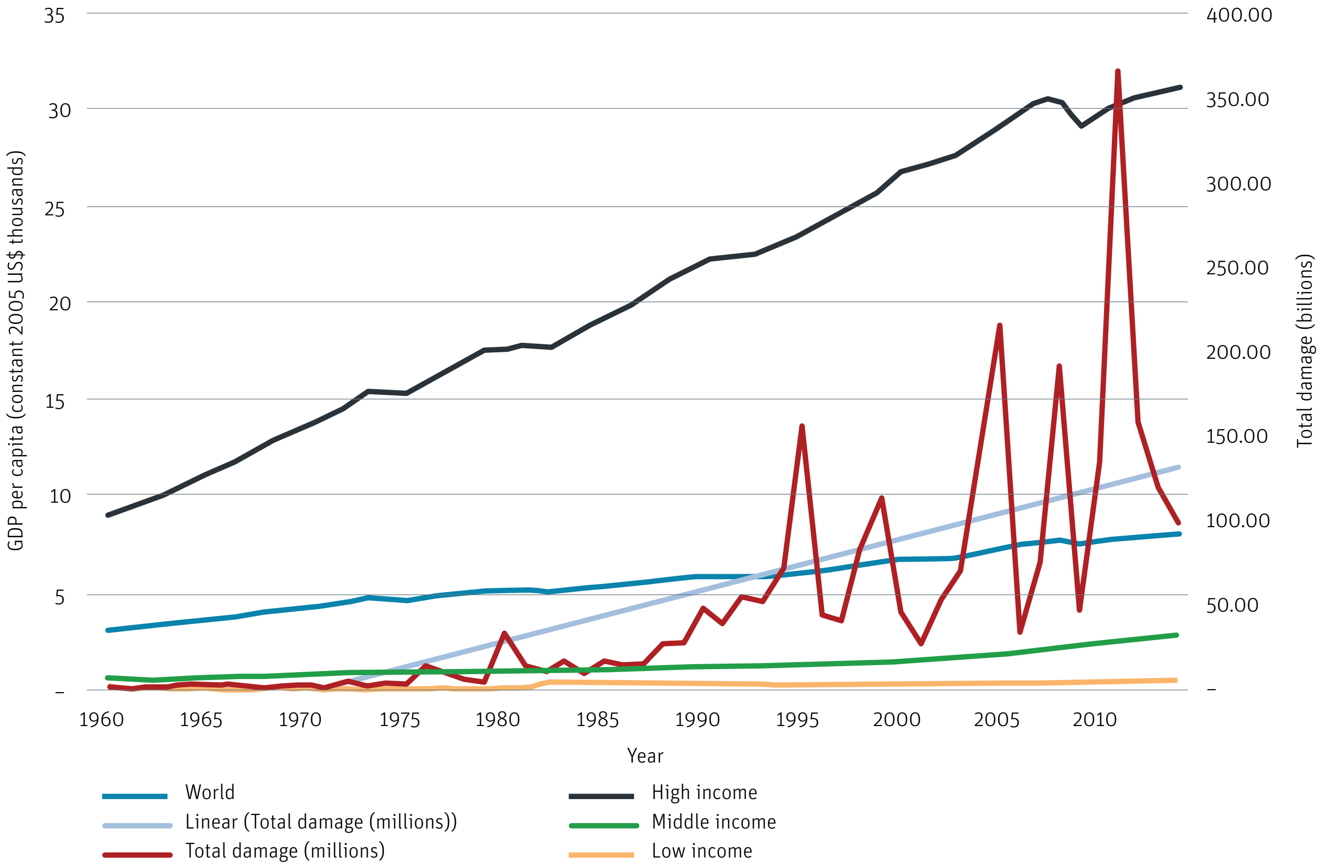
Cities are dense, highly concentrated locations of exposure, so when they are affected by a disaster, losses can be significant. Rapid and unplanned expansion of urban populations increases exposure either through increased density, as cities build upward, or by outward expansion, as the increasing population spreads over a wider area and causes changes in land use. The urbanization of unstable slopes or reclaimed land (which is often susceptible to flooding and liquefaction) leads to a disproportionate increase in exposure to hazards

Figure 4.1. Total population in World Bank income groups, 1960–2014, shown alongside total affected population.



Sources: World Development Indicators Database, World Bank, Washington, DC, http://data.worldbank.org/data-catalog/world-development-indicators (for total population); D. Guha-Sapir, R. Below, and Ph. Hoyois, EM-DAT: International Disaster Database, www.emdat.be, Université Catholique de Louvain, Brussels, Belgium (for total affected population).

Figure 4.2. GDP per capita (constant 2005 US$) in World Bank income groups, 1960–2014, shown alongside total damage (2014 US$).

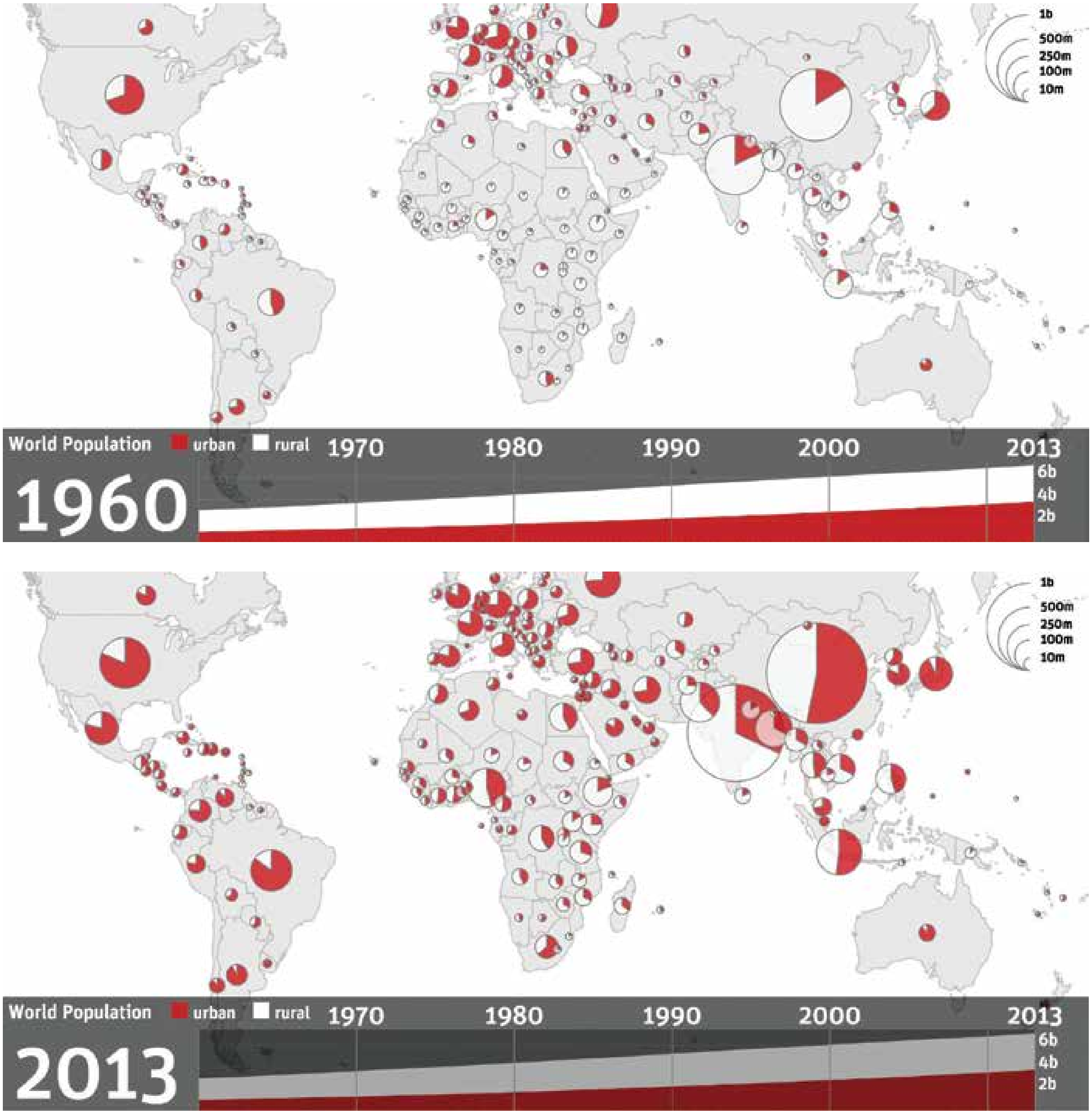


Sources: World Bank, World Development Indicators Database, http://data.worldbank.org/data-catalog/world-development-indicators (for GDP per capita); D. Guha-Sapir, R. Below, and Ph. Hoyois, EM-DAT: International Disaster Database, www.emdat.be, Université Catholique de Louvain, Brussels, Belgium (for total affected population).

and socioeconomic vulnerability. Urbanization can change disaster risk significantly. Evolution of flood risk varies regionally, but also differs in urban and rural contexts. The global flood model GLOFRIS (Global Flood Risk with IMAGE Scenarios) was used to estimate regional urban and rural population at risk of flooding for 2010, 2030, and 2050 (Ligtvoet et al. 2014). The study found a significant increase in urban population at risk of flooding for the whole world, developing countries, and each World Bank region. However, rural population at risk of flooding was found to decline in all regions except Sub-Saharan Africa. Urban and rural GDP exposed to 1-in-10-year floods was found to increase significantly between 2010 and 2050 in all regions, with smaller increases found for urban and rural GDP exposed to 1-in-100-year floods across the same time scales.

Increased exposure in coastal cities is an important driver of risk. These cities are already among the most populous in the world (Hallegatte et al. 2013) and have a huge amount of infrastructure exposed to coastal flooding and storm surge. These cities are also some of the most rapidly growing in terms of population (see table 4.1). Coupled with the effects of evolving coastal hazards, this swift increase in exposure makes cities such as Mumbai, Karachi, Jakarta, and Lagos among the key areas in which to address evolving disaster risk. It is important to note that increased exposure to hazards does not occur only in expanding urban areas. One example of increased exposure in low-density areas—those that could still be considered rural—is the observed movement of population to locations at risk of wildfire, such

Figure 4.3. **Growth in population between 1960 (above) and 2013 (below). Size of pie chart shows total population, while segments indicate what proportion is urban and rural.**



Sources: World Development Indicators Database, World Bank, 2015, http://data.worldbank.org/data-catalog/world-development-indicators.

Table 4.1. Top 20 Cities by Population in 2015 and 2030, with Change in Rank and Percentage Change in Population in the Intervening Years

Country or area	Urban agglomeration	2015 population (1,000s)	2015 rank	2030 population (1,000s)	2030 rank	Rank change	Percentage change in population
India	Delhi	25,703	1	36,060	1	=	40
India	Mumbai	21,043	2	27,797	2	=	32
China	Beijing	20,384	3	27,706	3	=	36
Bangladesh	Dhaka	17,598	4	27,374	4	=	56
Pakistan	Karachi	16,618	5	24,838	5	=	49
Nigeria	Lagos	13,123	6	24,239	6	=	85
China	Guangzhou	12,458	7	17,574	8	–	41
Congo, Dem. Rep.	Kinshasa	11,587	8	19,996	7	+	73
Indonesia	Jakarta	10,323	9	13,812	11	–	34
India	Bangalore	10,087	10	14,762	9	+	46
India	Chennai	9,890	11	13,921	10	+	41
India	Hyderabad	8,944	12	12,774	13	+	43
Pakistan	Lahore	8,741	13	13,033	12	–	49
China	Chengdu	7,556	14	10,104	18	–	34
China	Nanjing	7,369	15	9,754	19	–	32
India	Ahmadabad	7,343	16	10,527	15	+	43
Vietnam	Ho Chi Minh City	7,298	17	10,200	17	=	40
Malaysia	Kuala Lumpur	6,837	18	9,423	21	-	38
Iraq	Baghdad	6,643	19	9,710	20	-	46
China	Hangzhou	6,391	20	8,822	22	-	38
Tanzania	Dar es Salaam	5,116	26	10,760	14	+	10
Angola	Luanda	5,506	23	10,429	16	+	89

Source: United Nations, Department of Economic and Social Affairs 2014.

as areas close to national parks in the United States (Hammer, Stewart, and Radeloff 2009).

Increased socioeconomic activity

A major component of increased socioeconomic activity is the development of concentrations of industrial, service, and trade activity. Wherever these concentrations develop, they drive large increases in high-value assets; in hazardous areas, these assets can be significantly affected by a single event. These concentrations also drive increases in residential exposure in the form of the population that works in and is supported by the activities. Given the national and global connectivity of so many trade and industry networks, impacts at one location can propagate disruption and loss to other parts of the network. The 2011 Thailand floods, for example, inundated 7,500 industrial facilities in 40 provinces, disrupting production (and global supply) of automobiles and electronics.

The effect of socioeconomic activity on flood losses has been demonstrated by several studies, but few present the relative contributions of evolving hazard *and* exposure. In a study presenting a new framework for the global flood risk model GLOFRIS, Winsemius et al. (2013) showed that socioeconomic change has a greater influence than climate change on future flood risk. Asset values exposed to flood in Bangladesh in 2050 could be 2.7–3.7 times those exposed in 2010, and exposed GDP could be 3.2–4.2 that exposed in 2010. A study of drought by Veldkamp et al. (2015) also considered exposure as well as hazard. It assessed changes in water scarcity between 1960 and 2000, accounting for changes in socioeconomic conditions as well as hydroclimatic variability. While hydroclimatic variability was found to be responsible for the largest share (79 percent) of year-to-year changes in water scarcity, socioeconomic changes (population growth and increasing water demand per capita) were the main drivers behind long-term increases in water scarcity. The study emphasized that socioeconomic factors interact with and can strengthen or attenuate each other, which suggests an integrative modeling approach is needed to account for such changes effectively.

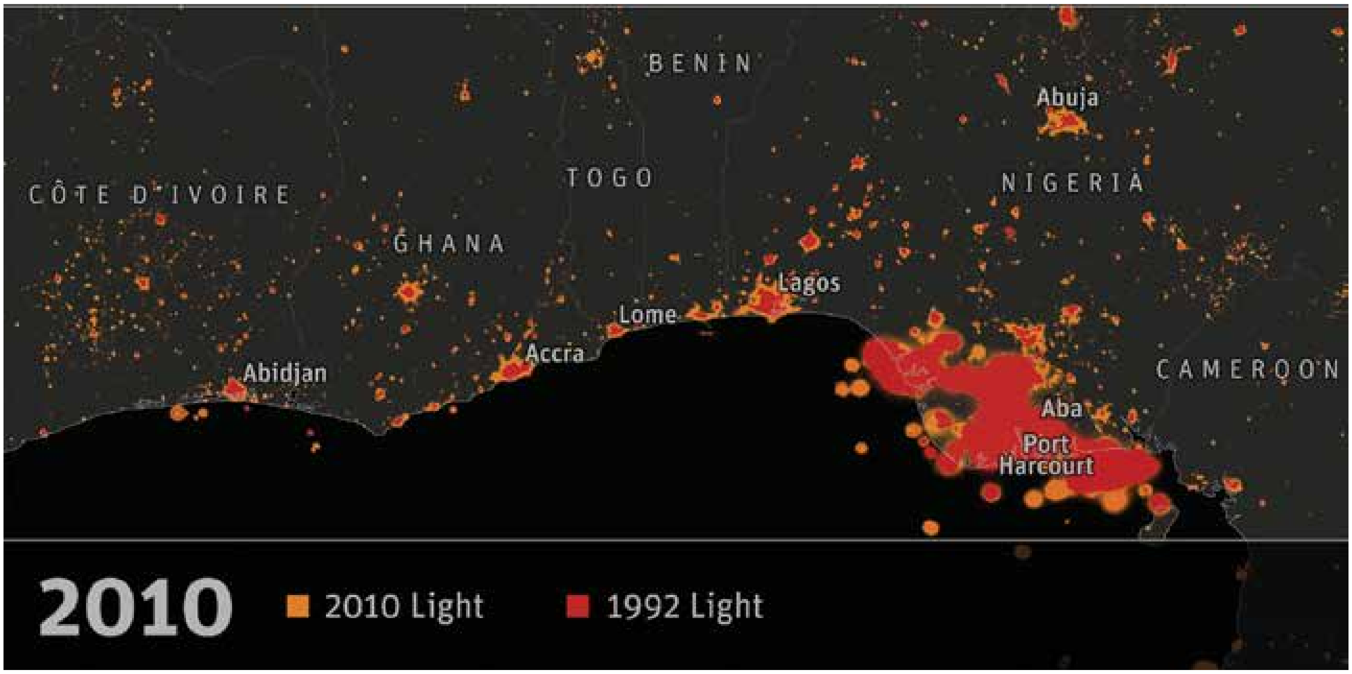
Land-use change

In addition to increasing exposure to hazards, population growth and increased socioeconomic activity drive land-use change, which alters ground surface conditions and can increase hazard (see section on flooding in chapter 3). Between 1970 and 2010, the total urban surface area exposed to flooding more than doubled, from 18,000 km^2 to 44,000 km^2 (Jongman, Ward, and Aerts 2012). The increase in urban land use is expected to continue, and to do so particularly rapidly in developing countries. Approximately 38 percent of Africa's population (297 million people) currently lives in urban areas, but the proportion of urban population is expected to rise to 54 percent by 2030 (CLUVA 2015). Africa's urban population is expanding into existing and new urban areas at the fastest rate in the world—3.5 percent per year—and driving a significant amount of land-use change. In developed countries, a trend of large cities becoming less dense reflects the expansion of urban development into rural areas previously dominated by natural surfaces.

Data on evolving exposure

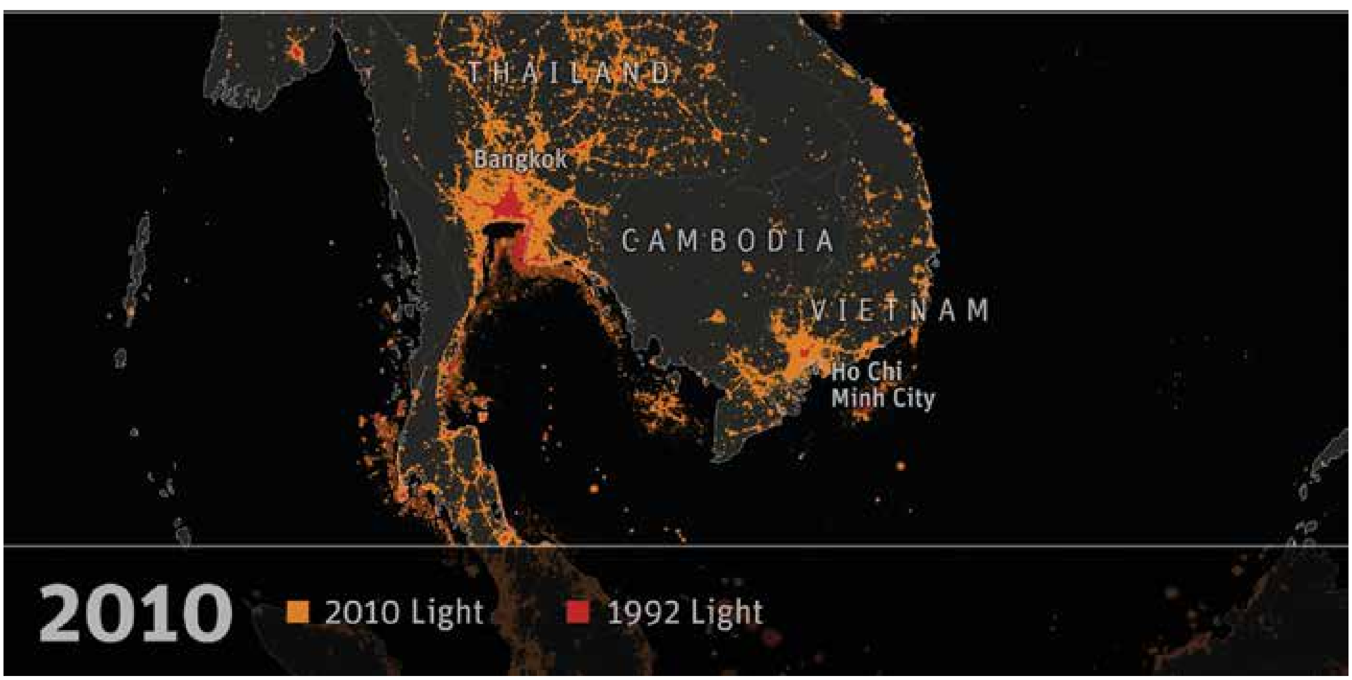
Data showing changes in global exposure have been collected via remote sensing technologies, primarily low-light imagery, from the U.S. Air Force Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) since the 1970s, and from the NASA/NOAA Visible Infrared Imaging Radiometer Suite (VIIRS) instrument since 2011 (Elvidge et al. 2013). The night-time light data have been used to show economic activity and population (Elvidge et al. 1997) and trends in urbanization (Zhang and Seto 2011), and have been used as a proxy for poverty (Noor et al. 2008; Wang, Cheng, and Zhang 2012). Time series of regional night-time light data between 1992 and 2012 for West Africa (figure 4.4) and Southeast Asia (figure 4.5) show the patterns of steadily increasing concentrations of people and economic activity in cities and coastal areas and along transport networks.

Figure 4.4. **Night-time light coverage in 1992 (red) and 2010 (orange), showing expansion of multiple urban areas, e.g., Accra, Ghana, and Lagos and Abuja, Nigeria. Small pockets of light in 2010 show increased economic activity and the presence of night-time light in rural areas since 1992. The large area of intense light around Port Harcourt indicates high levels of industrial activity in that area in 1992 and 2010.**



Source: World Bank based on data from NOAA National Centers for Environmental Information 2015.

Figure 4.5. **Night-time light coverage in 1992 (red) and 2010 (orange), showing expansion of Bangkok and Ho Chi Minh City, and increased economic activity along transport routes and coastal areas in Thailand, Cambodia, and Vietnam.**



Source: World Bank based on data from NOAA National Centers for Environmental Information 2015.

Drivers of Evolving Disaster Risk: Vulnerability

5

Vulnerability refers to the susceptibility of exposed people, assets, and livelihoods to the harmful effects of natural hazards. Physical, or structural, vulnerability refers to the damage associated with buildings and infrastructure, which determines asset losses. These losses are typically the concern of the (re)insurance and engineering industries, which focus on estimating loss to insured assets and mitigating structural damage, respectively. Social vulnerability refers to people's ability to cope with the impacts of asset losses on their livelihoods and security. These impacts, along with losses to public assets, are a focus for governments.

It is vital to improve the way the evolution of vulnerability in time and space is incorporated into disaster risk assessment.

Structural vulnerability

The physical vulnerability of a structure or piece of infrastructure determines the level of damage the asset sustains in response to a given level of hazard intensity. Physical vulnerability is usually presented in the form of a vulnerability curve (or fragility curve; see figure 5.1), which shows the probability of a damage state being exceeded for a given hazard intensity. The primary factors determining a structure's vulnerability to damage are construction type (e.g., timber, unreinforced masonry, reinforced concrete, or steel), number of stories, and (for wind hazards) roof construction. For example, a tsunami occurring with flow depth of 2 m may cause collapse (100 percent damage) of a timber house, but cause only minor damage to a less vulnerable reinforced concrete building (Suppasri et al. 2013). Multiple other factors contribute to vulnerability, including the quality of construction (e.g., the type of connection between structural components, which is an important

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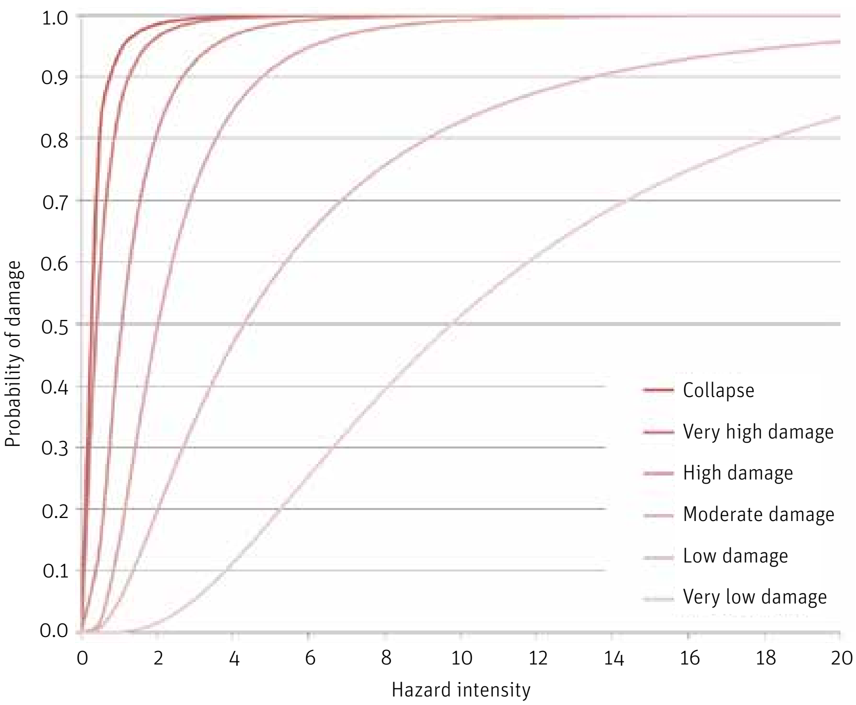
Thousands displaced due to flooding in Cap-Haïtien, Haiti, after days of continuous rains. The region suffered serious flooding, leaving more than a dozen dead and thousands homeless. Photo credit: UN Photo/Logan Abassi

Figure 5.1 Sample fragility curves. Each curve shows the probability of a particular level of damage occurring for the hazard intensity experienced.



factor in the extent of earthquake damage) and quality of construction material. The configuration (shape) of a structure also influences the seismic damage level. Daniell (2014) shows that as building stock becomes newer, earthquake vulnerability declines (see case study D).

Physical vulnerability can increase over time if a structure or infrastructure is inadequately maintained such that connections and material deteriorate. Vulnerability of supporting systems is intrinsically linked to evolution of exposure. As population grows, the demand for functioning infrastructure grows. Without proper development and maintenance, interrelated infrastructure systems may suffer from insufficient capacity, deterioration, and ultimately less redundancy in case of shocks. Poor maintenance of drainage systems and blockage by solid waste, for example, have been shown to increase flood vulnerability in Jakarta, Indonesia (Marfai, Sekaranom, and Ward 2014). Poorly designed or unfinished drainage systems contributed significantly to flooding in Jeddah, Saudi Arabia, in 2009 (Verner 2012). As infrastructure becomes more susceptible to damage in disasters, the populations it supports become more susceptible to disruption and loss.

Even a structure maintained to avoid deterioration—that is, kept in its original condition but without improvement—can become relatively more vulnerable if the hazard it is designed to protect against intensifies. Increases in physical vulnerability are often seen in structures that are intended to be in use for at least several decades (the design life) and that remain in use much longer than that. A house built in 1960, for example, may have a floor level that is above the 1-in-100-year flood level; but as a result of increased frequency and severity of flooding over time, by 2100 the floor level exceeds only that of a 1-in-50-year flood. That building has become more susceptible to flooding and may require improvements (i.e., installation of flood defenses) to maintain low vulnerability.

Vulnerability also evolves as a result of modifications made to structures. Informal construction is common in many parts of the world, given inadequate building standards and informal planning and construction practices in many rapidly developing urban areas (Lallemant, Wong, and Kiremidjian 2014). Where individuals undertake expansion of their own buildings without planning restrictions or engineering guidance—and when these buildings were likely nonengineered to begin with—the construction of additional stories and changes to buildings' configuration can increase vulnerability (case study E).

A community's vulnerability may evolve due to widespread changes in the building stock, such as occurs when building practices adopted from other regions replace traditional local practices that developed in the context of local risks. The adoption of or improved adherence to building design standards (i.e., structural

Destroyed house after an earthquake near Mount Kinabalu, Malaysia, July 11, 2015. Photo credit: © Muslianshah Masrie

codes) can reduce vulnerability; the decrease in masonry construction in New Zealand since the 1930s, for example, has led to a decrease in vulnerability (see box 7.2). Of course, it sometimes happens that construction practices intended to reduce vulnerability to one hazard inadvertently increase vulnerability to another. This can occur when focus on the more obvious or well-known hazard in an area results in neglect of other hazards present. Specifically, it can occur when design or construction takes one hazard into account but neglects another. For example, installation of a heavy roof to minimize cyclone damage can result in greater earthquake vulnerability. Unfortunately, the consideration of multiple hazards, let alone the interrelated nature of those hazards, is often overlooked. As one study says,

> *Risk reduction strategies for one hazard should take into account coincidental and chains of hazards both in the short and long term, to ensure that decisions made to mitigate hazards today do not increase vulnerability to future events* (Duncan 2014; see also case study F).

Social vulnerability

Depending on their level of vulnerability, different groups and communities are more or less able to respond during a disaster, cope in its aftermath, and subsequently recover. Socioeconomic or social vulnerability may evolve over time positively or negatively in response to many influences, including education, age, wealth, degree of access to resources, and political power (see for example Cutter, Boruff, and Shirley 2003; Cutter et al. 2013; Fekete 2009; Koks et al. 2015). Vulnerability is found to be higher in low-income countries than in high-income countries, and global vulnerability is gradually declining (Mechler and Bouwer 2015; Jongman et al. 2015). This is reflected in decreasing life loss in developed countries (UNISDR 2011; World Bank and United Nations 2010); the fact that fatalities are rising slower than exposed population in lower-middle-income countries; and the absence of a clear trend in low-income countries in the face of rising exposure (Jongman et al. 2015).

According to Wisner et al. (2004), development processes produce or influence the vulnerability of certain social and economic sectors; this view suggests that vulnerability is an ever-evolving component of disaster risk. Social vulnerability is influenced by multiple interacting social, cultural, and economic factors, including the following:

- Population size and demographics (age, gender, disabilities)
- Household structures, gender roles
- Income, poverty, economic activity and resources
- Access to education, health care
- Institutional capacity and governance, including political corruption and political stability

- Environment, particularly susceptibility to hazards
- Infrastructure, including power, water, transportation, communication, sanitation

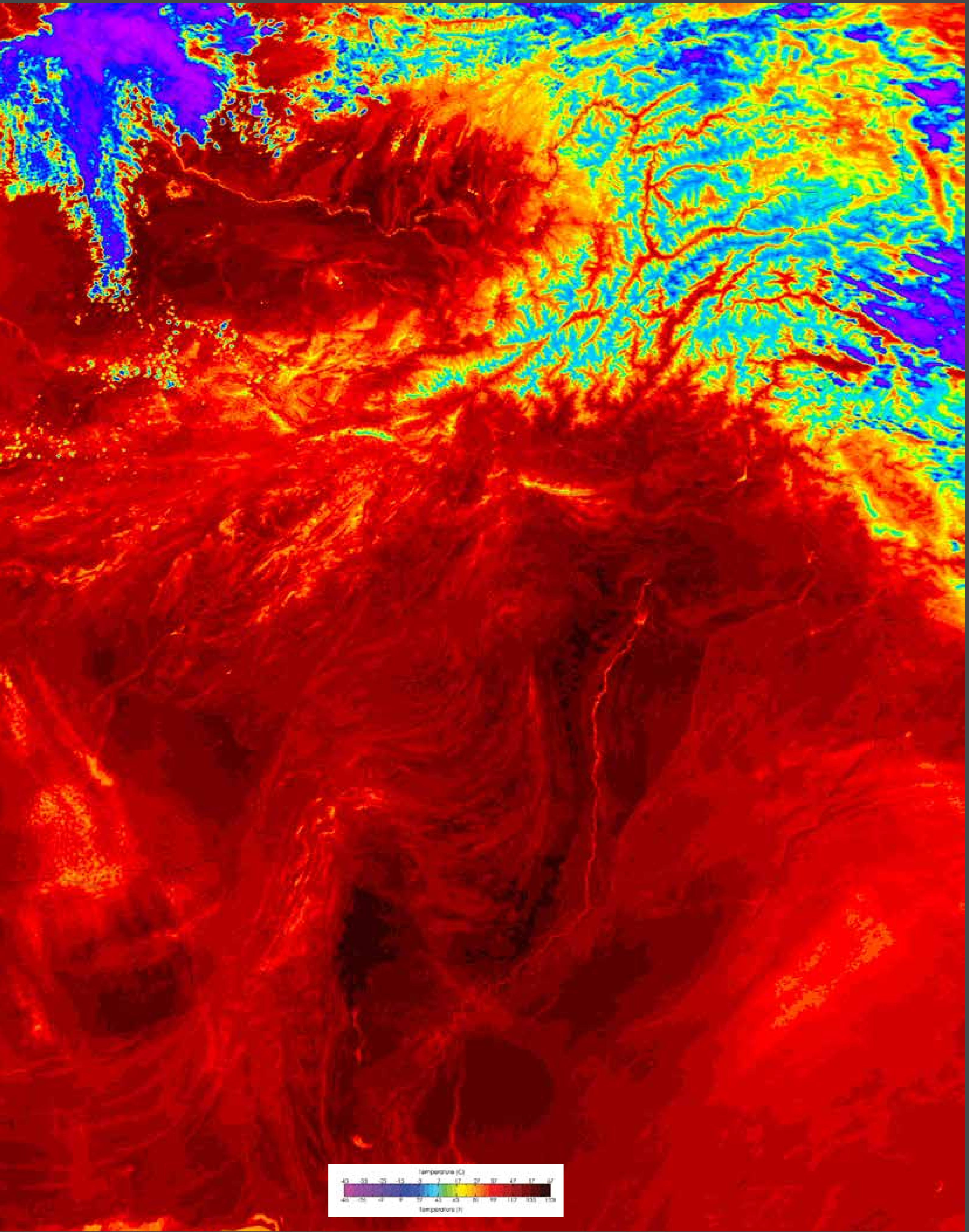
The evolution of social vulnerability can be gradual or almost instantaneous. Long-term trends in vulnerability are influenced by population trends, such as demographic skewing toward the elderly or very young—segments of the population that are more susceptible to injury or loss of life in a disaster (e.g., Cutter, Boruff, and Shirley 2003; Sorensen and Vogt-Sorensen 2006; Guha-Sapir et al. 2006; Brunkard, Namulanda, and Ratard 2008). Periods of political instability, weak governance, or low institutional capacity may weaken economic resources, infrastructure, health and education systems, and social welfare, resulting in a population with higher vulnerability. Gradual environmental improvement or degradation can influence vulnerability by building up or eroding a population's resources or health. Rapid or almost instantaneous changes in vulnerability may occur in response to a disaster that destroys property and livelihoods, increases poverty, disrupts infrastructure, and interrupts access to health care.

A high level of vulnerability created by a sudden shock may persist for a short or long time, depending on the reconstruction and adaptation processes in that location. During the recovery period, when resources, infrastructure, and means of income generation are being restored, there may be little to provide resilience if another disaster occurs. Vulnerability can remain high following a shock if appropriate reconstruction or adaptation is not undertaken, or if maladaptation occurs during unplanned or poorly planned development (Birkmann 2011). In Haiti in 2010, for example, a combination of factors—a long-term situation of poor infrastructure and health care, a major earthquake in January and hurricane in November that caused further deterioration in systems (Butler 2010), and slow recovery from the earthquake—compounded vulnerability and contributed to the rapid spread of cholera following its outbreak in October of that year.

Social vulnerability also has an important spatial dimension. A study by Koks et al. (2015) emphasizes that the level of social vulnerability varies substantially not only between countries, but within the same country and even on a subcity level; decisions on the implementation of disaster risk management strategies need to take this variability into account. Neglecting social vulnerability in risk assessment or assuming homogeneous vulnerability may lead to unsuitable or ineffective strategies. For example, a concentration of elderly people may not be easily evacuated from the hazard zone in case of a rapidly occurring flood or tsunami, but may be better protected by physical infrastructure, vertical evacuation, or shelter-in-place strategies. Similarly, a homogenous flood insurance scheme may not be viable in parts of the city where disposable household income is too low to afford the premiums. In such a case, vulnerability is likely to evolve differently in some locations than in others and to exacerbate any preexisting disparity. Regarding the spatial dimensions of vulnerability, it is important to note that when a person or group of people is considered vulnerable to one hazard, they may not be equally vulnerable to another. As hazard distributions change, some vulnerabilities in a given area may decline and others become more important. For example, elderly populations in Europe are likely to become more vulnerable in future as extreme heat events become more frequent.

Implementation of development programs and infrastructure projects can lessen vulnerability by strengthening social safety nets, enhancing income, and reducing the proportion of the population in poverty. Recent evidence shows that global vulnerability to flooding is declining, especially in low- income regions, in response to rising income per capita and adaptation efforts (Jongman 2014; Jongman et al. 2015). A key aim for disaster risk management strategies is to similarly reduce vulnerability in the context of all hazards. To achieve this, and to account for the influence of vulnerability on developing effective, equitable, and acceptable risk management strategies, it is vital to improve the way the evolution of vulnerability in time and space is incorporated into disaster risk assessment.

Nepal, 2015. Earthquake damage in Bhaktapur, located 30 km east of Kathmandu, once rich with Buddhist and Hindu temples and a popular tourist spot.
Photo credit: Julian Bound | Dreamstime.com


Temperature (C)
Temperature (F)

Quantifying the Evolution of Disaster Risk

6

Most risk assessments do not accurately reflect longer-term dynamics, and decisions based upon these assessments may not be optimal.

Most disaster risk assessment tools developed to date focus on the static assessment of current risk. Thus most risk assessments do not accurately reflect longer-term dynamics, and decisions based upon these assessments may not be optimal. Over time, disaster risk assessment has improved and grown more sophisticated (GFDRR 2014a), but due to the large uncertainties in projecting risk, and a focus on near-term time horizons for managing risk (particularly in the financial sector), efforts to model the evolution of risk have only recently been undertaken. A recent review of 80 open source and open access risk assessment tools (GFDRR 2014b) found none that included explicit modeling of future risk. However, risk models can be augmented with data representing future conditions (e.g., higher sea level, increased population density, or changing climatic conditions; see box 6.1 for an account of how a set of emissions scenarios—the Representative Concentration Pathways—are used to model future climate). As more input data become available, and as hazard and exposure projection data are developed, assessments are better able to consider evolving risk. Although an increasing number of analyses are using these projection data sets, the current state-of-the-art in modeling of evolving disaster risk still has various limitations. This chapter considers these limitations and discusses some of the key issues and challenges involved in projecting future disaster risk.

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Temperatures soared to 47 degrees Celsius (116 Fahrenheit) in central Pakistan on May 21 and 22, 2004. Photo credit: NASA image courtesy Jacques Descloitres and Ana Pinheiro

Box 6.1 Representative Concentration Pathways

The Representative Concentration Pathways are a set of emissions scenarios, each of which provides a trajectory of greenhouse gas (GHG) emissions and concentrations to 2100 (figure B6.1.1). Four RCPs have been developed from the many emissions scenarios in the published climate literature. The four RCPs are therefore representative of a wider base of emissions scenarios, and they provide a simplified basis from which to model future climate and a way to account for the uncertainty in the future trajectory of emissions. RCPs are used to input initial conditions for ocean-atmosphere climate models and to develop Shared Socioeconomic Pathways (SSPs), which are “reference pathways describing plausible alternative trends in the evolution of society and ecosystems over a century timescale” (O’Neill et al. 2014, 387). The RCPs do not include the impacts of socioeconomic change or climate policies.

RCPs are labeled according to radiative forcing (the balance of incoming and outgoing energy in the earth-atmosphere system) at the year 2100, in watts per square meter (W/m2) (table B6.1.1). The higher the radiative forcing, the greater the climate warming; the warming occurs because there is more incoming solar energy and absorption of energy by GHGs than outgoing reflected energy.

To summarize the assumptions of RCPs: Air pollution controls becomes more stringent, due to rising income levels, causing decline in air-polluting emissions (SO_2, NO_x); GHG concentrations (CO_2, CH_4, N_2O) match the emission trajectories of these GHGs. Thus in all RCPs, radiative forcing continues on its current trajectory until 2025. For RCP8.5, radiative forcing continues to increase at the same rate throughout the 21st century; for RCP2.6, decline in radiative forcing begins at 2030; and for the other RCPs, radiative forcing increases at a slower rate than for RCP8.5.

RCPs provide input to general circulation models, or global climate models (GCMs), which model atmospheric, ocean, or coupled atmosphere-ocean processes. These models simulate fluid motion in the atmosphere and oceans on three-dimensional grids through time in order to simulate the changes in and interactions between various climatic parameters: flow of air and water, surface pressure, temperature, water vapor, and radiation. GCMs produce spatial atmosphere, ocean, and land-surface data, such as monthly mean or time-dependent wind speed, humidity, air pressure, sea-level change, sea ice area/thickness, ocean heat flux, precipitation. These parameters can be incorporated into cyclone or flood models to simulate the effects of future climate on these hazards.

GCMs operate at spatial resolutions in the tens of kilometers, and are unable to resolve features of the atmosphere finer than the model resolution. In order to resolve smaller features, GCMs are downscaled by nesting regional climate models (RCMs) within GCMs (using global variables as boundary conditions) to produce regional estimates of climate and weather. Alternatively, statistical downscaling can be used to relate global variables to regional or local variables. These downscaled regional and local variables are used as inputs to physical models (e.g., hydrological models, crop response models, and drought models) to generate hazard-specific event catalogs under future climate conditions.

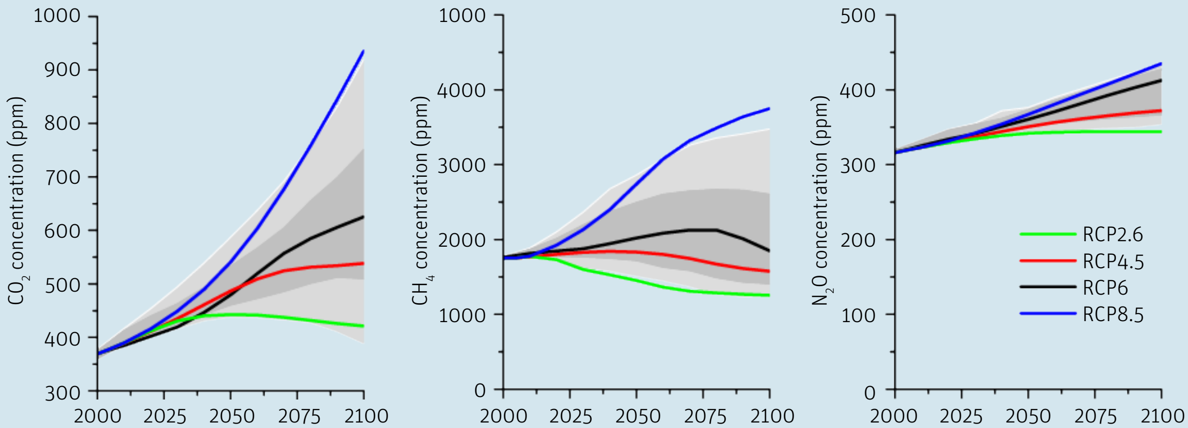
Table B6.1.1 Comparison of RCPs

RCP	Radiative forcing	CO_2 equivalent (ppm)	Temperature anomaly (°C)
RCP8.5	8.5 W/m^2 in 2100	1,370	4.9
RCP6.0	6 W/m^2 post 2100	850	3.0
RCP4.5	4.5 W/m^2 post 2100	650	2.4
RCP2.6	3 W/m^2 before 2100, declining to 2.6 W/m^2 by 2100	490	1.5

Source: Moss et al. 2010, table 1. Note: ppm = parts per million.

Box 6.1 **Continues**

Figure B6.1.1. **Trends in concentrations of greenhouse gases under each RCP. Grey area indicates the 98th and 90th percentiles (light/dark grey) of the recent EMF-22 study (Clarke et al. 2009).**



Source: Van Vuuren et al. 2011.

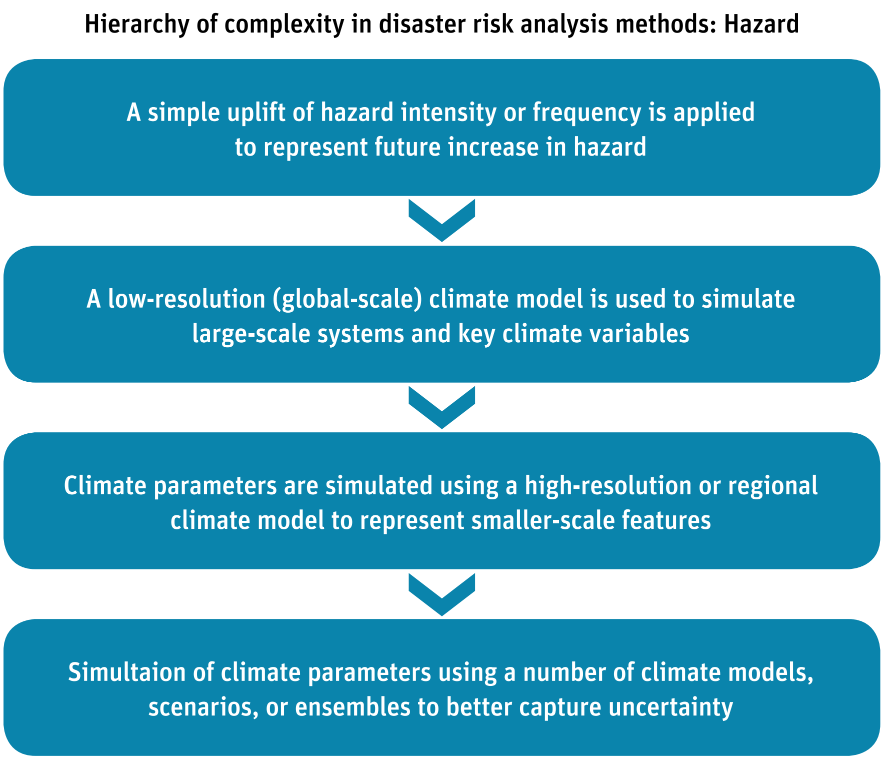
Simple or complex approach

Disaster risk assessments vary greatly in complexity. They can be as simple as producing an order-of-magnitude loss estimate by overlaying exposure on a hazard scenario and assuming a damage ratio for each unit of exposure. Risk assessments can also be based on expert judgment to assess the likelihood of different risk components, or of overall loss. One structured method of collecting expert judgement is the Delphi method (e.g., Elmer et al. 2010), a weighted ranking approach based on expert judgement, which can be employed to rank events or scenarios with a high degree of uncertainty in order to estimate risks in the future. Complexity increases through a range of approaches; the most complex comprise statistical distributions to represent probability of hazard intensity and damage, and they compute uncertainty at each step of the modeling. In these models, the hazard component provides the georeferenced event severity (e.g., maximum wind speed, flow depth, or ground-shaking intensity) and frequency (how often the event is expected to occur) at each modeled location. Georeferenced exposure data provide population, asset characteristics, and value at each location. The vulnerability component relates an event's intensity to its impact based on the statistical relationship between intensity and probability of damage, number of fatalities, or impact on coping capacity and poverty.

Risk assessments can be deterministic or probabilistic. Deterministic modeling uses event scenarios to provide the hazard data. Probabilistic modeling combines many thousands of different events of varying frequency (annual occurrence probability) and severity. The loss from each event in a probabilistic event catalog can be used to establish a loss exceedance probability and average annual loss (AAL), whether in terms of monetary value, population, or asset units (e.g., number of buildings).

Evolving hazard has been quantified in a number of studies investigating the effect of climate change on flood, cyclone, drought, wildfire, and extreme temperatures. The analyses have accounted for climate using various methods (summarized in figure 6.1), including a simple factor to increase frequency or intensity of the hazard (at the less complex end of the spectrum) and simulation of multiple climate scenarios using

Figure 6.1. **Features of the hazard component of models that seek to quantify evolving disaster risk, specifically for climate-related hazards. Complexity of analysis increases from top to bottom.**



Source: Modified from Bouwer 2013, table 1.

a number of regional-scale climate models to provide the range of climate futures (at the more complex end). The benefit of the simple approaches is their relatively low computational cost, which makes them replicable across large areas or for numerous case studies. More complex modeling, while restricted to smaller study areas, is more suited to capturing important details required for planning and implementing risk reduction strategies.

Modeling interrelated and evolving hazards

Current risk assessments generally deal with one hazard at a time, although a few consider multiple factors that influence the hazard, for example flood assessments that include rising sea levels, changing storm intensity, *and* subsidence. A major limitation of disaster risk assessments in general is that too few simulate interrelated—that is, cascading and coincident—hazards (see case study F). Such interrelationships cause compounded risks under present conditions, and they become increasingly important when investigating future risk. The way interrelated risks are likely to evolve together in the future is uncertain (i.e., will they increase linearly or will we observe nonlinear effects?), so risk assessments should strive to account for such interrelationships.

Multiple influences on coastal flood risk

Coastal flood risk is a good example of a risk that is affected by interrelated factors: sea-level rise and cyclone storm surge (which induce flooding from the coast), precipitation (which causes flash flooding or river flooding in the coastal city), and subsidence (which fundamentally changes the topographic influence on flooding patterns). The coastal flood risk assessments described below include multiple factors—and show that the contribution of each factor can be quantified.

Analyzing flood hazard in Jakarta, Budiyono et al. (2015) estimated climate-affected precipitation intensity using 20 combinations of GCMs and RCPs, low and high scenarios of sea-level rise, and a scenario in which subsidence continued to 2025. The omission of subsidence alone would have resulted in a significant underestimation of damage, as this factor contributed an increase in damage of 173 percent—a significant proportion of the total increase of 263 percent by 2030. The different approaches taken to account for precipitation, sea-level rise, and subsidence reflect the different levels of data availability and uncertainty for each of the contributing factors. Sea-level rise is commonly accounted for as a series of scenario-based increases, owing to uncertainty in the rate of future change. In the absence of data on historical rates of subsidence in many cities, Hanson et al. (2011) applied a uniform rise in sea level of 0.5 m between 2005 and

2075 to all cities. They also applied a 10 percent increase in extreme water levels to represent increased storm intensity. In an update of that analysis, Hallegatte et al. (2013) assessed loss for two sea-level rise scenarios (20 cm and 40 cm) and one subsidence scenario (40 cm).

The importance of combining multiple factors in assessment was shown again in a cost-benefit assessment of coastal protection schemes in New York City (Aerts et al. 2014). The authors probabilistically simulated storm surge events under present conditions and under conditions at 2040 and 2080, incorporating adjusted surge probabilities, higher sea levels, and increased urban exposure in flood hazard zones. These analyses were used to estimate the benefits of different proposed defense schemes (that is, the extent to which they avoided costs of surge-induced damage) over a 100-year period. The inclusion of all factors had a significant impact on the results. When only sea-level rise was included, none of the proposed schemes was estimated to be cost-effective (costs avoided did not exceed the cost of implementation), but the schemes became cost-effective in scenarios that combined sea-level rise and increased storm activity and—in the high scenario—rapid ice melt.

Time dependency

Many models assume that hazard events are time-independent of each other and that they form what is called a “Poisson process,” in which the probability of one event occurring is not influenced by the occurrence of any other event. It is well known, however, that geophysical and meteorological hazards can exhibit clustering, with multiple events occurring close together in time and space (see text box 6.2). Time dependency can

Box 6.2 Time-Dependent Hazards

Cyclones can occur in clusters because the large-scale atmospheric conditions suitable for their formation and propagation—e.g., El Niño–Southern Oscillation (ENSO) and other naturally cyclical conditions—can persist for periods of several weeks (not just for the period of one storm). As a result, there may be periods of higher activity in which losses are more substantial than in periods of average activity. For example, in Europe, extratropical cyclone losses were particularly severe in 1990 (four events each caused over US$1.9 billion in losses) and 1999 (three events each caused over US$3 billion in losses).

Earthquake clusters occur in the short term and long term. A short-term cluster is the series of foreshocks, mainshock, and aftershocks that comprises an earthquake sequence. Such sequences may last many months, as occurred in the 2010–2011 earthquake sequence in Canterbury, New Zealand. Long-term clusters are defined by the increased probability of large-magnitude earthquakes occurring on the same plate boundary as a result of increased stress transfer from an earlier earthquake. Time-dependent models of earthquake recurrence are used widely.

River floods are often the result of large-scale weather systems, which may cause intense precipitation over large areas within a short time. In June 2013, for example, nine countries in Central and Eastern Europe were hit by a series of river floods causing over US$15 billion in damages. Jongman et al. (2014) showed that different parts of Europe are interconnected by these large-scale weather systems, and that failing to take into account these effects in continental-level risk assessment may strongly underestimate the risk.

> There is significant uncertainty around regional and local climate change impacts, particularly around changes in frequency and intensity of precipitation and cyclone winds.

influence disaster loss estimates significantly; omitting time dependency can underestimate the frequency of severe events, thereby underestimating not only the losses from each event but also the potential for multiple events to compound impacts that occur in a short space of time. Expectations vary as to how climate change might influence time-dependency in meteorological hazards. In the quantification of evolving risk, it is ever more important to simulate disaster risk with time-dependent hazard; thus the application of additional statistical methods will be required.

Uncertainty in risk assessment

There is uncertainty in all risk assessments, whether they are assessing present risk or projecting future risk. Uncertainty arises in each of the hazard, exposure, and vulnerability components, as the result either of natural variability (aleatory uncertainty) or of limitations in our knowledge and data (epistemic uncertainty).

Hazard uncertainty

Hazard data availability varies between world regions and for different hazards, and in many cases the instrumental or historical record of observations is very short compared to the long-term recurrence of events and cycles of natural variability. For example, meteorological and geophysical monitoring are now typically conducted with excellent geographic coverage in developed countries using well-established and widespread or dense networks of monitoring stations; but in many developing countries, monitoring facilities are much sparser or only recently implemented, providing fewer data points over a shorter time period. Inhospitable conditions and limitations on resources mean that some hazards remain poorly monitored; even now, only a minority of active volcanoes around the globe is monitored, limiting our knowledge on the eruptive history in many regions at risk. Paleoseismic and paleoclimate studies provide data from before the instrumental record in tsunami, seismic, and climate analyses through the analysis of sediment and ice cores that record signatures of previous conditions and events. However, in many cases the accuracy of dating remains uncertain, and interpretation of what certain paleo signatures represent is not straightforward (e.g., tsunami deposits are difficult to distinguish from other high-energy marine events in some sediment cores). Technological capabilities can also limit our knowledge of certain physical processes. For example, if the resolution at which we can monitor and investigate small-scale atmospheric phenomena, such as cloud formation, is low, a degree of uncertainty is introduced into results that rely on that process. As a result, there is significant uncertainty around regional and local climate change impacts, particularly around changes in frequency and intensity of precipitation and cyclone winds. These factors introduce uncertainty into assessment of present-day hazard and, by extension, evolving hazard.

Use of climate projections in disaster risk assessment

There is a high level of uncertainty associated with many of the climate processes that contribute to meteorological hazards, and these are present in models that attempt to represent future climate conditions. Climate conditions are already being influenced by greenhouse gas emissions and the atmospheric concentrations of greenhouse gas. Emissions are driven by many different factors (including technological adaptation and changes in consumption behaviors) in multiple sectors (including energy, agriculture, transport). Given the complex range of influences, each of which is difficult to determine, uncertainty in long-term climate projections is addressed by using emissions and concentrations scenarios as well as ensemble studies that apply multiple models. Exercises that compare the results of multiple models, such as the Coupled Model Intercomparison Project (CMIP5), demonstrate the ability of climate models to reproduce current climate and historical climate trends, provide spatial patterns of atmospheric circulation, and consistently predict a warming climate.

Climate projections are widely used as input to hazard modeling for heat, drought, wind, and flood risk assessments. In particular, drought in its various forms—meteorological, agricultural, hydrological, and socioeconomic—is a complex hazard, driven by the interaction of climatic and socioeconomic factors over different time periods. To simulate these factors, modeling of drought risk under future climatic and socioeconomic conditions requires the use of climate models. Analyses of the evolution of drought risk in the past and the future have been conducted at varying scales. Using four global climate models to drive six regional climate models, Jeong, Sushama, and et al. (2014) generated drought scenarios based on the simulated effects of future temperature and evapotranspiration in North America to 2069. Projected increases of more than 2°C result in increased future risk of long-term and extreme drought in the United States and southern Canada. Risk of short-term and moderate drought is also increased, but to a lesser extent. Hirabayashi et al. (2008) used GCMs to assess low-resolution (1.1 degree) global change in precipitation, evapotranspiration, and mean surface temperature to 2100. The change in number of annual drought days (days when daily discharge was lower than the 10th percentile of all river discharge data from the 20th-century simulation) is projected to increase significantly over North and South America, central and southern Africa, the Middle East, southern Asia, and central and western Australia. Li et al. (2009) used the results of 20 GCMs and six emissions scenarios to assess future impact of drought on crop yield. They estimated an increase in drought-affected land area of 15.4–44.0 percent by 2100, and a yield reduction in major crops of >50 percent in 2050 and 90 percent in 2100.

GCMs are also used to explore potential changes in cyclone frequency. GCMs have been used to project atmospheric parameters that can be downscaled to regional modeling to generate synthetic cyclone track catalogs. As part of the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI), Arthur, Woolf, and Dailey (2014) analyzed present and future tropical cyclone risk for 15 Pacific countries. They applied the most extreme RCP scenario, RCP8.5, in which annual global temperature anomalies reach +4°C by 2100. Using GCM projections of future climate to condition tropical cyclone catalogs, they modeled future cyclone activity for 2050 and 2081–2100. Their analysis found that the only significant change (greater than intermodel standard deviation) in parameters is an eastward shift in cyclone genesis, of 10 degrees longitude. This shift results in an increase in 1-in-250-year loss in most of the studied countries, but the potential total loss for the entire region may in fact decrease, according to two of the five models used. The complex interaction of frequency and intensity means that there are nonlinear effects on losses. In terms of cyclone frequency, they estimate more tropical depressions and tropical storms, fewer cyclones of Category 1–4, and more cyclones of Category 5.

Flood modeling has recently begun to make frequent use of GCMs, specifically to estimate precipitation in future climates as input to hydrological models. Hirabayashi et al. (2013) showed the importance of using a suite of GCMs to determine the direction of future flood frequency in different regions, since any one model may predict an increase or decrease. Arnell and Lloyd-Hughes (2014) also investigated the change in global flood exposure in the 2050s and 2080s compared to 1960–1990, using four RCP scenarios modeled in 19 GCMs. They showed that there is little difference in estimated

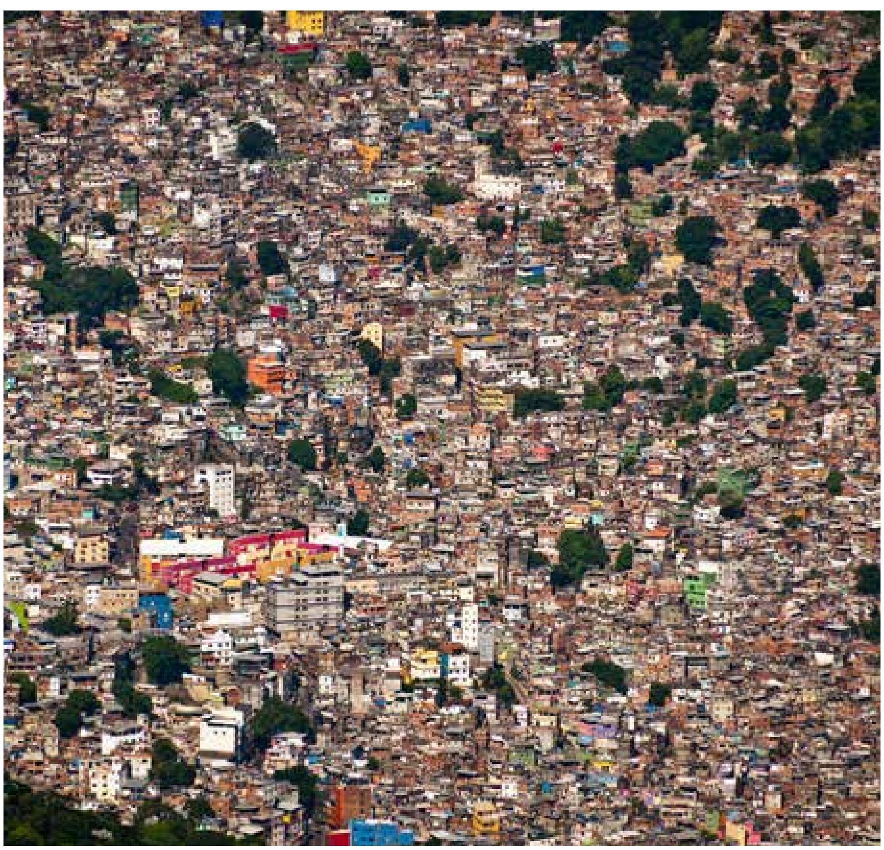
Given the complex range of influences, each of which is difficult to determine, uncertainty in long-term climate projections is addressed by using emissions and concentrations scenarios as well as ensemble studies that apply multiple models.

flood-prone population for RCP2.6, RCP4.5, and RCP6.0 at 2050, and for RCP4.5 and RCP6.0 at 2080. They also showed the considerable uncertainty involved in projecting spatial and seasonal patterns in climate change—globally, between 100 million and 580 million people are expected to experience an increase in flood frequency by 2050; between 80 million and 310 million people are expected to experience a decrease in flood frequency in the same period. One other flood modeling project relevant here is a recent World Bank assessment of current and future flood risk in Europe and Central Asia, which uses the GLOFRIS model in conjunction with multiple climate scenarios and socioeconomic developments (see case study G).

While the evolution of flood risk under future climate conditions is receiving considerable attention, flood risk is also influenced by nonstationary interannual variability and climate cycles, ENSO (Ward et al. 2014; Ward et al. 2013; Ward et al. 2010). With ENSO a significant influence on the intensity of annual floods—indeed affecting flood risk across major parts of the world (Ward et al. 2014)—it is important to develop methods of assessing future flood risk that incorporate this factor.

Uncertainty in exposure data and projections

There is significant uncertainty about current exposure (i.e., people, infrastructure, and assets located in hazard-prone areas), especially in data-scarce areas in low-income countries. Additional uncertainty arises from projecting spatial and temporal changes in exposure into the future. The availability of current exposure data is being addressed through the use of open data and crowd-sourced mapping (see box 6.3), and several spatial data sets now provide global coverage of population and human settlement (see box 6.4), which provide baseline data on present exposure. Exposure data are projected from these baseline data to the current year and future years using growth projections from national data and economic models. The methods used to project data from the past to present day, or from present day into the future, can be a source of uncertainty, as the relationships used may not accurately represent past or future growth in such a complex system of population changes and movement. For example, the majority of current global disaster risk projections have so far relied on the extrapolation of current spatial population density based on national-level population and/or gross domestic product (GDP) growth figures (Hinkel et al. 2014; Jongman, Ward, and Aerts 2012; UNISDR 2011). Such studies therefore assume that the distribution of people and cities will remain stable going forward, an assumption that has a strong effect on the outcomes of any projection, and any risk assessment that incorporates that projection.

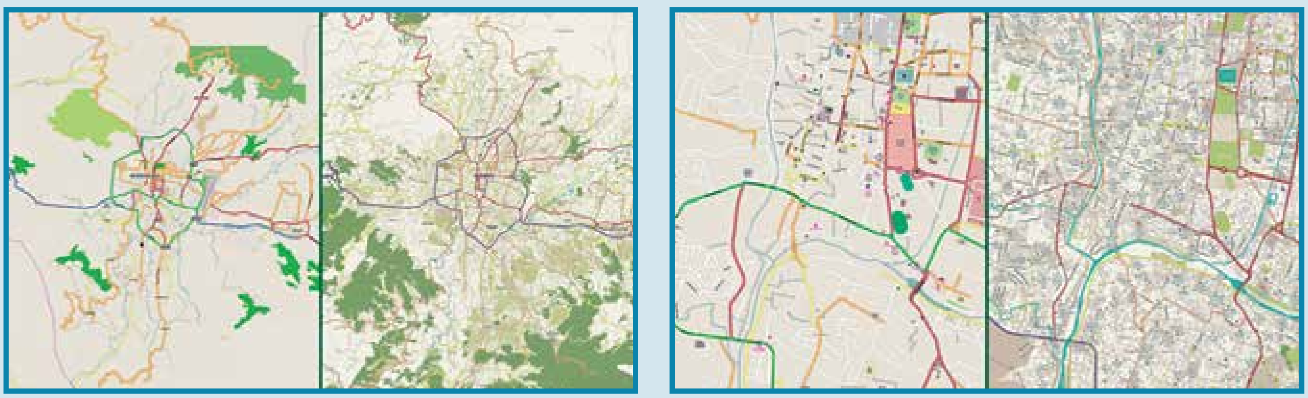


Favela Rocinha, largest in Rio de Janeiro, Brasil. Photo credit: Thinkstock.com

Box 6.3 Open Cities Mapping and Development

Timely collection and sharing of exposure data are vital for generating data that are as accurate and up-to-date as possible. Collecting data in the same area continuously over long periods of time can help to improve the temporal resolution of exposure data and to capture changes in the ongoing development of urban areas. The World Bank/Global Facility for Disaster Reduction and Recovery (GFDRR) Open Data for Resilience Initiative (OpenDRI) uses tools such as **OpenStreetMap** to conduct community mapping initiatives under its **Open Cities** project (http://www.worldbank.org/en/region/sar/publication/planning-open-cities-mapping-project). This type of community mapping makes it possible to update exposure data more frequently. Ultimately, these data can be incorporated in disaster risk assessments and inform projections of exposure for assessing future disaster risk. Case Study H provides insight into the benefits of an OpenDRI project in Malawi.

Figure B6.2.1. Maps of Kathmandu, developed by OpenStreetMap before (left) and after (right) the MW 7.8 2015 Gorkha earthquake in Nepal. The left panes show a view of Kathmandu city, the right panes show greater detail at the building level. These images suggest how substantial increases in mapped information produced by the OSM community can improve maps when the need arises.



Source: © OpenStreetMap contributors (CC BY-SA, https://creativecommons.org/licenses/by-sa/3.0/).

Figure B6.2.2. Maps of Monrovia, Liberia, developed by OpenStreetMap before (left) and after (right) the 2014–2015 Ebola crisis in West Africa. The left panes show a view of Monrovia city, the right panes show greater detail at the building level.

Source: © OpenStreetMap contributors (CC BY-SA, https://creativecommons.org/licenses/by-sa/3.0/).

The Open Cities Project was launched in November 2012 to create open data ecosystems that will facilitate innovative, data-driven urban planning and disaster risk management in South Asian cities. Open Cities represents a scalable approach to developing open, accurate, up-to-date spatial data on the characteristics and location of built and natural environments.

continues

Box 6.3 Continues

Since its start, Open Cities has brought together stakeholders from government, donor agencies, the private sector, universities, and civil society groups to create usable information through community mapping techniques, to build applications and tools that inform decision making, and to develop the networks of trust and social capital necessary for these efforts to become sustainable.

The Open Cities Project launched its efforts in three cities: Batticaloa, Sri Lanka; Dhaka, Bangladesh; and Kathmandu, Nepal. In these cities, the project has led to development of comprehensive and accessible databases of the built environment. For instance, Batticaloa now has a detailed structural database of every building, and Kathmandu has a database of all schools and hospitals that can be used for risk assessment. The Open Cities Project has improved in-country capacity to update, maintain, and use key data sets; it has created innovation spaces (such as the Kathmandu Living Labs), internship opportunities, and university curricula that provide students with employable skills; and it has mainstreamed open data use and strengthened data collection and management processes at different levels of government. The Sri Lanka Survey Department, for example, asked for support to start incorporating crowd-sourcing and community mapping approaches into its regular work flow, and the government of Sri Lanka has sought support for the creation of an Open and Spatial Data Infrastructure.

Another outcome of Open Cities is the adoption of new applications by multiple levels of government and World Bank–financed projects, as well as development of complementary new partnerships and increased collaboration. New partners to implement projects include the U.S. Department of State, the United States Agency for International Development (USAID), the Humanitarian OpenStreetMap Team (HOT), and the American Red Cross.

Producing detailed risk assessments

The end goal of a disaster risk assessment often determines the resolution of modeling that is required. A national-level risk profile used for identifying hot spots on a large scale can be prepared using lower-resolution data than would be required to better assess the impact of mitigation strategies. A range of limitations exists in producing detailed estimates of current and future risk, especially in data-scarce areas. For flood risk, for example, information on the status of flood management (such as flood protection standards and early warning systems) is not yet available globally (Ward et al. 2015), precluding its use in global models. Local coastal flood and river flood assessments have the advantage of including such important information about flood protection on the local scale where these data are available for small study areas, but these studies face other uncertainties. For example, in order to represent evolving risk at a local scale, one needs to translate changes in global climate into analysis of changes in local flood frequency and intensity. To obtain high-resolution estimates of future flood risk, it is necessary to downscale projections of precipitation to the local level and implement those inputs into detailed hydrologic and hydraulic models. Furthermore, given the strong topographic effects on flood depth, improved elevation data are also required at this detailed level.

The availability of high-resolution elevation data is one of the most significant limitations on accurate analyses of flood and sea-level rise, including those that incorporate flood management strategies. The wider availability of high-resolution topography data such as LIDAR has made possible the analysis of coastal flood risk. Figure 6.2 demonstrates the detail that can be obtained from high-resolution data sets such as LIDAR for topographically sensitive analyses, such as analysis of coastal flooding due to sea-level rise. With the recent release of WorldDEM, a new digital elevation model (DEM) product with improved vertical accuracy, the accuracy of coastal (and river) flood modeling is set to improve further.

Because of the effects of local environmental factors and small-scale physical processes, high-resolution modeling is also required to fully define the local effects of temperature extremes. One of the effects of climate change in conditions of extreme heat is a surface moisture feedback, which contributes to amplified heat

Box 6.4 Global Population Data Sets

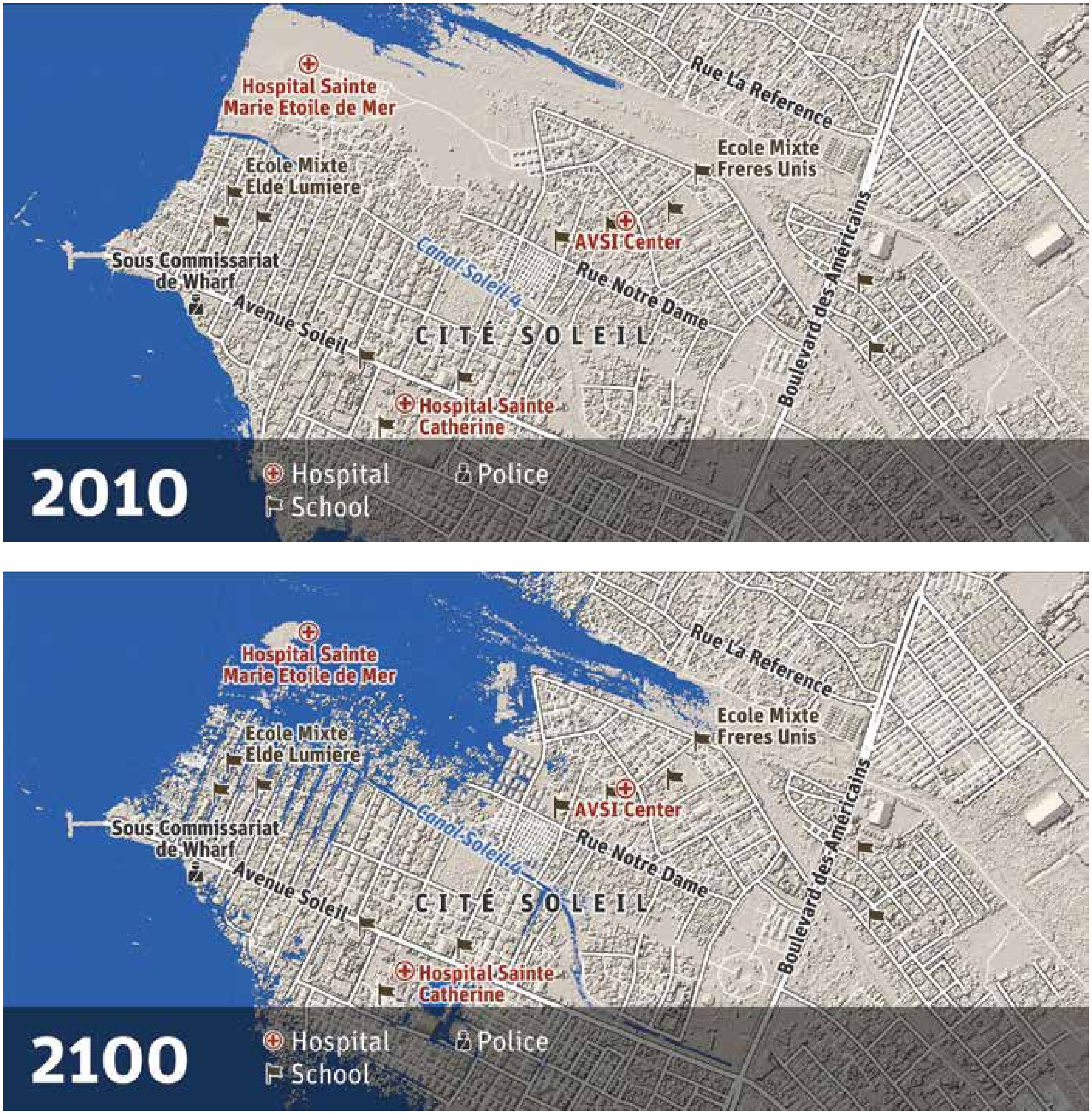
An increasing number of spatial data sets provide estimates of human settlement through absolute population values, population density, characterization of land use, and delineation of urban/rural extents, and they therefore have the potential to be used in disaster risk assessment. These data sets are generally derived from census data and satellite imagery, and vary in available resolution. They can be used as baseline data sets for projecting exposure into the future. Among the most commonly used global data sets are the following:

- **Landscan** (www.ornl.gov/landscan/) offers annually updated global population distribution at a spatial resolution of 30 arc seconds (c. 1 km2 at the equator), generated using census data, administrative boundaries, high-resolution land-use data, and topographic data to identify areas of land unsuitable for habitation or development, and aerial imagery to identify settlement patterns.
- The **Global Rural-Urban Mapping Project** (GRUMP) (http://sedac.ciesin.columbia.edu/data/collection/grump-v1/methods) has generated gridded population at 30 arc seconds resolution for 1990, 1995, and 2000 using census data and satellite data. Urban extents have been derived from NOAA's night-time lights data set, and this project also provides a point data set of all urban areas with populations of > 1,000.
- The **Gridded Population of the World** (GPWv4) (http://www.ciesin.columbia.edu/data/gpw-v4/) provides a 30 arc-second (1 km at the equator) resolution population data set, consisting of population estimates at five-year intervals between 2005 and 2020.
- **WorldPop** (http://www.worldpop.org.uk/) provides freely available gridded population data at 100 m resolution for all low- and middle-income countries. The data are developed using high-resolution land cover, settlement, and census data (Linard, Gilbert, and Tatem 2011; Tatem et al. 2007). This level of detail enables the mapping of rural settlements and provides information on the accessibility of population centers to rural populations.
- The **Global Earthquake Model (GEM) Global Exposure Database** (http://www.globalquakemodel.org/) is an open database of global building stock and population distribution for earthquake vulnerability assessments. It provides multi-scale data (national to per-building scale) derived using multiple sources and homogenized to form a consistent data set (Dell'Acqua, Gamba, and Jaiswal 2012).
- The **Global Human Settlement Layer** (GHSL) (http://ghslsys.jrc.ec.europa.eu/) is the first attempt to produce a high-resolution global data set of human settlement, through automatic image information retrieval of very high-resolution (0.5–10 m) remotely sensed image data input (Pesaresi et al. 2013). In places where no high-resolution imagery is available, the GHSL presents best estimates of human settlements using Landscan population and Modis 500 m urban extent data.
- The **Integrated Model to Assess the Global Environment** (IMAGE) (http://themasites.pbl.nl/models/image/index.php/Welcome_to_IMAGE_3.0_Documentation) provides global downscaled model output data for a wide range of environmental and socioeconomic indicators, including global population and GDP per capita projections. The IMAGE model includes results from the HYDE history database on the global environment (Klein Goldewijk et al. 2011), which contains freely available raster data layers on estimated population, GDP, land use, greenhouse emissions, industrial production, and several agricultural indicators for the period 10,000 BCE–2005 CE.

stress—and such an effect can be captured only in complex, land-atmosphere coupled models that capture evapotranspiration as well as changes in temperature. Moreover, ocean-atmosphere coupling is required to show influence of sea surface temperatures on coastal areas, and fine-scale models are required to simulate onshore/offshore winds, which could affect temperature response to climate change in coastal areas (Diffenbaugh et al. 2007).

Urban centers are susceptible to amplified heat extremes because of waste heat emission from buildings and transport, and because of urban construction materials' thermal properties (McCarthy, Best, and Betts 2010, and McCarthy et al. 2012). Simulation of urban effects involves the representation of urban land cover at a resolution finer

Figure 6.2. **The effect of projected sea-level rise between 2010 (top) and 2100 (bottom) at Cité de Soleil, Port-au-Prince, Haiti.**



Source: World Bank; Imagecat Inc.; RIT Haiti earthquake LIDAR data set (http://opentopo.sdsc.edu/) overlaid with OpenStreetMap data. Sea-level rise scenarios are based on IPCC data in Church et al. (2013).

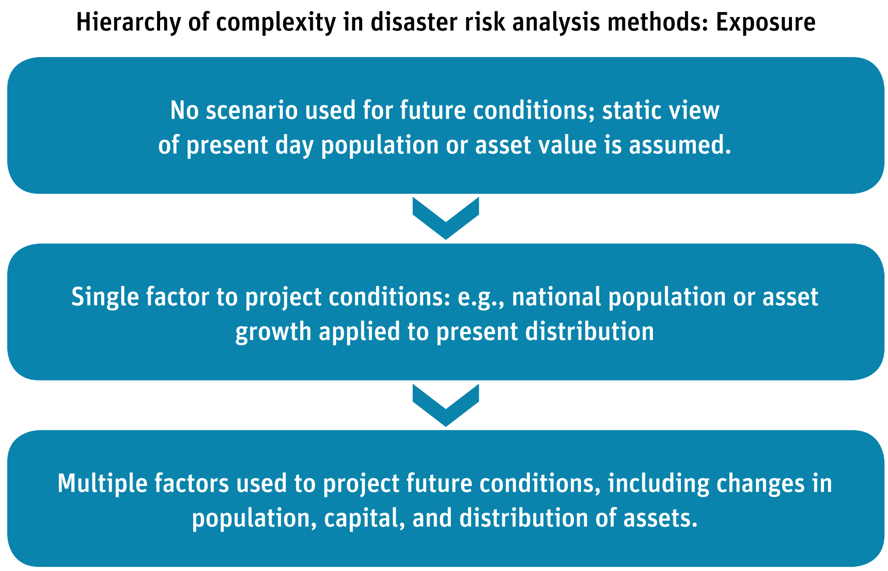
than GCM or RCM grid cells, and thus requires downscaling of GCM results to the urban scale. Without the detailed representation of urban effects, local analyses of heat extremes may result in a lower daily minimum and lower daily maximum temperature than analysis with urban land cover.

Complexities in modeling evolving exposure

Many disaster risk assessments use a static view of exposure: a snapshot of data, taken from the present time or from the point in the past when the data were collected. Recently, however, new methodologies have been developed for representing trends in exposure change, so that both past and future changes in population and economic activity in hazard-prone areas are taken into account, to different levels of complexity (figure 6.3).

A common example of a static exposure assessment is the use of census data or household surveys to establish the population at risk, or use of current estimates of asset value and replacement cost to produce static views of residential or commercial exposure. National censuses are generally carried out on a regular cycle, once every 5 to 10 years, and are more comprehensive than household surveys (though the latter often include data not contained in a census and can be seen as complementary). This temporal resolution, combined with typical delays in publishing census data, means that risk assessments always have an outdated view of

Figure 6.3. Features of the exposure component of models that seek to quantify evolving disaster risk. Complexity of analysis increases from top to bottom.



Source: Modified from Bouwer 2013, table 1.

exposure. At best, a static exposure assessment might use estimated current population and asset values generated by scaling past population and GDP change to the present day. Such assessments present an estimate of potential losses for the current or past situation, but do not incorporate projected risk. The use of a selection of data sets also presents the issue of nonstationarity in the data. This issue arises when two or more data sets of different exposure indicators are created at different points in time and therefore do not represent the same baseline situation. In these cases, projection of combined exposure to the current situation will have begun from different points in time.

Constantly evolving exposure can have particularly important impacts in areas of rapidly expanding population and urban development, or in areas that are particularly susceptible to changes in hazard, such as low-lying coastal areas or Small Island Developing States, which are highly susceptible to rising sea levels. Evolving exposure can be incorporated into existing model frameworks by projecting spatial trends in land use (indicating urbanization), population growth, and economic assets. Whereas detailed projections of exposure change are integrated in local-scale risk assessments and in national risk assessments in a few high-income countries, they are more difficult to include at the global scale or in data-scarce areas.

Using socioeconomic scenarios to project population

The collaborative development of future socioeconomic scenarios (first SRES and later SSPs) has established a common framework for implementing socioeconomic projections in disaster risk assessments. These scenarios are not relevant only to exposure—socioeconomic evolution should also be taken into account in considering how future hazard might be influenced by certain changes in society, such as climate policy or economic activities, which affect future climate conditions. According to the IPPC (Field et al. 2014, 56),

> *Uncertainties about future vulnerability, exposure, and responses of interlinked human and natural systems are large (high confidence). This motivates exploration of a wide range of socioeconomic futures in assessments of risks.*

The IPCC *Special Report on Emissions Scenarios* (Nakicenovic et al. 2000) developed emission scenarios that included socioeconomic evolution as one of several drivers of change in future emissions, along with changing population and land use, economic and social development, and technological development in the agricultural and energy sectors. Four scenario "families" containing 40 scenarios of theoretical futures were developed based on storylines for the future situation in each of the above drivers. These theoretical futures are each associated with future levels of GHG emissions, which are used as inputs to climate modeling.

More recently, the Shared Socioeconomic Pathways were developed as part of the shared scenario framework (along with the RCPs); these are described by O'Neill et al. (2014). The SSPs include a narrative storyline of socioeconomic development, and they quantify development, independent of climate change or climate policy. Implementation of the SSPs and the development of increasingly sophisticated methods for projecting global population, economic activity, *and* urban extent provide new exposure scenarios for incorporation into disaster risk assessments. These scenarios take into account heterogeneous development patterns, based on improved understanding of historical trends in population growth and urban development. The studies described below demonstrate integration of evolving exposure in global-scale flood, cyclone, and drought modeling and reiterate the important influence of evolving exposure on disaster risk losses.

Arnell and Lloyd-Hughes (2014) estimated future population exposed to water scarcity and flood hazard under future climate and socioeconomic conditions. They projected from a baseline of population at 2000, using the GRUMP data set to provide spatial distribution of population. National population was projected to 2050 and 2080 using the five SSPs. Projected population was rescaled to a higher-resolution grid using a single urbanization projection from SRES scenario A1B. The authors acknowledge that the use of a single urbanization projection may affect their estimates of flood-prone populations, as the various growth scenarios in the SSPs may not occur with the same spatial distribution. The impact of population growth and urbanization on flood risk is demonstrated by assuming current climate conditions continue while population increases. The population living in flood-prone areas globally could increase by 33–64 percent by 2050, and by 20–91 percent by 2080 (table 6.1).

In projecting global coastal flood exposure in port cities, Hanson et al. (2011) defined population distribution at 2005 from Landscan data and mapped this to SRTM (NASA's Shuttle Radar Topography Mission) topography data to obtain population at different elevations. Population distribution was projected to 2075 using regional population scenarios from the projected urbanization rate (extrapolated from the 2005–3030 rate) of the Organisation for Economic Co-operation and Development (OECD). The analysis assumed that any new urban areas in each city would have the same proportion of buildings exposed as existing urban areas in that city. GDP growth rate was based on OECD projections of national GDP, with all cities assumed to grow at the national rate. Socioeconomic change was shown to be the most significant driver of population and assets exposed to the 100-year coastal flood hazard.

Jongman, Ward, and Aerts (2012) studied the socioeconomically driven evolution of global river and coastal flood risk between the present day and 2050. They demonstrated the significant increase in exposure in developing countries even without climate change factors. Using World Bank

Table 6.1. Population (millions) in Flood-Prone Areas Resulting from Socioeconomic Change, 2050 and 2080

	SSP1	SSP2	SSP3	SSP4	SSP5
2050	847 (34)	931 (47)	1041 (64)	907 (43)	846 (33)
2080	763 (20)	936 (48)	1213 (91)	931 (47)	768 (21)

Source: Arnell and Lloyd-Hughes (2014).

Note: Population is shown for the five SSPs. Numerals in parentheses show percentage increase in population relative to the year 2000 flood-prone population of 634 million.

population and GDP projections based on baseline data from the HYDE database, the study made projections of global population and assets by projecting current population density and land use. The proportion of urban land use per country was projected in line with population increase. Two methods were used to obtain projected exposure: GDP per capita based on population, and a commonly used depth-damage ratio combined with value of maximum damage per unit area, dependent on land-use type. Like other global risk assessments, this study did not account for detailed data such as flood defenses. Estimated global population exposed to river and coastal flood is expected to increase from 992 million in 2010 to 1.3 billion in 2050, with corresponding assets increasing from US$46 trillion to US$158 trillion. Urban land exposed to floods increases from 44,000 km^2 in 2010 to 72,000 km^2 in 2050, with corresponding damage increasing from US$27 trillion to US$80 trillion in that period.

Projecting urban expansion

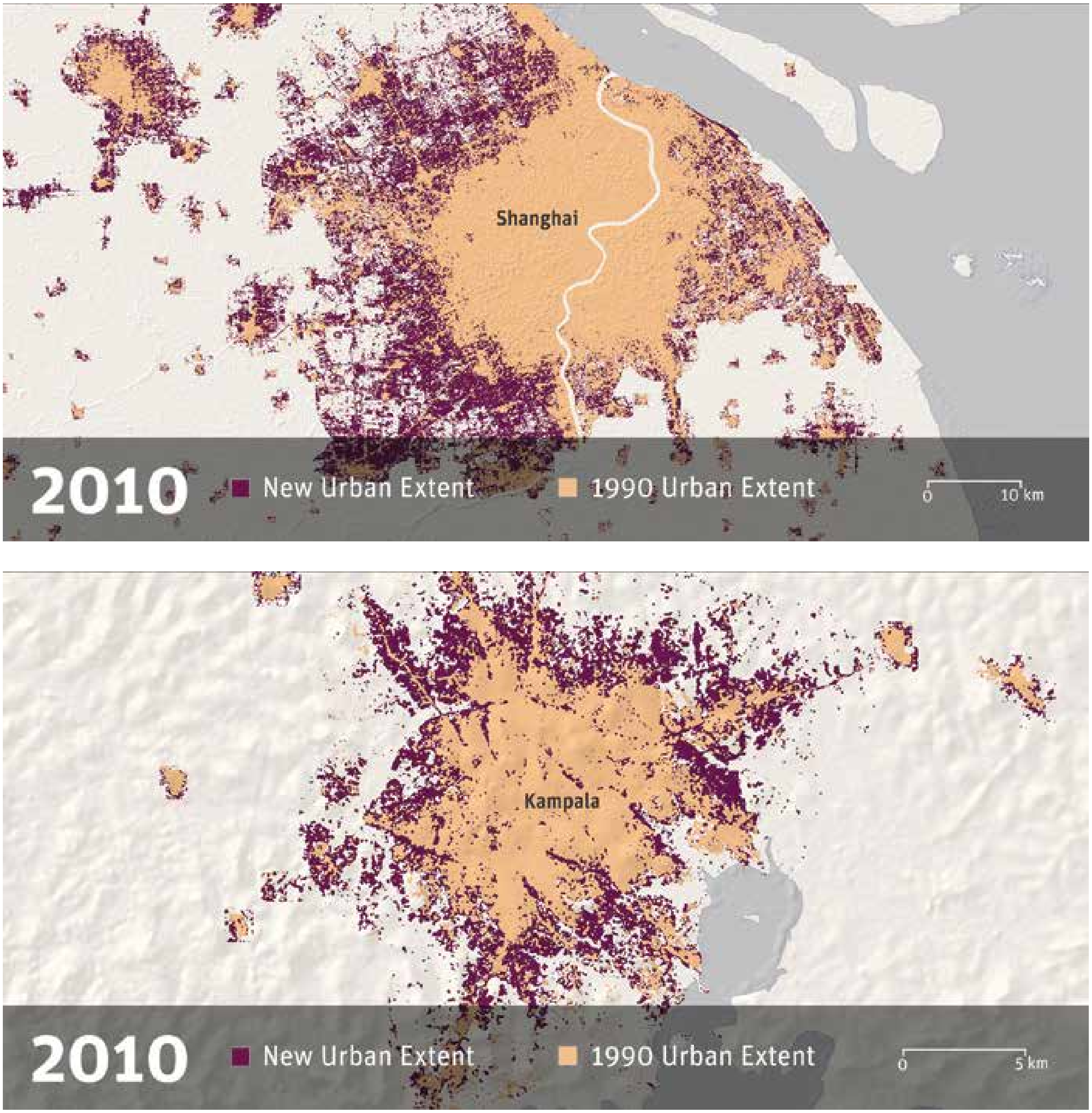
As populations grow and economic activity increases, urban areas extend; the built environment does not remain confined to its present footprint. Different urbanization patterns will influence the locations in which population growth and economic activity occur, and therefore influence the evolution of disaster risk. Thus it is just as important for assessments to include projections of how and where urban development occurs as to include the projected change in population and asset values.

In order to project urban development into the future, past urban development must be characterized. On a global scale and for data-scarce areas, analysis of past and future human settlement has relied on satellite data. Angel et al. (2005) characterized urban area based on 30 m resolution Landsat imagery combined with census data from 1990 and 2000, and highlighted a gradual decline in urban density globally. The Global Urban Footprint, developed by the German Aerospace Center (DLR), used synthetic aperture radar (SAR) and optical satellite data to map the urbanized areas of megacities for 1975, 1990, 2000, and 2010 (Taubenböck et al. 2012). The Earth Observation Data Integration & Fusion Initiative (EDITORIA) of the University of Tokyo produced a Landsat-based global urban area map for five-year intervals between 1990 and 2010; examples are shown in figure 6.4. Satellite-derived night-time light information was used by Ceola, Laio, and Montanari (2014) to analyze changes in human settlement along rivers worldwide between 1992 and 2012.

Concerning the projection of urban expansion, Seto, Güneralp, and Hutyra (2012) demonstrated that the analysis of an historical time series of satellite images can be used to derive regionally specific probabilistic urban expansion patterns; the study goes on to apply these patterns to develop a global data set of urban land cover in 2030. The authors expect that between 2000 and 2030, the area of urban land use in developing countries will triple, while population is expected to double. There is likely to be more urban expansion in the period 2000–2030 than ever before, and—based on probabilistic modeling of population densities and location of new urban land—this expansion will likely be highly variable in magnitude and location within countries. The probabilistic global urban expansion model developed in this study has been applied to estimate trends in global exposure to floods and droughts (Güneralp, Güneralp, and Liu 2015) and used for probabilistic risk assessment on a national scale in Indonesia (Muis et al. 2015).

An ongoing challenge is that global assessments, as well as several studies of developing countries, estimate exposure changes using

Figure 6.4. Expansion of urban land-use from 1990 (orange) to 2010 (purple) in Shanghai, China (top) and Kampala, Uganda (bottom).



Source: World Bank based on analysis by EDITORIA, University of Tokyo, using Landsat data.

relatively low-resolution globally available data (> 1 km x 1 km) on population and land use; more detailed spatial information is not available. In several countries and cities, changing exposure has been mapped at a much higher level of detail, using fine-resolution land-use data or even building-level information (Aerts et al. 2014; Jongman et al. 2014). Box 6.5 describes an approach to urban expansion at the city level that is based on historical trends provided in the Atlas of Urban Expansion (Angel et al. 2013). The Atlas of Urban Expansion provides measures of population growth, annual expansion of the urban area, fragmentation, compactness, and annual change in population density along with maps and spatial data for urban land-use expansion between around 1990 and 2000 for 120 cities globally, and between 1800 and 2000 at 25-year intervals (for 30 cities). Metrics are provided for the study city, the regional average, and the global average.

Box 6.5 describes a method that uses past urbanization trends to characterize relationships between urban features, which are then used to project expansion forward. This methods avoids basic extrapolation of past growth trends, which are valid for short time horizons of 20–30 years, but not for longer time horizons (Masson et al. 2014). Modeling of urban development on longer time horizons benefits from economic models that include behavior of residents and developers as well as construction and rental markets.

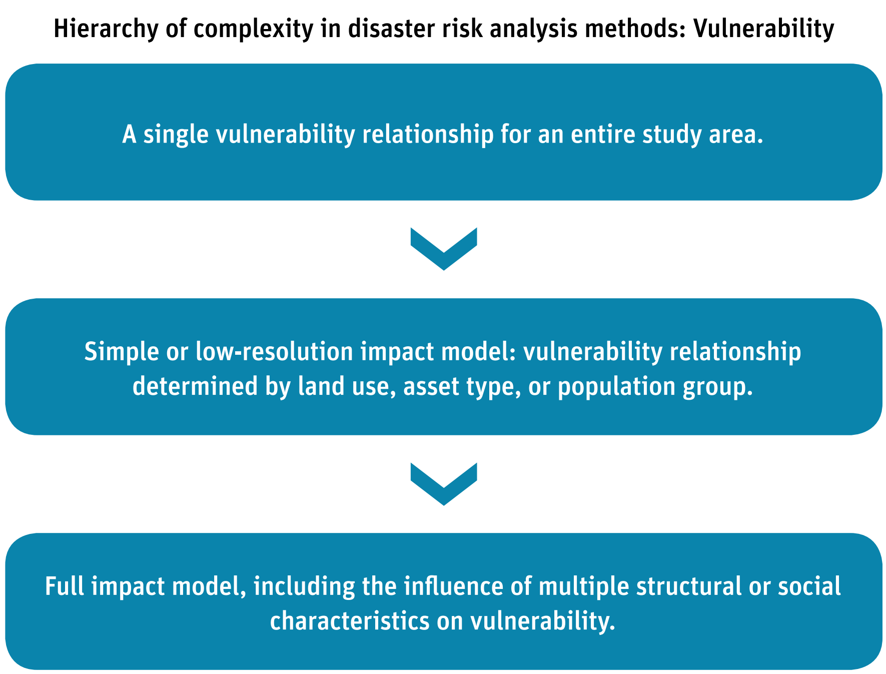
Evolving vulnerability: An ongoing challenge

Compared to hazard and exposure, vulnerability has, to date, been quantified to a very limited extent in the context of evolving risk. Global changes in vulnerability and their effects on disaster risk therefore remain highly uncertain. Some methodologies have been developed that project social vulnerability in terms of socioeconomic conditions and structural vulnerability based on development of the building stock (figure 6.5), but these approaches have been implemented in a few cases only.

Since vulnerability is influenced by a wide range of factors, it is a complex task to estimate how vulnerability might evolve over time and to incorporate changing vulnerability into disaster risk assessments. This remains a major challenge to quantifying evolving risk, but it is being tackled by an increasing number of studies.

Changes in vulnerability are linked closely to socioeconomic scenarios and policy decisions. Communities can decrease vulnerability by raising hazard awareness, developing appropriate responses to hazards (e.g., evacuation planning and exercises), implementing warnings systems, constructing properties in a hazard-resistant way, and promoting household/institutional preparedness. A country's levels of income and development have a strong relation with the level of

Figure 6.5. Features of the vulnerability component of models that seek to quantify evolving disaster risk. Complexity of analysis increases from top to bottom.



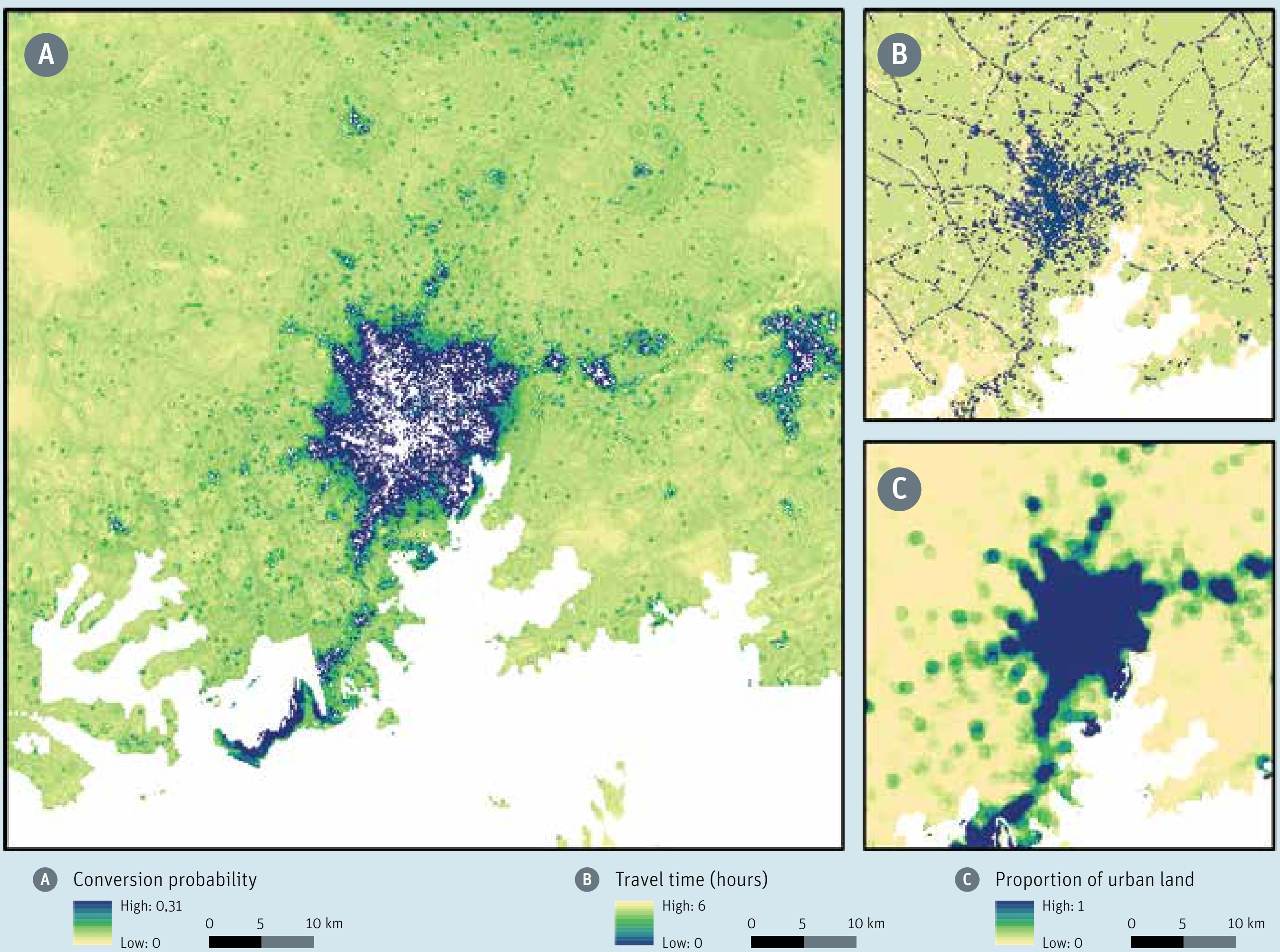
Source: Modified from Bouwer 2013, table 1.

Box 6.5 Spatial Patterns of Urban Growth in Africa

Urbanization has profound social, environmental, and epidemiological implications. Spatial and quantitative estimations of urban change and population density are valuable information for vulnerability assessment. A model has been developed to predict the spatial pattern of urban growth in African cities to 2020 and 2030, based on the observed growth of 20 large African cities between 1990 and 2000 (Angel et al. 2013).

The model combined a parsimonious set of generalizable factors that influence spatial patterns of urban growth: slope angle derived from a digital elevation model; accessibility represented by travel time to the central business district along the transport network; and neighborhood indexes such as the proportion of urbanized land within a given buffer distance (150 m, 1 km, and 5 km). Boosted regression trees (BRTs) were developed using classification of Landsat images into urban and nonurban pixels (30 m resolution) between 1990 and 2000 for 20 African cities as training data. The BRT model was then used to generate predictions of the rural to urban conversion probability for every 100 m pixel in the study cities (figure B6.5.1A) and predict their urban growth pattern (figure B6.5.2).

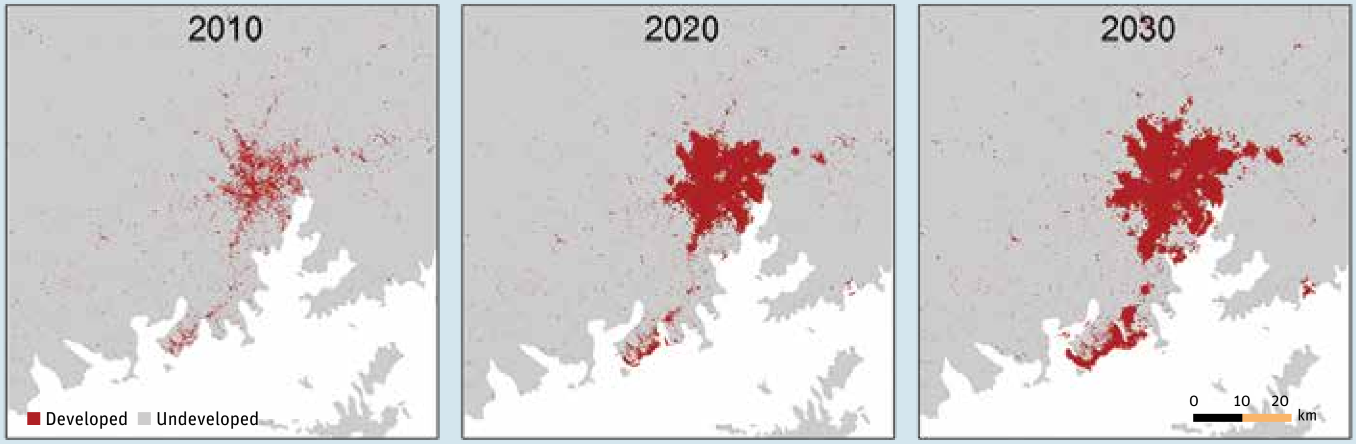
Figure B6.5.1. Rural to urban conversion probability of 100 m pixels in Kampala, Uganda (A) and the two main urban expansion predictors: travel time to central business district (B) and proportion of urban land within 1 km (C).



Source: Catherine Linard.

Box 6.5 Continued

Figure B6.5.2. Predicted urban extents in Kampala, Uganda, in 2010, 2020, and 2030.



Source: Linard et al. 2014.

Results showed that accessibility (figure B6.5.1B) and proportion of urban land within 1 km (figure B6.5.1C) were the most influential predictors of urban expansion. BRT models were found to have greater predictive power than a simple distance-based model (i.e., a model in which the rural to urban conversion probability is proportional to the distance from the nearest urban pixel, resulting in spatially uniform urban growth). Predictive power was low overall, however. The model predicted spatial growth well for small, rapidly growing cities, but it performed less well for large, slowly expanding cities—i.e., cities in later phases of urbanization. It is difficult to adequately capture all spatial heterogeneities of cities and temporal influences on development in a statistical model, and further models need to be developed to account for urban growth patterns in their different phases.

The simple and generalizable model developed in this work is now being used to produce the most detailed Africa-wide urban expansion predictions that have yet been made, and it will provide realistic scenarios of urban growth to 2020 and 2030. Future work will use a version of the model presented here to simulate the urban expansion of every large African city to 2020 and 2030 and to produce projected population distribution data sets under a range of growth scenarios following AfriPop/WorldPop methods (Linard et al. 2012; www.worldpop.org.uk).

Source: Catherine Linard, Université Libre de Bruxelles.

vulnerability to disasters, as has been emphasized in a number of statistical analyses. Toya and Skidmore (2007) analyzed the relationship between disaster impacts (mortality, losses as a share of GDP), GDP, education, and the level of government for 151 countries. They found evidence that countries with a high GDP and high levels of education and government have significantly lower disaster impacts. This relationship between disaster impacts on the one hand and income and governmental strength on the other was later reestablished for overall disaster impacts (Felbermayr and Gröschl 2014), and specifically for floods (Ferreira, Hamilton, and Vincent 2011) and tropical cyclones (Bakkensen 2013).

Jongman et al. (2015) analyzed the differences in vulnerability between countries as well as changes over time. Using high-resolution global flood inundation and exposure maps, they showed that vulnerability to global flood declined between 1980 and 2010, in terms of mortality and losses as a share of the population and GDP exposed to inundation. This decline coincided with rising per capita income globally and converging levels of vulnerability in low- and high-income countries (a function of declining vulnerability in developing countries). Projections of future losses and fatalities were made using a combination of climate models, emission scenarios, socioeconomic pathways, and adaptation scenarios. Assuming that vulnerability levels in low-income countries decline as their income converges to the income level of high-income countries, these projections show a possible strong reduction in future global vulnerability. However, if the effective adaptation that contributes to lessening vulnerability in low-income countries does not happen, future losses and fatalities could increase very steeply. The authors conclude that reducing vulnerability could counteract a large part of the increase in exposure and hazard under socioeconomic growth and climate change.

Hallegatte (2012) argues for caution in making assumptions about converging vulnerability levels in high-income and low-income countries as income rises in the latter. He considers it questionable that Bangladesh would have the same level of vulnerability as Sweden in case these two countries reached the same level of income at some point in the future, and argues that other factors such as geography may also affect the relationship between income and losses. In terms of structural vulnerability, Lallemant, Wong, and Kiremidjian (2014) demonstrated a potential framework for evolution of exposure and vulnerability using simulations of 2,500 equally likely scenarios of an historical earthquake in Kathmandu, Nepal. Exposure was projected to 2015, 2020, and 2025 on the basis of a quadratic fit of census data (1991, 2001, 2011). To account for evolution of vulnerability, the study applied three examples of structural expansion typical of the case study area to represent

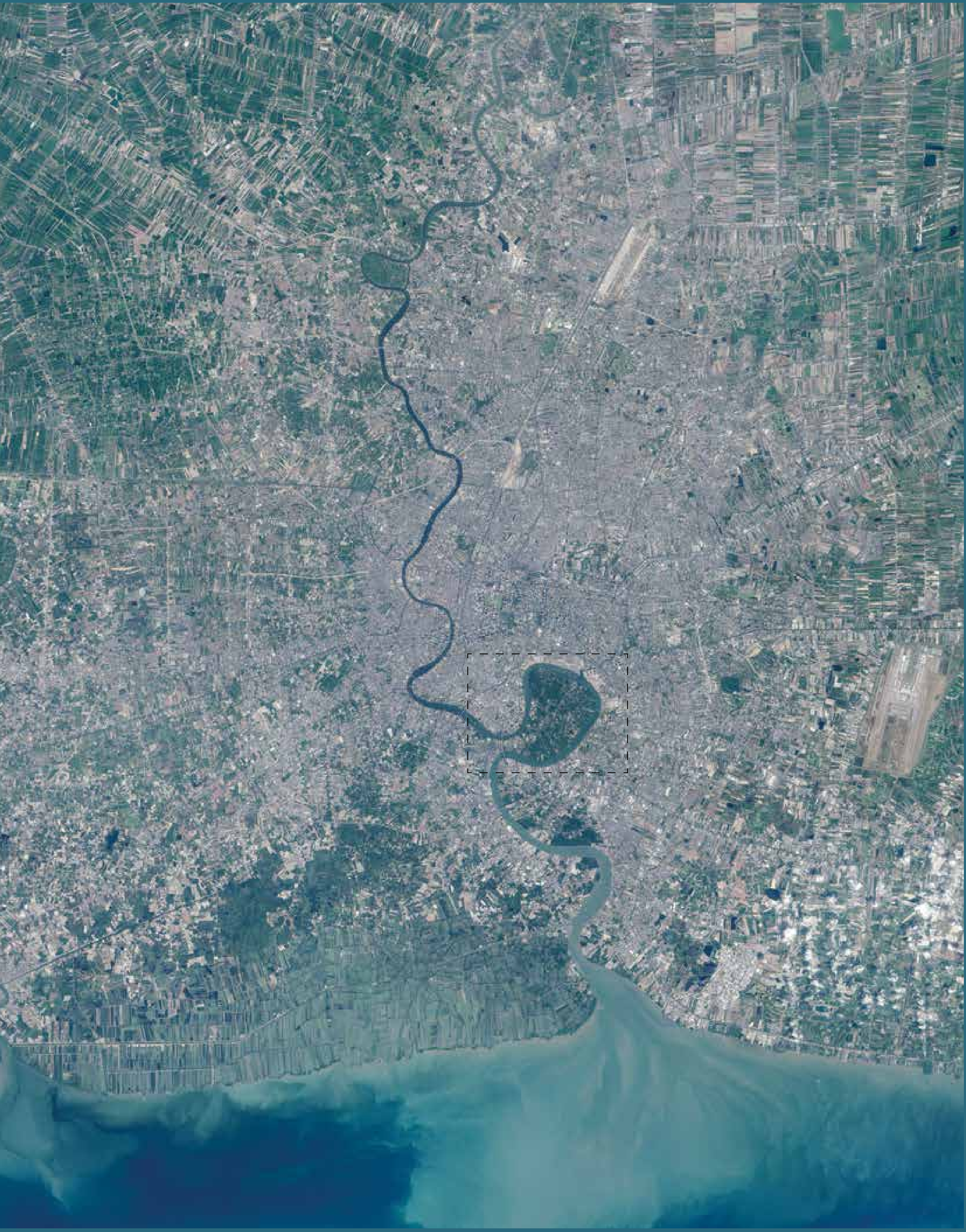
Varanasi, India, flash flood. Photo credit: Danielrao/Thinkstock.com incremental construction over time. With each expansion of the structure, the vulnerability curve changed to relfect the new vulnerablity. The projected changes in exposure and vulnerability were shown to increase risk significantly. This framework is extended into a more detailed analysis of the evolution of structural vulnerability in case study E.

Hinkel et al. (2014) investigated the influence of dike protection on projected vulnerability to coastal flood damage under scenarios of sea-level rise and socioeconomic changes using the RCPs and SSPs. Two scenarios of adaptation were applied: dikes are maintained at their present height into the future; and dikes are raised as the demand for safety increases with growing affluence and increasing population density. The analysis showed that the number of people flooded each year rises significantly with each degree of global temperature increase if dikes are maintained at their present height (for all RCPs and SSPs). If dike height is raised, the number of people flooded would decrease relative to the present day. Expected annual flood cost would rise with increasing global temperature, but would rise by a much smaller amount if dike heights are raised rather than maintained at current heights. With raised dike heights, the global annual cost of adaptation plus the annual flood cost are much lower than the annual cost if dike heights are maintained at the present height.

Hallegatte et al. (2013) used estimates of capital production per person to estimate AAL due to coastal flood. They also included the effects of evolving vulnerability on annual flood loss by implementing two scenarios of flood protection and assumptions about levels of adaption in the future. Their analysis showed that socioeconomic change led to an increase in annual global flood loss in the 136 coastal cities, from US$6 billion to US$50 billion in 2050; when the additional effects of climate change and subsidence are included, the annual global loss in 2050 is over US$1 trillion. Under an adaptation scenario assuming that flood protection will be increased in height to maintain the probability of flooding at present levels, estimated losses by 2050 are limited to US$60 billion to US$63 billion. The authors therefore argue that a future protection strategy that reduces annual flood probability is required to avoid an increase in risk. Muis et al. (2015) also emphasize the importance of flood protection in a national-level study of coastal and river floods in Indonesia, where they find that increasing flood protection to a 1-in-100-year standard could prevent 93 percent of all flood losses.

With respect to changing social vulnerability, several multifactor indexes have been developed to quantify this on a local to national level, specifically for the United States (Cutter, Boruff, and Shirley 2003), the Netherlands (Koks et al. 2015), and China (Zhou et al. 2014). To determine spatial and temporal patterns in social vulnerability, the U.S. social vulnerability index was applied to county-level data from the four decades 1960–2000 (Cutter and Finch 2008). The majority (85 percent) of counties showed no statistically significant change in vulnerability over the four decades; only 2 percent showed a statistically significant and clear increase or decrease in vulnerability. Cutter and Finch (2008) used the baseline data to project vulnerability forward to 2010, based on linear trends in county-level vulnerability. While this is a simple approach, based on relatively few (four) data points, it demonstrates a possible method for producing projections of social vulnerability into the future for incorporation into disaster risk assessment.

Compared to hazard and exposure, vulnerability has, to date, been quantified to a very limited extent in the context of evolving risk. Global changes in vulnerability and their effects on disaster risk therefore remain highly uncertain.



Identifying Effective Policies for a Resilient Future 7

The preceding chapters have shown that currently available disaster risk assessment methodologies can provide detailed insights into past, current, and future disaster risk. Existing models and data are able to incorporate the evolution of hazard from the simulation of climate change scenarios in global- and regional-scale climate models; they can incorporate the evolution of exposure through the projection of population growth and socioeconomic change, and the resulting patterns of urbanization and urban expansion. Models have incorporated evolving vulnerability to a lesser extent, but methods to project future levels of adaptation and structural vulnerability are being developed and applied.

Methods to project future levels of adaptation and structural vulnerability are being developed and applied.

Increases in disaster risk can be limited by a number of disaster risk management (DRM) policy tools and strategies related to data improvements, risk analysis methods, planning and development, and design of mitigation and adaptation programs. There are also policies that spread the financial consequences of disasters when they do occur. From the wide range of DRM tools available, this chapter selects and describes several key interventions that can either improve risk assessment or directly inform policy decisions.

FACING PAGE

Bang Kachao: Bangkok's Green Lung. In the heart of Thailand's most populous city, an oasis stands out from the urban landscape like a great "green lung." That's the nickname given to Bang Kachao—a lush protected area that has escaped the dense development seen elsewhere in Bangkok. Photo credit: NASA, acquired February 2, 2014

Mitigate climate change

Mitigating emissions to limit the continued increase in global temperatures that is expected in the next decades is key to mitigating disaster risk (manifested as changes in the rate of sea-level rise and the intensity, frequency, and spatial distribution of cyclone, flooding, and drought). There is a wide body of literature on the mitigation of climate change and the strategies that decision makers can use to reduce emissions, such as implementing new technologies and changing consumption behaviors through taxation and regulation. Mitigation policies can operate at the national economy level and within specific sectors (IPCC 2014; OECD 2008). For example, the energy sector could move from investment in extraction of fossil fuels to investment in renewables, nuclear energy, and carbon capture and storage technologies. In agriculture and forestry, conservation and management of land and food resources could decrease deforestation and maximize supply from agricultural land while reducing emissions (FAO 2013). The Infrastructure and settlement planning sector should also incorporate climate action plans at the urban scale to ensure energy and transport infrastructure are effective in providing required services with least environmental cost. This sector is considered particularly important in rapidly urbanizing areas, which are in the process of developing new infrastructure systems.

Manage urbanization

Limit harmful land-use change and resource consumption

Land-use changes related to urbanization—deforestation, more extensive impermeable surfaces, increased groundwater extraction—have an important impact on disaster risk. Deforestation and impermeable surfaces lead to faster run-off of precipitation and increased surface flood hazard; groundwater extraction leads to subsidence in coastal cities; and new human settlements in hazard-prone areas put more and more people at risk. Even changes in the use of existing developments can change disaster risk, for example by increasing a building's capacity or its vulnerability. Too often, planning decisions are made without considering the implications for local hazard. Changes in upper river catchments that increase the speed of water flow into swollen rivers, for example, may reduce flood hazard in the upper catchment, but they increase the hazard downstream. Thus catchment-level analyses are often required to investigate changes in the disaster risk of the whole catchment.

The impacts of increased urban expansion must be considered and accounted for in effective urban planning and resource management. These impacts include subsidence, which is a very important factor in relative sea-level change, as well as expansion of impermeable surfaces and land-use changes that alter the risk environment. Effective planning must also avoid making structures and communities more susceptible to loss from some hazards (e.g., extreme temperatures) while focusing on reducing vulnerability to other hazards (e.g., earthquake).

In large established cities such as Bangkok and Tokyo, policies to restrict groundwater extraction have been shown to effectively reduce the rate of subsidence and restore groundwater levels (case study C). Where high rates of subsidence have been identified, restrictions can be applied in conjunction with artificial recharge of aquifers and development of alternative supply solutions. Planners and policy makers in rapidly growing urban centers have the opportunity to address the potential for subsidence before it becomes an issue by establishing good management of water resources as part of integrated urban floodwater and pollution management plans; this approach will ensure a sustainable water supply without incurring the detrimental effects of subsidence.

Control increases in exposure

Exposure change is shown to be responsible for the majority of increase in disaster risk. In Indonesia, for example, urbanization is estimated to lead to at least a doubling of flood risk between 2010 and 2030, regardless of the uncertain effects of climate change (Muis et al. 2015). Where there is rapid urbanization and migration, risk evolves most rapidly in response to changes in exposure and vulnerability. Land-use planning policies that incorporate risk are important to controlling

Box 7.1 Land-Use Planning

Land-use planning is the primary tool for controlling exposure to hazards. Land-use planning tools can be used to prevent new development in hazardous areas, relocate assets to less hazardous locations ("managed retreat"), or restrict the types of land use that can be permitted in hazard zones. The absence of urban planning in many areas of the world, particularly in developing countries, has led to uncontrolled development in hazardous areas (such as on landslide-prone hillsides) and to rapid development into areas of high flood hazard (such as Jakarta, Manila, and Bangkok). Where unplanned or poorly planned development occurs in hazardous areas, exposure and vulnerability increase significantly.

Policies and regulations can undoubtedly be designed to limit exposure in hazard-prone areas. It is the enforcement of such policies that remains a big challenge. In many high-income countries it can be difficult, even with regulation effective by law, to prevent increasing exposure, either due to development or land-use changes, see Case Study I. In many low-income countries, the enforcement is even more limited, not only because governmental capabilities for enforcement are weak but because the areas themselves tend to be attractive in terms of jobs and services (Hallegatte et al. 2015).

In a national-level analysis of flood risk and adaptation options in Indonesia, Muis et al. (2015) show that land-use planning can be a key policy tool for reducing flood risk in rapidly urbanizing countries. The authors show that if no new cities were constructed in Indonesia's flood prone-areas between 2010 and 2030, annual expected losses from river and coastal floods would be 50–80 percent lower by the end of that time period than if cities were built. Without such limits on urban construction, it is estimated that flood risk may increase by as much as 166 percent (river floods) and 445 percent (coastal floods) over the three decades due to urbanization alone, with additional increases expected as a result of climate change and economic growth.

the evolution of disaster risk, primarily by providing a mechanism to prevent new development or detrimental change of use in hazard-prone areas (see box 7.1). For example, land-use planning policies can help to ensure that vulnerable or high-value assets and heavily occupied buildings (e.g., business or residential) are not located on hazard-prone land, and can seek to reduce exposure by placing low-density usage activities (agriculture, parks and recreational land) in those areas. Plans for designing structures and locating assets should also consider multiple interrelated hazards and should account for the impact of structures (e.g., impermeable surfaces) on the local environment. Building design should also aim for habitability in future climates as well as in the present climate.

Reduce vulnerability through urban design

Climate extremes pose serious health, safety, and financial risks to cities, where people and socioeconomic activity cluster together. Urban design can incorporate green infrastructure—eco-roofs, green spaces (parks and wetlands), and tree planting—to manage storm water and flooding and reduce ambient temperatures and the urban heat island effect. Green infrastructure, which moderates expected increases in extreme precipitation or temperature by its infiltration, shading, and evaporative capacities, has been cited as having multiple benefits in climate adaptation (Derkzen, van Teeffelen, and Verburg 2015b; Foster, Lowe, and Winkelman 2011). Trees planted in urban areas can contribute to carbon sequestration. In coastal areas, green infrastructure can also be used to combat effects of rising sea levels (see the section below on ecosystem-based risk management).

As cities generally suffer from a lack of space, the implementation and design of green infrastructure needs to be well thought out. First of all, there is no single recipe for reducing vulnerability through urban design: adaptation measures need to be tailored to the local context. A neighborhood-specific rather than a citywide approach is preferable because it can account for the biophysical and sociodemographic differences that exist within cities (Derkzen, van Teeffelen, and Verburg 2015b). Neighborhoods that are most vulnerable from a biophysical perspective may not necessarily benefit from or wish to implement the most effective adaptation measures. The importance of recognizing residents' needs and preferences leads to a second consideration in designing green infrastructure for risk reduction: informed decision making. For a legitimate implementation of adaptation measures, city planners need public support. Derkzen, van Teeffelen, and Verburg (2015a) suggest several ways to enhance public support, ranging from the promotion of popular green infrastructure benefits such as pollution control, to the prioritization of preferred measures on different scales, e.g., eco-roofs and gardens, small neighborhood parks, and canals along main roads. Green infrastructure designs should always incorporate recreational and aesthetic functions. Finally, it is essential to invest in raising public awareness—not only about climate change impacts, but also about the role of green infrastructure in limiting these impacts.

Even in countries with well-developed planning policies, the extent to which disaster risk is integrated into policy varies widely. Furthermore, planning policies are not always well enforced, and multi-hazard contexts may not be properly considered (see case study I). Existing well-known hazards, moreover, may be ignored in contemporary planning decisions. Some urban development of Christchurch, New Zealand, went ahead in recent decades without ground remediation, despite official knowledge of the liquefaction hazard; the result was significant liquefaction damage to several suburbs in the 2010–2011 earthquake sequence.

Land-use planning decisions related to hazards that can evolve in future climates must take future conditions into consideration. This requirement is exemplified by land-use restrictions within riverine or coastal flood hazard zones. Rising sea levels and more extreme precipitation should be accounted for in development being planned or approved now; this step will ensure that structures built today—and considered not at risk of flooding—continue to be found not at risk in several decades.

In the aftermath of a disaster, there is often a window of opportunity when decision makers can increase resilience to future events through land-use planning, specifically by relocating assets or critical infrastructure out of hazard zones. For example, reconstruction plans for Tohoku, Japan, relocate residential buildings, schools, and hospitals out of the tsunami hazard zone, to be replaced with low-density activities (such as light industry), with activities that need to be at the coast, or with open space that could be sacrificed with minimal economic and life loss in future events. Similarly, reconstruction in Christchurch, New Zealand, is reserving large areas of the city for use as green space due to the high liquefaction hazard.

Manage risk through construction

The construction of buildings, infrastructure, and urban developments should consider how design, construction practices, and construction materials will affect disaster risk in both current and future climates.

Building practices

Controlling building practices through legislation or nonstatutory means influences the evolution of vulnerability into the future. One approach to limiting vulnerability is regulating the type and design of buildings that can be constructed, based on the hazards likely to be faced by those buildings in their lifetime (see box 7.2).

Several key considerations can help to reduce vulnerability. The first is whether adopting building practices from a different region and using nontraditional approaches is appropriate in the context of disaster risk. Builders should consider, for example, what happens when stone walls and heavy tiled roofs are used in areas of high seismic hazard instead of the traditional timber frame construction that is less susceptible to collapse due to ground shaking. The second is the need for structural design and construction to consider all hazards present, since efforts to reduce vulnerability to one hazard can potentially increase vulnerability to another. Both of these considerations are part of good practice in any region. A third consideration is the need to account for evolving hazard in order to address expected climate extremes and new hazards that may affect the location in the future.

Resilience in construction is another important consideration. Some

Box 7.2 Reducing Building Vulnerability through Construction Legislation

Christchurch, New Zealand. Photo credit: Nigel Spiers | Dreamstime.com

The vulnerability of building stock can be reduced by adhering to building design and construction standards that consider the forces imparted during events like earthquakes and floods. The history of building standards in New Zealand, and the occurrence of the 2010–2011 Canterbury earthquake sequence, demonstrate the important influence that building codes can have. There were estimated to be 3,750 unreinforced masonry (URM; generally stone or clay brick) buildings in New Zealand in 2010 (Russell and Ingham 2010), the majority of which had been constructed prior to 1940. Construction in URM was regionally variable, driven by availability of other building material or occurrence of earthquakes. URM buildings are stiff, heavy, and brittle structures that are likely to suffer damage during ground shaking. Specific structural characteristics (e.g., height and configuration) affect the seismic resistance of different buildings within the general URM category, but overall these building are less seismically resistant than other construction types. They have little capacity to deform once the strength of their elements has been exceeded, leading to abrupt failure.

In 1931, a magnitude 7.8 earthquake destroyed many URM buildings in the city of Napier in Hawke's Bay, New Zealand. Subsequently, construction of URM buildings was discouraged and then finally prohibited by legislation. In 1935 a building standard was created that required buildings in New Zealand to withstand horizontal acceleration of 0.1 g, and that recommended reinforced concrete or steel frame for construction of public buildings (New Zealand Standards Institute 1935). In 1965, New Zealand standards prohibited the use of URM to various extents, depending on the seismic zone: entirely in zones of highest seismic risk; for buildings of more than one story in zones of moderate seismic risk; and for buildings of more than two stories in zones of low seismic risk (New Zealand Standards Institute 1965). In 1976, a more advanced loadings code explicitly prohibited the use of URM throughout the whole of New Zealand (Standards Association of New Zealand 1976; Russell and Ingham 2010).

While the New Zealand legislation applied to new buildings, from 1968 the government had powers to classify existing buildings as "earthquake prone" and require owners to reduce or remove the danger (Russell and Ingham 2010). Many earthquake-prone buildings were strengthened between 1968 and 2003. When the new Building Act came into force in 2004, strengthening of earthquake-prone buildings was required to achieve one-third or two-thirds of the new building standard.

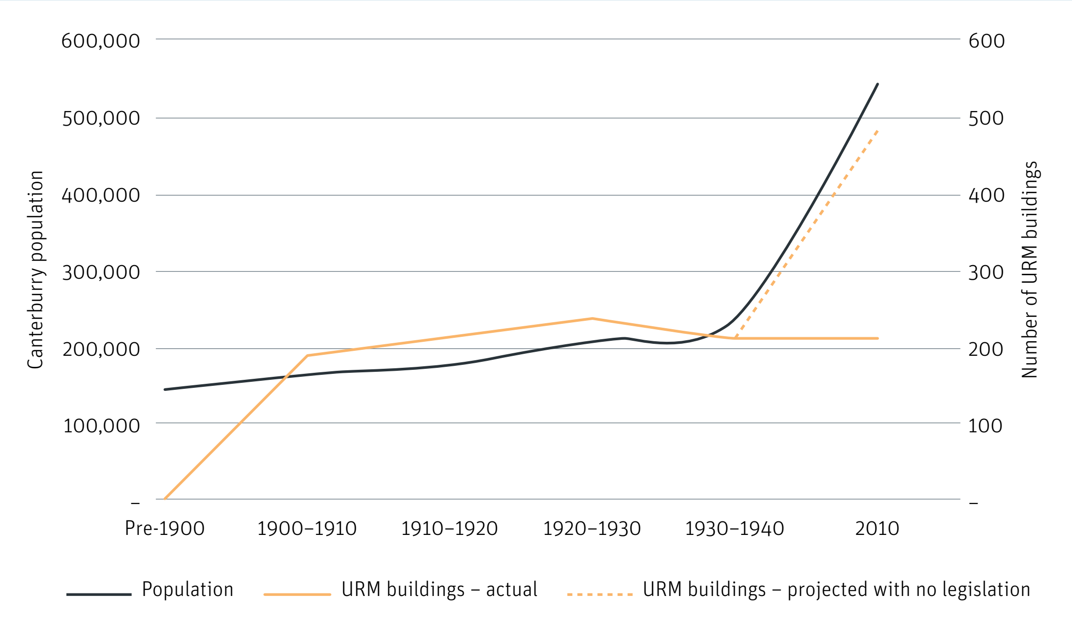
During the 2010–2011 earthquake sequence in the Canterbury region of New Zealand, a M_w 6.3 earthquake struck the city of Christchurch. The building stock in Christchurch in 2011 was primarily timber for residential buildings and reinforced concrete in commercial areas, with additional reinforced masonry buildings (Wilkinson et al. 2013) and a number of URM buildings. Thirty-nine of 185 fatalities in the February 2011 earthquake were attributed to the failure of URM construction, primarily in the central business district. Seismic retrofit was shown to be important in mitigating the damage: URM buildings strengthened to 100 percent of the new building standard performed well, those strengthened to 67 percent performed moderately well, and those strengthened to less than 33 percent did not perform significantly better than those that had not been strengthened. Ingham and Griffith (2011) showed that the risk to building occupants and public space occupants (those in the street near the building) was higher for buildings that received no strengthening than for those where walls, connections, or the entire structure had been strengthened, or elements (gables, parapets) secured. Another study showed that not all strengthening systems achieved the level of damage mitigation expected, partially due to the quality of the original construction material, and partially due to shortfalls in design and implementation of the strengthening mechanisms (Wilkinson et al. 2013).

continues

Box 7.2 Continued

Based on the 130 percent increase in the population of Canterbury, New Zealand, between 1930–1940 and 2010, a projection of the number of potential URM buildings in Canterbury suggests that there could have been an additional 275 URM buildings in the region in 2010 had legislation not prohibited their construction (Figure B7.2.1). All other thing being equal (including other trends in construction practices and rates of seismic retrofit), it would follow that the number of casualties in the 2011 Christchurch earthquake would also have been higher. The patterns of damage also suggest that had a smaller proportion of URM building been strengthened, the number of fatalities due to URM damage or collapse could have been higher. This short example thus demonstrates how disaster risk can be mitigated by prohibiting (or requiring retrofit and structural strengthening of) construction types with high seismic vulnerability.

Figure B7.2.1. The projected number of URM buildings that might have existed in Canterbury, New Zealand, without building legislation to prevent their construction.



Source: Based on data from Russell and Ingham 2010.

continue normal function. Generally, performance-based building codes require critical facilities (e.g., schools or hospitals) to maintain functionality in the event of a disaster; less vital buildings (e.g., shops or offices) prioritize occupants' ability to get out alive, and they would likely require significant repair or rebuilding. Resilience also extends to critical contents of buildings—power supply and equipment that is crucial to continued function in hospitals, for example. Thus in a flood hazard zone, the facility should not rely on power systems and communications equipment located on the ground floor or basement.

Continuing habitability of structures

The habitability of structures is an important issue for a future in which extreme temperatures are expected to shift in several regions, resulting in more hot days and fewer cold days. Regions with high temperatures tend to use traditional construction techniques that allow buildings to remain cool, including building orientation, thickness of walls, curved exterior surfaces (e.g., domes), height of rooms, presence of courtyards, areas shielded from direct sunlight, features that funnel cool airflow into the building, and shutters (Khalili and Amindeldar 2014).

Where traditional construction has been replaced by other modes of construction that discard these cooling principles, buildings either become uninhabitable or require another (often technological) means of cooling the interior, such as air conditioning. Reliance on technological means of cooling significantly increases power consumption and generation, as the experience in the United Arab Emirates over the last few decades makes clear (Radhi 2009); it can thus present a feedback of increased emissions into the climate change process. Policy makers should consider such indirect impacts and include them when commissioning buildings and developments; construction that promotes passive cooling techniques to minimize heat gain and maximize heat loss (such as those shown in table 7.1) will last for decades.

Table 7.1. Techniques to Achieve Passive Cooling of Buildings in a Warm Climate

Minimizing heat gain	Maximizing heat loss through natural cooling
■ Shade windows, walls, and roofs from direct solar radiation ■ Use light-colored roofs to reflect heat ■ Use insulation and buffer zones to minimize conducted and radiated heat gains ■ Make selective or limited use of thermal mass to avoid storing daytime heat gains	Take advantage of the following: ■ Air movement ■ Cooling breezes ■ Evaporation ■ Earth coupling ■ Reflection of radiation

Source: Government of Australia 2013.

Consider ecosystem-based risk management

Engineered structures such as dikes, dams, and flood retention areas are commonly installed along riverbanks and coastlines to provide defense against flooding. Engineered solutions can provide a high level of protection against floods, but they often harm natural processes—for example, by disturbing ecosystem function, and in turn reducing the well-being of local communities (van Wesenbeeck et al. 2014). One concern is that altering a river channel to smooth the channel or increase capacity at one point may have the effect of channeling flow faster through the river network, and thus transfer flood risk to, or exacerbate it in, downstream locations. A second concern is that construction of "hard" defenses at the coastline and construction of dams on rivers can compromise the coastal sediment budget and lead to increased coastal erosion. A third concern about engineered defenses is the need to ensure that investment in them remains effective into the future; they must be maintained (which can be costly) to an effective standard of performance in terms of strength and height, and should account for expected sea-level rise and increased flood levels. Note that engineered solutions are also considered for tackling drought (e.g., irrigation, wells, and drought-resilient crops) and heat waves (e.g., air-conditioning, urban planning).

Engineered approaches may be complemented by nature-based approaches, or by taking a hybrid approach, which can provide a balance of cost and effectiveness: "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" (Royal Society 2014, 62).

Ecosystem-based approaches to managing the risk of urban, riverine, and coastal flooding include maintenance of floodplains and increase in vegetation—specifically, forestation of landslide-susceptible slopes and river catchments prone to flash flooding, the greening of urban areas, use of vegetation for coastal protection instead of sea walls, and setting aside of land in floodplains (box 7.3). The expectation is that such approaches will be able to adapt in an evolving climate, maintaining their ability to mitigate evolving risk without incurring high maintenance and modification costs. For example, natural shorelines evolve on their own in response to changing conditions and require less maintenance than traditional protection structures (van Wesenbeeck 2013).

Box 7.3 Nonengineered Solutions to Flood Protection

Sustainable drainage systems (SuDS) are a means of reducing runoff from a site, encouraging settlement and infiltration of water, and treating surface water before it discharges into watercourses. These systems help to mitigate flood risk, and they also protect water quality, particularly in urban areas where surface water can be polluted by activities on roads and other paved surfaces (Charlesworth, Harker, and Rickard 2003). Relying on permeable rather than impermeable surfaces and on vegetation-based treatment of water, SuDS make use of soakaways, retention ponds, or wetland areas. They are a form of *green infrastructure*, offering an alternative to traditional *grey infrastructure* such as piped drainage and conventional water treatment systems (Andoh 2011).

Coastal vegetation plays an important role in flood protection. Previous studies have suggested that coastal forests, including mangroves, can help to reduce losses due to cyclones (Badola and Hussain 2005) and tsunami (e.g., Dahdouh-Guebas et al. 2005). While the trees may suffer damage, the presence of tree trunks in the water increases friction and slows the flow. Vegetation such as dune grasses can stabilize coastal dunes, which because of their high elevation form a physical barrier to flow from the coast; the grasses bind the dune and mitigate erosion due to storm waves and rising sea levels. Not only can coastal vegetation mitigate the impact of storm and tsunami waves, it can also provide ecosystems that support residents' livelihoods, for example through provision of timber and fisheries, or via social amenities and tourist activities.

Improve data for risk modeling

Improving the accuracy of data used in risk models and reducing data's uncertainty are key to improving the results of each component of the model, from modeled hazard intensity to calculation of loss. Among the data challenges that modelers confront are the static and incomplete nature of exposure and vulnerability data, the resolution of available topography data, the availability of flood protection data, and the uncertainty in climate projections. As data improve, a greater number of disaster risk assessments will ideally adopt the more robust methods for including evolving hazard, exposure, and vulnerability that studies cited in this publication have described.

Dynamic exposure and vulnerability data

To improve our understanding of trends in disaster impacts and accurately quantify risk, improved and ongoing data collection is key. In environments with rapidly changing exposure data (e.g., developing countries with rapidly growing urban populations), the use of snapshots of data from the past renders risk assessments out of date. In terms of vulnerability, there is a dearth of data about peoples' coping strategies in post-event situations; this must be addressed to better understand coping capacity and adaptive capacities.

Incomplete data are a major barrier both to understanding patterns of socioeconomic development and to modeling exposure and vulnerability changes for assessment of future disaster risks. Collecting exposure and vulnerability information in a timely manner and at suitable spatial *and* temporal resolution is vital; this allows development of robust baseline distributions and trends in information, which are needed to improve projections. Crowd-sourcing can aid the collection of such data, as can advances in the analysis of large amounts of earth observation data and subsequent projection of changing population, land use, and economic activity.

High-resolution elevation data

To accurately model localized, topographically sensitive hazards such as river flooding, high-resolution elevation data are crucial. Without these data, flood risk assessments retain significant uncertainty in depth values, which makes vulnerability analyses, as well as quantification of damage and losses, less reliable. As a result, poor resolution also hampers the analysis of individual DRM strategies.

The recent launch of the near-global 30 m resolution Shuttle Radar Topography Mission (SRTM) digital elevation data set (Simpson 2014) shows that there continue to be improvements in the horizontal resolution of digital elevation models (Ward et al. 2015). However, further refinement in vertical resolution is required to really improve the accuracy of elevation data for flood risk assessment (Schumann et al. 2014). Useful data are often collected during the post-disaster response phase, and they should be integrated into disaster risk assessment wherever possible, to improve assessments moving forward. LIDAR topography data that was collected in Haiti following the 2010 earthquake, for example, is now readily available for detailed modeling of future inundation due to sea-level rise.

Flood protection data

One of the biggest contributors to uncertainty in flood risk analysis remains the availability and quality of information on flood protection measures that are in place in the area of interest. Presently, the availability of such data is limited. Thus current flood risk assessments, on national to global scales, often assume either highly simplified flood protection standards or assume no protection. As a result, they overestimate exposure, and therefore risk. On a global scale, Ward et al. (2013) found that expected annual damage was about 40 percent lower than in the absence of protection, assuming that all areas were protected against a flood with a return period of only five years. Faced with this dearth of information, global models rely on an estimate of protection levels based on a region's or country's socioeconomic conditions, income level, or land use. Jongman et al. (2014) attempted to produce the first continent-wide flood protection database based on a modeling approach, which assigned expected protection values to river basins as a function of potential risk in combination with a number of available empirical data points. The authors then successfully included these protection estimates in a probabilistic continental risk model.

While these modeled estimates of flood protection standards indeed lead to improved validation results of flood damage simulations, estimates of flood protection for all river basins have not been extended beyond Europe, and the required available empirical information on protection levels is still extremely limited. An improved global database for flood protection would be extremely valuable because it would enable more accurate modeling of flood risk in present conditions and improve cost-benefit analysis of flood protection measures for future disaster risk management.

Implement robust, flexible adaptation

According to Hallegatte (2009), one problem for adapting to climate change is the rate at which conditions are changing: infrastructure and investments being implemented now must be robust enough to cope with a wider range of climate conditions in the future. This need incurs additional costs for designing that infrastructure. Hallegatte cites five methods to promote effective adaptation in an uncertain future climate:

One of the biggest contributors to uncertainty in flood risk analysis remains the availability and quality of information on flood protection.

1. *"No-regret" strategies.* These provide benefits regardless of whether the disaster risk evolves due to a changing climate. They include improved building insulation to provide energy-saving benefits from day one, and land-use planning to reduce losses under current and future climate conditions.
2. *Reversible and flexible options.* These options can be halted or adjusted at short notice, with little or no sunk cost. They include climate-proofing new buildings and erecting flood defenses that can easily be made higher and stronger at little cost.
3. *Safety margins in investments.* Design of infrastructure systems and structures should account for worst-case scenarios, rather than rely on later modification. For example, drainage systems should be designed with sufficient capacity to cope with anticipated runoff.
4. *Appropriate adaptation strategies*. These include "soft" adaptation strategies—such as early warning systems, evacuation plans, and insurance schemes—and long-term planning horizons with shorter-term revisions of plans.

Box 7.4 **Social Safety Nets**

Social safety nets are "non-contributory transfers designed to provide regular and predictable support to targeted poor and vulnerable people" (World Bank 2014, xiii). They include cash transfers (e.g., school stipends and cash to the elderly or orphans) and in-kind transfers (e.g., school meals and food supplements or vouchers). Transfers may be unconditional or they may be conditional on attendance at health centers, school, or skills programs. Public works programs, which engage people in manual work such as building community assets and infrastructure, may also be part of a social safety net.

Source: World Bank 2014.

5. *Shorter lifetime of investments*. This approach reduces uncertainty about climate in decision making.

Cost-benefit assessment of investments should account for future losses and costs as well as current costs; this approach is particularly important for long-term investments.

Enhance disaster resilience

Resilience determines the degree to which affected groups of people are able to bounce back—or, preferably, bounce forward—after a disaster hits (Manyena et al. 2011). Strengthening resilience is therefore crucial for ensuring that recovery from disasters occurs quickly, incorporates effective adaptation, and reduces vulnerability to ongoing hazards and the next disaster. But a community's resilience cannot be strengthened unless it is understood. Resilience is a product of a range of factors and has social, infrastructural, community capital, economic, institutional, and environmental dimensions (Cutter, Ash, and Emrich 2014). Measures that seek to increase resilience therefore need to address one or several of these dimensions.

The capacity to enhance resilience and adapt to climate change is not equal across all societies (van Aalst and Burton 2000). Capacity comprises financial and technical resources as well as governance to implement and use resources effectively. Capacity is undermined by lack of skills, poverty, and undeveloped social institutions. Social safety nets (box 7.4) have been effective in reducing poverty, improving food security and nutrition, stimulating local economies, and improving social cohesion (World Bank 2014, table 6), all of which can contribute to enhanced resilience. The World Bank (2014) reports that drought resilience increased in Zambia when households used unconditional cash transfers to diversify into a nonagricultural business, and in Ethiopia after a public works program allowed farmers to invest in land improvements and fertilizer. Coverage of some types of social protection is increasing, but improvements are still needed; access to social protection should be expanded, the value of some transfers should be increased, and distribution of transfers should not only be prompt but should more effectively target those who have been affected by a shock (Hallegatte et al. 2015).

Disaster risk financing can help to increase resilience at both national and community levels by contributing to a proactive DRM strategy. Risk financing involves assessing a government's contingent liability to disasters, establishing catastrophe insurance programs in country or across regions, and putting mechanisms in place for governments to fund post-disaster relief and reconstruction (Cummins and Mahul 2009). Insurance is a mechanism for risk transfer that operates by sharing the burden of risk (and losses when they occur) across a large number of policyholders— e.g., homeowners, businesses, and farmers. In the event of a disaster, it mitigates the detrimental impacts of a large loss on each person—but premiums must be affordable enough to encourage many people to become policyholders and fund potential payouts. Market-based catastrophe risk financing can be supported by donor and international financial institutions, which can help build technical capacity and develop complex financial products (Cummins and Mahul 2009). Catastrophe insurance schemes (see box 7.5) can be set up to enable sharing of risk by several governments (e.g., the Pacific Catastrophe Risk Assessment and Financing Initiative [PCRAFI] and the Caribbean Catastrophe Risk Insurance Facility [CCRIF]), or schemes can be funded via international reinsurance markets to offer additional diversification, thus making premiums more affordable for individuals (e.g., the Turkish Catastrophe Insurance Pool [TCIP]). Programs may be focused on insuring a particular type of risk (TCIP focuses on property; African Risk Capacity [ARC] focuses on agriculture). Payout from a scheme may be activated when a certain loss is incurred, or when a proxy parameter is achieved (e.g., a certain category of cyclone, or level of drought index). The latter is predefined and measured by an independent agency, facilitating transparent settlement and rapid disbursement of funds.

Plan recovery and reconstruction before the event

By anticipating disaster impacts, authorities can devise a recovery and reconstruction strategy that addresses the areas likely to be affected, as well as the resources and investment needed to repair or replace damaged infrastructure. If ex ante recovery planning is carried out, recovery can be actioned more quickly (reducing short-term shock-induced vulnerability), and reconstruction can make use of prior plans to incorporate effective adaptation strategies (Becker et al. 2008)—that is, embrace the "build back better" concept to reduce future disaster risk.

Ex ante reconstruction strategies should be based on risk assessments that include evolving disaster risk; and where ex post analyses are conducted in the required time scales, they should include environmental or social change due to the event (e.g., permanent ground displacement or relocation of exposure). If these changes are ignored, reconstruction activities may not achieve the full potential of resilience or sustainability, and may even be detrimental to resilience or sustainability.

In general, ex ante approaches are preferred: "Emergency loans for disaster recovery and rehabilitation tend to focus on the restoration of conditions to the pre-disaster state. They thus miss the opportunity to reduce vulnerabilities to future events, including increased risk from climate change" (van Aalst and Burton 2000, 97).

Box 7.5 Catastrophe Insurance Schemes

The *Caribbean Catastrophe Risk Insurance Facility* (Cummins and Mahul 2009) provides immediate funding to Caribbean governments in the event of a major hurricane or earthquake. The facility allows each participating country government to aggregate its risk into one portfolio. This diversifies the risks, and transfers some of the risk to the international reinsurance market, which reduces the premium each government pays to obtain insurance. Claims by participating governments are paid according to the occurrence of a predefined event (e.g., a hurricane of a given category within a predefined spatial extent).

The *Turkish Catastrophe Insurance Pool* (GFDRR 2011) is a public entity that provides compulsory property earthquake and fire insurance to homeowners through multiple insurance companies. Affordable premiums are offered through the pool by aggregating risks from policies across Turkey into one portfolio. The pool transfers a portion of risk to the international reinsurance markets. The pool has succeeded in growing the catastrophe insurance market in Turkey; 3.5 million policies were sold in 2010 compared to 600,000 before the TCIP was established in 2000.

The *Pacific Catastrophe Risk Assessment and Financing Initiative* includes the Catastrophe Risk Insurance Pilot, which allows Pacific countries to buy catastrophe insurance as a single group (pooling their risks into a single portfolio) (GFDRR 2015). Like the CCRIF, it uses predefined parametric triggers. The pilot provides an immediate payout to a participating government affected by an event meeting the predefined criteria.

African Risk Capacity (ARC) (African Risk Capacity 2013) is a parametric-based pan-African funding mechanism for extreme weather events, covering drought initially but with plans to also cover flood. By pooling risks from governments across Africa, those risks are diversified, with the pool paying out on some events and transferring some risk to the international markets. Governments may choose to retain low-level risk, which requires them to cover losses from frequent or small events themselves.

References

Executive Summary

Bouwer, L. M., R. P. Crompton, E. Faust, P. Hoppe, and R. A. Pielke Jr. 2007. "Disaster Management: Confronting Disaster Losses." *Science* 318, no. 5851: 753. doi:10.1126/science.1149628.

Hallegatte, S., M. Bangalore, L. Bonzanigo, M. Fay, T. Kane, U. Narloh, J. Rozenberg, D. Treguer, and A. Vogt-Schilb. 2015. "Shock Waves: Managing the Impacts of Climate Change on Poverty." World Bank Group, Washington, DC.

Hallegatte, S., C. Green, R. J. Nicholls, and J. Corfee-Morlot. 2013. "Future Flood Losses in Major Coastal Cities." *Nature Climate Change* 3, no. 9: 802–6. doi:10.1038/nclimate1979.

Jongman, B., P. J. Ward, and J. C. J. H. Aerts. 2012. "Global Exposure to River and Coastal Flooding: Long Term Trends and Changes." *Global Environmental Change* 22, no. 4: 823–35. doi:10.1016/j.gloenvcha.2012.07.004.

Muis, S., B. Güneralp, B. Jongman, J. C. J. H. Aerts, and P. J. Ward. 2015. "Flood Risk and Adaptation Strategies under Climate Change and Urban Expansion: A Probabilistic Analysis Using Global Data." *Science of the Total Environment* 538: 445–57.

1. Introduction

GFDRR (Global Facility for Disaster Reduction and Recovery). 2014. *Understanding Risk in an Evolving World: Emerging Best Practices in Natural Disaster Risk Assessment*. Washington, DC: World Bank. https://www.gfdrr.org/sites/default/files/publication/Understanding_Risk-Web_Version-rev_1.8.0.pdf.

IPCC (Intergovernmental Panel on Climate Change). 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*. Edited by C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, et al. Cambridge and New York: Cambridge University Press.

Royal Society. 2014. *Resilience to Extreme Weather*. London: Royal Society. https://royalsociety.org/policy/projects/resilience-extreme-weather/.

United Nations. 2015. *Sendai Framework for Disaster Risk Reduction 2015–2030*. Geneva, Switzerland. http://www.preventionweb.net/files/43291_sendaiframeworkfordrren.pdf.

3. Drivers of Evolving Disaster Risk: Hazard

Association of British Insurers. 2005. *Financial Risks of Climate Change*. London: Association of British Insurers.

Briffa, K. R., G. van der Schrier, and P. D. Jones. 2009. "Wet and Dry Summers in Europe Since 1750: Evidence of Increasing Drought." *International Journal of Climatology* 29, no. 1: 1894–1905. doi:10.1002/joc.1836.

Budiyono, Y., J. C. J. H. Aerts, D. Tollenaar, and P. Ward. 2015. "River Flood Risk in Jakarta under Scenarios of Future Change." *Natural Hazards and Earth System Sciences Discussions* 3, no. 7: 4435–78. doi:10.5194/nhessd-3-4435-2015.

Christchurch City Council. 2014. *Mayoral Flood Taskforce Temporary Flood Defence Measures Final Report—Part A: Key Findings and Recommendations*. Christchurch, New Zealand.

Church, J. A., P. U. Clark, A. Cazenave, J. M. Gregory, S. Jevrejeva, A. Levermann, M. A. Merrifield, et al. 2013. "Sea Level Change." In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, 1137–1216. Cambridge and New York: Cambridge University Press. http://www.climatechange2013.org/images/report/WG1AR5_Chapter13_FINAL.pdf.

Dai, A., K. E. Trenberth, and T. Qian. 2004. "A Global Data Set of Palmer Drought Severity Index for 1870–2002: Relationship with Soil Moisture and Effects of Surface Warming." *Journal of Hydrometeorology* 5, no. 6: 1117–30. doi:10.1175/JHM-386.1.

Deltares. 2014. "Sinking Cities." Deltares, Utrecht. https://www.deltares.nl/app/uploads/2015/01/Subsidence-Sinking-cities_Deltares.pdf.

Deryng, D., D. Conway, N. Ramankutty, J. Price, and R. Warren. 2014. "Global Crop Yield Response to Extreme Heat Stress under Multiple Climate Change Futures." *Environmental Research Letters* 9, no. 3: 034011. doi:10.1088/1748-9326/9/3/034011.

Elsner, J. B., J. P. Kossin, and T. H. Jagger. 2008. "The Increasing Intensity of the Strongest Tropical Cyclones." *Nature* 455, no. 7209: 92–95. http://dx.doi.org/10.1038/nature07234.

Field, C. B., V. R. Barros, K. J. Mach, M. D. Mastrandrea, M. van Aalst, W. N. Adger, D. J. Arent, et al. 2014. "Technical Summary." 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,* edited by C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, et al., 35–94. Cambridge and New York: Cambridge University Press. http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-TS_FINAL.pdf.

Flannigan, M. D., M. A. Krawchuk, W. J. de Groot, B. M. Wotton, and L. M. Gowman. 2009. "Implications of Changing Climate for Global Wildland Fire." *International Journal of Wildland Fire* 18, no. 5: 483. doi:10.1071/WF08187.

Giovinazzi, S., T. Wilson, C. Davis, D. Bristow, M. Gallagher, A. Schofield, M.

Villemure, J. Eidinger, and A. Tang. 2011. "Lifelines Performance and Management Following the 22 February 2011 Christchurch Earthquake , New Zealand: Highlights Of Resilience." *Bulletin of the New Zealand Society for Earthquake Engineering* 44, no. 4: 402–17.

Hallegatte, S., N. Ranger, O. Mestre, P. Dumas, J. Corfee-Morlot, C. Herweijer, and R. M. Wood. 2011. "Assessing Climate Change Impacts, Sea-Level Rise and Storm Surge Risk in Port Cities: A Case Study on Copenhagen." *Climatic Change* 104, no. 1: 113–37. doi:10.1007/s10584-010-9978-3.

Hirabayashi, Y., S. Kanae, S. Emori, T. Oki, and M. Kimoto. 2008. "Global Projections of Changing Risks of Floods and Droughts in a Changing Climate." *Hydrological Sciences Journal* 53, no. 4: 754–72. doi:10.1623/hysj.53.4.754.

Hirabayashi, Y., R. Mahendran, S. Koirala, L. Konoshima, D. Yamazaki, S. Watanabe, H. Kim, and S. Kanae. 2013. "Global Flood Risk under Climate Change." *Nature Climate Change* 3, no. 9: 816–21. doi:10.1038/nclimate1911.

Holland, G., and C. L. Bruyère. 2014. "Recent Intense Hurricane Response to Global Climate Change." *Climate Dynamics* 42: 617–27. doi:10.1007/s00382-013-1713-0.

IPCC (Intergovernmental Panel on Climate Change). 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*. Edited by C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, et al. Cambridge and New York: Cambridge University Press.

Karoly, D. 2010. "The Recent Bushfires and Extreme Heat Wave in Southeast Australia." *Bulletin of Australian Meteorological and Oceanographical Societies* 22: 10–13. http://www.amos.org.au/documents/item/165.

Kossin, J. P., K. R. Knapp, D. J. Vimont, R. J. Murnane, and B. A. Harper. 2007. "A Globally Consistent Reanalysis of Hurricane Variability and Trends." *Geophysical Research Letters* 34. doi:10.1029/2006GL028836.

Kundzewicz, Z. W., S. Kanae, S. I. Seneviratne, J. Handmer, N. Nicholls, P. Peduzzi, R. Mechler, et al. 2014. "Flood Risk and Climate Change: Global and Regional Perspectives." *Hydrological Sciences Journal*, 59, no. 1: 1–28. doi:10.1080/02626667.2013.857411.

Leckebusch, G. C., U. Ulbrich, L. Fröhlich, and J. G. Pinto. 2007. "Property Loss Potentials for European Midlatitude Storms in a Changing Climate." *Geophysical Research Letters* 34, no. 5: L05703. doi:10.1029/2006GL027663.

Liu, Y., J. Stanturf, and S. Goodrick. 2010. "Trends in Global Wildfire Potential in a Changing Climate." *Forest Ecology and Management* 259, no. 4: 685–97. doi:10.1016/j.foreco.2009.09.002.

Luber, G., and M. McGeehin. 2008. "Climate Change and Extreme Heat Events." *American Journal of Preventive Medicine* 35, no. 5: 429–35. doi:10.1016/j.amepre.2008.08.021.

Majer, E. L., R. Baria, M. Stark, S. Oates, J. Bommer, B. Smith, and H. Asanuma. 2007. "Induced Seismicity Associated with Enhanced Geothermal Systems." *Geothermics* 36, no. 3: 185–222. doi:10.1016/j.geothermics.2007.03.003.

McCarthy, M. P., M. J. Best, and R. A. Betts. 2010. "Climate Change in Cities due to Global Warming and Urban Effects." *Geophysical Research Letters* 37, no. 9. doi:10.1029/2010GL042845.

McCarthy, M. P., C. Harpham, C. M. Goodess, and P. D. Jones. 2012. "Simulating Climate Change in UK Cities Using a Regional Climate Model, HadRM3." *International Journal of Climatology* 32, no. 12: 1875–88. doi:10.1002/joc.2402.

McInnes, K. L., I. Macadam, G. Hubbert, and J. O'Grady. 2013. "An Assessment of Current and Future Vulnerability to Coastal Inundation due to Sea-Level Extremes in Victoria, Southeast Australia." *International Journal of Climatology* 33, no. 1: 33–47. doi:10.1002/joc.3405.

Mousavi, M., J. Irish, A. Frey, F. Olivera, and B. Edge. 2011. "Global Warming and Hurricanes: The Potential Impact of Hurricane Intensification and Sea-Level Rise on Coastal Flooding." *Climatic Change* 104, no. 3-4: 575–97. doi:10.1007/s10584-009-9790-0.

Murnane, R., and J. B. Elsner. 2012. "Maximum Wind Speeds and US Hurricane Losses." *Geophysical Research Letters* 39: L16707. doi:10.1029/2012GL052740

Nakićenović, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, et al. 2000. *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. New York: Cambridge University Press.

NOAA National Climatic Data Center. 2014. "NOAA NCDC State of the Climate—Global Analysis Annual 2014." http://www.ncdc.noaa.gov/sotc/global/2014/13.

Park, D.-S. R., C.-H. Ho, and J.-H. Kim. 2014. "Growing Threat of Intense Tropical Cyclones to East Asia over the Period 1977–2010." *Environmental Research Letters* 9: 014008. doi:10.1088/1748-9326/9/1/014008.

Petley, D. N., S. A. Dunning, and N. J. Rosser. 2005. "The Analysis of Global Landslide Risk through the Creation of a Database of Worldwide Landslide Fatalities." In *Landslide Risk Management*, edited by O. Hungr, R. Fell, R. Couture, and E. Eberhardt . London: Taylor & Francis.

Phien-wej, N., P. H. Giao, and P. Nutalaya. 2006. "Land Subsidence in Bangkok, Thailand." *Engineering Geology* 82, no. 4: 187–201. doi:10.1016/j.enggeo.2005.10.004.

Pielke Jr., R. A. 2007. "Future Economic Damage from Tropical Cyclones: Sensitivities to Societal and Climate Changes." *Philosophical Transactions. Series A, Mathematical, Physical, and*

Engineering Sciences 365, no. 1860: 2717–29. doi:10.1098/rsta.2007.2086.

Propublica. 2014. "Losing Ground." http://projects.propublica.org/louisiana/.

Rhodium Group LLC. 2014. *American Climate Prospectus: Economic Risks in the United States*. http://rhg.com/reports/climate-prospectus.

Rodolfo, K. S., and F. P. Siringan. 2006. "Global Sea-Level Rise Is Recognised, but Flooding from Anthropogenic Land Subsidence Is Ignored around Northern Manila Bay, Philippines." *Disasters* 30, no. 1: 118–39. doi:10.1111/j.1467-9523.2006.00310.x.

Roesner, L. A. 2014. "CSU's Urban Stormwater Program." *Colorado Water* 31, no. 2 (March-April): 2–6.

Romps, D. M., J. T. Seeley, D. Vollaro, and J. Molinari. 2014. "Projected Increase in Lightning Strikes in the United States due to Global Warming." *Science* 346, no. 6211: 851–54. doi:10.1126/science.1259100.

Savenije, H. H. G. 2004. "The Importance of Interception and Why We Should Delete the Term Evapotranspiration from Our Vocabulary." *Hydrological Processes* 18, no. 8: 1507–11. doi:10.1002/hyp.5563.

Sheffield, J., E. F. Wood, and M. L. Roderick. 2012. "Little Change in Global Drought over the Past 60 Years." *Nature* 491, no. 7424: 435–38. doi:10.1038/nature11575.

Simpson, D. W., S. Leith, and C. H. Scholz. 1988. "Two Types of Reservoir-Induced Seismicity." *Bulletin of the Seismological Society of America* 78, no. 6: 2025–40.

Stocker, T. F., D. Qin, G.-K. Plattner, L. V. Alexander, S. K. Allen, N. L. Bindoff, F.-M. Bréon, et al. 2013. Technical Summary. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley. Cambridge and New York: Cambridge University Press. http://www.ipcc.ch/report/ar5/wg1/.

Sun, Y., X. Zhang, F. W. Zwiers, L. Song, H. Wan, T. Hu, H. Yin, and G. Ren. 2014. "Rapid Increase in the Risk of Extreme Summer Heat in Eastern China." *Nature Climate Change* 4, no. 12: 1082–85. doi:10.1038/nclimate2410.

Tebaldi, C., B. H. Strauss, and C. E. Zervas. 2012. "Modelling Sea-Level Rise Impacts on Storm Surges along US Coasts." *Environmental Research Letters* 7, no. 1: 014032. doi:10.1088/1748-9326/7/1/014032.

Trewin, B., and H. Vermont. 2010. "Changes in the Frequency of Record Temperatures in Australia, 1957-2009." *Australian Meteorological and Oceanographic Journal* 60 (July): 113–19.

2009 Victorian Bushfires Royal Commission. 2010. *Victorian Bushfires Royal Commission Final Report*. http://www.royalcommission.vic.gov.au/Commission-Reports/Final-Report.html.

Veldkamp, T. I. E., Y. Wada, H. de Moel, M. Kummu, S. Eisner, J. C. J. H. Aerts, and P. J. Ward. 2015. "Changing Mechanism of Global Water Scarcity Events: Impacts of Socioeconomic Changes and Inter-annual Hydro-climatic Variability." *Global Environmental Change* 32: 18–29. doi:10.1016/j.gloenvcha.2015.02.011.

Visser, H., A. C. Petersen, and W. Ligtvoet. 2014. "On the Relation between Weather-Related Disaster Impacts, Vulnerability and Climate Change." *Climatic Change* 125, no. 3-4: 461–77. doi:10.1007/s10584-014-1179-z.

Wang, X. L., Y. Feng, G. P. Compo, V. R. Swail, F. W. Zwiers, R. J. Allan, and P. D. Sardeshmukh. 2013. "Trends and Low Frequency Variability of Extra-tropical Cyclone Activity in the Ensemble of Twentieth Century Reanalysis." *Climate Dynamics* 40: 2775–2800. doi:10.1007/s00382-012-1450-9.

Ward, P. J., S. Eisner, M. Flörke, M., D. Dettinger, and M. Kummu. 2014. "Annual Flood Sensitivities to El Nino-Southern Oscillation at the Global Scale." *Hydrology and Earth System Sciences* 18, no. 1: 47–66. doi:10.5194/hess-18-47-2014.

Winn, P., R. Young, and A. Edwards. 2003. "Planning for the Rising Tides: The Humber Estuary Shoreline Management Plan." *Science of The Total Environment* 314-316: 13–30. doi:10.1016/S0048-9697(03)00092-5.

World Bank. 2011a. "Climate Change Adaptation and Natural Disasters Preparedness in the Coastal Cities of North Africa." Slide presentation. World Bank, Washington, DC. http://resilient-cities.iclei.org/fileadmin/sites/resilient-cities/files/Resilient_Cities_2011/Presentations/F/F4_Multiple_Presenters.pdf.

———. 2011b. "Jakarta Case Study." In *Climate Change, Disaster Risk and the Urban Poor: Cities Building Resilience for a Changing World*." World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/6018.

———. 2012. *Turn Down the Heat: Why a 4°C Warmer World Must Be Avoided*. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/11860.

———. 2014. *Turn Down the Heat: Confronting the New Climate Normal*. Washington, DC: World Bank. http://documents.worldbank.org/curated/en/2014/11/20404287/turn-down-heat-confronting-new-climate-normal-vol-2-2-main-report.

Yan, J., and K. Kishore. 2014. "Detailed Island Risk Assessment in Maldives to Inform Disaster Risk Reduction and Climate Change Adaptation." In *Understanding Risk in an Evolving World: Emerging Best Practices in Natural Disaster Risk Assessment*, edited by Global Facility for Disaster Reduction and Recovery, 132–35. Washington, DC: World Bank. https://www.gfdrr.org/sites/default/files/publication/Understanding_Risk-Web_Version-rev_1.8.0.pdf.

4. Drivers of Evolving Disaster Risk: Exposure

Barredo, J. I. 2009. "Normalised Flood Losses in Europe: 1970–2006." *Natural Hazards and Earth System Science* 9, no. 1: 97–104. doi:10.5194/nhess-9-97-2009.

———. 2010. "No Upward Trend in Normalised Windstorm Losses in Europe: 1970–2008." *Natural Hazards and Earth System Science*, 10, no. 1: 97–104. doi:10.5194/nhess-10-97-2010.

Bouwer, L. M., R. P. Crompton, E. Faust, P. Hoppe, and R. A. Pielke Jr. 2007. "Disaster Management: Confronting Disaster Losses." *Science* 318, no. 5851: 753. doi:10.1126/science.1149628.

CLUVA (Cimate Change and and Urban Vulnerability in Africa). 2015. "Introduction." http://www.cluva.eu/index.php?option=com_content&view=article&id=46&Itemid=53.

Elvidge, C. D., K. E. Baugh, E. A. Kihn, H. W. Kroehl, and E. R. Davis. 1997. "Mapping City Lights With Nighttime Data from the DMSP Operational Linescan System." *Photogrammetric Engineering and Remote Sensing* 63, no. 6: 727–34. http://www.asprs.org/a/publications/pers/97journal/june/1997_jun_727-734.pdf.

Elvidge, C. D., K. Baugh, M. Zhizhin, and F. C. Hsu. 2013. "Why VIIRS Data Are Superior to DMSP for Mapping Nighttime Lights." *Proceedings of the Asia-Pacific Advanced Network* 35: 62–69. doi:10.7125/APAN.35.7.

Freire, S., and C. Aubrecht. 2012. "Integrating Population Dynamics into Mapping Human Exposure to Seismic Hazard. *Natural Hazards and Earth System Science* 12, no. 11: 3533–43. doi:10.5194/nhess-12-3533-2012.

Gerland, P., A. E. Raftery, H. Sevcíková, N. Li, D. Gu, T. Spoorenberg, L. Alkema, et al. 2014. "World Population Stabilization Unlikely This Century." *Science* 346, no. 6206: 234–37. doi:10.1126/science.1257469.

Hallegatte, S., C. Green, R. J. Nicholls, and J. Corfee-Morlot. 2013. "Future Flood Losses in Major Coastal Cities." *Nature Climate Change* 3, no. 9: 802–6. doi:10.1038/nclimate1979.

Hammer, R. B., S. I. Stewart, and V. C. Radeloff. 2009. "Demographic Trends, the Wildland-Urban Interface, and Wildfire Management." *Socety and Natural Resources* 22, no. 8: 12. doi:10.1080/08941920802714042.

IPCC (Intergovernmental Panel on Climate Change). 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*. Edited by C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, et al. Cambridge and New York: Cambridge University Press. doi:10.1017/CBO9781139177245.

Jongman, B., P. J. Ward, and J. C. J. H. Aerts. 2012. "Global Exposure to River and Coastal Flooding: Long Term Trends and Changes." *Global Environmental Change* 22, no. 4: 823–35. doi:10.1016/j.gloenvcha.2012.07.004.

Ligtvoet, W., H. Hilderink, A. Bouwman, P. van Puijenbroek, P. Lucas, and M. Witmer. 2014. *Towards a World of Cities in 2050: An Outlook on Water-Related Challenges. Background Report to the UN-Habitat Global Report*. The Hague: PBL Netherlands Environmental Assessment Agency. http://www.pbl.nl/publicaties/leven-met-water-in-explosief-groeiende-steden.

Mohleji, S., and R. Pielke. 2014. "Reconciliation of Trends in Global and Regional Economic Losses from Weather Events: 1980–2008." *Natural Hazards Review* 15, no. 4: 4014009. doi:10.1061/(ASCE)NH.1527-6996.0000141.

NOAA National Centers for Environmental Information. 2015. "Version 4 DMSP-OLS Nighttime Lights Time Series." http://ngdc.noaa.gov/eog/dmsp/downloadV4composites.html.

Noor, A. M., V. A. Alegana, P. W. Gething, A. J. Tatem, and R. W. Snow. 2008. "Using Remotely Sensed Night-Time Light as a Proxy for Poverty in Africa." *Population Health Metrics* 6, no. 5. doi:10.1186/1478-7954-6-5.

United Nations, Department of Economic and Social Affairs, Population Division. 2014. *World Urbanization Prospects: The 2014 Revision*. CD-ROM edition. http://esa.un.org/unpd/wup/CD-ROM/.

Veldkamp, T. I. E., Y. Wada, H. de Moel, M. Kummu, S. Eisner, J. C. J. H. Aerts, and P. J. Ward. 2015. "Changing Mechanism of Global Water Scarcity Events: Impacts of Socioeconomic Changes and Inter-Annual Hydro-Climatic Variability." *Global Environmental Change* 32: 18–29. doi:10.1016/j.gloenvcha.2015.02.011.

Visser, H., A. C. Petersen, and W. Ligtvoet. 2014. "On the Relation between Weather-Related Disaster Impacts, Vulnerability and Climate Change." *Climatic Change* 125, no. 3-4: 461–77. doi:10.1007/s10584-014-1179-z.

Wang, W., H. Cheng, and L. Zhang. 2012. "Poverty Assessment Using DMSP/OLS Night-Time Light Satellite Imagery at a Provincial Scale in China." *Advances in Space Research* 49, no. 8: 1253–64. doi:10.1016/j.asr.2012.01.025.

Winsemius, H. C., L. P. H. Van Beek, B. Jongman, P. J. Ward, and A. Bouwman. 2013. "A Framework for Global River Flood Risk Assessments." *Hydrology and Earth System Sciences* 17, no. 5: 1871–92. doi:10.5194/hess-17-1871-2013.

Zhang, Q., and K. C. Seto. 2011. "Mapping Urbanization Dynamics at Regional and Global Scales Using Multi-temporal DMSP/OLS Nighttime Light Data." *Remote Sensing of Environment* 115, no. 9: 2320–29. doi:10.1016/j.rse.2011.04.032.

5. Drivers of Evolving Disaster Risk: Vulnerability

Birkmann, J. 2011. "First- and Second-Order Adaptation to Natural Hazards and Extreme Events in the Context of Climate Change." *Natural Hazards* 58, no. 2: 811–40: doi:10.1007/s11069-011-9806-8.

Brunkard, J., G. Namulanda, and R. Ratard. 2008. "Hurricane Katrina Deaths, Louisiana, 2005." *Disaster Medicine and Public Health Preparedness* 2: 215–23.

Butler, D. 2010. "Cholera Tightens Grip on Haiti." *Nature News* 468, no. 7323: 483–84.

Cutter, S. L., B. J. Boruff, and W. L. Shirley. 2003. "Social Vulnerability to Environmental Hazards." *Social Science Quarterly* 84, no. 2: 242–61. http://www.colorado.edu/hazards/resources/socy4037/Cutter Social vulnerability to environmental hazards.pdf.

Cutter, S. L., C. T. Emrich, D. P. Morath, and C. M. Dunning. 2013. "Integrating Social Vulnerability into Federal Flood Risk Management Planning." *Journal of Flood Risk Management* 6, no. 4: 332–44. doi:10.1111/jfr3.12018.

Daniell, J. E. 2014. "Development of Socio-economic Fragility Functions for Use in Worldwide Rapid Earthquake Loss Estimation Procedures." PhD diss. Karlsruhe Institute of Technology.

Duncan, M. 2014. "Multi-hazard Assessments for Disaster Risk Reduction: Lessons from the Philippines and Applications for Non-governmental Organisations." EngD diss., University College London.

Fekete, A. 2009. "Validation of a Social Vulnerability Index in Context to River-Floods in Germany." *Natural Hazards and Earth System Sciences* 9: 393–403. doi:10.5194/nhess-9-393-2009.

Guha-Sapir, D., L. V. Parry, O. Degomme, P. C. Joshi, and J. P. Saulina Arnold. 2006. "Risk Factors for Mortality and Injury: Post-Tsunami Epidemiological Findings from Tamil Nadu." Centre for Research on the Epidemiology of Disasters (CRED), School of Public Health, Catholic University of Louvain, Brussels, Belgium.

Jongman, B. 2014. "Unravelling the Drivers of Flood Risk across Spatial Scales." PhD thesis, VU University, Amsterdam.

Jongman, B., H. C. Winsemius, J. C. J. H. Aerts, E. Coughlan de Perez, M. van Aalst, W. Kron, and P. J. Ward. 2015. "Declining Vulnerability to River Floods and the Global Benefits of Adaptation." *Proceedings of the National Academy of Sciences of the United States of America*. doi:10.1073/pnas.1414439112.

Koks, E. E., B. Jongman, T. G. Husby, and W. J. W. Botzen. 2015. "Combining Hazard, Exposure and Social Vulnerability to Provide Lessons for Flood Risk Management." *Environmental Science & Policy* 47: 42–52. doi:10.1016/j.envsci.2014.10.013.

Lallemant, D., S. Wong, and A. Kiremidjian. 2014. "A Framework for Modelling Future Urban Disaster Risk." In *Understanding Risk in an Evolving World: Emerging Best Practices in Natural Disaster Risk Assessment*, edited by Global Facility for Disaster Reduction and Recovery, 191–96. Washington, DC: World Bank. https://www.gfdrr.org/sites/default/files/publication/Understanding_Risk-Web_Version-rev_1.8.0.pdf.

Marfai, M. A., A. B. Sekaranom, and P. J. Ward. 2014. "Community Responses and Adaptation Strategies toward Flood Hazard in Jakarta, Indonesia." *Natural Hazards* 75, no. 2: 1127–44. doi:10.1007/s11069-014-1365-3.

Mechler, R., and L. M. Bouwer. 2015. "Understanding Trends and Projections of Disaster Losses and Climate Change: Is Vulnerability the Missing Link?" *Climate Change* 133, no. 1: 23–35. doi: 10.1007/s10584-014-1141-0.

Sorensen, J. H., and B. Vogt-Sorensen. 2006. "Community Processes: Warning and Evacuation." In *Handbook of Disaster Research*, edited by H. Rodríguez, E. L. Quarantelli, and R. R. Dynes, 183–99. New York: Springer Science + Business Media, LLC. doi:10.1007/978-0-387-32353-4_11.

Suppasri, A., E. Mas, I. Charvet, R. Gunasekera, K. Imai, Y. Fukutani, Y. Abe, and F. Imamura. 2013. "Building Damage Characteristics Based on Surveyed Data and Fragility Curves of the 2011 Great East Japan Tsunami." *Natural Hazards* 66, no. 2: 319–41. doi:10.1007/s11069-012-0487-8.

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

Verner, D., ed. 2012. *Adaptation to a Changing Climate in the Arab Countries: A Case for Adaptation Governance and Leadership in Building Climate Resilience*. Washington, DC: World Bank. License: Creative Commons Attribution CC BY 3.0. doi:10.1596/978-0-8213-9458-8.

Wisner, B., P. Blaikie, T. Cannon, and I. Davis. 2004. *At Risk: Natural Hazards, People's Vulnerability and Disasters*. 2nd ed. Trowbridge, UK: Taylor & Francis Group.

World Bank and United Nations. 2010. *Natural Hazards, UnNatural Disasters: The Economics of Effective Prevention*. Washington, DC: World Bank. http://econpapers.repec.org/RePEc:wbk:wbpubs:2512.

6. Quantifying the Evolution of Disaster Risk

Aerts, J. C. J. H., W. J. W. Botzen, K. Emanuel, N. Lin, and H. De. Moel. 2014. "Evaluating Flood Resilience Strategies for Coastal Megacities." *Science* 344, no. 6183: 473–75. doi:10.1126/science.1248222.

Angel, S., J. Parent, D. L. Civco, and A. M. Blei. 2013. *Atlas of Urban Expansion*. Cambridge, MA: Lincoln Institute of Land Policy.

Angel, S., S. C. Sheppard, D. L. Civco, R. Buckley, A. Chabaeva, L. Gitlin, A. Kraley, J. Parent, and M. Perlin.

2005. *The Dynamics of Global Urban Expansion*. Washington, DC: World Bank.

Arnell, N. W., and B. Lloyd-Hughes. 2014. "The Global-Scale Impacts of Climate Change on Water Resources and Flooding under New Climate and Socio-economic Scenarios." *Climatic Change* 122, no. 1-2: 127–40. doi:10.1007/s10584-013-0948-4.

Arthur, W. C., H. M. Woolf, and P. Dailey. 2014. "Delivering Risk Information for a Future Climate in the Pacific." In *Understanding Risk in an Evolving World: Emerging Best Practices in Natural Disaster Risk Assessment* , edited by Global Facility for Disaster Reduction and Recovery, 185–90. Washington, DC: World Bank. https://www.gfdrr.org/sites/default/files/publication/Understanding_Risk-Web_Version-rev_1.8.0.pdf.

Bakkensen, L. A. 2013. "Adaptation and Natural Disasters: Evidence from Global Tropical Cyclone Damages and Fatalities." EAERE Papers. http://webmeets.com/files/papers/EAERE/2013/1124/Cyclone_Adaptation.pdf.

Bouwer, L. M. 2013. "Projections of Future Extreme Weather Losses Under Changes in Climate and Exposure." *Risk Analysis* 33, no. 5: 915–30. doi:10.1111/j.1539-6924.2012.01880.x.

Budiyono, Y., J. C. J. H. Aerts, D. Tollenaar, and P. Ward. 2015. "River Flood Risk in Jakarta under Scenarios of Future Change." *Natural Hazards and Earth System Sciences Discussions* 3, no. 7: 4435–78. doi:10.5194/nhessd-3-4435-2015.

Ceola, S., F. Laio, and A. Montanari. 2014. "Satellite Nighttime Lights Reveal Increasing Human Exposure to Floods Worldwide." *Geophysical Research Letters* 41, no. 20: 7184–90. doi:10.1002/2014GL061859.

Church, J. A., P. U. Clark, A. Cazenave, J. M. Gregory, S. Jevrejeva, A. Levermann, M. A. Merrifield, et al. 2013. "Sea Level Change." In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, 1137–1216. Cambridge and New York: Cambridge University Press. https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter13_FINAL.pdf.

Clarke, L., J. Edmonds, V. Krey, R. Richels, S. Rose, and M. Tavoni. 2009. "International Climate Policy Architectures: Overview of the EMF 22 International Scenarios." *Energy Economics* 31: S64–S81. doi:10.1016/j.eneco.2009.10.013.

Cutter, S. L., B. J. Boruff, and W. L. Shirley. 2003. "Social Vulnerability to Environmental Hazards." *Social Science Quarterly* 84, no. 2: 242–61. http://www.colorado.edu/hazards/resources/socy4037/Cutter Social vulnerability to environmental hazards.pdf.

Cutter, S. L., and C. Finch. 2008. "Temporal and Spatial Changes in Social Vulnerability to Natural Hazards." *Proceedings of the National Academy of Sciences of the United States of America* 105, no. 7: 2301–6. doi:10.1073/pnas.0710375105.

Dell'Acqua, F., P. Gamba, and K. Jaiswal. 2012. "Spatial Aspects of Building and Population Exposure Data and Their Implications for Global Earthquake Exposure Modeling." *Natural Hazards* 68, no. 3: 1291–1309. doi:10.1007/s11069-012-0241-2.

Diffenbaugh, N. S., J. S. Pal, F. Giorgi, and X. Gao. 2007. "Heat Stress Intensification in the Mediterranean Climate Change Hotspot." *Geophysical Research Letters* 34, no. 11: 1–6. doi:10.1029/2007GL030000.

Elmer, F., I. Seifert, H. Kreibich, and A. H. Thieken. 2010. "A Delphi Method Expert Survey to Derive Standards for Flood Damage Data Collection." *Risk Analysis* 30, no. 1: 107–24. doi:10.1111/j.1539-6924.2009.01325.x.

Felbermayr, G., and J. Gröschl. 2014. "Naturally Negative: The Growth Effects of Natural Disasters." *Journal of Development Economics* 111: 92–106. doi:10.1016/j.jdeveco.2014.07.004.

Ferreira, S., K. Hamilton, and J. R. Vincent. 2011. "Nature, Socioeconomics and Adaptation to Natural Disasters: New Evidence from Floods." Policy Research Working Paper, World Bank, Washington, DC. http://elibrary.worldbank.org/doi/abs/10.1596/1813-9450-5725.

Field, C. B., V. R. Barros, K. J. Mach, M. D. Mastrandrea, M. van Aalst, W. N. Adger, D. J. Arent, et al. 2014. "Technical Summary." 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* , edited by C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, et al., 35–94. Cambridge and New York: Cambridge University Press. http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-TS_FINAL.pdf.

GFDRR (Global Facility for Disaster Reduction and Recovery). 2014a. *Understanding Risk in an Evolving World: Emerging Best Practices in Natural Disaster Risk Assessment*. Washington, DC: World Bank. https://www.gfdrr.org/sites/default/files/publication/Understanding_Risk-Web_Version-rev_1.8.0.pdf.

———. 2014b. *Understanding Risk: Review of Open Source and Open Access Software Packages Available to Quantify Risk from Natural Hazards*. Washington, DC: World Bank.

Güneralp, B., I. Güneralp, and Y. Liu. 2015. "Changing Global Patterns of Urban Exposure to Flood and Drought

Hazards." *Global Environmental Change* 31: 217–25. doi:10.1016/j.gloenvcha.2015.01.002.

Hallegatte, S. 2012. "Economics: The Rising Costs of Hurricanes." *Nature Climate Change* 2, no. 3: 148–49. doi:10.1038/nclimate1427.

Hallegatte, S., C. Green, R. J. Nicholls, and J. Corfee-Morlot. 2013. "Future Flood Losses in Major Coastal Cities." *Nature Climate Change* 3, no. 9: 802–6. doi:10.1038/nclimate1979.

Hanson, S., R. J. Nicholls, N. Ranger, S. Hallegatte, J. Corfee-Morlot, C. Herweijer, and J. Chateau. 2011. "A Global Ranking of Port Cities with High Exposure to Climate Extremes." *Climatic Change* 104, no. 1: 89–111. doi:10.1007/s10584-010-9977-4.

Hinkel, J., D. Lincke, A. T. Vafeidis, M. Perrette, R. J. Nicholls, R. S. J. Tol, B. Marzeion, X. Fettweis, C. Ionescu, and A. Levermann. 2014. "Coastal Flood Damage and Adaptation Costs under 21st Century Sea-Level Rise." *Proceedings of the National Academy of Sciences of the United States of America* 111, no. 9: 3292–97. doi:10.1073/pnas.1222469111.

Hirabayashi, Y., S. Kanae, S. Emori, T. Oki, and M. Kimoto. 2008. "Global Projections of Changing Risks of Floods and Droughts in a Changing Climate." *Hydrological Sciences Journal* 53, no. 4: 754–72. doi:10.1623/hysj.53.4.754.

Hirabayashi, Y., R. Mahendran, S. Koirala, L. Konoshima, D. Yamazaki, S. Watanabe, H. Kim, and S. Kanae. 2013. "Global Flood Risk under Climate Change." *Nature Climate Change* 3, no. 9: 816–21. doi:10.1038/nclimate1911.

IPCC (Intergovernmental Panel on Climate Change). 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*. Edited by C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, et al. Cambridge and New York: Cambridge University Press. doi:10.1017/CBO9781139177245.

Jeong, D. I., L. Sushama, and M. Naveed Khaliq. 2014. "The Role of Temperature in Drought Projections over North America." *Climatic Change* 127, no. 2: 289–303. doi:10.1007/s10584-014-1248-3.

Jongman, B., E. E. Koks, T. G. Husby, and P. J. Ward. 2014. "Increasing Flood Exposure in the Netherlands: Implications for Risk Financing." *Natural Hazards and Earth System Sciences* 14: 1245–55. doi:10.5194/nhess-14-1245-2014.

Jongman, B., P. J. Ward, and J. C. J. H. Aerts. 2012. "Global Exposure to River and Coastal Flooding: Long Term Trends and Changes." *Global Environmental Change* 22, no. 4: 823–35. doi:10.1016/j.gloenvcha.2012.07.004.

Jongman, B., H. C. Winsemius, J. C. J. H. Aerts, E. Coughlan de Perez, M. van Aalst, W. Kron, and P. J. Ward. 2015. "Declining Vulnerability to River Floods and the Global Benefits of Adaptation." *Proceedings of the National Academy of Sciences of the United States of America*.doi: 10.1073/pnas.1414439112.

Klein Goldewijk, K., A. Beusen, G. Van Drecht, and M. De Vos. 2011. "The HYDE 3.1 Spatially Explicit Database of Human-Induced Global Land-Use Change over the Past 12,000 Years." *Global Ecology and Biogeography* 20, no.1: 73–86.

Koks, E. E., B. Jongman, T. G. Husby, and W. J. W. Botzen. 2015. "Combining Hazard, Exposure and Social Vulnerability to Provide Lessons for Flood Risk Management." *Environmental Science & Policy* 47: 42–52. doi:10.1016/j.envsci.2014.10.013.

Lallemant, D., S. Wong, and A. Kiremidjian. 2014. "A Framework for Modelling Future Urban Disaster Risk." In *Understanding Risk in an Evolving World: Emerging Best Practices in Natural Disaster Risk Assessment*, edited by Global Facilty for Disaster Reduction and Recovery, 191–96. Washington, DC: World Bank. https://www.gfdrr.org/sites/default/files/publication/Understanding_Risk-Web_Version-rev_1.8.0.pdf.

Li, Y., W. Ye, M. Wang, and X. Yan. 2009. "Climate Change and Drought: A Risk Assessment of Crop-Yield Impacts." *Climate Research* 39 (June): 31–46. doi:10.3354/cr00797.

Linard, C., M. Gilbert, A. E. Gaughan, F. R. Stevens, and A. J. Tatem. 2014. "Urban Expansion Forecasts and Changing Human Population Distribution in Africa." Paper presented at the Global Land Project Open Science Meeting, "Land Transformations: Between Global Challenges and Local Realities," Berlin, March 19–21.

Linard, C., M. Gilbert, R. W. Snow, A. M. Noor, and A. J. Tatem. 2012. "Population Distribution, Settlement Patterns and Accessibility across Africa in 2010." *PloS One* 7, no. 2: e31743. doi:10.1371/journal.pone.0031743.

Linard, C., M. Gilbert, and A. J. Tatem. 2011. "Assessing the Use of Global Land Cover Data for Guiding Large Area Population Distribution Modelling." *GeoJournal* 76, no. 5: 525–38. doi:10.1007/s10708-010-9364-8.

Masson, V., C. Marchadier, L. Adolphe, R. Aguejdad, P. Avner, M. Bonhomme, G. Bretagne, et al. 2014. "Adapting Cities to Climate Change: A Systemic Modelling Approach." *Urban Climate* 10: 407–429. doi:10.1016/j.uclim.2014.03.004

McCarthy, M. P., M. J. Best, and R. A. Betts. 2010. "Climate Change in Cities due to Global Warming and Urban Effects." *Geophysical Research Letters* 37, no. 9. doi:10.1029/2010GL042845.

McCarthy, M. P., C. Harpham, C. M. Goodess, and P. D. Jones. 2012.

"Simulating Climate Change in UK Cities Using a Regional Climate Model, HadRM3." *International Journal of Climatology* 32, no. 12: 1875–88. doi:10.1002/joc.2402.

Moss, R. H., J. A. Edmonds, K. A. Hibbard, M. R. Manning, S. K. Rose, D. P. van Vuuren, T. R. Carter, et al. 2010. "The Next Generation of Scenarios for Climate Change Research and Assessment." *Nature* 463, no. 7282: 747–56. doi:10.1038/nature08823.

Muis, S., B. Güneralp, B. Jongman, J. C. J. H. Aerts, and P. J. Ward. 2015. "Flood Risk and Adaptation Strategies under Climate Change and Urban Expansion: A Probabilistic Analysis Using Global Data." *Science of the Total Environment* 538: 445–57.

Nakicenovic, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, et al. 2000. *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*, New York: Cambridge University Press.

O'Neill, B. C., E. Kriegler, K. Riahi, K. L. Ebi, S. Hallegatte, T. R. Carter, R. Mathur, and D. P. van Vuuren. 2014. "A New Scenario Framework for Climate Change Research: The Concept of Shared Socioeconomic Pathways." *Climatic Change* 122, no. 3: 387–400. doi:10.1007/s10584-013-0905-2.

Pesaresi, M., H. Guo, X. Blaes, D. Ehrlich, S. Ferri, L. Gueguen, M. Halkia, et al. 2013. "A Global Human Settlement Layer From Optical HR/VHR RS Data: Concept and First Results." *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 6, no. 5: 2102–31. doi:10.1109/JSTARS.2013.2271445.

Seto, K. C., B. Güneralp, and L. R. Hutyra. 2012. "Global Forecasts of Urban Expansion to 2030 and Direct Impacts on Biodiversity and Carbon Pools." *Proceedings of the National Academy of Sciences of the United States of America* 109, no. 40: 16083–88. doi:10.1073/pnas.1211658109.

Tatem, A. J., A. M. Noor, C. von Hagen, A. Di Gregorio, and S. I. Hay. 2007. "High Resolution Population Maps for Low Income Nations: Combining Land Cover and Census in East Africa." *PloS One* 2, no. 12: e1298. doi:10.1371/journal.pone.0001298.

Taubenböck, H., T. Esch, A. Felbier, M. Wiesner, A. Roth, and S. Dech. 2012. "Monitoring Urbanization in Mega Cities from Space." *Remote Sensing of Environment* 117: 162–76. doi:10.1016/j.rse.2011.09.015.

Toya, H., and M. Skidmore. 2007. "Economic Development and the Impacts of Natural Disasters." *Economics Letters* 94 no. 1: 20–25. doi:10.1016/j.econlet.2006.06.020.

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

Van Vuuren, D. P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. C. Hurtt, et al. 2011. "The Representative Concentration Pathways: An Overview." *Climatic Change* 109, no. 1: 5–31. doi:10.1007/s10584-011-0148-z.

Ward, P. J., W. Beets, L. M. Bouwer, J. C. J. H. Aerts, and H. Renssen. 2010. "Sensitivity of River Discharge to ENSO." *Geophysical Research Letters* 37, no. 12: 1–6. doi:10.1029/2010GL043215.

Ward, P. J., M. D. Dettinger, B. Jongman, M. Kummu, F. Sperna Weiland, and H. C. Winsemius. 2013. "Flood Risk Assessment at the Global Scale: The Role of Climate Variability." In *EGU General Assembly Conference Abstracts*. http://www.geophysical-research-abstracts.net/volumes.html.

Ward, P. J., S. Eisner, M. Flörke, M., D. Dettinger, and M. Kummu. 2014. "Annual Flood Sensitivities to El Niño-Southern Oscillation at the Global Scale." *Hydrology and Earth System Sciences* 18, no. 1: 47–66. doi:10.5194/hess-18-47-2014.

Ward, P. J., B. Jongman, P. Salamon, A. Simpson, P. Bates, T. De Groeve, S. Muis, et al. 2015. "Usefulness and Limitations of Global Flood Risk Models." *Nature Climate Change* 5, no. 8: 712–15. doi:10.1038/nclimate2742.

Zhou, Y., N. Li, W. Wu, J. Wu, and P. Shi. 2014. "Local Spatial and Temporal Factors Influencing Population and Societal Vulnerability to Natural Disasters." *Risk Analysis: An Official Publication of the Society for Risk Analysis* 34, no. 4: 614–39. doi:10.1111/risa.12193.

7. Identifying Effective Policies for a Resilient Future

African Risk Capacity. 2013. "African Risk Capacity: Sovereign Disaster Risk Solutions: A Project of the African Union." http://www.africanriskcapacity.org/c/document_library/get_file?uuid=79be2055-4576-4157-b7ff-396970d8a512&groupId=350251.

Andoh, R. 2011. "Blue, Green and Grey Infrastructure: What's the Difference—and Where Do They Overlap?" *Engineering Nature's Way* (blog). September 2. http://www.engineeringnaturesway.co.uk/2011/blue-green-and-grey-infrastructure-what%E2%80%99s-the-difference-%E2%80%93-and-where-do-they-overlap//.

Badola, R., and S. A. Hussain. 2005. "Valuing Ecosystem Functions: An Empirical Study on the Storm Protection Function of Bhitarkanika Mangrove Ecosystem, India." *Environmental Conservation* 32, no. 1: 85–92. doi:10.1017/S0376892905001967.

Becker, J. S., W. S. A. Saunders, L. Hopkins, K. Wright, and J. Kerr. 2008. "Pre-event Recovery Planning for Land Use in New Zealand: An Updated Methodology." GNS Science Report

2008/11. Lower Hutt, New Zealand: GNS Science.

Charlesworth, S. M., E. Harker, and S. Rickard. 2003. "A Review of Sustainable Drainage Systems (SuDS): A Soft Option for Hard Drainage Questions?" *Geography* 88, no. 2: 99–107. http://www.jstor.org/stable/40573828.

Cummins, J. D., and O. Mahul. 2009. *Catastrophe Risk Financing in Developing Countries: Principles for Public Intervention*. Washington, DC: World Bank.

Cutter, S. L., K. D. Ash, and C. T. Emrich. 2014. "The Geographies of Community Disaster Resilience." *Global Environmental Change* 29: 65–77. http://www.sciencedirect.com/science/article/pii/S0959378014001459.

Dahdouh-Guebas, F., L. P. Jayatissa, D. Di Nitto, J. O. Bosire, D. Lo Seen, and N. Koedam. 2005. "How Effective were Mangroves as a Defence against the Recent Tsunami?" *Current Biology* 15, no. 12: R443–7. doi:10.1016/j.cub.2005.06.008.

Derkzen, M. L., A. J. A. van Teeffelen, and P. H. Verburg. 2015a. "Green Infrastructure for Climate Adaptation: A study of Awareness, Perceptions, and Preferences in Rotterdam, the Netherlands." Paper presented at eighth conference of the Ecosystem Services Partnership, Stellenbosch, South Africa, November 9–13.

———. 2015b. "Quantifying Urban Ecosystem Services Based on High-Resolution Data of Urban Green Space: An Assessment for Rotterdam, the Netherlands." *Journal of Applied Ecology* 52: 1020–32. doi:10.1111/1365-2664.12469.

FAO (Food and Agriculture Organization). 2013. *Climate-Smart Agriculture Sourcebook*. http://www.fao.org/docrep/018/i3325e/i3325e.pdf.

Foster, J., A. Lowe, and S. Winkelman. 2011. "The Value of Green Infrastructure for Urban Climate Adaptation." Center for Clean Air Policy, Washington, DC.

GFDRR (Global Facility for Disaster Reduction and Recovery). 2011. "Turkish Catastrophe Insurance Pool: Disaster Risk Financing and Insurance Case Study." GFDRR, Washington, DC. http://www.gfdrr.org/sites/gfdrr.org/files/documents/DFI_TCIP_Jan11.pdf.

———. 2015. *Advancing Disaster Risk Financing & Insurance in the Pacific*. Washington, DC: World Bank. https://www.gfdrr.org/sites/default/files/publication/2015.06.25_PCRAFI_Combined-%5BCompressed%5D-rev-0.9.pdf.

Government of Australia. 2013. "Your Home—Australia's Guide to Environmentally Friendly Sustainable Homes: Passive Cooling." http://www.yourhome.gov.au/passive-design/passive-cooling.

Hallegatte, S. 2009. "Strategies to Adapt to an Uncertain Climate Change." *Global Environmental Change* 19, no. 2: 240–47. doi:10.1016/j.gloenvcha.2008.12.003.

Hallegatte, S., M. Bangalore, L. Bonzanigo, M. Fay, T. Kane, U. Narloh, J. Rozenberg, D. Treguer, and A. Vogt-Schilb. 2015. "Shock Waves: Managing the Impacts of Climate Change on Poverty." World Bank Group, Washington, DC.

Ingham, J. M., and M. C. Griffith. 2011. *The Performance of Earthquake Strengthened URM Buildings in the Christchurch CBD in the 22 February 2011 Earthquake: Addendum Report to the Royal Commission of Inquiry*. Christchurch, New Zealand: Canterbury Earthquakes Royal Commission.

IPCC (Intergovernmental Panel on Climate Change). 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*, edited by C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, et al., 1–31. Cambridge and New York: Cambridge University Press.

Jongman, B., S. Hochrainer-Stigler, L. Feyen, J. C. J. H. Aerts, R. Mechler, W. J. W. Botzen, L. M. Bouwer, et al. 2014. "Increasing Stress on Disaster-Risk Finance Due to Large Floods." *Nature Climate Change* 4, no. 4: 264–68. doi:10.1038/nclimate2124.

Khalili, M., and S. Amindeldar. 2014. "Traditional Solutions in Low Energy Buildings of Hot-Arid Regions of Iran." *Sustainable Cities and Society* 13: 171–81. doi:10.1016/j.scs.2014.05.008.

Manyena, S. B., G. O'Brien, P. O'Keefe, and J. Rose. 2011. "Disaster Resilience: A Bounce Back or Bounce Forward Ability?" *Local Environment* 16, no. 5: 417–24. http://dx.doi.org/10.1080/13549839.2011.583049.

Muis, S., B. Güneralp, B. Jongman, J. C. J. H. Aerts, and P. J. Ward. 2015. "Flood Risk and Adaptation Strategies under Climate Change and Urban Expansion: A Probabilistic Analysis Using Global Data." *Science of the Total Environment* 538: 445–57.

New Zealand Standards Institute. 1935. "NZSS No. 95:1935, Model Building By-Law." New Zealand Standards Institute, Wellington, New Zealand.

———. 1965. "NZSS 1900:1965, Model Building By-Law. Chapter 8: Basic Design Loads." New Zealand Standards Institute, Wellington, New Zealand.

OECD (Organisation for Economic Co-operation and Development). 2008. "Climate Change Mitigation: What Do We Do?" http://www.oecd.org/env/cc/41751042.pdf.

Radhi, H. 2009. "Evaluating the Potential Impact of Global Warming on the UAE Residential Buildings: A Contribution to Reduce the CO2 Emissions." *Building and Environment* 44, no. 12: 2451–62. doi:10.1016/j.buildenv.2009.04.006.

Royal Society. 2014. *Resilience to Extreme Weather*. London: Royal Society. https://royalsociety.org/policy/projects/resilience-extreme-weather/.

Russell, A. P., and J. M. Ingham. 2010. "Prevalence of New Zealand's Unreinforced Masonry Buildings." *Bulletin of the New Zealand Society for Earthquake Engineering* 43, no. 3: 182–202.

Schumann, G. J-P., P. D. Bates, J. C. Neal, and K. M. Andreadis. 2014. "Technology: Fight Floods on a Global Scale." *Nature* 507, no. 169. doi:10.1038/507169e.

Simpson, A. 2014. "Better Understanding Disaster Risk: A New Dataset Is Set to Make a Difference." *World Bank Voices Blog*. September 24. http://blogs.worldbank.org/voices/better-understanding-disaster-risk-new-dataset-set-make-difference.

Standards Association of New Zealand. 1976. "NZS 4203: Code of Practice for General Structural Design and Design Loadings for Buildings." Standards Association of New Zealand, Wellington, New Zealand.

Van Aalst, M. K., and I. Burton. 2000. "Climate Change from a Development Perspective." In *Managing Disaster Risk in Emerging Economies*, edited by A. Kreimer and M. Arnold, 91–98. Disaster Risk Management Series no. 2. Washington, DC: World Bank.

Van Wesenbeeck, B. K. 2013. "Nature-Based Coastal Defences: Can Biodiversity Help?" In *Encyclopedia of Biodiversity*, 2nd ed., 451–58. Amsterdam: Academic Press.

Van Wesenbeeck, B. K., J. P. Mulder, M. Marchand, D. J. Reed, M. B. de Vries, H. J. de Vriend, and P. M. J. Herman. 2014. "Damming Deltas: A Practice of the Past? Towards Nature-Based Flood Defenses." *Estuarine, Coastal and Shelf Science* 140: 1–6. doi:10.1016/j.ecss.2013.12.031.

Ward, P. J., B. Jongman, P. Salamon, A. Simpson, P. Bates, T. De Groeve, S. Muis, et al. 2015. "Usefulness and Limitations of Global Flood Risk Models." *Nature Climate Change* 5, no. 8: 712–15. doi:10.1038/nclimate2742.

Ward, P. J., B. Jongman, F. S. Weiland, A. Bouwman, R. van Beek, M. F. P. Bierkens, Ligttvoegt. W., et al. 2013. "Assessing Flood Risk at the Global Scale: Model Setup, Results, and Sensitivity." *Environmental Research Letters* 8, no. 4: 044019. doi:10.1088/1748-9326/8/4/044019.

Wilkinson, S., D. Grant, E. Williams, S. Paganoni, S. A. Fraser, D. Boon, A. Mason, and M. Free. 2013. "Observations and Implications of Damage from the Magnitude M_w 6.3 Christchurch, New Zealand Earthquake of 22 February 2011." *Bulletin of Earthquake Engineering* 11, no. 1: 107–40. doi:10.1007/s10518-012-9384-5.

World Bank. 2014. "State of Social Safety Nets 2014." Washington, DC, World Bank. http://documents.worldbank.org/curated/en/2014/05/19487568/state-social-safety-nets-2014.

Case Studies

8

CASE STUDY A

World Weather Attribution

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One of the most significant effects of climate change is its impact on extreme weather. Changes are projected in the frequency and intensity of floods, droughts, and heat waves around the world, but extreme weather is not only a future concern. We already live in a climate that has changed, and the risks of extreme weather events have already been altered.

The continual question, therefore, is whether climate change plays a role in each specific extreme event that we observe today (Trenberth, Fasullo, and Shepherd 2015). During and after a disaster, the media and impacted stakeholders continually speculate about the link to climate change. Between 2011 and 2014, for example, 42 articles about the California drought mentioned the possible connection to climate change, and within those articles there was no agreement about whether climate change did or did not play a role in the drought.

The continual question, therefore, is whether climate change plays a role in each specific extreme event that we observe today (Trenberth, Fasullo, and Shepherd 2015).

Until recently, scientists did not have an answer to this question. Certainly many studies showed that, from a global perspective, the frequency and intensity of extreme events like heat waves and floods were rising or projected to rise; but such findings are not applicable to individual extreme events. This is because computing how the probability of an extreme event has changed is not easy; indeed, it is even harder than making regional climate projections. Human-induced alterations of the atmosphere through greenhouse gas emissions not only lead to warming and hence increased moisture in the air, but also induce changes in the atmospheric circulation. Regionally, or in specific seasons, such changes can have opposing effects on weather events and lead, for example, to a decrease in the risk of extreme precipitation instead of an increase. Thus in order to assess the true risks of harmful extreme events in regional contexts, and to assess as well the current impacts of climate change, the full role of human-induced climate change in individual extreme events needs to be explored.

In the past, we did not have the tools to explain how climate change might have impacted a specific event. Hence many people around the world see "climate change" as a problem of the future, not as something that is already happening today. But over the past decade, a new field of science called "extreme event attribution" has emerged, which addresses the gap in our knowledge and answers the question: did climate change play a role in this specific extreme event? Early breakthroughs both characterized how specific events can be examined in the context of climate change and analyzed several examples, such as the 2003 heat wave in Europe (e.g., Stott, Stone, and Allen 2004).

Operationalization

While the scientific community is now able to determine whether an event was influenced by climate change, findings are not immediately available; because of the time scale of academic publishing, studies usually become available a year or longer after an event has taken place. To encourage event attribution analyses, the *Bulletin of the American Meteorological Society* has published a yearly collection of attribution studies since 2011; each issue focuses on events of the previous year. However, these studies do not provide answers to the questions asked during and immediately after an event.

Recognizing that scientific advancements coupled with an operational setup would provide answers more quickly, a group of organizations formed a partnership called World Weather Attribution (WWA). This initiative brings together Climate Central, the University of Oxford Environmental Change Institute, the Royal Netherlands Meteorological Institute (KNMI), the University of Melbourne, and the Red Cross/Red Crescent Climate Centre to analyze extreme events in real time using a set of complementary methods.

The team begins by defining the "event" based on observations and reports of impacts. Next, team members estimate the probability of the event occurring in both the current and the pre-industrial climate, using several independent methods to determine whether the event occurs more frequently in one case than the other. Methods include a comparison of observations from the past as well as many simulations of a world with and without climate change. Finally, carefully calibrated statements about the results are issued to the public. The partnership carefully considers the uncertainties in the analysis, and communicates these openly as part of the results. The methods and protocol are reviewed by a Science Oversight Committee that is composed of leading researchers in the field of extreme event attribution and risk management.

Based on the results of the team's analysis, we are able to compute to what extent, if any, the risk of an extreme event has changed due to anthropogenic climate change. In the case of major disasters, this is a crucial question: *have the risks been changing, and if so, why?*

Attribution in Brazil

One of the first events analyzed by the WWA group was the 2014–2015 drought in Brazil (Otto et al. 2015; the result was published well after the analysis). In early 2015, Southeast Brazil was suffering from major water shortages. From January 2014 to February 2015—including most of two rainy seasons—the region received very little precipitation. The affected area included Greater São Paolo, the largest city in the country, with a population of over 20 million.

The goal was to characterize how drought risk is changing over time, and identify the main drivers that are contributing to those changes. The risk of this drought event is a function of the hazard, vulnerability, and exposure in the area, and the WWA group set out to examine how each of these components had changed over time.

Did the hazard change?

The WWA group determined that the probability of a rainfall deficit as experienced by Southeast Brazil in 2014–2015 had not changed much due to climate change. There are several examples of similar events in the historical record, including 1953–1954, 1962–1963, 1970–1971, and 2001. In the model data, the likelihood of this drought happening now is not appreciably different from the likelihood of it happening in a world without climate change. In fact, in the observations-based approach and one of the two modeling studies used in the analysis, the risk of a precipitation deficit decreased slightly under current conditions. The analysis also took into account the fact that in a warming world evaporation increases, and in this example the combination of effects—fewer rainfall deficits and increased evaporation—led to no change in the likelihood of the overall drought hazard occurring.

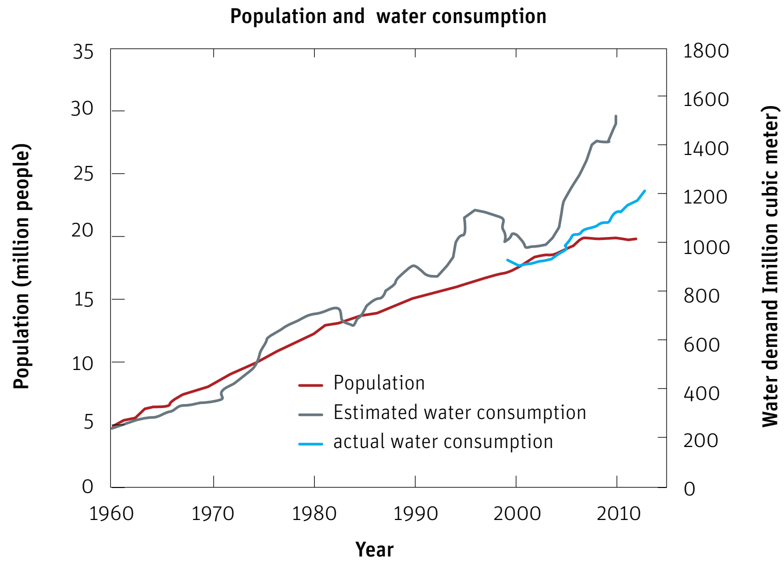
Did the exposure change?

Yes. Analysis of population trends showed that São Paulo had quadrupled in size since 1960.

Did vulnerability change?

Vulnerability to water shortages certainly increased over time, as water usage per person has increased. Combined with the population boom, the total water usage has increased substantially, and this has put a great strain on water supplies (see figure A.1). As a result of major public health investments between 1980 and 2005, however, vulnerability to cholera impacts from drought has essentially vanished. Indeed, there was no cholera reported during this drought.

Figure A.1. **Population and water consumption in São Paulo. The figure shows São Paulo's metropolitan population from 1960 to 2010 (red line) and estimated water use over the same period (blue line); actual water use in Greater São Paulo (defined slightly differently) is shown for the period 1999–2013 (aqua line).**



Source: Otto et al. 2015. Data on actual water use are from São Paulo state water/waste management company (SABESP).

Building back better

Ultimately, an analysis of trends in each of the components of disaster risk is key to making good decisions. Extreme events can catalyze game-changing investments in "building back better," reducing exposure and vulnerability so that the next event is not as catastrophic. But information is needed to guide the size and type of investment. During the 1953–1954 drought, Brazil constructed its largest water supply system, Cantareira, to provide water to the people of São Paulo. The attribution analysis of the 2014–2015 drought shows that it would not be necessary to take into account more frequent precipitation deficits in the design of such a system.

In the case of Hurricane Sandy in New York, scientists provided a clear partial attribution statement about the storm surge, explaining that because of sea-level rise, the huge waves that crashed down on the city were higher than they would otherwise have been. Climate change had played an appreciable role in this event; much of the damage from the storm was due to the storm surge. Increased sea surface temperatures were also shown to have increased the intensity of the storm (Magnusson et al. 2014), but a full analysis including all factors has not yet been performed.

After Sandy, New Yorkers and politicians demonstrated a marked shift in their commitment to climate change adaptation. While information about sea-level rise had been available before the storm, attributing a portion of the storm surge to climate change catalyzed new policies to build back better and take into account this pattern of rising risks. For example, the Hurricane Sandy Rebuilding Task Force (2013) acknowledges that "it is important not just to rebuild but to better prepare the region for the existing and future threats exacerbated by climate change. President Obama's Climate Action Plan clearly states that 'climate change is no longer a distant threat—we are already feeling its impacts across the country'" (3). In light of these changing risks, the task force "is developing 21st century solutions to the 21st century challenges facing our Nation" (4). Updated flood risk maps have now been issued for the area, and rebuilding is taking into account the changed risks.

As the experience during Hurricane Sandy showed, a major breakthrough of the WWA team is the ability to carry out attribution analyses in real time—when everyone is listening. By the time most event attribution studies are published (many months after the event itself), interest has waned, communication opportunities have closed, and critical decisions have already been made about how to rebuild. By committing to set up models in advance, the WWA team has positioned itself to provide information when it is most needed—in the immediate aftermath of the event.

Attribution in real time: Europe

In July 2015, extreme heat waves set in across the Netherlands, Spain, Germany, France, and Switzerland (figure A.2). Heat waves disproportionately affect the elderly, the sick, and infants, and each country put in place measures to reduce the vulnerability of its population (largely in reaction to the heat waves of 2003 and 2006, when lack of preparedness led to thousands of deaths). As the heat waves were occurring, the WWA team carried out an analysis of the extreme temperatures and provided up-to-the-moment scientific analysis to the public. Detailed graphics and analysis were made available online (http://www.climatecentral.org/europe-2015-heatwave-climate-change) for the public to access during the event.

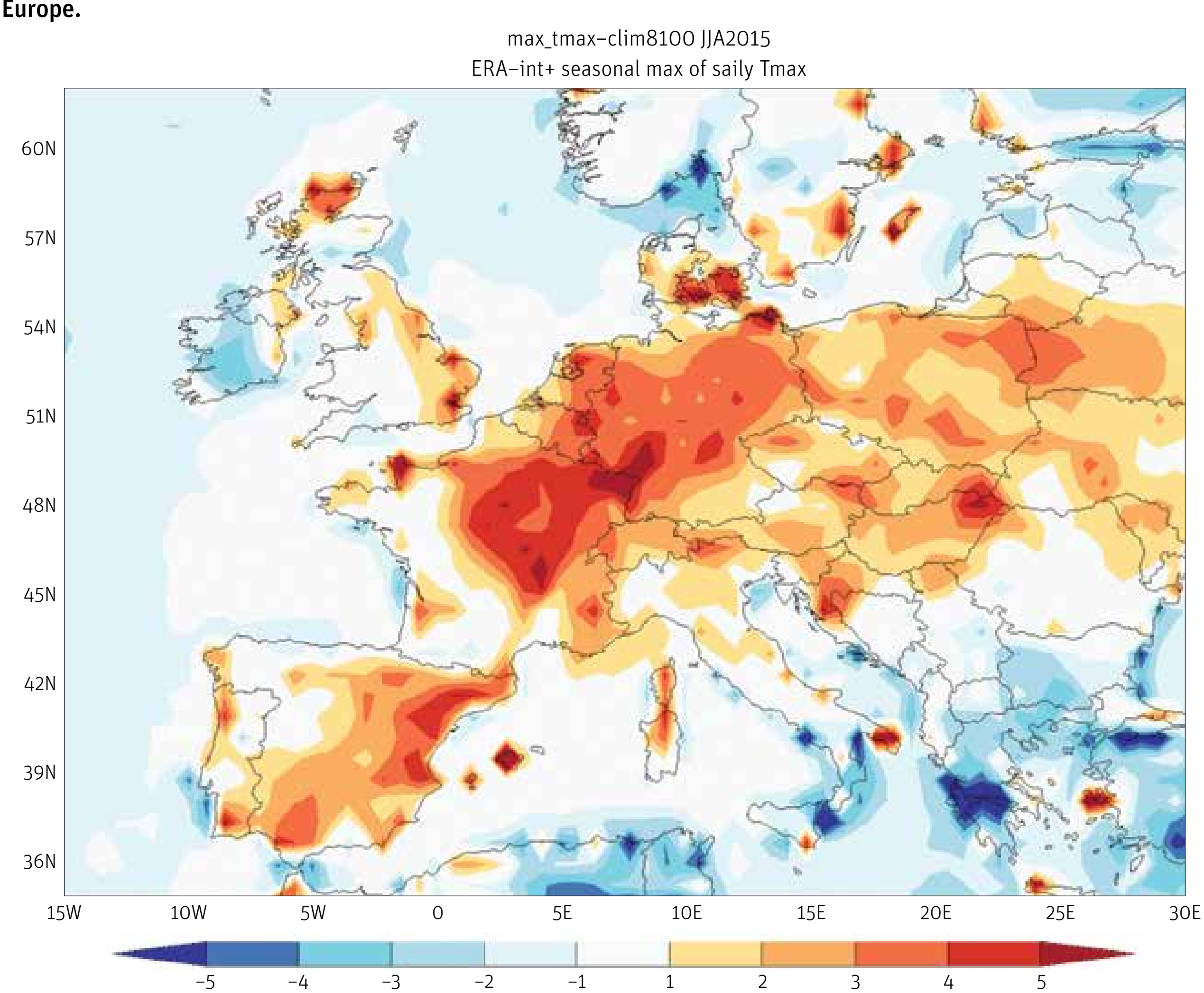
In this case, the evidence was overwhelming: climate change increased the likelihood of each of the heat waves. France and Germany set records for the hottest day ever observed, and the WWA team is "virtually certain" that because of climate change, heat waves of this type are more likely to happen now than in the past in this part of the world. In fact, many of the extremes were found to be at least twice as likely to happen today as they would have been in a world without climate change. Note that attribution studies tend to report the lower boundary of the often large uncertainty range, as it is easier to compute and society demands conservative numbers. The best estimate of the increase is much larger than a factor two.

Conclusion

Ultimately, understanding trends in disaster risk is crucial for better decision making, and trends in hazards are an essential component of risk. Extreme event attribution offers the opportunity to analyze how hazard events might have been influenced by climate change, and to dissect the components of events to inform efforts to "build back better." This type of analysis can reveal what steps are needed for successful adaptation to climate change. After the 2003 heat wave in France, for example, heat-health early warning plans and procedures were put in place to prevent the loss of life in future, and these were shown to be effective in the 2006 heat wave that followed (Fouillet et al. 2008).

Attribution of extreme events makes it easier for society to accept the reality of climate change and helps to identify whether climate change is playing a role in specific events or not. Projections then guide policy makers and the public in selecting and implementing the adaptations needed to reduce exposure and

Figure A.2. Observed/forecast three-day maximum temperature in Europe in summer 2015 as departure from average June-July-August maximum (1981–2010). This plot was available to the public during the heat wave of July 2015 in Europe.



Source: Climate Central, http://www.climatecentral.org/europe-2015-heatwave-climate-change.

vulnerability to changing hazards, and in this way keep the risk at an acceptable level.

References

Fouillet, A., G. Rey, V. Wagner, K. Laaidi, P. Empereur-Bissonnet, A. Le Tertre, P. Frayssinet, et al. 2008. "Has the Impact of Heat Waves 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, no. 2: 309–17. doi:10.1093/ije/dym253.*

Hurricane Sandy Rebuilding Task Force. 2013. "Hurricane Sandy Rebuilding Strategy." http://portal.hud.gov/hudportal/documents/huddoc?id=hsrebuildingstrategy.pdf.

Magnusson, L., J.-R. Bidlot, S. Lang, A. Thorpe, N. Wedi, and M. Yamaguchi. 2014. "Evaluation of Medium-Range Forecasts for Hurricane Sandy." Monthly Weather Review 142: 1962–81. doi:10.1175/MWR-D-13-00228.1.

Otto, F. E. L., C. A. S. Coelho, A. King, E. Coughlan de Perez, Y. Wada, G. J. van Oldenborgh, R. Haarsma, et al. 2015. "Factors Other Than Climate Change, Main Drivers of 2014/15 Water Shortage in Southeast Brazil." Bulletin of the American Meteorological Society 96, no. 8 (September). doi:10.1175/BAMS-D-15-00120.1.

Stott, P. A., D. A. Stone, and M. R. Allen. 2004. "Human Contribution to the European Heatwave of 2003." Nature 432: 610–14. doi:10.1038/nature03130.

Trenberth, K. E., J. T. Fasullo, and T. G. Shepherd. 2015. "Attribution of Climate Extreme Events." Nature Climate Change 5: 725–30.

CASE STUDY B

Catastrophe Models to Assess Future Risk

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Evolving risk and catastrophe models

Catastrophe models are an established and critical component of how catastrophe insurers and reinsurers manage their business. These models are routinely used to help answer key (re)insurance questions, such as how much premium should be charged for a risk, or how much capital should be held against the potential for extreme losses. Catastrophe models help to answer such questions by providing synthetic catalogs of extreme events, often representing hundreds of thousands of years of activity and thus reducing dependence on limited historical experience of catastrophic loss.

These stochastic catalogs are derived from a combination of statistical and physics-based models; this basis ensures that the catalogs are composed of physically realistic events and that they accurately extrapolate the historical experience to encompass all physically possible scenarios. Catastrophe models are extensively validated both internally by the vendor company and externally by users of the models. For a model to be accepted, it must be able to both replicate the actual losses experienced in recent events and show that the loss exceedance probability distribution, at shorter return periods, is consistent with the past few decades of loss experience.

The structure of catastrophe models can be described as four related but independently validated and calibrated components: hazard, exposure, vulnerability, and loss.

The hazard component is used to characterize the frequency, intensity, and spatial distribution of a particular peril (which may also include secondary perils such as storm surge or inland flooding in the case of tropical storms). While this component is often calibrated to the long-term climatology, for many climate-related perils frequency and severity show time dependence on multiyear to decadal time scales. To account for this, catastrophe modelers will periodically assess and update modeled event frequencies to reflect the current activity. Where there is sufficient evidence to indicate that current activity rates differ from the long-term historical average, and forecasts can be made with sufficient skill, activity rates projecting the expected activity over the next few years may also be embedded within the model as a recommended reference or alternative view.

The exposure component quantifies the people or property exposed to a particular hazard and is the primary user-defined input into catastrophe model software. At a minimum, exposure-related information includes the location and value of exposed assets, but the information can be as detailed a representation of the exposure as the model and user can support. For property exposures, for example, information such as construction type, occupancy, elevation, and presence of basements may be specified. Regular updates to insured exposure, reflecting changes in an insurance portfolio, are often the biggest driver of changes in catastrophe risk year-on-year for insurance companies and are closely monitored by users of these models. On an industry-wide level, the changes in population, building stock, and urbanization are all important factors reflecting the dynamic and evolving nature of exposure.

The vulnerability component accounts for the response of the exposure to the hazard. For property exposures, vulnerability functions estimate the damage to structures and their contents that result from a given hazard level, as well as the amount of time required for rebuilding. The implicit assumption is a static time-invariant response to the hazard. In reality vulnerability is far from a static quantity, and sophisticated catastrophe models account for the evolution of the risk by making the vulnerability dependent on time-varying factors such as changes in building design codes, the age of the structure (i.e., degradation), and other relevant regulatory changes. While the burden is on the user to capture detailed exposure information, the model framework is designed to allow for this.

The final component is the loss component or financial model that is used to estimate the impacts—

most often monetary costs of property damage—produced by the combination of hazard, exposure, and vulnerability. In commercial models this component will also account for any insurance-related factors or policy terms.

Catastrophe models, particularly commercial vendor models, have not traditionally been used as part of climate change impact analysis. When suitably modified, however, these models can offer powerful business- and policy-relevant insights into future risk. For example, as part of the World Bank's Pacific Catastrophe Risk Assessment and Financing Initiative, AIR used its Pacific basin tropical cyclone model, modified based on the output from 11 general circulation models provided by Geoscience Australia, to assess how tropical cyclone risk would impact 15 Pacific islands. In a similar manner, for the Risky Business Project (2014), RMS was able to address the future risks arising from climate change along the U.S. coastline by partnering with experts in the field of climate change and hurricane risk to integrate the latest projections of local sea-level rise and potential hurricane activity changes into the RMS North Atlantic hurricane model.

Risky business: The economic risks of climate change to the United States

Given the importance of climate conditions to U.S. economic performance, climate change presents meaningful risks to the financial security of American businesses and households alike. The Risky Business Project, cochaired by former New York City mayor Michael Bloomberg, former U.S. Treasury secretary Henry Paulson, and Farallon Capital founder Tom Steyer, was set up to quantify and publicize these risks to the business and financial communities, so that decision makers in business and government would have information about the economic risks and opportunities climate change poses.

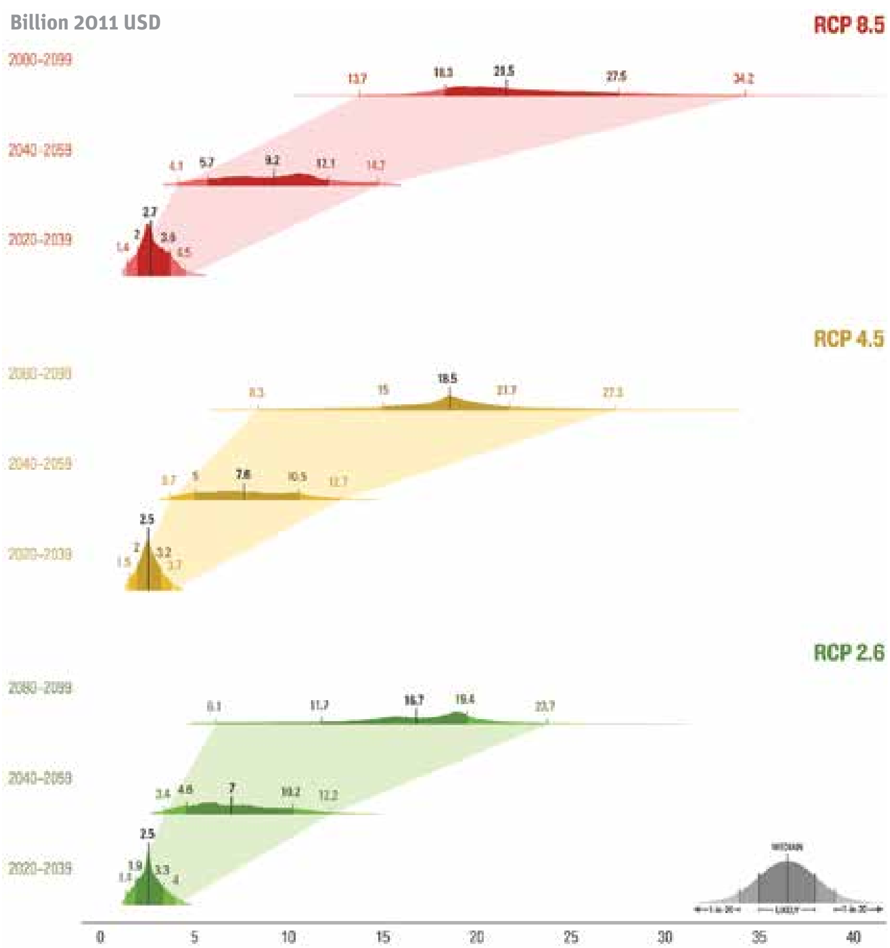
Led by Next Generation, a not-for-profit think tank addressing key challenges for the next generation of Americans, and the Rhodium Group, a policy and econometric consultancy, the project used meta-analysis of microeconometric research and detailed sector models, including the RMS North Atlantic hurricane catastrophe model, in conjunction with the best available scientific evidence, including that of the Intergovernmental Panel on Climate Change (IPCC) and the U.S. National Climate Assessment. This approach made it possible to establish the impact of potential changes in temperature, precipitation, sea level, and extreme weather events on different sectors of the economy and regions of the country (Houser et al. 2014).

The U.S. coastline is a key to the U.S. economy. Counties touching the coast account for 39 percent of total U.S. population and 28 percent of national property by value. These vast exposure concentrations, particularly on the East Coast and along the Gulf of Mexico, are at risk of hurricanes and other coastal storms, which inflict billions of dollars of property and infrastructure damage each year. Climate change will elevate these risks. If preventive measures are not taken, rising sea levels will over time inundate low-lying property and increase the amount of flooding that occurs during coastal storms. Warmer sea surface temperatures may also change the frequency and intensity of those storms.

> Catastrophe models can offer powerful business- and policy-relevant insights into future risk.

In consultation with Dr. Robert Kopp, RMS sought to simulate the effects of future sea-level rise by adjusting the surge heights for each of the over 50,000 events in our synthetic tropical cyclone hazard catalog (Kopp et al. 2014); these adjustments were meant to reflect changes in local sea level for a range of climate change projections as defined by the IPCC's latest Coupled Model Intercomparison Project Phase 5 (CMIP5) Representative Concentration Pathways (RCPs). Integrating the modified catalogs into RMS's software allowed the financial impacts to be analyzed. Because there is considerable uncertainty surrounding future coastal development patterns, accurately projecting exposure is challenging. Over the past few decades, population and property values in coastal counties have

Figure B.1 shows the increase in expected annual property losses as a result of local sea-level rise, assuming no change in hurricane activity for three RCPs. The distributions reflect the uncertainty in the climate response to each RCP.



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grown faster than the national average. The extent to which this trend will continue is unclear, given constraints to further development and expansion in many coastal areas. The analysis therefore did not attempt to predict how the built environment will evolve in the decades ahead; instead, it used RMS's in-house database of current commercial and residential property exposures to calculate the impact of future changes in sea level and storm activity relative to the coastline as it exists today.

Figure B.1. Increase in expected annual property losses in billions of U.S. dollars (shown along the x-axis) averaged over the two-decade intervals 2020–2039, 2040–2059, and 2080–2099 as a result of local sea-level rise, assuming no change in hurricane activity for three RCPs. The distributions reflect the uncertainty in the climate response to each RCP, specifically local sea-level rise (see Kopp et al. 2014). The current annual average baseline of coastal storm damages to commercial and residential property, including business interruption along the East Coast and Gulf of Mexico, is estimated to be roughly $27 billion.

Taking this analysis one step further, the impact of projected changes in hurricane frequency and intensity was also investigated. There is considerable uncertainty about how climate change will influence the frequency and intensity of hurricanes going forward, but the impact of potential hurricane activity change is significant. For example, using ensemble projections from Professor Kerry Emanuel (2013) for changes in hurricane frequency and intensity under RCP 8.5 to further modify the RMS hazard catalog, the analysis showed that average annual damage from East Coast and Gulf of Mexico hurricanes will likely grow by between $3.0 billion and $7.3 billion by 2030, an 11–22 percent increase from current levels. By 2050, the combined impact of higher sea levels and modeled changes in hurricane activity will likely raise annual losses by between $11 billion and $23 billion, roughly twice as large an increase as that from changes in local sea levels alone. By the end of the century, the combined likely impact of sea-level rise and modeled changes in hurricane activity raise average annual losses by between $62 billion and $91 billion, three times as much as higher sea levels alone.

Conclusions

Catastrophe models are an established framework for quantifying the cost of disasters. Partnerships between catastrophe modeling companies and experts in the physical implications of climate change can allow these models to be adjusted to represent future climates and the elevated risks of catastrophic losses under a changing climate. The collaboration between Risky Business and RMS has highlighted just one such application via modification of the hazard component of RMS's North Atlantic hurricane model. Further modifications that would explore the combined impact of changes in exposure or vulnerability—i.e., quantify the cost-benefit of possible mitigation and adaption measures—are also possible.

References

Emmanuel, K. 2013. "Downscaling CMIP5 Climate Models Shows Increased Tropical Cyclone Activity over the 21st Century." *Proceedings of the National Academy of Sciences of the United States of America 110: 12219–24.*

Houser, T., R. Kopp, S. Hsiang, M. Delgado, A. Jina, K. Larsen, M. Mastrandrea, S. Mohan, R. Muir-Wood, D. J. Rasmussen, J. Rising, and P. Wilson. 2014. American Climate Prospectus: Economic Risks in the United States. New York: Rhodium Group. http://rhg.com/reports/climate-prospectus.

Kopp, R. E., R. M. Horton, C. M. Little, J. X. Mitrovica, M. Oppenheimer, D. J. Rasmussen, B. H. Strauss, and C. Tebaldi. 2014. "Probabilistic 21st and 22nd Century Sea-Level Projections at a Global Network of Tide Gauge Sites." *Earth's Future 2: 287–306. doi:10.1002/2014EF000239*.

Risky Business Project. 2014. Risky Business: The Economic Risks of Climate Change in the United States. Risky Business Project. http://riskybusiness.org/uploads/files/RiskyBusiness_Report_WEB_09_08_14.pdf.

CASE STUDY C

Sinking Cities: An Integrated Approach to Solutions[1]

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In many coastal and delta cities, land subsidence exceeds absolute sea-level rise up to a factor of 10. Without action, parts of Jakarta, Ho Chi Minh City, Bangkok, and numerous other coastal cities will sink below sea level. Increased flooding and other widespread impacts of land subsidence result in damage totaling billions of dollars per year. A major cause of severe land subsidence is the excessive groundwater extraction that accompanies rapid urbanization and population growth. To deal with the hidden but urgent threat of subsidence, the problem must be thought about in new ways. The Deltares Research Institute presents a comprehensive approach that addresses land subsidence from the perspective of more sustainable and resilient urban development.

There is abundant evidence that land subsidence causes major problems worldwide:

In many coastal megacities around the world, land subsidence increases flood vulnerability (frequency, inundation depth, and duration of floods), and hence contributes to major economic damage and loss of lives. Land subsidence is responsible for significant economic losses in the form of structural damage and high maintenance costs; it affects roads and transportation networks, hydraulic infrastructure (river embankments, sluice gates, flood barriers, and pumping stations), sewage systems, buildings, and foundations. The total damage associated with subsidence worldwide is estimated at billions of dollars annually.

Because of ongoing urbanization and population growth in delta areas, in particular in coastal megacities, there is and will continue to be more economic development in subsidence-prone areas. Detrimental impacts will increase in the near future, making it necessary to address subsidence-related problems now.

The impacts of subsidence are further exacerbated by extreme weather events (short term) and rising sea levels (long term).

Subsidence is an issue that involves many policy fields, complex technical factors, and potential actors in governance. An integrated approach is needed in order to manage subsidence and develop efficient and effective approaches for both the short and long term. Urban (ground)water management, adaptive flood risk management, and related spatial planning strategies are just a few examples of the options available.

Figure C.1 illustrates the current subsidence problems related to socioeconomic development and climate change.

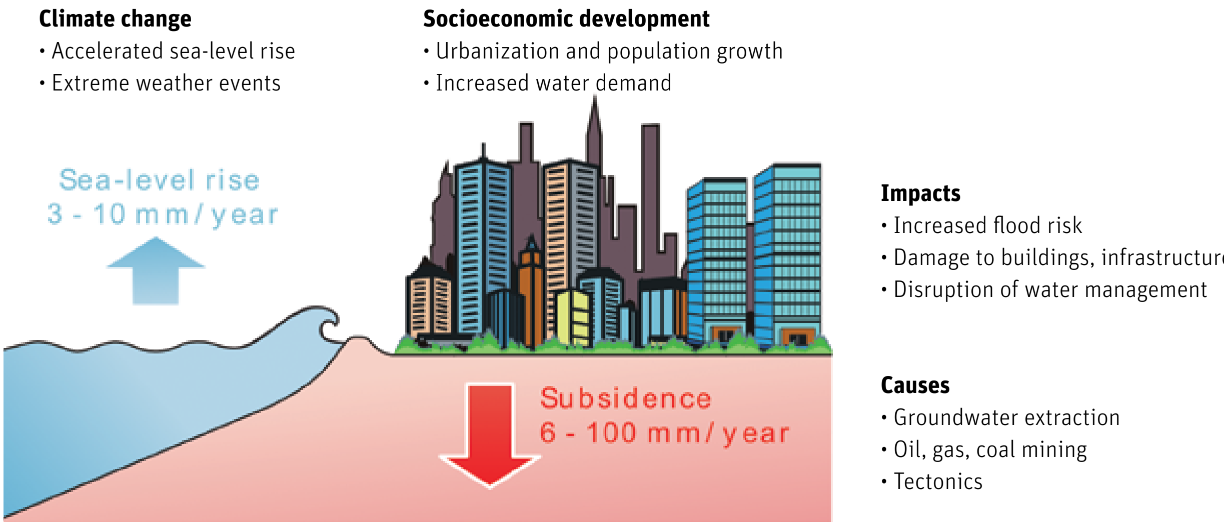
Currently, global mean absolute sea-level rise is around 3 mm/year (table C.1), and projections until 2100 based on Intergovernmental Panel on Climate Change scenarios expect a global mean absolute sea-level rise in the range of 3–10 mm/year. However, currently observed subsidence rates in coastal megacities are in the range of 6–100 mm/year (table C.2), and projections until 2025 expect similar subsidence rates, depending on what policies are adopted (figure C.2).

Monitoring

To determine land subsidence rates, accurate measuring techniques are required. These are also essential to validate subsidence prediction models. Ongoing subsidence monitoring provides the necessary insight into changes—ranging from minor to very significant—in the topography of the urban area. Such monitoring could be used to develop a so-called dynamic digital elevation model (DEM). This is not just a static, one-time (preferably high-resolution) recording of the local topography, but an elevation model that can be corrected and updated from time to time, and that

[1] Material from this case study may be cited freely but must be attributed as follows: Erkens, Gilles, Tom Bucx, Rien Dam, Ger de Lange, and John Lambert. 2015. "Sinking Cities: An Integrated Approach to Solutions." In *The Making of a Riskier Future: How Our Decisions Are Shaping Future Disaster Risk*, edited by Global Facility for Disaster Reduction and Recovery. Washington, DC: World Bank.

Figure C.1. Drivers, impact, and causes of land subsidence in coastal cities from a multi-sectoral perspective.



Source: Modified from Bucx, Ruiten, and Erkens 2013.

Table C.1. Sea-Level Rise

	Cumulative mean sea-level rise, 1900–2013 (mm)	Current rate (mm/year)	Maximum rate (mm/year)	Possible additional future sea-level rise until 2025 (mm)
Worldwide mean	195	3	—	86

Sources: Church and White 2011; Slangen 2012.
Note: — = not available.

Table C.2. Subsidence in Sinking Cities

	Mean cumulative subsidence, 1900–2013 (mm)	Mean current subsidence rate (mm/year)	Maximum subsidence rate (mm/year)	Estimated additional mean cumulative subsidence until 2025 (mm)
Jakarta	2,000	75–100	179	1,800
Ho Chi Minh City	300	Up to 80	80	200
Bangkok	1,250	20–30	120	190
New Orleans	1,130	6	26	› 200
Tokyo	4,250	Around 0	239	0
West Netherlands	275	2-10	› 17	70

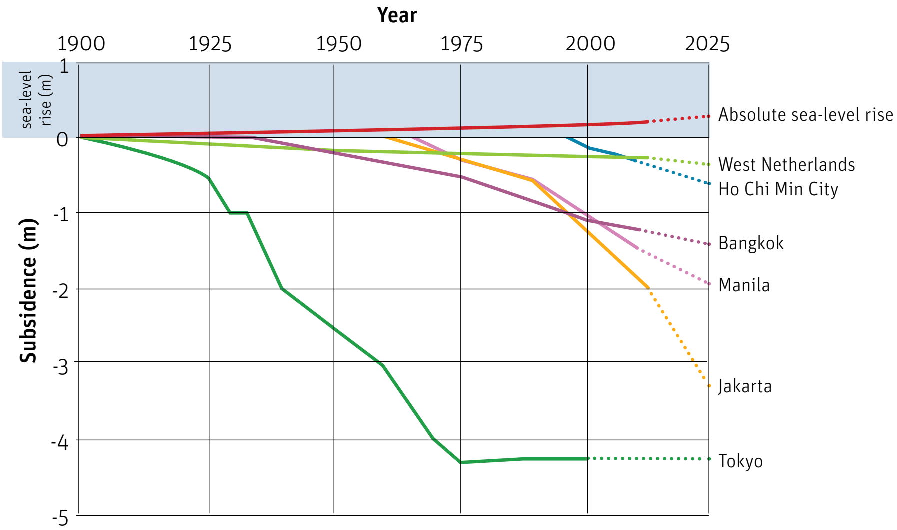
Sources: MoNRE-DGR 2012 (Bangkok); Van Trung and Minh Dinh 2009 (Ho Chi Minh City); JCDS 2011 (Jakarta); Eco, Lagmay, and Bato 2011 (Manila); Van de Ven 1993 (West Netherlands); Kaneko and Toyota 2011 (Tokyo).

can be used in hydraulic models for flood prediction and urban water management.

The following observation methods are being used to monitor subsidence:

- Optical leveling
- Global Positioning System (GPS) surveys
- Laser Imaging Detection and Ranging (LIDAR)
- Interferometric synthetic aperture radar (InSAR) satellite imagery
- Field observations (ground-truthing of buildings and infrastructure, including through the use of extensometers)

Figure C.2. Global sea-level rise and average land subsidence for several coastal cities. Subsidence can differ considerably within a city area, depending on groundwater levels and subsurface characteristics.



Source: Modified from Bucx, Ruiten, and Erkens 2013.

Following early work with systematic optical leveling, observation nowadays deploys GPS surveys and remote sensing techniques (LIDAR and InSAR) with impressive results. In contrast to surveys, LIDAR and InSAR images give a spatially resolved subsidence signal. InSAR images date back to the 1990s. Application of this technique is for the moment limited to the urban environment.

Periodic and systematic surveys remain essential for ground-truthing of subsidence rates derived from remote sensing and for validating subsidence prediction models.

Causes

Subsidence can have natural as well as anthropogenic causes. The natural causes include tectonics, glacial isostatic adjustment, and natural sediment compaction. Anthropogenic causes include compression of shallow layers (0–20 m) by loading (with buildings), or as a result of drainage and subsequent oxidation and consolidation of organic soils and peat. Alluvial sediments consisting of alternating layers of sand, clay, and peat are specifically compressible and vulnerable to oxidation. This makes low-lying coastal and delta areas very prone to subsidence. In deeper layers subsidence is caused by extraction of resources such as oil, gas, coal, salt, and groundwater.

In most of the large delta cities where subsidence is severe (Jakarta, Ho Chi Minh City, Bangkok, Dhaka, Shanghai, and Tokyo), the main cause is extraction of groundwater (figure C.3 shows the Jakarta situation). Rapidly expanding urban areas require huge amounts of water for domestic and industrial water supply. This need often leads to overexploitation of groundwater resources, especially when surface waters are seriously polluted (Jakarta, Dhaka). In Dhaka continuous large-scale extractions have caused groundwater levels to fall by on average 2.5 m per year in recent years (Hoque, Hoque, and Ahmed 2007). Moreover, in many developing cities, foundation excavations for multiple large construction activities require site dewatering. This also causes lowering of the groundwater level, resulting in soil compression and land subsidence.

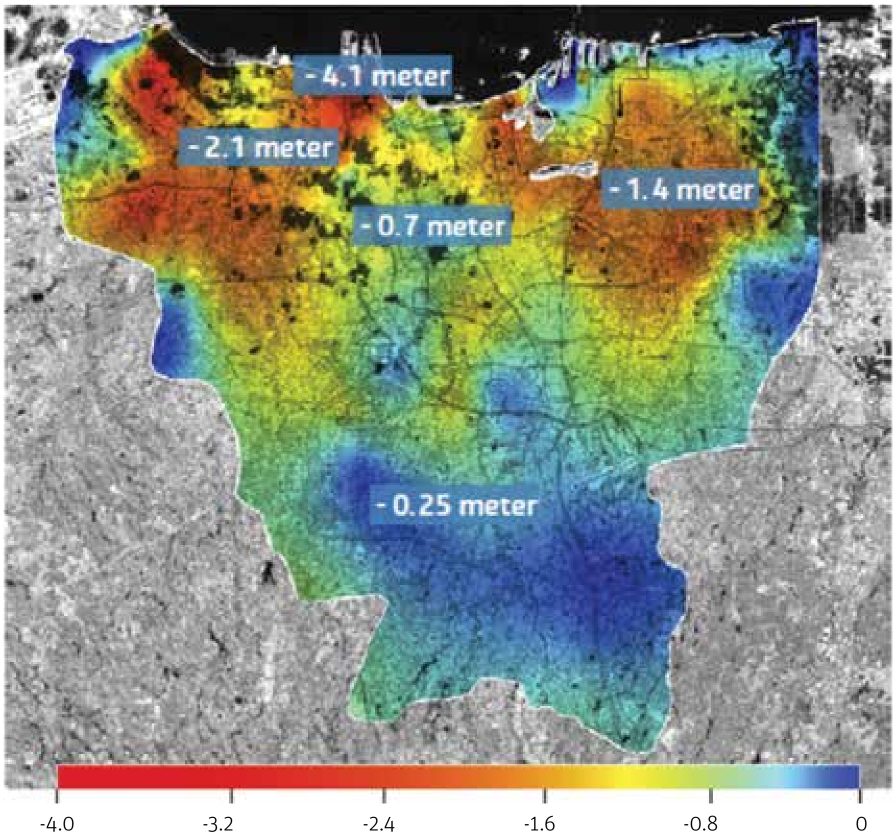
Studies in many cities have revealed a distinct relation between falling groundwater levels and subsidence (figure C.4). The resulting spatial pattern of subsidence and its progress over time are strongly related to the local composition of the subsurface and the number and location of groundwater wells.

New Orleans is a prominent example of a city where shallow drainage causes subsidence. After the organic rich soils are drained, they start to oxidize, which adds to the overall subsidence rate of 6 mm/year (Dixon et al. 2006). This process, which will go on as long as organic material is available, contributes to the sinking of the already low-lying coastal city.

State-of-the-art subsidence modeling

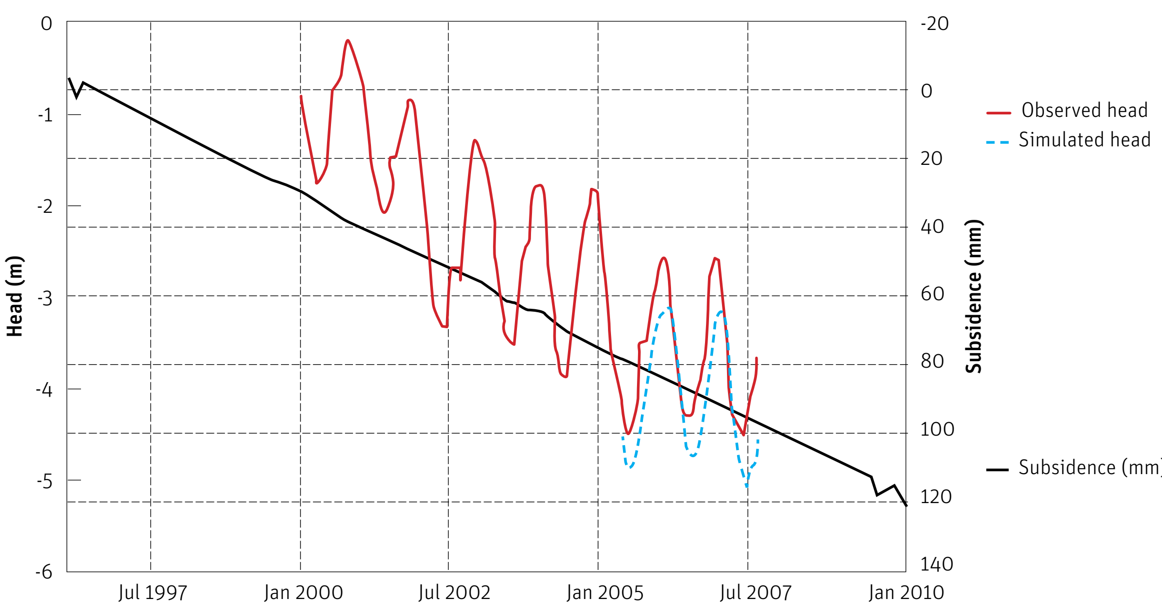
Land subsidence modeling and forecasting tools are being developed that enable Deltares Research Institute to quantitatively assess medium- to long-term land subsidence rates, and to determine and distinguish between multiple causes. Modeling tools are used as

Figure C.3. Cumulative land subsidence over the period 1974–2010 in Jakarta, Indonesia, based on GPS (Institut Teknologi Bandung) and conventional benchmark measurements (Water Resources Management Study).



Source: Modified from JCDS 2011.

Figure C.4. Distinct relation between falling groundwater level (hydraulic head) and subsidence in Ho Chi Minh City, Vietnam.



Source: Royal Haskoning-DHV and Deltares Research Institute 2013.

part of our integrated approach and are complemented with monitoring techniques (i.e., GPS leveling, InSAR monitoring). The required primary monitoring data and analytical results (of the various modeling tools) should if possible be stored in a central database.

Because land subsidence is so closely linked to excessive groundwater extraction, Deltares Research Institute has developed modeling tools that calculate land subsidence—vertical compaction—in regional groundwater flow models (figure C.5). These models enable us to make predictions for land subsidence under different scenarios of groundwater usage, understand the environmental and socioeconomic impacts of using groundwater, and contribute to integrated management of water resources.

The subsidence modeling approach uses changes in groundwater storage in subsurface layers (aquifers and aquitards) and accounts for temporal and spatial variability of geostatic and effective stresses to determine layer compaction. The modeling tool is a modified version of the groundwater flow model (developed by the U.S. Geological Survey). It has been used in several studies (Jakarta, Ho Chi Minh City) to assess the adverse consequences of groundwater extraction and to determine medium- to long-term land subsidence trends and consequences for urban flood management and vulnerability.

Impacts

Major impacts of subsidence include the following:

- Increased flood risk (due to increased frequency, depth, and duration of inundation) and more frequent rainfall-induced floods due to ineffective drainage systems
- Damage to buildings, foundations, infrastructure (roads, bridges, dikes), and subsurface structures (drainage, sewerage, gas pipes, etc.)
- Disruption of water management and related effects (changing gradient of streams, canals, and drains; increased saltwater intrusion; increased need for pumping)

As available space for building and development decreases, there is an increase in housing, industrial estates, and infrastructure situated in subsidence-prone (marginal) lands, such as floodplains and coastal marshes (Jakarta, New Orleans)—with obvious consequences.

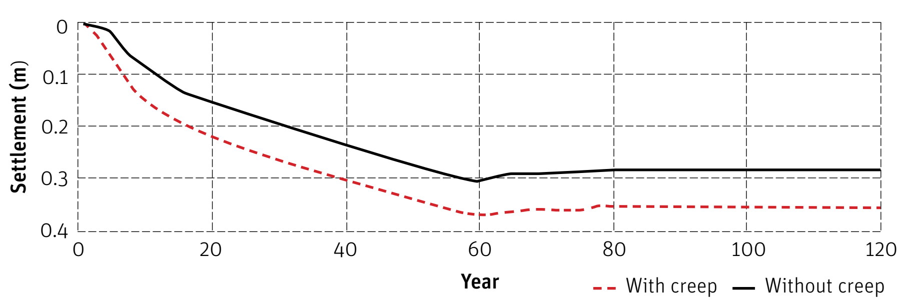
These impacts will be aggravated over the long term by future climate change impacts, such as sea-level rise, increased storm surges, and changes in precipitation.

Subsidence leads to direct and indirect damage. Direct effects include loss of functionality or integrity of structures like buildings, roads, and underground utility networks (critical infrastructure). The most common indirect effects of damage are related to changes in relative water levels, both for groundwater and surface water.

The estimation of associated costs is very complex. In practice, operational and maintenance costs are considered in several short- and long-term policies and budgeting. The costs appear on financial sheets as ad hoc investments or planned maintenance schemes, but not as damage costs related to subsidence.

In China, the average total economic loss due to subsidence is estimated at around US$1.5 billion per year, of which 80–90 percent is from indirect losses. In Shanghai, over the period 2001–2010, the total loss

Figure C.5. The influence of creep, the slow and largely irreversible component of subsidence, as determined by Deltares's new subsidence model. Specifically in aquifers with many fine-grained interbeds, creep clearly adds to the total amount of settlement over time and should not be neglected.



Source: Deltares Research Institute.

cumulates to approximately US$2 billion (Tiefeng 2012). In Bangkok, where many private and public buildings, roads, pavements, levees, and underground infrastructure (sewerage, drainage) are severely damaged by subsidence, proper estimates of the costs of damage are not available.

In 2006, the total cost of subsidence-related damage in the Netherlands was estimated at over €3.5 billion per year (Muntendam-Bos et al. 2006). The majority of these costs will not be recognized directly as damage due to subsidence. Note that the construction site preparation and construction costs in soft-soil areas should be considered as subsidence-related costs, as these are mainly incurred to prevent consolidation. Because of ongoing economic and urban development, the potential damage costs for subsidence will increase considerably in the future, especially in subsidence-prone areas such as floodplains.

Responses

In pristine deltas, the naturally occurring subsidence is compensated for by the sediment delivered by the river. Nowadays, however, many river systems deliver much less sediment to their deltas because sediment is trapped by upstream dams or is extracted for building material. With limited sediment supply, natural subsidence remains inadequately compensated. In many delta cities, there is additional human-induced subsidence, making these urban areas the delta subsidence hot spots. Measures to counteract anthropogenic subsidence are in most cases initiated only when the detrimental impacts become apparent, in the form of flooding or serious damage to buildings and infrastructure. Responses until now have largely focused on restricting groundwater extraction, making some spatial planning adjustments, or locally raising the level of the land. A comprehensive and integrated (multi-sectoral) approach is often lacking.

In the **Greater Jakarta area** (figure C.3), metropolitan authorities and technical agencies are advocating the reduction of groundwater extraction in vulnerable areas. The goal is to completely phase out the use of groundwater and tax groundwater consumption, an approach that would require developing an alternative water supply for large industrial users or relocating large groundwater users outside the so-called critical zones. The number of unregistered users is still a problem. Ongoing economic development and city expansion lead to the filling of low-lying and flood-prone lands with mineral aggregates and (often) waste materials. To some extent, spatial planning measures were applied to avoid subsidence-prone areas, but fast growth of informal settlements has made many of these plans obsolete. Recently the Jakarta Coastal Defence Strategy program integrated the results of various subsidence studies and tried to obtain reliable figures for current and future subsidence (JCDS 2011). This subsidence prognosis is regarded as an extremely vital component of an integrated flood management and coastal defense strategy.

In **Bangkok**, regulation of and restrictions on groundwater extraction have successfully reduced extreme land subsidence. A specific law (the Groundwater Act) was enacted in 1977. The most severely affected areas were designated as critical zones, and the government was given more control over private and public groundwater activities in these areas. Groundwater use charges were first implemented in 1985 and have gradually increased. Currently, about 10 percent of the total water use in Bangkok is from groundwater extraction. Subsidence continues but at a much slower pace than before.

Although land subsidence in **Ho Chi Minh City** has been observed since 1997, there is still considerable disagreement about its causes and impacts. This is partly due to poor monitoring data on land subsidence and groundwater extraction. Restrictions on groundwater extraction have been initiated, but it is too early to observe effects. Besides the registered groundwater exploitation, which draws mainly from the deeper aquifers, there is significant unregistered extraction for domestic water supply. The total drawdown rate shows no sign of decreasing because of these unofficial activities and perhaps also because urbanization has reduced the infiltration area, which in turn hinders recharge.

In **New Orleans** and the Mississippi delta, there is as yet no coordinated strategy for mitigating subsidence.

The extraction of oil and gas is of great economic importance for the region, and economic pressures will likely stimulate rather than limit it. The debate on groundwater use in New Orleans has only recently started, as its contribution to subsidence is so far unknown. The recently published water management strategy for New Orleans, however, recommends raising water levels in areas with organic rich soils, reducing oxidation of organic matter, and mitigating subsidence. The Mississippi delta is starved of sediment because of construction of dams and erosion-prevention measures upstream in the catchment. The Coastal Master Plan for the Mississippi delta includes plans to reintroduce sediment-loaded floodwaters to the delta once more.

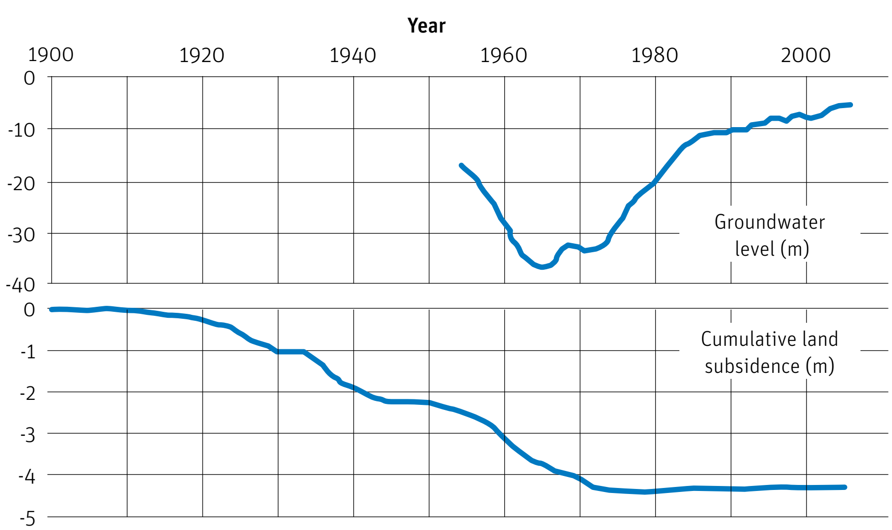
In Tokyo, regulations restricting groundwater use were imposed in the early 1960s. The groundwater levels began to increase as a result and after around 10 years the subsidence was stopped (see figure C6).

As the relationship between groundwater extraction and land subsidence came to be better understood, techniques were developed in **Shanghai** to restore groundwater levels with active or passive recharge. Although this approach reduced the further lowering of groundwater tables and limited subsidence, it did not solve immediate problems, notably the effect of subsidence on infrastructure, roads, and buildings. Further developments in Shanghai have shown that active and substantial recharge makes sustainable groundwater use possible, without severe subsidence, provided that average yearly pumping rates are in balance with the average yearly recharge.

In **Dhaka**, increasing problems with flooding and water supply are resulting in more attention to excessive groundwater extraction and subsidence. Although many areas are subsidence prone in this rapidly expanding city, data on subsidence and its impacts are currently lacking. At present, 87 percent of the supplied water is from groundwater extraction (Sengupta, Kang, and Jacob 2012), and it has been acknowledged that a shift to using surface water is necessary. However, treating surface water is much more technically complex and expensive than using groundwater, in part because the large rivers nearest to Dhaka are polluted by the economically important textile industry, among others.

A flood event can lead to more attention for subsidence. This happened in November 2007, for example, when the northern part of Jakarta, which is heavily subsided and below sea level, was flooded by the sea during an extremely high tide. For a long time, land subsidence was not really seen as one of the root causes of flooding. Nowadays, there is increasing awareness that land subsidence has to be integrated into long-term flood management and mitigation strategies.

Figure C.6. **Land subsidence and groundwater level in Tokyo area.**

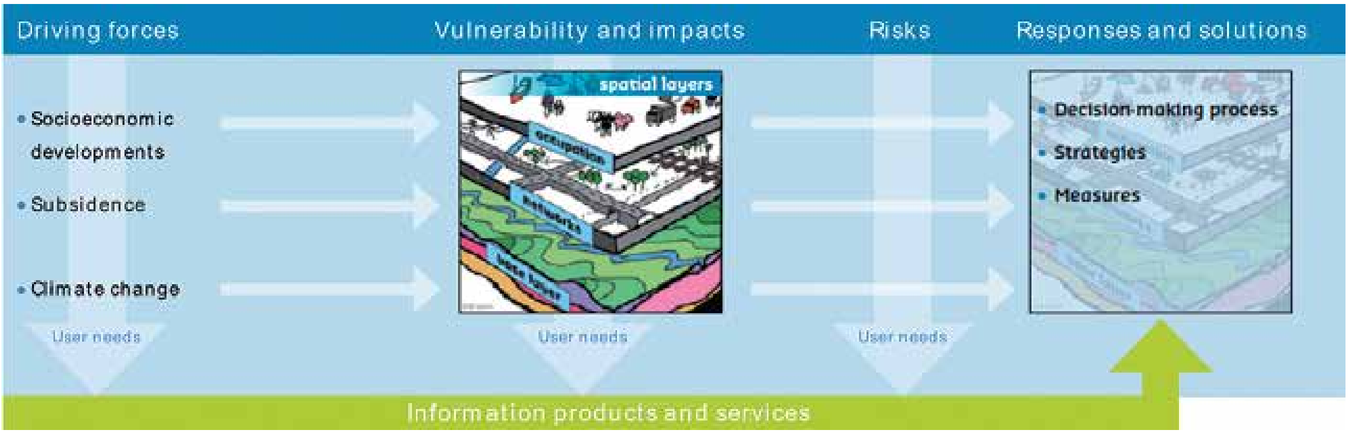


Source: Modified from Kaneko and Toyota 2011.

Integrated approach

Land subsidence is often literally a hidden issue. Not only does it take place out of sight, but its complex, cross-sectoral nature means that it is rarely fully recognized (or acknowledged), especially in the domain of governance and institutional mandates and responsibilities. As yet, insufficient account is taken of natural resource management, regional (urban) development, and strategic spatial planning, and in particular urban

Figure C.7. DPSIR approach to subsidence.



Source: Bucx, Ruiten, and Erkens 2013.

flood management, infrastructure design, and infrastructure maintenance. The detrimental effects of subsidence are ignored until they become a serious and costly issue, one causing significant economic losses and posing a nuisance to millions of people. A further difficulty is that acquiring, processing, and disseminating land subsidence information so that it reaches diverse stakeholders and decision makers is a complicated and multifaceted task.

If proper attention is paid to developing the required technical, administrative, and institutional capabilities, the harmful impacts of land subsidence can be mitigated and the process largely stopped. A comprehensive and integrated approach is therefore needed. It would carry out the following:

- *Raise awareness* about land subsidence, to involve relevant stakeholders and to determine ownership and responsibilities
- *Organize systematic monitoring* and ensure that data are reliable and easily accessible
- *Develop in-depth knowledge* about the process of subsidence and develop models and tools to assess and forecast subsidence and to measure the effects of mitigative efforts
- *Assess vulnerabilities, risks, and impacts* regarding flooding, buildings, infrastructure, roads, and subsurface infrastructure, in the short and long term, including costs
- *Develop responses and solutions* in a context of sustainable natural resources management, climate change scenarios, and socioeconomic development
- *Address governance* by means of multi-sectoral policy development and coordination; seek participation of all relevant stakeholders; and develop innovative financing structures
- *Support decision makers* with models and tools for selecting the most appropriate adaptive measures (best practices), including their costs and benefits
- *Facilitate exchange of knowledge and best practices* in order to avoid repetitive problems and duplication of (research) activities

Deltares Research Institute has developed an integrated assessment framework that can be applied to any subsidence case. It is based on the DPSIR (driving forces, pressures, state, impacts, and responses) approach and on a spatial layer model (see figure C.7). The DPSIR elements cover the cause-effect-response chain being elaborated for three spatial layers: the occupation layer (land and water use), network layer (infrastructure), and base layer (natural resources subsurface).

The DPSIR assessment uses a set blueprint to look at a city's science and policy activities in order to address subsidence. It asks a series of questions that are commonly relevant for developing a successful subsidence coping strategy (table C.3): What are the main causes? What is the current subsidence rate? What are future scenarios? What are the impacts and risks? How can adverse impacts be mitigated or compensated for? Who is involved and responsible to act? As cities seek to answer these technical and governance questions, the integrated approach supports the (policy) development path that cities should follow, from problem identification to planning and implementation of solutions and their evaluation. Every subsiding city is somewhere along this development path (see table C.3), ranging from an early analysis stage (for instance Dhaka, Bangladesh) to a stage at the other end of the spectrum where the problem seems more or less to have been solved (for instance Tokyo, Japan).

Table C.3. Questions That Need to Be Addressed to Develop a Successful Coping Strategy for Subsidence

Steps	Questions	Technical aspects	Governance aspects	City example (state of development)
1. Problem analysis	How much subsidence is there? What are the causes? Who is involved and responsible?	Measurement data collection Data analyses to disentangle subsidence causes (Inverse) modeling to make predictions	Awareness raising Stakeholder analysis and identification of problem owners	Dhaka Manila New Orleans Jakarta
2. Planning	How much future subsidence is predicted? What are the current and future impacts (monetized)? What are most vulnerable areas? What are possible solutions?	Scenario constructions Modeling/forecasting Damage assessments Vulnerability and risk assessments Decision support systems (6) Cost-benefit analyses/ Multicriteria analysis Selection of structural measures in an integrated multi-sectoral perspective	Capacity building and education Multi-sectoral planning, participation, stakeholder engagement, and commitment (4, 5) Political action; development of policy, strategy, and legal instruments Planning and design of buildings and infrastructure, including building codes (8) Decision making on implementation (5) Selection of nonstructural measures	Ho Chi Minh City
3. Implementation	What will be done, how and when and by whom?	Installation of monitoring systems (7) Establishment of pilot projects Proposals for innovative (alternative) solutions (3) Implementation of structural mitigating and/or adapting measures (1, 2, 3) Exchange of knowledge and best practices (10)	Multi-sectoral cooperation and organizational structure Implementation of nonstructural measures (1) Legal framework and operational procedures/ guidelines Enforcement of laws and regulations Financing mechanisms and asset management (9)	Bangkok
4. Evaluation	Is the problem under control?	Monitoring, remodeling Compliance checking Assessment and outlook	Stakeholder evaluations Public hearing	Tokyo Shanghai

Note: The numbers in parentheses refer to the following key issues, discussed in more detail below: (1) Restriction of groundwater extraction; (2) natural and artificial recharge of aquifers; (3) development of alternative water supply (instead of groundwater); (4) integrated (urban) floodwater management; (5) improving governance and decision making; (6) decision support models and tools; (7) appropriate monitoring and database system; (8) integration of geotechnical aspects in planning and design of buildings and infrastructure; (9) asset management, financing, and public-private partnerships; (10) exchange of knowledge and best practices.

Key issues in subsidence policy and research

In the framework of an integrated approach to subsidence, 10 key issues are presented here along with possible solutions.

1. Restriction of groundwater extraction

This measure is very important for counteracting human-induced subsidence.
In vulnerable areas, extraction of groundwater should be reduced or completely phased out. Any relevant legislation or regulation, such as the following, should be consistently implemented and enforced:

- Designation of groundwater regions and critical zones
- Restricted licensing and compliance checking for groundwater well drilling
- Universal groundwater use metering and charges for groundwater use

2. Natural and artificial recharge of aquifers

When addressed consistently and effectively, the reduction of groundwater mining can eliminate one of the primary causes of land subsidence. However, the prolonged effects of settlement, possibly taking up to 10 years, are not immediately solved. Natural and/or controlled groundwater recharge may be applied to speed up recovery, as well as controlled aquifer storage and recovery, a practice currently being developed and implemented in Shanghai and Bangkok.

3. Development of alternative water supply (instead of groundwater)

To meet the increasing (urban) water demand, an alternative water supply for industry and domestic users is required. The process of shifting to an alternative supply should include water demand assessments (water footprint) and cost/benefit assessments. Addressing and reducing surface water pollution is vital for developing a sustainable alternative water supply.

4. Integrated (urban) floodwater management

Improved groundwater management and subsidence studies should be part of an integrated urban water (resources) management strategy that includes the whole water-subsurface system. Water resources management should be linked to flood mitigation. Ultimately, land subsidence is closely linked to integrated land and water management, including surface as well as subsurface resources and constraints.

5. Improving governance and decision making

In many cases, current governance is inadequate to address subsidence through an integrated multi-sectoral approach and to develop sustainable short- and long-term solutions. Improving governance involves raising (public) awareness, encouraging (public) participation, fostering cooperation and coordination between stakeholders at different scales and levels, and enabling good decision making buttressed by decision support models and tools.

6. Decision support models and tools

To support good decision making, models and tools are needed.
It is especially important to analyze the relationship between groundwater level and subsidence, develop modeling and forecasting capabilities, and implement an integrated groundwater-subsidence monitoring and analytical model. Moreover, it is essential that local agencies have the expertise and tools to conduct studies, and that they are engaged in ongoing capacity building, training, and knowledge exchange.

7. Appropriate monitoring and database system

Ongoing studies show that the weak spot in efforts to reduce subsidence and related flood risk is access to reliable ground-truth data. To strengthen this area of weakness and build a good database with long-time measurements of subsidence, it is necessary to develop and maintain geodetic monitoring networks throughout the metropolitan areas, with stable, precisely calibrated benchmarks and periodic leveling surveys.

8. Integration of geotechnical aspects in planning and design of buildings and infrastructure

In the planning and design of (heavy) buildings and road infrastructure, geotechnical research and modeling of the subsoil should be taken into account in order to avoid subsidence problems, including differential settlements, in the short or long term. This approach will avoid considerable damage and high maintenance costs of infrastructure and buildings (foundations). During underground construction activities (those for deep parking lots or metro stations or involving tunneling), the effects of dewatering should be minimized and, if necessary, monitored and/or mitigated.

9. Asset management, financing, and public-private partnerships

To minimize damage caused by subsidence, the main financial risks associated with investments and maintenance of assets (buildings, infrastructure) should be assessed. This approach, which will lead to improved design options, programming, and prioritization of investments, involves determining performance indicators, functional specifications, risk mitigation measures, and bonus/malus in (innovative) contracts. Moreover, public-private partnerships and private financing approaches that build on sustainable business models should be explored.

10. Exchange of knowledge and best practices

Through international conferences, workshops, expert meetings, and courses, knowledge and best practices can be exchanged to extend the common knowledge base efficiently and effectively. This step can be further supported by development of collaborative research projects, preferably in the framework of international (research) networks and initiatives such as UNESCO and the Delta Alliance.

References

Bucx, T., K. van Ruiten, and G. Erkens. 2013. "An Integrated Assessment Framework for Land Subsidence in Delta Cities." Abstract EP34B-03 presented at American Geophysical Union fall meeting, San Francisco, December 5–9.

Church, J. A., and N. J. White. 2011. "Sea-Level Rise from the Late 19th to the Early 21st Century." *Surveys in Geophysics* 32, no. 4–5: 585–602.

Dixon, T. H., F. Amelung, A. Ferretti, F. Novali, F. Rocca, R. Dokka, G. Sella, and S. W. Kim. 2006. "Subsidence and Flooding in New Orleans: A Subsidence Map of the City Offers Insight into the Failure of the Levees During Hurricane Katrina." *Nature* 441: 587–88.

Eco, R. C., A. A. Lagmay, and M. P. Bato. 2011. "Investigating Ground Deformation and Subsidence in Northern Metro Manila, Philippines Using Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR)." Abstract G23A-0822 presented at American Geophysical Union fall meeting, San Francisco, December 5–9.

Hoque, M. A., M. M. Hoque, and K. M. Ahmed. 2007. "Declining Groundwater Level and Aquifer Dewatering in Dhaka Metropolitan Area, Bangladesh: Causes and Quantification. *Hydrogeology Journal* 15: 1523–34.

JCDS (Jakarta Coastal Defence Strategy). 2011. "Atlas JCDS." Jakarta, Ministry of Public Works, Deltares Research Institute, and Urban Solutions.

Kaneko, S., and T. Toyota. 2011. "Long-Term Urbanization and Land Subsidence in Asian Megacities: An Indicators System Approach." In *Groundwater and Subsurface Environments: Human Impacts in Asian Coastal Cities, ed. Makoto Taniguchi, 249–70.Tokyo: Springer.*

MoNRE-DGR (Ministry of Natural Resources and Environment, Department of Groundwater Resources). 2012. "The Study of Systematic Land Subsidence Monitoring on Critical Groundwater Used Area Project." Study by Phisut Technology, Bangkok, Thailand, for the Department of Groundwater Resources of the Ministry of Natural Resources and Environment, Bangkok, Thailand. Report number 2555.

Muntendam-Bos, A. G., I. C. Kroon, P. A. Fokker, and G. de Lange. 2006. "Bodemdaling in Nederland." TNO (Dutch Geological Survey).

Royal Haskoning-DHV and Deltares Research Institute. 2013. "Annex 3: Land Subsidence." In *Ho Chi Minh City Flood and Inundation Management: Final Report*. Vol. 2: *IFRM Strategy*. Report number 9T4178.21 for the Client Steering Centre for Urban Flood Control Program, Ho Chi Minh City, Vietnam.

Sengupta, S., A. Kang, and N. Jacob. 2012. "Water Wealth: A Briefing Paper on the State of Groundwater Management in Bangladesh." Centre for Science and Environment Bangladesh. http://www.cseindia.org/userfiles/groundwater_management_bangladesh.pdf.

Slangen, A. B. A. 2012. "Towards Regional Projections of Twenty-First Century Sea-Level Change Based on IPCC SRES Scenarios." *Climate Dynamics* 38: 5–6.

Tiefeng, Li. 2012. "Land Subsidence Monitoring, Prevention and Controlling in Coastal Cities in China." Contribution to the Expert Meeting on Land Subsidence in Coastal Megacities, Malaysia, November 9.

Van de Ven, G. P. 1993. *Man-Made Lowlands: History of Water Management and Land Reclamation in the Netherlands*. Utrecht: Uitgeverij Matrijs.

Van Trung, L., and H. T. Minh Dinh. 2009. "Monitoring Land Deformation Using Permanent Scatterer INSAR Techniques (Case Study: Ho Chi Minh City)." Paper presented at the seventh International Federation of Surveyors (FIG) Regional Conference, Hanoi, October 19 –22.

CASE STUDY D

The Evolving Risk of Earthquakes: Past, Present, and Future

James Edward Daniell (Karlsruhe Institute of Technology)

Earthquakes have always had the power to shape nations and their path through history. The major earthquakes—such as those in Lisbon in 382 and 1755, Shemakha in 1667 and 1902, Tokyo in 1703 and 1923, Managua in 1972, the Indian Ocean in 2004, Hawkes Bay in 1931, and Christchurch in 2011—cause major losses within seconds, but exert an influence on countries for years afterward.

The world today is very different from what it was 100 years ago. Global trade makes it more interconnected; building standards and engineering quality have improved; the impacts of earthquakes are better understood; and populations and exposure have increased in certain locations. As a result of these changes, some aspects of the world are less vulnerable today than they once were, and some are more. In most earthquake-prone countries, the traditional nonengineered masonry structures are slowly being phased out in response to better knowledge of the way these structures react to earthquakes; however, in some megacities, where rapid expansion is occurring due to uncontrolled population increase, nonengineered building is still occurring at an alarming rate.

As the world continues to evolve, the removal of historically vulnerable building stock and improvement of capital will lead to a reduction in losses as a total percentage of that stock. Global changes will also affect the economic flow processes of production, so that in certain cases services will be significantly affected. This study explores these trends, starting from the past and moving through the present to the future.

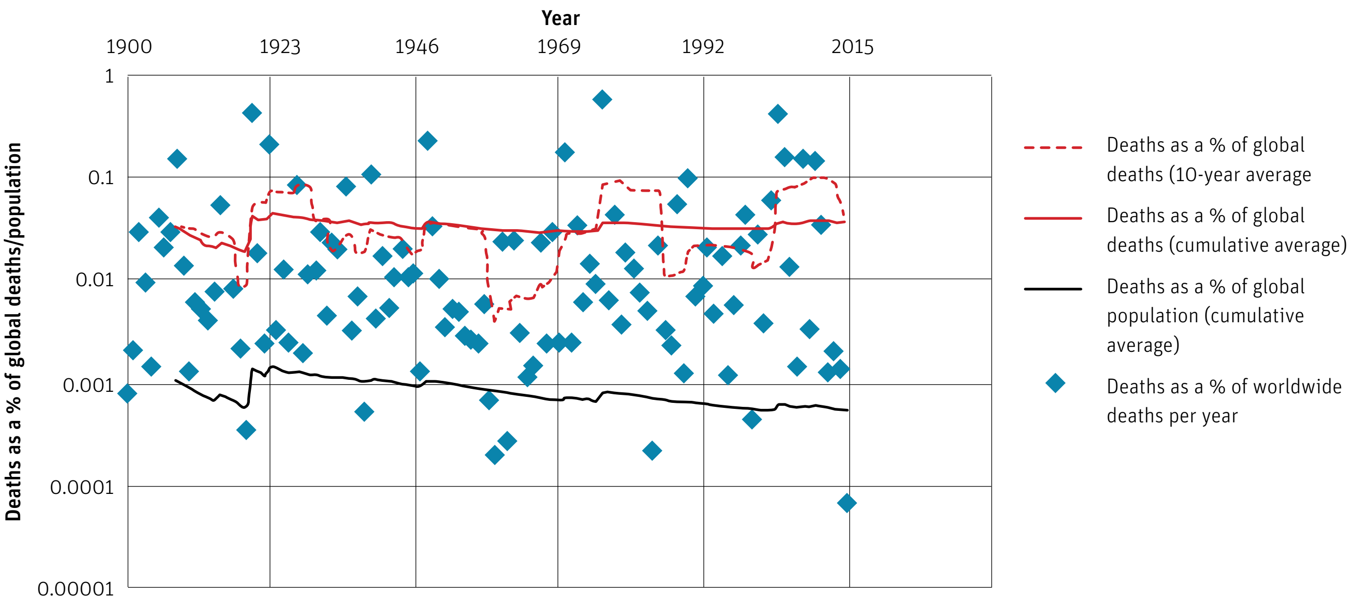
Historical global trends of earthquakes

Information about countries' earthquake risk is available in the natural disaster databases collected in CATDAT, the largest global database of historical damaging earthquake events. The data set for each new event is available in annual releases on www.earthquake-report.com, and as part of collaboration projects for subsets of data. CATDAT includes not only the historical loss estimates of over 13,000 damaging earthquakes (more than 7,500 since 1900) and footprints of each earthquake, but also socioeconomic indicators through time, such as population, human development, economic inflation estimates, and other key characteristics that allow earthquake trends to be examined. Data in CATDAT on the economic loss and death toll from each of the damaging earthquakes from 1900 to 2014 were used to calculate the temporal trend of disaster losses discussed below (Daniell et al. 2011).

The losses were adjusted to 2014 dollars using the HNDECI, a hybrid index of inflation metrics that is better suited than a consumer price index to the capital and flow losses seen in natural disasters (Daniell, Wenzel, and Khazai 2010). Using information for the period 1900–2014 on the global population as well as the global death rate, which takes into account war and disaster deaths as well as all non-disaster-related deaths, figure D.1 shows the long-term averages of earthquake deaths from nearly 2,100 fatal events as a percentage of worldwide deaths and population.

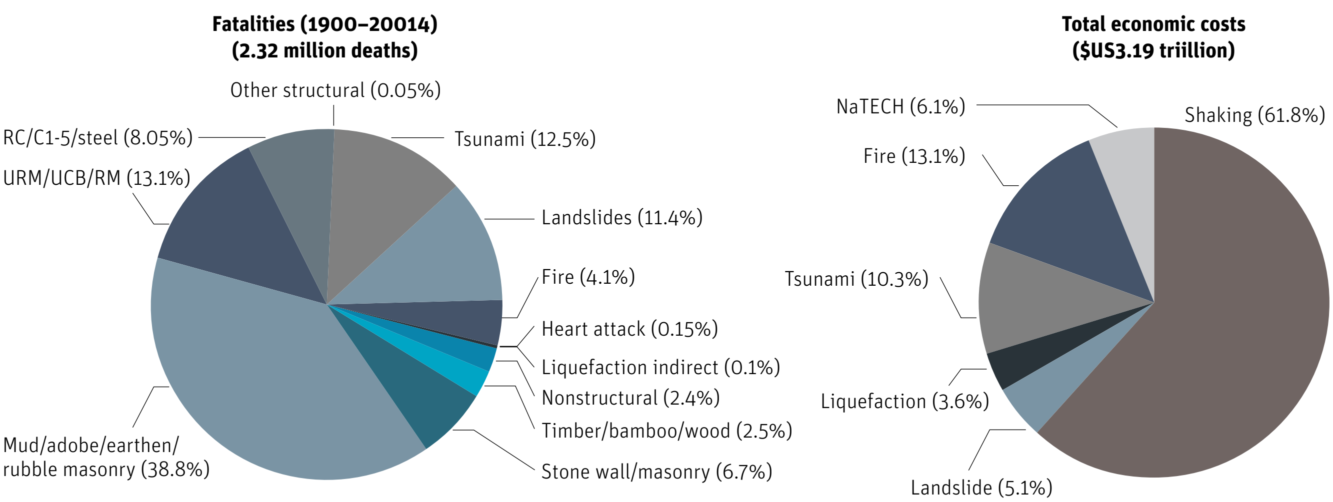
The death rate from all causes worldwide decreased as the average life expectancy worldwide was increasing. A range of 48.1 million to 77.9 million deaths per year is seen globally, with a maximum in 1918 and minimum in 1972. Using a 10-year average for yearly deaths worldwide makes it possible to determine the general trend for earthquake deaths per year as a percentage of total global deaths. The death rate is affected by the major events and is periodic, but it is constant as a percentage of global deaths per year. Although the 10-year average has been increasing, the last four-year period since 2011 has been one of the quietest on record, meaning a current return to the long-term average. As a percentage of global population, the deaths from earthquakes have also been decreasing, meaning that even with increasing life expectancy, a declining earthquake fatality rate is observed. Categorizing each of the earthquake-related fatalities by source of fatality shows that just under 60 percent of fatalities have occurred as a result of masonry failures (figure D.2).

Figure D.1. Fatalities from earthquakes as a percentage of global deaths and as a percentage of global population, summed in each year. The trend relative to the population decreases, but the trend as a percentage of global deaths is constant.



Source: Calculations based on data in CATDAT.

Figure D.2. The reason for fatalities from about 2,100+ fatal earthquakes in the period 1900–2014 (left), and the disaggregated total economic costs cumulated from 7,500+ damaging earthquakes (right).



Source: Calculations based on data in CATDAT.

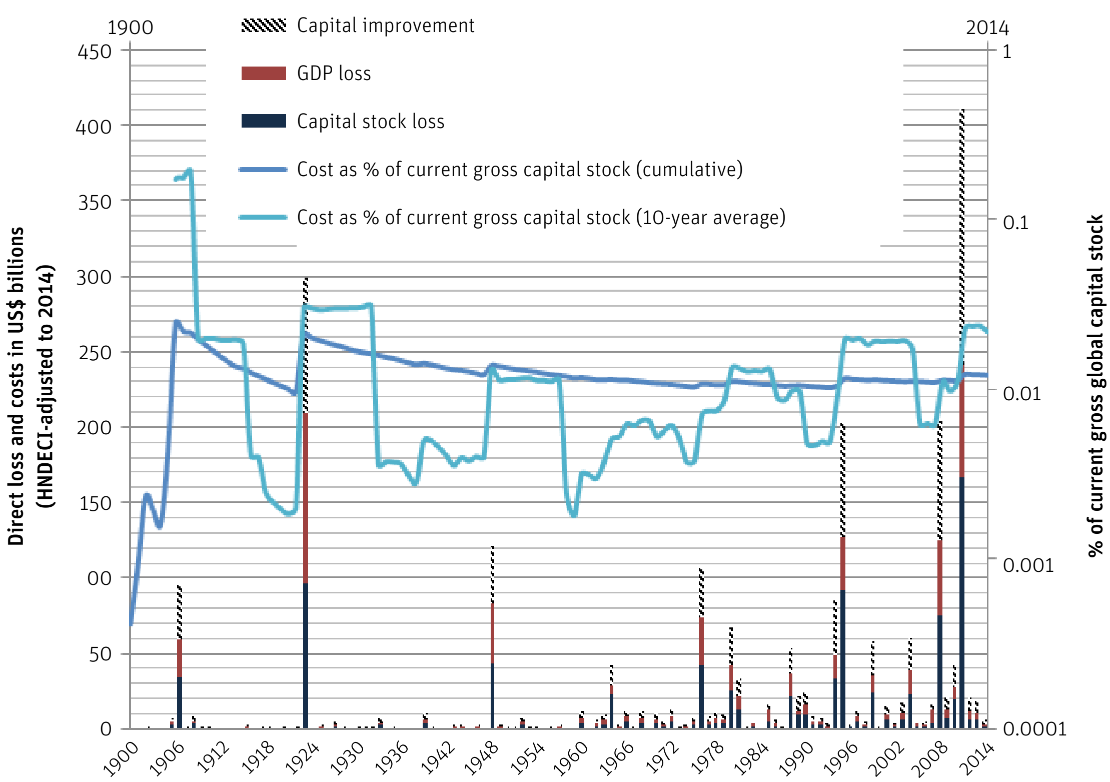
Note: RC/C1-5 = reinforced concrete/concrete building typologies; URM/UCB/RM = unreinforced masonry/unreinforced concrete block masonry/reinforced masonry; Lq = liquefaction; NaTECH = natural hazard triggering a technological disaster. Dollar amount in right-hand figure was adjusted to 2014 dollars using the HNDECI.

In contrast with the decreased fatality rate, absolute loss is observed to increase through the period from 1900 to 2014, as seen in figure D.3. An order of magnitude change in baseline losses can be seen when the period is split into two component parts (1900–1956 and 1957–2014). The losses increase as an absolute number, but there is a reduction in losses as a percentage of global gross domestic product (GDP) or gross capital stock. The resulting earthquake loss has two components associated with it: the capital stock loss (building and infrastructure losses) and the GDP loss (split from capital). The cost of an earthquake includes these two components as well as a third: the capital improvement as a result of the reconstruction from net (depreciated) to gross (new) capital stock. This analysis suggests that buildings are becoming safer, but because safer building typologies are more expensive to construct, damage to those buildings incurs greater reconstruction costs.

The age of infrastructure and the impact of building standards in recent earthquakes

The data suggest that the relative losses from disasters are decreasing slightly over time, while absolute losses are increasing. This finding seems to match the preconception that the building standards for life safety improve with development via performance-engineered structures and better building standards globally, as seen from the fatality trends in developed countries from 1900 to 2014. A key indicator of the economic damage ratio is building age. As newer building stock replaces the old stock, the damage ratio will continue to decrease over time. This change is directly correlated to the Human Development Index (HDI) (UNDP 2014), with the socioeconomic fragility functions of Daniell (2014) showing highly

Figure D.3. **Economic losses and costs from earthquakes occurring 1900–2014, as well as the relative cost versus the global gross capital stock. A reduction over time can be seen as a percentage of gross capital stock or GDP.**



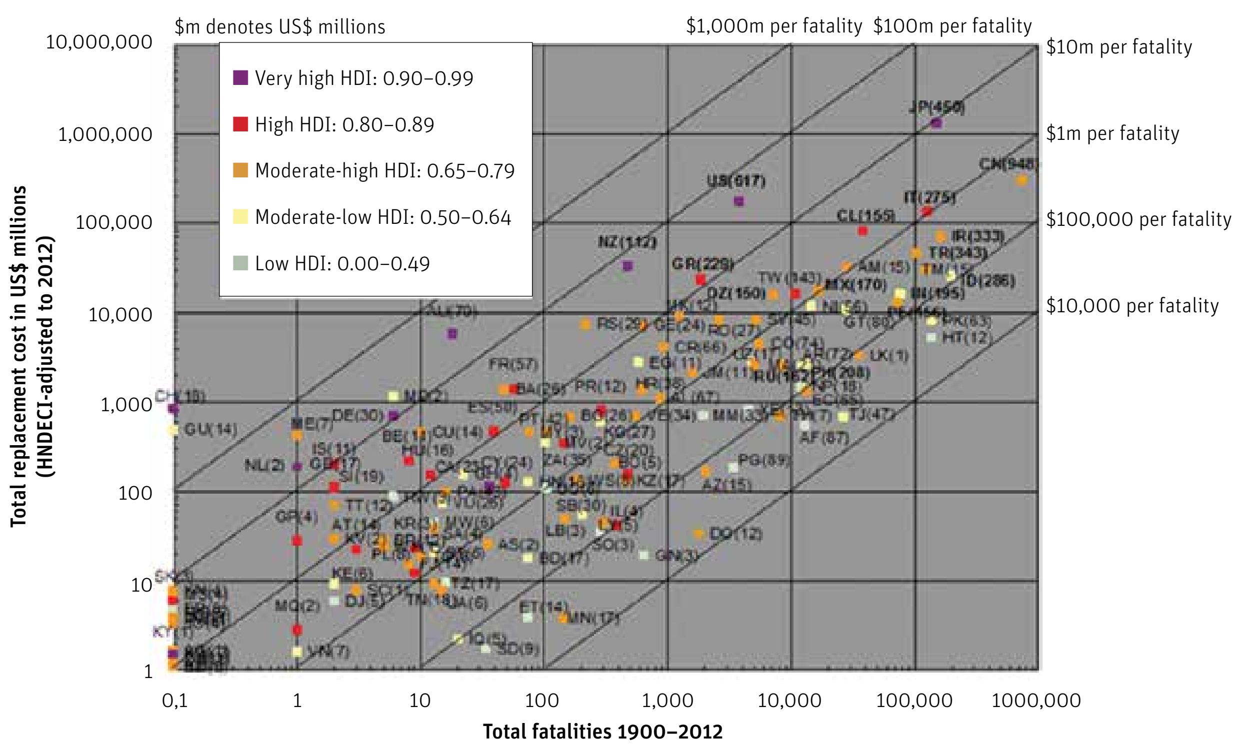
Source: CATDAT.

developed nations reducing earthquake damage ratios from major events over time. Daniell (2014) correlates 7,200 individual events against the province and subprovince HDI of the event, and against the damage ratios from 1900 to 2012. As shown in figure D.4, the higher-HDI countries generally have a higher loss-per-fatality ratio, demonstrating the reduction in fatality rate (via improved construction standards) and increase in economic loss as HDI increases.

A good example of the change over time is the 1995 Kobe earthquake. As shown in figure D.5, older buildings were far more vulnerable in this event than newer ones. Of the buildings destroyed or demolished in the Kobe earthquake, 99 percent were built before 1980, although pre-1980 buildings represented only 64 percent of the total building stock. This means that the remaining 36 percent of stock, built after 1980, suffered only 1 percent of the destruction. Clearly, lesser age, better building standards, and greater earthquake knowledge are key parameters for better earthquake outcomes.

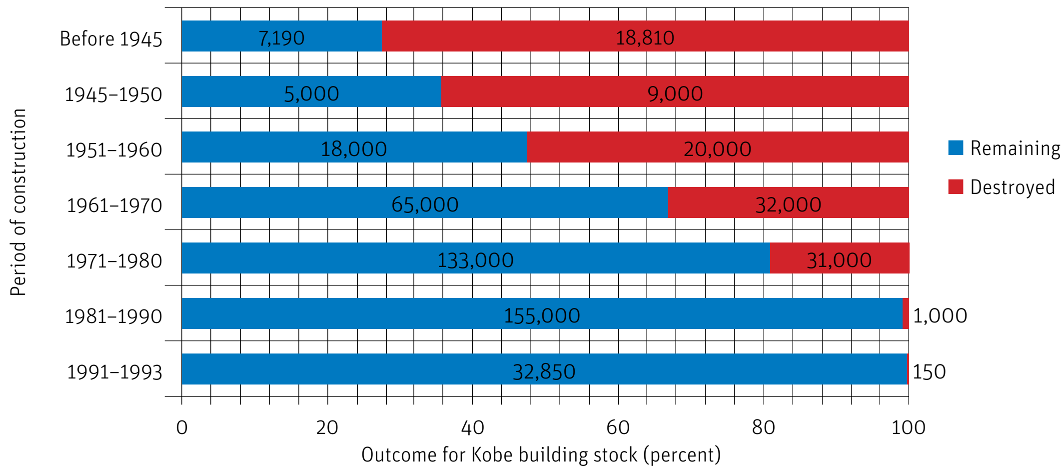
The gross (replacement value of assets) and net (depreciated value of assets at book value) capital stock loss ratios for Kobe are shown in figure D.6, with the striped portion indicating the loss and the entire column indicating the percentage of total building value. Losses for the newer building stock (under code, and better built) represent a smaller share of the total value than losses for the older building stock. In total globally, building stock replacement is occurring at a fast rate, with at least 1–2 percent of capital being replaced annually. When the ratio of gross capital stock to net capital stock in 1995—1.685—is used to calculate actual loss, the result is US$66.5 billion, reduced from the US$112 billion replacement cost/repair cost quoted post-disaster. Based on the sum of the value of all buildings in Kobe, the average construction year of net capital stock was 1976 (meaning that buildings were on average 19 years old at the time of the earthquake). When using the year of construction as the basis and using the weighted losses of each building, the average construction year of buildings contributing to total loss in dollar

Figure D.4. The effect of HDI versus the fatality and replacement cost ratios for each country (number of damaging earthquakes used indicated in parentheses).



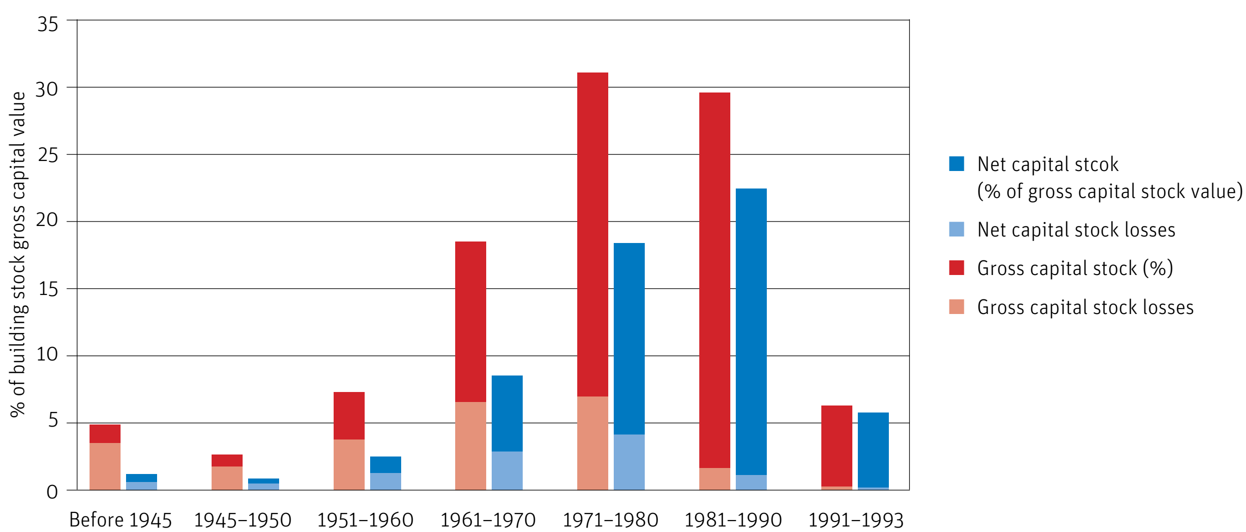
Source: CATDAT.

Figure D.5. Outcomes for buildings in the 1995 Kobe earthquake by period of construction.



Source: Adapted from Kobe municipal government statistics.

Figure D.6. Net capital and gross capital stock estimates for the dwelling portion of the losses/costs incurred in the 1995 Kobe earthquake.



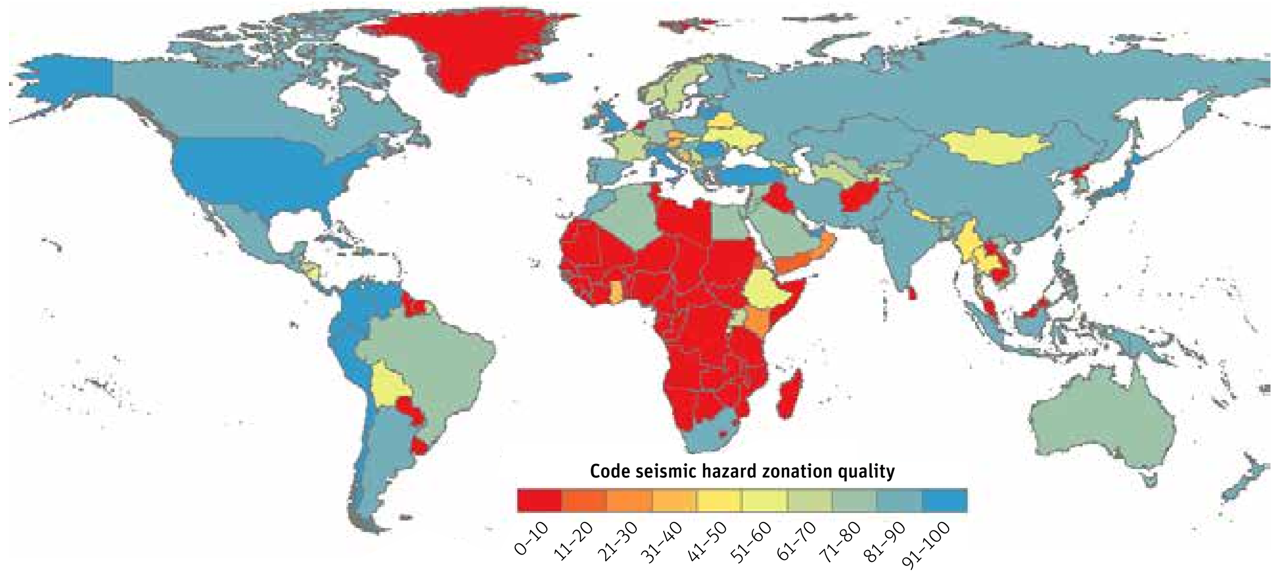
Source: CATDAT.

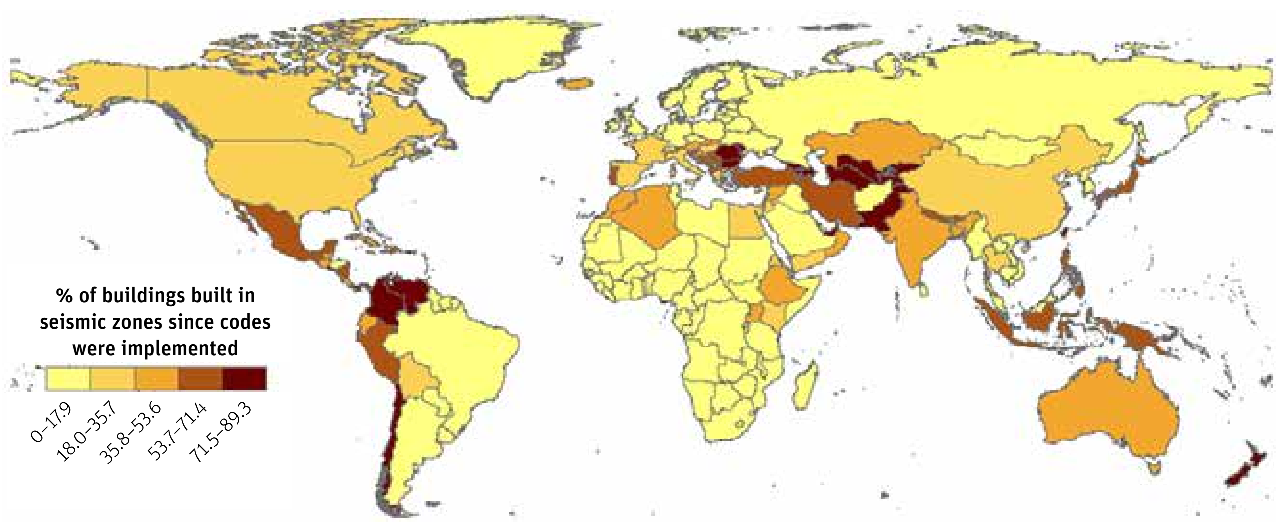
values was 1966. This 10-year difference between the average year of construction for net capital stock and for buildings contributing to total loss in dollar values indicates that damage was proportionally greater in older building stock. In smaller earthquakes, or earthquakes where old and new buildings incur equal losses, this effect will be nil.

Globally, building stock and thus vulnerability vary significantly, with many different factors at play, such as building materials, the quality of the seismic hazard zonation used to define seismic-resistant codes (figure D.7, top), enforcement of building standards, and the age of buildings. A recent study (Daniell et al. 2014) sheds light on the influence of these factors on differences between countries. Figure D.7 (bottom) shows that, globally, relatively few buildings and infrastructure have been built in the time that seismic-resistant codes have been in place in each country; thus countries tend to rely on better building quality, rather than codes, to withstand earthquakes.

Figure D.7 (bottom) shows the percentage of buildings built since the code implementations for zones in the countries—but it cannot be assumed that engineering standards were adhered to in every case. Following the trends into the future, the percentage of buildings built under code is increasing in developed nations. There is rapid expansion in certain locations that are at risk of earthquake, such as Kathmandu and Istanbul. The trends of future building stock losses will clearly be substantially influenced by countries' political and socioeconomic climate (Ambraseys and Bilham 2011; Spence 2007).

Figure D.7. The quality of seismic hazard zonation, based on past earthquakes, which determines requirements of seismic design code (top); and the percentage of buildings that have been built since the implementation of seismic codes in each country within the hazardous zones (bottom).





Source: Daniell et al. 2014.

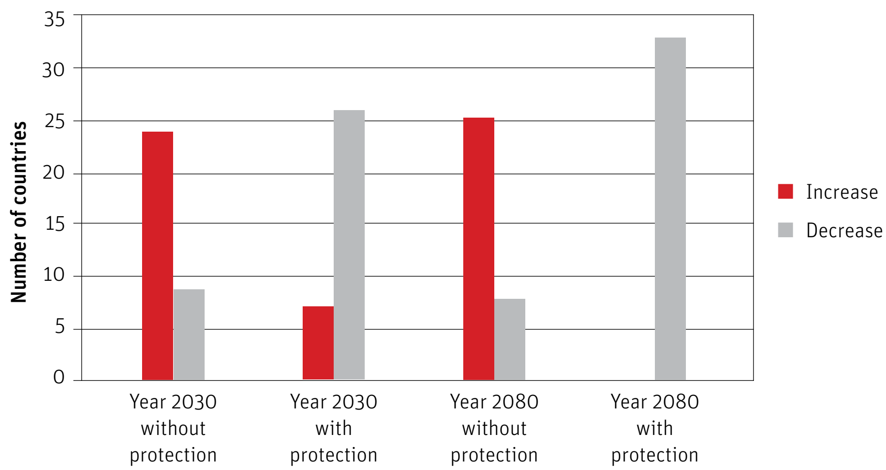
The future risk of earthquakes

By studying the past, the absolute and relative trends of earthquake losses can be seen. The capital replacement, potentially better building standards, and relative frequency of earthquake occurrence have been combined together with the future population and GDP estimates of the Shared Socioeconomic Pathways[2] to calculate earthquake risk.

A study by Daniell and Schaefer (2014) looks at the risk of earthquake loss currently, in 2030, and in 2080 for 33 countries in Eastern Europe and Central Asia, taking into account the improvement of building stock. The study (the results of which are shown in case study G below) undertakes a stochastic risk assessment that simulates all possible earthquake events over a 10,000-year period in each of the countries using data about the frequency of earthquake events over the past 2,000 years as well as geology and tectonics.

The analysis by Daniell and Schaefer (2014) shows that some of the 33 countries will have a future reduction in risk simply due to reduction in population and GDP in vulnerable areas. The analysis also takes into account the effect of adding protection—that is, the effect of renewing 1 percent of building stock per year with a reduced vulnerability (to near earthquake-resistant standard quality). Figure D.8 summarizes the loss results for the 33 countries for fatalities and economic losses in the present compared to the future for the 200-year return period value (PML200). It shows the benefit of adding protection to the building stock over time. In terms of the average annual loss, many more benefits arise from adding greater protection immediately, with 32 of 33 countries indicating a reduction in loss by 2030, compared to 26 of 33 in terms of the PML200 value. Some countries will naturally have varying patterns of socioeconomic change that benefit their earthquake risk, meaning that even without additional protection, they have a reduction in risk in 2030 and 2080.

Figure D.8. **Comparison of present losses to future losses (in 2030 and 2080) for 33 nations in Eastern Europe and Central Asia for the probable maximum loss in 200 years (PML200) scenario and for average annual loss.**



Source: Daniell and Schaefer 2014.

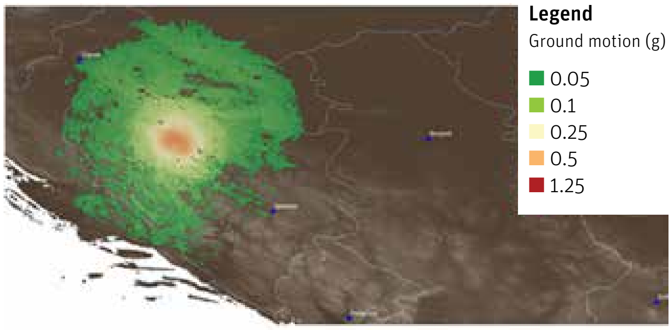
Footprint analysis of historic earthquake scenarios throughout the region as part of CATDAT mimics the results; however, this analysis shows that there are significant changes due to better building standards and materials or changing global patterns of economy and population. Figure D.9 shows examples from the CATDAT catalog for Bosnia (the 1969 Banja Luka earthquake series) and Croatia (the 1667 Dubrovnik event) for past, present, and future (with and without protection of stock).

Conclusion

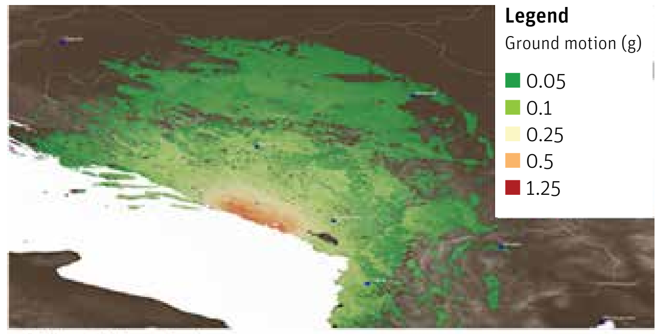
The study of historical, present, and future earthquake footprints in conjunction with socioeconomic loss analysis and indicators helps to highlight key trends. The distribution of development throughout the world shows a changing climate of earthquake losses, where potential direct hits on major urban centers may have huge consequences. As a

2 SSP Database, 2012, https://secure.iiasa.ac.at/web-apps/ene/SspDb, 27.06.2014.

Figure D.9. Past, present, and future losses for the 1969 earthquake in Banja Luka, Bosnia (left), and 1667 earthquake in Ragusa (Dubrovnik), Croatia (right).



M6.4 at 16km depth
1969 population in Banja Luka: 90,000
2014 population in Banja Luka: 250,000
Original loss: 14 dead due to multiple shocks; 1,100 injured; economic loss of U$50 million (US$682 adjusted to 2014 dollars)
Loss today: 405 dead; economic loss of US$4.08 billion (22% of GDP)
Loss in 2030 with protection: US$5.64 billion (17.4% of GDP)
Loss in 2030 without protection: US$6.40 billion (19.7% of GDP)
Loss in 2080 with protection: US$4.52 billion (8.8% of GDP)
Loss in 2080 without protection: US$8.88 billion (17.3% of GDP)



M7.4 at 23km depth
Original loss: 3,000 dead; fall of Republic of Ragusa Dubrovnik completely destroyed (5,000 homes). Fifty years of economic downturn due to multiple shocks; 1,100 injured: economic loss of US$50 million (US$682 adjusted to 2014 dollars
Loss today: 1,520 dead; US$7.02 billion (12.5% of GDP)
Loss in 2030 with protection: US$6.73 billion (9.5% of GDP)
Loss in 2030 without protection: US$7.68 billion (10.8% of GDP)
Loss in 2080 with protection: US$4.42 billion (5.0% of GDP)
Loss in 2080 without protection: US$9.05 billion (10.2% of GDP)

Source: CATDAT; Daniell and Schaefer 2014.

Note: With protection = 1% improved/code stock per year.

percentage of total GDP, capital stock, and population, the general trend of losses and fatalities is decreasing globally; however, in absolute terms, the losses are increasing. Appropriate building standards, replacement of stock with better enforcement, increased development, and distributed GDP and population over countries will allow for further reductions in the future.

References

Ambraseys, N. N., and R. Bilham. 2011. "Corruption Kills." *Nature* 469, no. 7329: 153–55.

Daniell, J. E. 2014. "Development of Socio-economic Fragility Functions for Use in Worldwide Rapid Earthquake Loss Estimation Procedures." PhD diss. Karlsruhe Institute of Technology.

Daniell, J. E., B. Khazai, F. Wenzel, and A. Vervaeck. 2011. "The CATDAT Damaging Earthquakes Database." *Natural Hazards and Earth System Sciences* 11, no. 8: 2235–51. doi:10.5194/nhess-11-2235-2011.

Daniell, J. E., and A. M. Schäfer. 2014. "Eastern Europe and Central Asia Region Earthquake Risk Assessment Country and Province Profiling." ECA Region Report, World Bank, Washington, DC.

Daniell, J. E., F. Wenzel, and B. Khazai. 2010. "The Cost of Historic Earthquakes Today—Economic Analysis Since 1900 through the Use of CATDAT." Paper no. 07, Australian Earthquake Engineering Society Conference, Perth, Australia.

Daniell, J. E., F. Wenzel, B. Khazai, J. G. Santiago, and A. M. Schäfer. 2014. "A Worldwide Seismic Code Index, Country-by-Country Global Building Practice Factor and Socioeconomic Vulnerability Indices for Use in Earthquake Loss Estimation." Paper no. 1400, 15th European Conference on Earthquake Engineering, Istanbul, Turkey.

Spence, R. J. S. 2007. "Saving Lives in Earthquakes: Successes and Failures in Seismic Protection Since 1960." *Bulletin of Earthquake Engineering* 5, no. 2: 139–251.

UNDP (United Nations Development Programme). 2014. *Human Development Report 2013.* New York: United Nations.

CASE STUDY E

Changing Earthquake Vulnerability Linked to Informal Building Expansion

David Lallemant, Henry Burton, Luis Ceferino, Zach Bullock, Anne Kiremidjian (Stanford University)

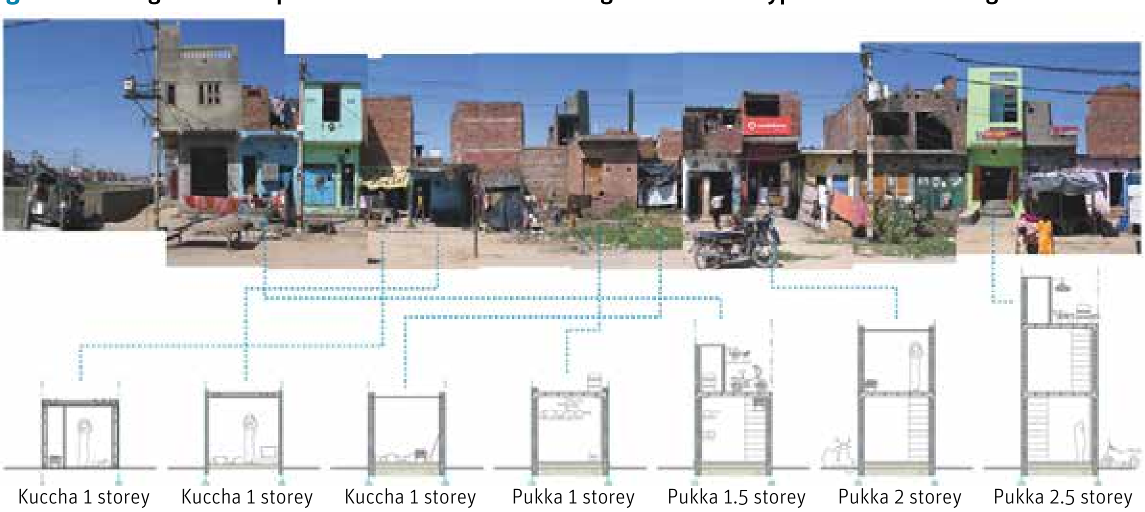
This study investigates the impact on earthquake vulnerability of incremental building expansion in rapidly urbanizing areas in developing countries. Earthquake engineers understand that incremental expansion—adding over time to what were originally one- or two-story buildings—increases buildings' vulnerability, but little has been done to model and quantify this increase.

This study aims to help fill this gap in knowledge. It focuses on infill frame buildings, which are ubiquitous in cities in developing countries around the world, and presents a catalog of common building expansions. Using vulnerability curves developed through incremental dynamic structural analysis for each possible building configuration, it presents a stochastic building expansion model to simulate possible expansion sequences over the lifetime of a building. The model is then used to simulate an entire neighborhood in the Kathmandu valley area, and analyzed to understand neighborhood-level risk over time, based on a reproduction of the 1934 Nepal-Bihar earthquake that destroyed the city. The study demonstrates that informal expansions significantly increase the collapse risk of buildings. It points to the need to limit such expansions, or develop methods to safely construct them.

Background

The year 2008 marked a significant threshold in the history of human settlement, when for the first time urban dwellers outnumbered rural dwellers. This dramatic transformation has been described as "one of the most powerful, irreversible, and visible anthropogenic forces on Earth" (IHDP 2005). By 2030, the global population will reach 9 billion, of which 60 percent will reside in cities (United Nations 2006). To put this into perspective, twice as many people will live in cities in 2030 as there were total people living in 1970. Most of this urban growth will occur in cities in developing countries (United Nations 2006), where the pay-as-you-go process of informal building expansion is the de facto pattern of growth. Households start with simple one- or two-story shelters, which over time—and given sufficient resources—are transformed incrementally to multistory homes and rental units, as can be seen in figure E.1. Indeed, the concept of a "static" building—designed by an architect or engineer, constructed according to plan, and subsequently remaining as such for its lifetime—is the exception rather than the norm. Buildings are not static but evolve over time, reflecting patterns of cash

Figure E.1. Diagram of the process of incremental building construction typical of cities throughout the world.



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flow, family expansions, investments in home businesses, and other factors. While structural building types and construction materials vary from context to context, the basic incremental building process is ubiquitous in developing countries across the world. This bottom-up approach to city building has received increasing attention by researchers, as it is one of the only ways for cities to respond to their massive housing and infrastructure needs. Researchers are attempting to find ways to harness this organic process and ensure that it is coupled with adequate infrastructure and services.

Despite the fact that buildings are rarely static, one of the assumptions implicit in current risk assessment models is that vulnerability is constant over time. The current study proposes a framework for incorporating time-dependent fragility into large-scale risk assessment models, focusing on incremental building expansion as a significant driver of changes in vulnerability. Empirical evidence suggests that such expansions significantly increase the vulnerability of buildings to natural hazards, particularly to earthquakes. Damage assessments conducted following the 2010 earthquake in Haiti reported that buildings expanded to two or more stories collapsed at a higher rate than others. This finding is expected, since the majority of such buildings were not designed anticipating the loads of additional stories, nor were they strengthened in the expansion process. While the greater vulnerability of expanded buildings is known, this study is the first attempt at quantifying the increases in earthquake vulnerability linked to common building expansions. It further looks at a case study in Kathmandu, Nepal, to explore the impact of building expansion at a neighborhood scale. The study hints at possible approaches to reducing earthquake risk, such as a simple policy limiting building expansions, or linking expansions with strengthening.

Incrementally expanding building morphologies

The two most common building expansions are vertical extensions (additional stories) and cantilevered horizontal extensions (additional stories cantilevered above sidewalks or streets). These two basic extensions can be combined to form a variety of building morphologies.

For the purposes of this study, a standard building layout was developed for a typical residential building. This study focuses specifically on concrete-frame buildings with masonry infill, which represent a very common construction type in developing countries around the world. It further focuses on buildings that expand to no more than three stories. The catalog of common expansion morphologies presented in figure E.2 includes 10 building morphologies, from which numerous evolutionary building sequences are possible.

In order to keep the study as general as possible while reflecting reality, building morphologies were developed that are emblematic of real buildings found in Kathmandu, Nepal, as pictured in figure E.3.

Building vulnerability modeling

The earthquake vulnerability of buildings is defined by fragility curves (also called vulnerability curves). These describe the relationships between the intensity of earthquake ground motion and the probability of experiencing or exceeding a particular level of damage.

Figure E.2. Ten common building morphologies.

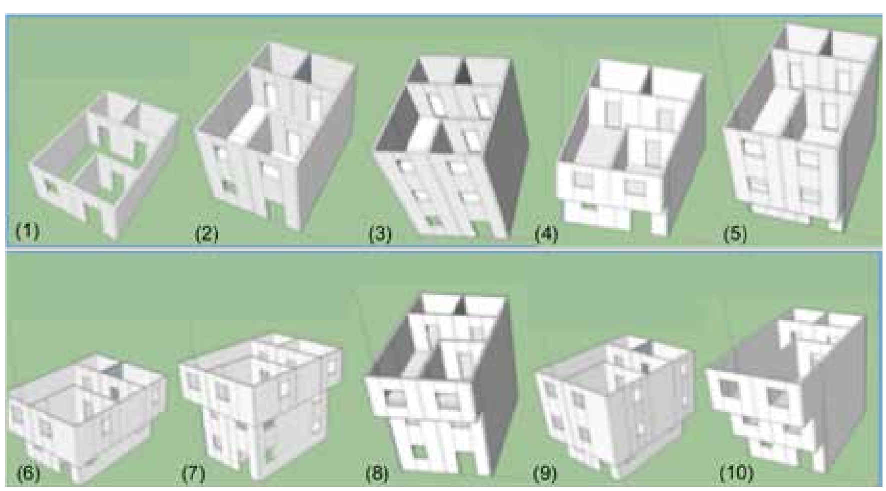

Figure E.3. Buildings in Kathmandu, Nepal, showing typical incrementally expanded building morphologies.

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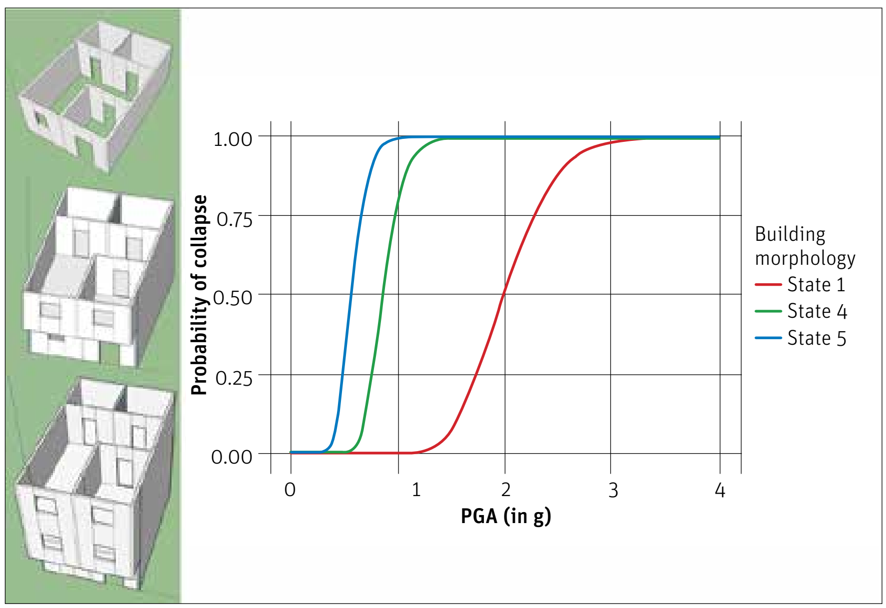
In this study, analytical collapse fragility curves were developed for each of the 10 common building morphologies. These relate the intensity of the earthquake shaking (measured in terms of acceleration of the ground) to the probability of the building collapsing. Specific structural parameters were defined based on Nepal National Building Code guidelines for reinforced concrete buildings with masonry infill (Government of Nepal 1994). The collapse performance assessment was conducted using the Incremental Dynamic Analysis (IDA) technique (Vamvatsikos and Cornell 2002). The overall analysis approach is based on the methodology developed by Burton and Deierlein (2014) for simulating the seismic collapse of nonductile reinforced concrete frame buildings with infill. Sample fragility curves for a specific building sequence are shown in figure E.4.

Figure E.4. Sample building sequence and associated changes in vulnerability curve.

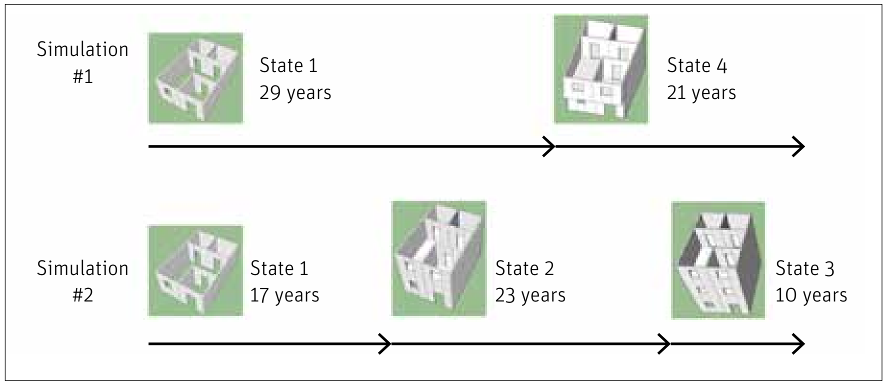


Note: PGA = peak ground acceleration; g = acceleration of gravity.

Rate of building expansion

In order to model the expansion of buildings over time, a simulation algorithm was developed. For any given time increment, a building may expand or may stay in its current state. In order to simulate this, a Markov chain process model was developed. Markov chains are used to simulate mathematical systems that transition from one state to another in state space. These models are "memoryless," such that the next state depends only on the current state, not on the sequence of events that preceded it. A transition matrix is used to define the probability of transitioning from any state to another in a given time period, and it can be calibrated to context-specific state-change rates based on observations of buildings over time. Because data from Kathmandu were not available, the study assumed and tested certain transition rates to check reasonable outcomes of building states after 10-, 25-, and 50-year simulations. For any given starting state, an expansion sequence can be simulated and tracked over time, as demonstrated in figure E.5.

Figure E.5. **Sample simulation of stochastic building expansion over time based on Markov chain process.**

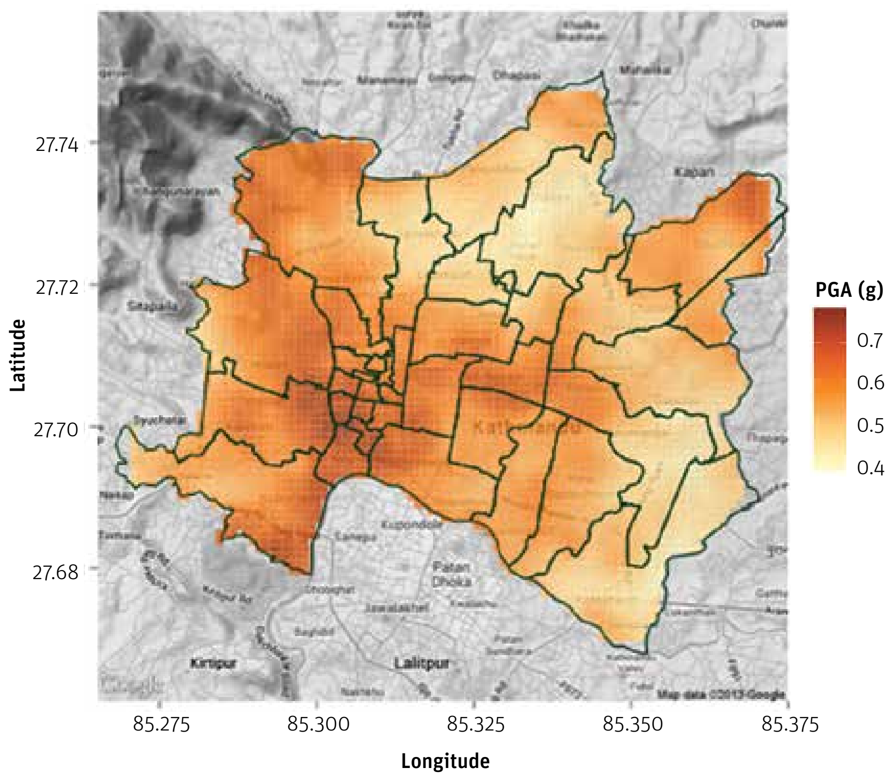


Earthquake scenario

Kathmandu is located in a seismically active region. It has a long history of earthquake, with 71 events of magnitude 5 or greater recorded between 1911 and 1991. The largest earthquake in the recent history of the region, the Great Nepal-Bihar Earthquake, occurred on January 16, 1934. The event was estimated to be of magnitude 8.1 and caused extensive damage in the region.

A reproduction of the same earthquake was chosen for this scenario. Spatially correlated earthquake ground motion fields were simulated, reflecting the fact that shaking at sites close to each other is expected to be similar in intensity. This approach was used to investigate the predicted loss for a portfolio of buildings evolving and changing over time, based on the same baseline earthquake scenario. An example of a spatially correlated ground motion field simulation for Kathmandu is shown in figure E.6.

Figure E.6: **Spatially correlated earthquake ground motion field based on a reproduction of the 1934 Great Nepal-Bihar Earthquake.**

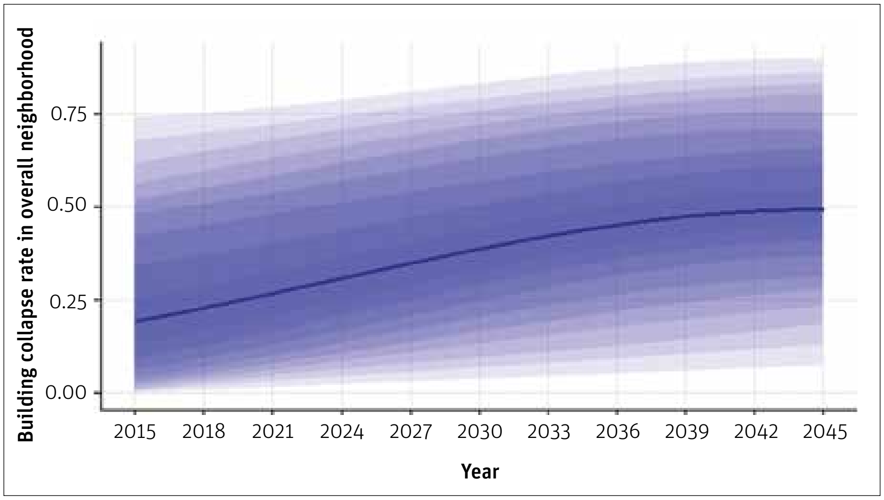


Note: PGA = peak ground acceleration; g = acceleration of gravity.

Neighborhood case study

In order to demonstrate the impact of incremental expansion on vulnerability over time at a community scale, a hypothetical neighborhood was created consisting of 100 buildings on the outskirts of Kathmandu city. It is a "young" neighborhood, with all buildings of either one or two stories. The growth of this neighborhood is simulated over 30 years, and the collapse rate of buildings in the neighborhood computed every three years based on the Nepal-Bihar earthquake scenario. Figure E.7 shows the rate of building collapse over time, driven by the increasing vulnerability of buildings as they expand vertically and horizontally. The figure demonstrates that 25 percent of buildings could be expected to collapse if the earthquake occurred in 2021, while 50 percent of buildings would collapse if it occurred in 2045. The blue bands in the figure indicate that significant uncertainty

Figure E.7. **Building collapse rate over time in a neighborhood on the outskirts of Kathmandu in Nepal, due to a reproduction of the 1934 Great Nepal-Bihar Earthquake.**



surrounds these estimates; this arises from uncertainty in the intensity of ground shaking caused by the fault rupture, uncertainty in the fragility curves, and uncertainty in the building growth over time. The trend however is clear. Note that the increase in vulnerability is doubly troubling, because it is linked with an increase in occupancy as buildings get larger.

Conclusion

This study showcases a model for understanding how the vulnerability of buildings changes over time due to typical expansions. Young urban settlements grow over time through the informal expansions of individual buildings. In many parts of the world, including the fast-growing urban centers in developing countries, these informal expansions constitute the main process of city building. This study looks at the impact of such a process on the earthquake vulnerability of neighborhoods. Two main conclusions can be drawn from this study's findings:

1. **Driven by informal building expansion, risk increases with time.** There is a significant earthquake risk linked with informal building expansion. The risk is easy to overlook for a single building or short time frame, but given enough time and scaled to entire neighborhoods, the incremental expansion process can profoundly shift earthquake risk. Governments should consider policies to control the most dangerous expansions and/or should develop design guidelines for expanding safely. Both of these steps would have significant impact on reducing the future risk of cities.

2. **The change in risk is predictable.** The disaster risk of rapidly changing cities is predictable, even if it has significant uncertainty. Probabilistic hazard models can be combined with modern structural analysis tools, simulated building expansion, and other models to gain an understanding of the main trends in the disaster risk of cities. As part of efforts to ensure that cities are resilient to future disasters, these tools can serve as the basis for risk-informed urban planning and policy analyses that place urban environments on a trajectory to minimize future risk.

References

Burton, Henry, and G. G. Deierlein. 2014. "Simulation of Seismic Collapse in Non-Ductile Reinforced Concrete Frame Buildings with Masonry Infills." *Journal of Structural Engineering 140: A4014016.*

Government of Nepal. 1994. "Mandatory Rules of Thumb - Reinforced Concrete Buildings with Masonry Infill." Ministry of Planning and Works, Department of Urban Development and Building Construction. Babar Mahal, Kathmandu, Nepal.

IHDP (International Human Dimensions Programme). 2005. "Urbanization and Global Environmental Change." http://www.ihdp.unu.edu/file/get/8556.pdf.

King, Julia. 2011. "Early Results from Savda Ghevra Field Work, Delhi." Incremental Housing (website). http://web.mit.edu/incrementalhousing/articlesPhotographs/pdfs/Julia-King-ARTICLE-e.pdf.

United Nations. 2006. *World Urbanization Prospects: The 2005 Revision*. New York: United Nations. http://www.un.org/esa/population/publications/WUP2005/2005WUPHighlights_Final_Report.pdf.

Vamvatsikos, Dimitrios, and C. Allin Cornell. 2002. "Incremental Dynamic Analysis." *Earthquake Engineering & Structural Dynamics* 31, no. 3: 491–514. doi:10.1002/eqe.141.

CASE STUDY F

An Interrelated Hazards Approach to Anticipating Evolving Risk

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Any disaster risk management strategy needs to account for the dynamic nature of risk and its components over time, which can interact and result in emergent threats. Risk interaction can occur at the hazard, exposure, and vulnerability level. This discussion focuses on hazard interrelations, which include a number of influences, including interactions, between hazards. Evidence suggests that assessments that do not account for the interrelations between hazards might underestimate risk (e.g., Marzocchi et al. 2012; Budimir, Atkinson, and Lewis 2014; Mignan, Wiemer, and Giardini 2014). Thus strategies based on such assessments could actually increase vulnerability by focusing on primary hazards at the expense of secondary hazards. Multi-hazard assessments should account for these interrelations; but, in reality, assessments rarely consider the full spectrum of hazards and even less the interrelations between hazards (Kappes et al. 2012; Duncan 2014; Gill and Malamud 2014).

In the context of evolving risk, there is evidence to suggest that humanitarian actors—particularly international humanitarian and development nongovernmental organizations (NGOs)—are particularly preoccupied with climate change rather than the full range of threats (Duncan 2014). Unless approaches are strengthened to assess multiple and interrelated hazards, there is the possibility that decisions could be leading to maladaptation. The following discussion presents a brief overview of interrelated hazard assessment approaches, summarizes a study of nongovernmental organizations (NGOs) in this context, and examines findings of particular relevance to evolving risk.

Interrelated hazards and evolving risk

Multi-hazard assessments have long been advocated as an approach to risk reduction, but little attention has been given to what a multi-hazard approach requires (Duncan 2014). Most assessments described as "multi-hazard" tend to account for more than one hazard in a place in order to (ultimately) prioritize risks. However, since hazards are related and can interact, these assessments should also account for the interrelations between hazards. Despite growing recognition of the importance of these interrelations, there is no agreed-upon terminology for interrelated hazards (Kappes et al. 2012). Interrelated hazards are often categorized by the process (e.g., one hazard triggering another), actual examples of interaction (e.g., earthquake triggering landslide), and/or the effect (e.g., positive or negative impact on the subsequent hazard). The coincidental occurrence of hazards ("risk migration") and the triggering or cascade ("chains") of hazards ("risk amplification") are generally the most considered processes (UNISDR 2011; Kappes et al. 2012; Marzocchi et al. 2012; Mignan Wiemer, and Giardini 2014). However, hazard interrelations can be further differentiated into (for instance) four interdependent categories (table F.1).

Each of these interrelated hazard processes can occur during a single disaster, depending on the analytical spatial and temporal scale considered (Duncan 2014). For instance, in the Philippines, the 1991 eruption of Mount Pinatubo is associated with the preceding 1990 Luzon earthquake (Bautista et al. 1996). Moreover, during the eruption, the coincidental occurrence of Typhoon Yunya resulted in the saturation of accumulating volcanic materials with rainfall, the weight of which caused the roofs of homes and businesses to collapse, resulting in most of the 200–300 deaths directly associated with the eruption (Wolfe and Hoblitt 1996). After the eruption, large lahars were triggered by monsoon and typhoon rainfall

[3] Funding for the project on which this study was based came from the UK Engineering and Physical Research Council and the Catholic Agency for Overseas Development.

Table F.1. **Categories of Interrelated Hazard Processes**

Category	Description	Example
Causation	Hazards generate secondary events, which may occur immediately or shortly after the primary hazard (including cascading hazards).	An earthquake-triggered landslide, which blocks a river and later leads to flooding from a dam burst
Association	Hazards increase the probability of secondary events, but it is difficult to quantify this link and therefore confirm causation.	Stress transfer along faults
Amplification (or alleviation)	Hazards exacerbate (or reduce) future hazards.	The effect of coastal erosion from an earlier event (e.g., tsunami) on the subsequent impact of coastal flooding and tsunami inundation
Coincidence	Hazards occur in the same place simultaneously (or closely timed), resulting in compounded effects or secondary hazards.	The coincidence of a typhoon with a volcanic eruption (lahar hazard) or a windstorm and an earthquake (firestorm hazard)

Source: Duncan 2014.

(Newhall, Hendley, and Stauffer 2005).

Interrelated hazard processes can emerge over different time periods. In the case of causation, the secondary hazard may occur immediately or shortly after the event. Identifying this time window makes constraint of disaster events challenging, particularly for the insurance sector (Selva 2013). In the context of assessing long-term evolving risk, particularly changes in the environment, association between hazards (increased probability) and the amplification effect are of particular interest because the influence of these processes may not be immediate.

In addition to hazards' direct influence on other hazards, the influence of interrelated hazards on exposure, vulnerability, and risk (loss) is increasingly being considered. Elements at risk can have vulnerabilities specific to different hazards, a fact that has implications for the mitigation of coincidental hazards. In the context of cascading or closely occurring hazards, vulnerability can also be time-variant; in other words, the occurrence of the first event may increase vulnerability to the second. A study in Italy, for instance, demonstrated that volcanic and industrial risks are underestimated if the link between them is not considered. Although a small accumulation of ash may not lead to building collapse, it could cause casualties through an industrial accident, thereby increasing the risk posed by an eruption when considering this secondary effect (Marzocchi et al. 2012). The consideration of time-variant vulnerability owing to the influence of hazards is in addition to the consideration of dynamic vulnerability (e.g., changes in poverty, physical changes in buildings over time), which should be considered in risk assessments regardless of whether they incorporate interrelated hazards.

Addressing sequential damage and the separation of the respective impact of each hazard is rare in risk assessments (Kappes et al. 2012). Furthermore, where interrelated hazards are considered, the focus is more upon physical vulnerability (e.g., the vulnerability of a building already covered by snow or volcanic ash to an earthquake; see Lee and Rosowsky [2006]) rather than socioeconomic vulnerability.

Methods for assessing interrelated hazards

Understanding of hazard interrelations has tended to emerge from the assessment of discrete cases. However, there have been recent attempts to establish generic approaches to the analysis of interrelated hazards. One such approach is the generic multi-risk framework designed by Mignan, Wiemer, and Giardini (2014), which incorporates coinciding events, triggered chains of events, and changes in vulnerability and exposure over time. Another approach is the development of global frameworks for the assessment and visualization of interacting hazards, such as the matrixes designed by Gill and Malamud (2014) (discussed

Multi-hazard assessments have long been advocated as an approach to risk reduction, but little attention has been given to what a multi-hazard approach requires.

in greater detail below). These generic and global frameworks cannot account for the complexity of assessment scenarios for actual places. They may, however, help policy makers address evolving risk by providing information about the potential for hazard interrelations, hazards' spatial and temporal overlap, and the intensity of subsequent hazards.

There is a growing number of methods for the assessment of interrelated hazards. These can be distinguished by what scale they use, whether they adopt a qualitative or quantitative approach, and whether they anticipate the location, timing, and severity of the subsequent hazard. In terms of statistical analysis, the challenge of assessing interrelated hazards is that they cannot be treated in the same way that a single hazard is treated in typical assessments. For instance, many studies consider hazard event sets as stochastic (random) and independent, but secondary and cascading hazards are dependent on previous events and require the use of conditional probabilities.

In the case of global and generic assessments, the identification of hazard interrelations is through a combination of the review of literature and intuitive judgment (e.g., Mignan, Wiemer, and Giardini 2014; Gill and Malamud 2014). For specific case studies, interrelations are recognized by identifying spatially and temporally overlapping hazards using a combination of geographical information systems (GIS) and matrixes. GIS can be used to identify which hazards might interact and where interactions and coincidences might occur, but this information needs to be supported by scenarios of the likely occurrence of these interrelations (Kappes et al. 2012). Network analysis, matrixes, and event trees have been utilized to identify and predict interrelated hazards. These are briefly described here with examples of recent applications.

1. *Network analysis* was used by Gill and Malamud (2014) to identify the existence of interrelated hazards based on the review of 200 papers. After normalization, they found that geophysical and atmospheric hazards were the predominant triggers of other hazards, but also that geophysical as well as hydrological hazards are triggered by the most hazards. These initial rankings do not reflect the overall extent of spatial overlap and temporal likelihood of these interrelations.

2. *Matrixes* are typically used to identify hazard interrelations in a qualitative or semi-quantitative manner. These are often termed "interaction" matrixes, although this implies a mutual influence between two processes when in fact some of these matrixes have been utilized only to identify a sequential cause and effect. Matrixes are used to identify the existence of interactions (e.g., Tarvainen, Jarva, and Grieving 2006) and, recently, to quantify the frequency of these interactions, the spatial overlap of interacting hazards and temporal likelihood of the triggered secondary hazard, and the intensity relationship between the primary hazard and secondary hazard (e.g., Gill and Malamud 2014). This final application is important, since underestimating the intensity of the primary hazard has been shown to result in unexpected cascading disasters, such as the 2011 Japanese earthquake and subsequent tsunami and nuclear disaster.

3. *Event trees* emerged from volcanology. The move toward more probabilistic approaches in volcanic risk assessment created two challenges: (a) the difficulty of assessing the relative likelihoods of different ways in which a multi-hazardous volcanic system could evolve in the future or during a real-time crisis; and (b) the difficulty of communicating probabilistic information to decision makers (Martí et al. 2008). To address these difficulties, event trees of impact scenarios were developed for volcanic crisis and, more recently, for the assessment of interrelated

hazard, such as rock slides in Norway (Lacasse et al. 2008). Event trees are graphical representations of events with branches that represent logical steps from a general event through increasingly specific subsequent events and final outcomes (Newhall and Hoblitt 2002). In contrast to event trees for volcanic settings, those for interrelated hazards might begin with a number of branches before focusing toward a single outcome. Event trees tend to employ conditional probabilities in order to account for the influence of previous events. These probabilities are assigned to each of the branches and are determined from historical or geological data and often by expert judgment (see Lacasse et al. [2008]).

Each of these methods has application to the assessment of evolving risk. Network analysis may be most useful in identifying past occurrences of hazard interrelations as a guide to interrelations that may occur due to evolving spatial and temporal ranges of hazards in the future. The other methods could account for evolving risk by incorporating predicted patterns of future risk. GIS could incorporate layers of future flood risk based on global river flood models that utilize global climate models to simulate higher precipitation, or future coastal flood hazard due to subsidence of land. In matrix approaches, the spatial domain and frequency of each hazard can be adjusted to anticipated or simulated future conditions, and for event trees analyses, conditional probabilities can be proposed based on simulated changes in environment and hydrometeorological systems, in place of probabilities based on current conditions.

In the long term, assumptions can be made about the risk of secondary hazards assuming a constant rate of primary hazards over time; however, these assumptions become irrelevant when changes in the environment—for instance climate change—are taken into consideration (Marzocchi et al. 2012). While some studies of interrelated hazards recognize the need to incorporate anthropogenic influences, including environmental and climate change, into frameworks (e.g., Marzocchi et al. 2012; Gill and Malamud 2014; Duncan 2014), the application of these has generally been limited to specific cases, such as coastal risk (Garcin et al. 2008) rather than within studies considering the full spectrum of risk in an area.

There are only a few studies that have focused on the capacity of end-users with a nonscientific background to implement multi-hazard assessments. Komendantova et al. (2014) studied the needs and capacity of risk managers and discovered a number of barriers to the uptake of multi-hazard assessments, including lack of clarity regarding a multi-hazard approach and concern over the level of expertise required to implement methods (see also Scolobig et al. [2014]). Furthermore, a number of studies of interrelated hazards are confined to case studies in developed countries (e.g., De Pippo et al. 2008; Marzocchi et al. 2009, 2012), where data on hazards tend to be more plentiful than in developing countries. In developing countries, community knowledge is essential since it might be the only information available to scientists regarding the hazard context (Mercer 2012); but it also needs to be integrated with available scientific insight. Community-based risk assessments are therefore an integral component of reducing risk, and a number of NGOs conduct risk assessments at this level. Whether these assessments truly account for multiple and interrelated hazards, however, has received little attention until now.

> Many studies consider hazard event sets as stochastic (random) and independent, but secondary and cascading hazards are dependent on previous events and require the use of conditional probabilities.

NGOs, interrelated hazards, and evolving risk

NGOs typically work in developing countries, acting as key facilitators in the implementation of community-based risk assessments. The application of multi-hazard assessments by NGOs was evaluated by a doctoral research project on multi-hazard assessments for disaster risk reduction (DRR) that addressed NGO approaches to multi-hazard assessment, particularly in the Philippines (Duncan 2014).[4] The project studied NGO toolkits and conducted interviews with humanitarian/development NGO staff from DRR and climate change adaptation (CCA) backgrounds. Interviews were conducted between December 2009 and August 2011 with 22 NGO staff members in head offices and 13 staff members in country (11 of the 13 were based in the Philippines). In addition, a case study of the 2006 Typhoon Durian–triggered lahars at Mayon volcano was analyzed. A number of findings related to perceptions and assessments of evolving risk emerged from this study.

In interviews, most head office staff emphasized the importance of integrating DRR and CCA approaches and described their own community hazard assessments as adopting a multi-hazard approach. In reality, however, these assessments did not always fully consider the multiple threats communities face, even less so the interrelations between these hazards. The study identified a number of practical and perceived constraints on the process of multi-hazard assessment, but three are of particular interest here: approaches are designed to look at risk through a DRR or CCA lens; NGOs rely almost totally on community knowledge; and analysis is constrained in its spatial and temporal scales.

All interviewees expressed concern about an uncertain future, but did so largely in the context of climate change, regardless of whether they had a DRR or CCA background. There was a shared preconception that emergent threats and unknown future risk are purely driven by climate change, whereas DRR adopts a historical approach and deals with "known" hazards. This preconception highlights a shortcoming in the implementation of DRR, since it is conceptualized to adopt a long-term perspective (see Mercer [2010]). Furthermore, the perception that DRR deals with "known" hazards overlooks instances where hazards might occur coincidentally or in close succession, resulting in an overall impact that far exceeds the "known" impact of the individual hazards. Notably, perceptions differed slightly among Philippine interviewees; although they also emphasized climate change, they tended to better recognize the interrelations between hazards and to appreciate that all hazards (not just those related to climate) are dynamic and need to be reviewed over time. This periodic review is critical when considering evolving risk, especially if approaches are not particularly anticipatory. In reality, however, interviewees across the study stated that review of hazards was unlikely to occur.

Hazard interrelations are identified through an appropriate spatial and temporal extent of analysis. However, the interviews indicated that NGO assessments of hazards are typically limited to the geographical scale of a community and tend to reflect on past events, without necessarily anticipating future change. Historical analysis is a strong component of the NGO claim to a multi-hazard approach to community-based assessments because different hazards are identified through the creation of time lines and seasonal calendars. Temporally, the process of hazard analysis is constrained by the extent and degree to which communities can reliably remember disasters—especially when specific data (e.g., frequency and impact) are required—and by their perception of risk. What is apparent from both this study and the literature is that in spite of the emphasis on a long-term approach, both DRR and CCA are primarily addressing risk in the short term, partly owing to the overreliance on community knowledge for assessment purposes. NGOs are struggling to address CCA because they are trying to look at time frames 30 to 50 years in advance, while ensuring that they address communities' immediate concerns. There is, however, a need to adopt an anticipatory approach to all hazards: given that conditions for hazard interaction may not have been met before and that risk evolves (due to changes in environmental conditions, for instance), communities may not have experienced certain disasters in the past. Likewise, even if communities have previously experienced specific hazard-related disasters, they may be at risk to higher intensity events in

[4] Except where otherwise specified, the source for all material in this section is Duncan (2014).

the long term; for instance, many communities at Mayon volcano had experienced lahars before Typhoon Durian in 2006, but not of the magnitude of that event.

While the data resolution and uncertainty of climate science arguably hinder their applicability to community-based risk reduction work carried out by NGOs, they have highlighted the need for agencies to (a) integrate risk science with community knowledge and (b) consider larger geographical and prospective scales in their risk reduction work to better anticipate the possible occurrence of disasters. Addressing both these areas could help build capacity to implement assessments that adopt an integrated DRR and CCA approach to assessing future and evolving risk. An evolving risk approach to risk assessment should incorporate the wider natural (and not just socioeconomic) systems in order to account for hazards and environmental change that might occur at a distance from communities but still have a notable impact upon them. But there is also evidence to support a community-focused approach to interrelated hazard assessments since interrelated hazards can be apparent at the community level. Some of the tools discussed earlier (GIS, matrixes, event trees) may be able to assist NGOs in (at least) the visualization of interrelated hazards and evolving risk over different spatial and temporal scales. However, Duncan's (2014) study found that NGOs (with some exceptions in the Philippines) tend not to integrate science into their multi-hazard assessments—an oversight that acts as a major barrier to implementing the methods suggested above. Partnership and collaboration between NGOs and risk scientists is therefore imperative, but is hindered by a series of institutional, practical, and perceived barriers.

Implications for policy makers and practitioners

Interrelations between hazards and their influence on vulnerability are fundamental to the understanding and assessment of evolving risk. Risk reduction strategies for one hazard should take into account coincidental and chains of hazards both in the short and long term, to ensure that decisions made to mitigate hazards today do not increase vulnerability to future events. Furthermore, hazards are dynamic, and there is also a need to account for how past hazards might increase the probability or amplify the location, timing, and severity of future events (Duncan 2014).

While there are a number of hazard interrelations, not all processes require consideration within a multi-hazard risk assessment (Marzocchi et al. 2012; Gill and Malamud 2014). Some hazard interrelations may decrease probability or lower the intensity of the subsequent hazard (see Duncan 2014); but it has been noted that these positive effects are unlikely to be included in risk assessments, which tend to adopt a conservative approach (Gill and Malamud 2014). At the local level, however, these positive effects may become more relevant, so organizations implementing community-based DRR may consider it essential to incorporate the positive as well as negative interrelations. For instance, the Philippine Institute of Volcanology and Seismology observed that the 2006 eruption of Mayon, which occurred prior to the Typhoon Reming–triggered lahars, produced a lava flow that actually protected the provincial capital from the worst effects of the typhoon lahars that followed two months later (see Duncan 2014). However, as in the case of the 2006 lahar disaster at Mayon volcano, it may be easier to identify the positive influences of hazards after rather than before a disaster.

Interrelations between hazards and their influence on vulnerability are fundamental to the understanding and assessment of evolving risk.

Methods for assessing interrelated hazards vary depending on their analytical scale, whether they adopt a qualitative or quantitative approach, and whether they anticipate the location, timing, and intensity of subsequent events. For policy makers, the recent attempts at generic and global analyses may be useful for resource allocation; but practitioners require specific details about the local level. While methods for assessing interrelated hazards have application to evolving risk, there need to be more applications that incorporate the influence of environmental changes, such as climate change.

Furthermore, although the number of methods being explored is growing, the assessment of interrelations is largely (a) absent from single or "multi-hazard" risk assessments; (b) confined to engineering, spatial planning, and hazard science; and (c) not systematically accounted for by NGOs.

The space-time window and design of the assessment should arguably meet the requirements of the end-user (Kappes et al. 2012; Marzocchi et al. 2012). But there are few studies of the capacity of end-users to implement multiple and interrelated hazard assessments (exceptions being the study by Komendantova et al. [2014] of risk managers, and Duncan's [2014] analysis of international and Philippines-based NGOs). With regard to NGOs' risk assessments, the constrained spatial and temporal scales of analysis and the emphasis on climate change further underline the need for an integrated, evolving risk approach across disaster risk assessment.

The methods being developed for assessing interrelated hazards have very visual outputs (e.g., maps, network analysis, matrixes, and event trees), which may help NGOs and other practitioners, as well as the communities they work with, appreciate and capture the dynamic nature of hazards more widely (see Komendantova et al. [2014]). However, the data and expert judgment required to identify and quantify interrelated hazards (and their uncertainty) emphasize both the need to build the capacity of nonscientists to understand and utilize science[5] and the need to facilitate NGOs' engagement, communication, and participation with hazard and risk scientists.

References

Bautista, B. C., M. L. P. Bautista, R. S. Stein, E. S. Barcelona, R. Punongbayan, E. P. Laguerta, A. R. Rasdas, G. Ambubuyog, and E. Q. Amin. 1996. "Relationship of Regional and Local Structures to Mount Pinatubo Activity." In *Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines*, edited by C. Newhall and R. Punongbayan, 351–70. Quezon City and Seattle: Philippine Institute of Volcanology and Seismology and University of Washington Press. http://pubs.usgs.gov/pinatubo/bbautist/index.html.

Budimir, M. E. A., P. M. Atkinson, and H. G. Lewis. 2014. "Earthquake-and-Landslide Events Are Associated with More Fatalities than Earthquakes Alone." *Natural Hazards* 72: 895–914.

De Pippo, T., C. Donadio, M. Pennetta, C. Petrosino, F. Terlizzi, and A. Valente. 2008. "Coastal Hazard Assessment and Mapping in Northern Campania, Italy." *Geomorphology* 97: 451–66.

Duncan, M. 2014. "Multi-hazard Assessments for Disaster Risk Reduction: Lessons from the Philippines and Applications for Non-governmental Organisations." EngD diss., University College London.

Duncan, M., K. Crowley, R. Cornforth, S. Edwards, R. Ewbank, P. Karbassi, C. Mclaren, et al. 2014. "Integrating Science into Humanitarian and Development Planning and Practice to Enhance Community Resilience: Guidelines for NGO Practitioners." http://www.ukcds.org.uk/resources/integrating-science-into-humanitarian-and-development-planning.

Garcin, M., J. F. Desprats, M. Fontaine, R. Pedreros, N. Attanayake, S. Fernando, C. H. E. R. Siriwardana, U. De Silva, and B. Poisson. 2008. "Integrated Approach for Coastal Hazards and Risks in Sri Lanka." *Natural Hazards and Earth System Science* 8: 577–86.

Gill, J. C., and B. D. Malamud. 2014. "Reviewing and Visualizing the Interactions of Natural Hazards." *Reviews of Geophysics* 52: 680–722. doi:2013RG000445.

Kappes, M., M. Keiler, K. Elverfeldt, and T. Glade. 2012. "Challenges of Analyzing Multi-hazard Risk: A Review." *Natural Hazards* 64: 1925–58.

Komendantova, N., R. Mrzyglocki, A. Mignan, B. Khazai, F. Wenzel, A. Patt, and K. Fleming. 2014. "Multi-hazard and Multi-risk Decision-Support Tools as a Part of Participatory Risk Governance: Feedback from Civil Protection Stakeholders." *International Journal of Disaster Risk Reduction* 8: 50–67.

Lacasse, S., U. Eidsvig, F. Nadim, K. Høeg, and L. H. Blikra. 2008. "Event Tree Analysis of Åknes Rock Slide Hazard." In *Comptes rendus de la 4e Conférence canadienne sur les géorisques: des causes à la gestion [Proceedings of the 4th Canadian Conference on Geohazards: From Causes to Management], edited by J. Locat, D. Perret, D. Turmel, D. Demers, and S. Leroueil,* 551–57. Québec: Laval University Press.

Lee, K., and D. Rosowsky. 2006. "Fragility Analysis of Woodframe Buildings Considering Combined Snow and Earthquake Loading." *Structural Safety* 28: 289–303.

Martí, J., W. P. Aspinall, R. Sobradelo, A. Felpeto, A. Geyer, R. Ortiz, P. Baxter,

[5] See the integrating-science guidelines produced by Duncan et al. 2014.

et al. 2008. “Long-Term Volcanic Hazard Event Tree for Teide-Pico Viejo Stratovolcanoes (Tenerife, Canary Islands).” *Journal of Volcanology and Geothermal Research* 178: 543–52.

Marzocchi, W., A. Garcia-Aristizabal, P. Gasparini, M. L. Mastellone, and A. D. Ruocco. 2012. “Basic Principles of Multi-risk Assessment: A Case Study in Italy.” *Natural Hazards* 62: 551–73.

Marzocchi, W., M. Mastellone, A. Di Ruocco, P. Novelli, E. Romeo, and P. Gasparini. 2009. *Principles of Multi-risk Assessment: Interaction Amongst Natural and Man-induced Risks.* Brussels: European Commission. http://ec.europa.eu/research/environment/pdf/multi-risk_assessment.pdf.

Mercer, J. 2010. “Disaster Risk Reduction or Climate Change Adaptation: Are We Reinventing the Wheel?” *Journal of International Development* 22: 247–64.

———. 2012. “Knowledge and Disaster Risk Reduction.” In *Handbook of Hazards and Disaster Risk Reduction*, edited by B. Wisner, J. Gaillard, and I. Kelman, 96–108. Abingdon, UK: Routledge.

Mignan, A., S. Wiemer, and D. Giardini. 2014. “The Quantification of Low-Probability-High-Consequences Events: Part I. A Generic Multi-risk Approach.” *Natural Hazards* 73: 1999–2022.

Newhall, C., J. W. Hendley II, and P. H. Stauffer. 2005. “The Cataclysmic 1991 Eruption of Mount Pinatubo, Philippines.” U.S. Geological Survey Fact Sheet 113-97. http://pubs.usgs.gov/fs/1997/fs113-97/.

Newhall, C. and Hoblitt, R. 2002. “Constructing Event Trees for Volcanic Crises.” *Bulletin of Volcanology 64, 3–20.*

Selva, J. 2013. “Long-Term Multi-Risk Assessment: Statistical Treatment of Interaction among Risks.” *Natural Hazards* 67: 701–22.

Scolobig, A., A. Garcia-Aristizabal, N. Komendantova, A. Patt, A. Di Ruocco, P. Gasparini, D. Monfort, et al. 2014. “From Multi-Risk Assessment to Multi-Risk Governance: Recommendations for Future Directions.” In *Understanding Risk in an Evolving World: Emerging Best Practices in Natural Disaster Risk Assessment,* edited by Global Facility for Disaster Reduction and Recovery, 163–67. Washington, DC: World Bank.

Tarvainen, T., J. Jarva, and S. Grieving. 2006. “Spatial Pattern of Hazards and Hazard Interactions in Europe.” In *Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions,* edited by P. Schmidt-Thomé, 83–92. Geological Survey of Finland, Special Paper 42.

UNISDR (United Nations International Strategy for Risk Reduction). 2011. *Global Assessment Report on Disaster Risk Reduction 2011.* Geneva: UNIDSR. http://www.preventionweb.net/english/hyogo/gar/2011/en/home/index.html.

Wolfe, E. W., and R. P. Hoblitt. 1996. “Overview of the Eruptions.” In *Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines*, edited by C. Newhall and R. Punongbayan, 3–20. Quezon City and Seattle: Philippine Institute of Volcanology and Seismology and University of Washington Press. http://pubs.usgs.gov/pinatubo/wolfe/.

CASE STUDY G

Evolution of Risk in Eastern Europe and Central Asia

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Table G.1. RCP and SSP Scenario Combinations Used to Estimate Future Flood Risk

RCP scenario	SSP scenario	Scenario characterization
RCP4.5	SSP2	Cautiously optimistic
RCP8.5	SSP2	Present trends continue
RCP8.5	SSP3	Worst case

Table G.2. Climate Models Used for Flood Risk Estimates

Climate model	Description
GFDL ESM2M	GFDL Earth System Model 2 with medium resolution
HadGEM2-ES	Hadley Global Environment Model 2–Earth System
MIROC-ESM-CHEM	MIROC (Model for Interdisciplinary Research on Climate) Earth System CHASER-coupled Model (Atmospheric Chemistry version)
IPSL-CM5A	IPSL Coupled Model 5
NorESM1-M	Norwegian Earth System Model with medium resolution

Introduction

In this study we investigate the evolution of estimated flood and earthquake risk for Turkey. We use values in 2010 and a range of possible values in 2030 and 2080 that are consistent with hazard and exposure as specified by Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) created by the Intergovernmental Panel on Climate Change (IPCC) for the Fifth Assessment Report (AR5). For flood risk, we use a combination of two RCPs, two SSPs, and five global climate models to create an ensemble of risk estimates. The combinations of RCPs and SSPs used for the flood model are listed in table G.1. Short descriptions of the five climate models used for estimated future flood risk are listed in table G.2. We assume earthquake risk is independent of climate, and we thus use five SSPs to create an ensemble of risk estimates for the 2010, 2030, and 2080 time slices.[6]

The risk assessments provide first-order estimates of the spatial distribution of flood and earthquake risk and how it could evolve over time. The results will be used for opening discussions with governmental institutions in the Europe and Central Asia (ECA) region as defined by the World Bank.[7] Due to a number of limitations (see below), the results should not be used for making any decisions regarding specific mitigation and planning measures.

Flood and earthquake losses estimated by the project are presented in terms of population and gross domestic product (GDP) for areas that experience floodwater at any depth, or ground motion with an intensity consistent with Modified Mercalli Intensity (MMI) equal to VI or greater. Ground motion at MMI VI is felt by almost everyone; furniture sometimes moves, and some buildings may experience slight damage. In addition, for the earthquake model, vulnerability functions are used to estimate fatalities and capital loss. The losses are calculated as average annual loss (AAL) and are for a variety of return periods.

In the following sections, we discuss the methodology associated with the flood and earthquake models, provide an overview of the exposure data used to estimate the risk at the three time slices, and summarize the different RCP and SSP scenarios. We then present the results of the risk assessment and finally discuss the relative importance of changes in climate and exposure for the future evolution of risk.

[6] For more information on the RCPs, see Meinshausen et al. (2011). For information on the SSP scenarios, see *Climatic Change* 122, no. 3 (2014), a special issue on new socioeconomic scenarios for climate change research (e.g., Nakićenović, Lémpert, and Janetos 2014).

[7] See http://www.worldbank.org/en/region/eca.

Exposure

Future exposure data (GDP and population) were developed using the IMAGE model of PBL Netherlands Environmental Assessment Agency, forced by the socioeconomic conditions associated with the SSPs in table G.1. The population estimates were further modified to be consistent on a level 1 administrative (province) level using the 2010 round of census data, hindcasted and forecasted using census growth rates to the year 2010 for each of the 863 units included.

The GDP data were adjusted to match the individual level 1 administrative GDP per capita data built from provincial and municipal government and bank estimates and forecasted and hindcasted to 2010 in the CATDAT database from Daniell, Wenzel, and Khazai (2012). Each administrative level 1 region had separate values of GDP per capita, distributed via 1 km resolution population data. The 2030 and 2080 scenarios were similarly adjusted using this distribution, but remain consistent with the SSPs and IMAGE model.

Hazard models

Risk modeling for large areas such as the ECA region requires global-scale data on exposure and hazard. Site-specific data are not available in most cases, and even if they were, their computational requirements would be prohibitive. We therefore rely here on globally applicable models to estimate hazard and exposure, which are consequently combined into risk estimates. The models are briefly described below.

Flood model

The flood modeling results are derived using several modules of the GLOFRIS (Global Flood Risk with IMAGE Scenarios) global flood risk modeling cascade. The first step is the simulation of daily discharge at a horizontal resolution of 0.5° x 0.5° using the PCR-GLOBWB global hydrological model (Van Beek and Bierkens 2009; Van Beek, Wada, and Bierkens 2011). For the present-day climate, the model was forced with daily meteorological data at 0.5° x 0.5° resolution. These data are derived from reanalysis data for the years 1960–1999 and are provided by the EU-WATCH project (Weedon et al. 2010). The second step in the hazard modeling is the simulation of daily within-bank and overbank flood volumes, again at a spatial resolution of 0.5° x 0.5°. This is carried out using DynRout extension (PCR-GLOBWB-DynRout), which simulates flood-wave propagation within the channel as well as overbank. For a detailed description of this approach, see Winsemius et al. (2013) and Ward et al. (2013).

From this daily time series of flood volumes, estimates of flood volumes per grid cell (0.5 °x 0.5°) were derived for selected return periods (2, 5, 10, 25, 50, 100, 250, 500, and 1,000 years). The estimates used extreme value statistics based on the Gumbel distribution and the daily nonzero flood volume time series derived from the hydrological model. These flood volumes were then used as input to the GLOFRIS downscaling module to calculate flood depths at the 30” x 30” level (Winsemius et al. 2013).

The GDP and population affected by floods for each return period were based on the population or GDP in each grid cell that had nonzero flood depths at the selected return periods. The average annual values at each grid point were derived by integrating over the nine return-period loss estimates. The annual average and return period values for GDP and population affected by floods in the level 1 administrative regions were determined by summing the losses within each area as defined using shape files.

To estimate the GDP and population affected by flooding in 2030 and 2080, both flood hazard and exposure for those time periods were simulated. The future flood hazard maps were simulated using the same GLOFRIS model as described above, but forced by daily future climate data from the five climate models (see table G.2) forced by the two RCPs (see table G.1). The precipitation estimates for the climate models are bias corrected using the 1960–1999 EU-WATCH data and a methodology developed by the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP). For details on the bias correction, see Hempel et al. (2013). The previously described methodology uses estimates of future precipitation generated by the five climate models as boundary conditions for estimating flood depths.

Earthquake model

The stochastic earthquake model follows a standard risk modeling approach that uses exposure (see above), a hazard component that represents earthquake events as finite and point sources, and vulnerability functions to estimate the loss caused by an earthquake affecting the exposure. The losses caused by all the events are used to estimate risk in the form of return periods and AAL. Like the flood model, the earthquake model quantifies exposure in terms of population and GDP, although it also includes data on capital stock (Daniell 2014).

The earthquake hazard is quantified using a 10,000-year stochastic catalog of over 15.8 million synthetic earthquake events of at least magnitude 5 in the ECA region. The earthquake model contains 1,437 source zones and 744 faults incorporating various regional and local studies over the past 30 years. The source zones are used to account for seismicity of unknown faults and in regions with low seismicity. The frequency and magnitude of earthquakes within each zone are specified using historical data and a Gutenberg-Richter (G-R) relationship that relates earthquake magnitude to number of occurrences. Specific characteristics (e.g., location or epicenter, fault motion, hypocentral depth, fault length) of each earthquake are defined using known faults and fault models, previously derived source regions, and geophysical knowledge.

Ground motion prediction and estimates of local site conditions are used to determine peak ground acceleration (PGA) at each grid point. Local soil conditions are based on tectonic regime and topographic slope following Allen and Wald (2007). Vulnerability is quantified using relationships that estimate loss as a function of MMI and others that estimate MMI from PGA, as in Daniell (2014).

Earthquake risk is assumed to be independent of climate. Thus, estimates of return period and annual average GDP and population affected by earthquakes for 2030 and 2080 change only in response to GDP and population exposure. We provide estimates of earthquake risk consistent with all five SSPs associated with IPCC AR5.

Results

Figures G.1 and G.2 provide an example of how Turkey's annual average GDP and population at risk of flooding evolve from 2010 to 2030 and 2080, based on the future scenarios of flood hazard and exposure. The seven different panels in each figure show the evolution in flood risk due to variations in flooding associated with climate change produced by greenhouse gas concentrations consistent with RCP4.5 and RCP8.5, exposure consistent with SSP2 and SSP3, and climate and exposure consistent with three combinations of RCPs and SSPs. The growth in flood risk for GDP seen in the combined scenarios in the top row of figure G.1 is driven primarily by future increases in GDP as specified by the SSPs. Flood risk for population in the combined scenarios remains nearly unchanged. Changes in climate associated with RCP4.5 and RCP8.5 cause, on average, a slight decrease in future flooding risk for population. This slight decrease is essentially offset by an increase in exposure as specified by the SSPs (figure G.2).

Figures G.3 and G.4 show estimates of how Turkey's current annual average GDP and population at risk of earthquakes with intensity of VI or greater evolve in response to changes in exposure associated with five different SSPs. There is a monotonic increase in annual average GDP risk, and the range of future possibilities grows significantly from the 2030 conditions to the 2080 conditions. The annual average population at risk of earthquakes also increases with time, but much of the increase occurs by 2030, and there is a significant variation in the scenarios for 2080.

Discussion and summary

There is a significant increase in Turkey's annual average GDP at risk of earthquakes with MMI equal to or greater than VI. The earthquake hazard is assumed to be independent of changes in climate. This increase is driven by changes in exposure consistent with the five SSPs. The evolution of Turkey's annual average flood risk for GDP is much more modest than that for earthquake. The RCP- and SSP-specific model runs show that the changes are largely driven by changes in the SSPs.

Figure G.1. Annual average GDP at risk of flooding in 2010, 2030, and 2080. The results are shown for five different climate models forced by RCP4.5 and RCP8.5 and exposures consistent with SSP2 and SSP3. The risk is assessed on the basis of changes in climate only (two bottom left panels), on the basis of changes in exposure only (two bottom right panels), and for three combinations of changes in climate and exposure (top three right panels).

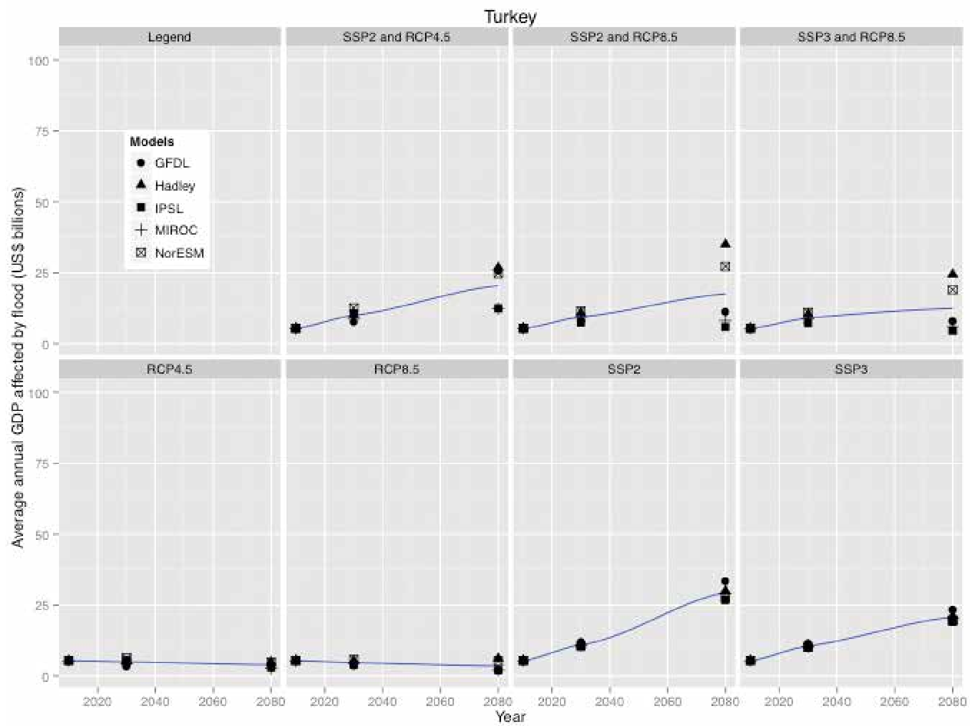


Figure G.2. Annual average population at risk of flooding in 2010, 2030, and 2080. The results are shown for five different climate models forced by RCP4.5 and RCP8.5 and exposure consistent with SSP2 and SSP3. The risk is assessed on the basis of changes in climate only (two bottom left panels), on the basis of changes in exposure only (two bottom right panels), and for three combinations of changes in climate and exposure (top three right panels).

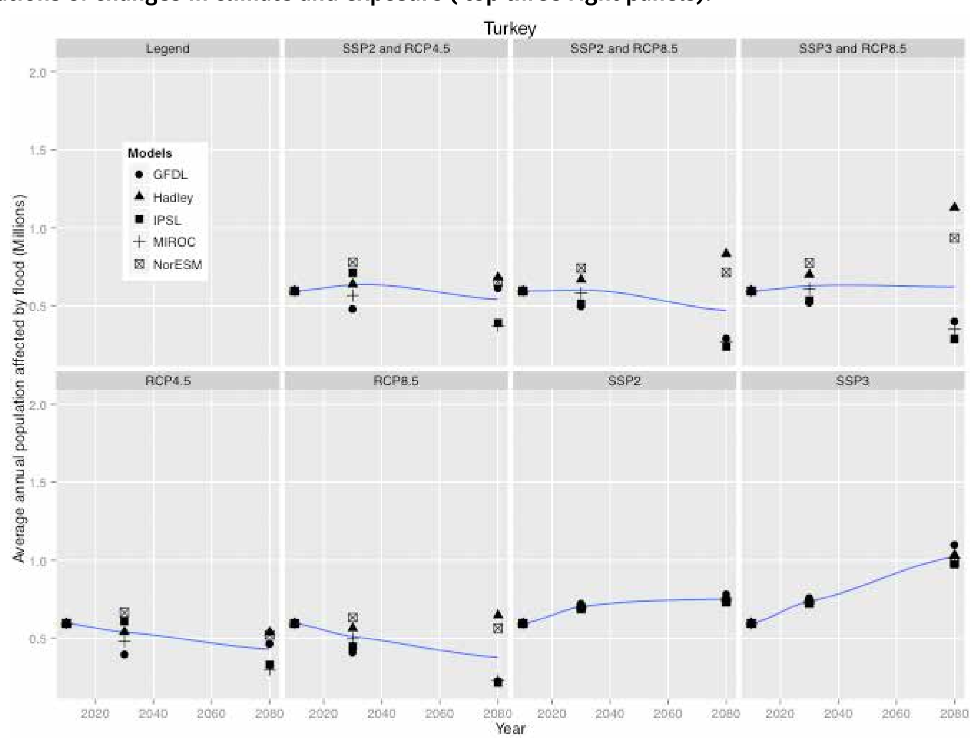


Figure G.3. Annual average GDP at risk of earthquakes with intensity greater than or equal to VI in 2010, 2030, and 2080. The results are shown for five different SSPs.

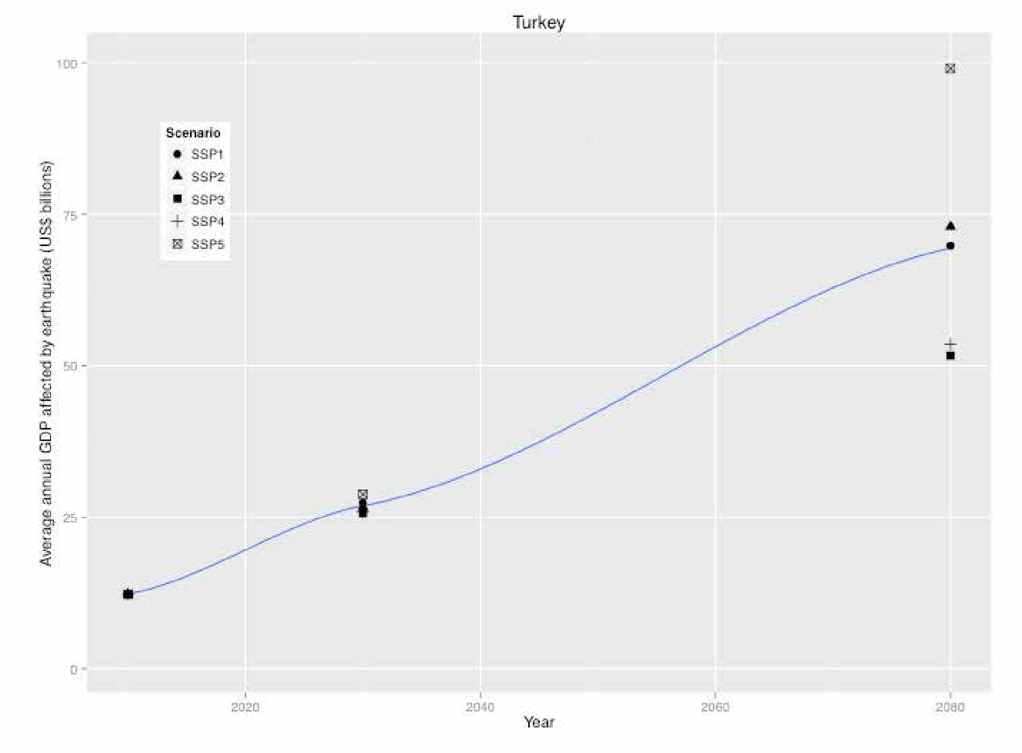
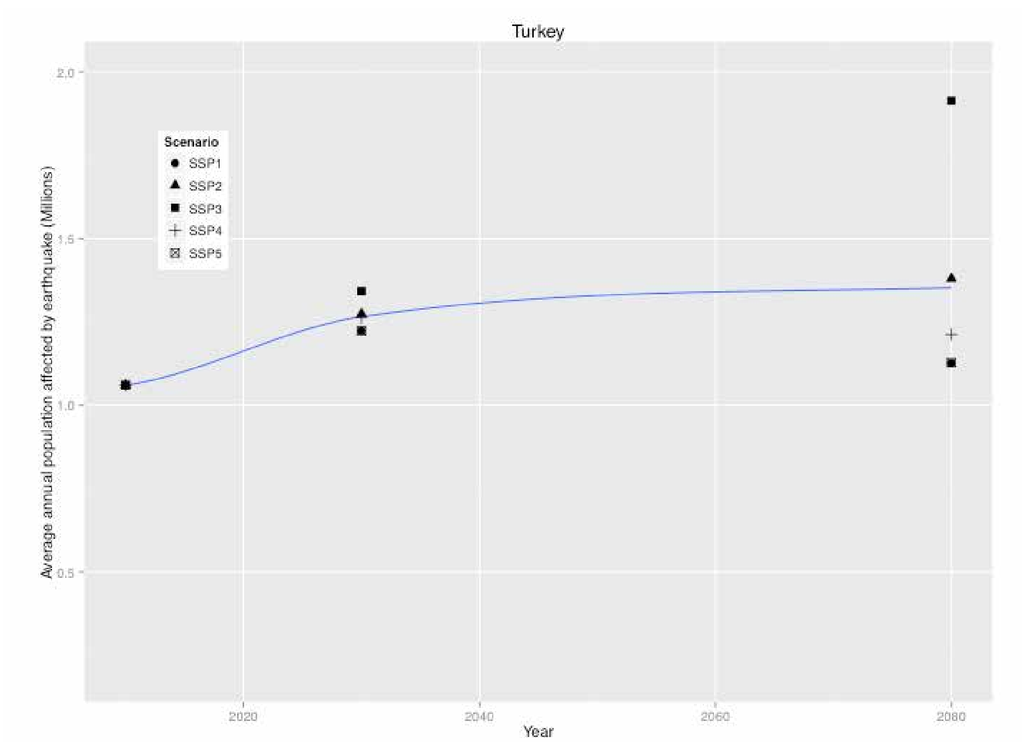


Figure G.4. Annual average population at risk of earthquakes with intensity greater than or equal to VI in 2010, 2030, and 2080. The results are shown for five different SSPs.



There is very little change in Turkey's annual average population at risk of flooding. While the climate-driven changes in population risk are somewhat larger than those for GDP, they are largely offset by exposure-specific changes, and as a result the combined RCP and SSP results show relatively little increase through time. However, the spread in combined results for 2030, and in particular for 2080, are larger than those for RCP- and SSP-specific model runs.

In contrast to the results for GDP at risk of flooding, the evolution of GDP at risk of earthquakes is significant and seen in all 5 SSPs, even though (not surprisingly) the uncertainty in the results grows with time. The evolution of the annual average population at risk of earthquake is less obvious. Most of the change occurs by 2030, with some of the SSPs in 2080 showing a decrease in population exposed to earthquakes.

The earthquake and flood results shown in figures G.1–4 highlight the importance for Turkey of changes in exposure as specified in the SSPs. In addition, both the overall risk and the relative increase in earthquake risk tend to be larger than the risk for flood. While further analysis is required to definitively identify the reason why this is so, we speculate that it is due to the limited spatial area subjected to flooding relative to the area subject to earthquake-induced ground motion, and to the distribution of population and GDP outside of flood-prone regions. Another consideration is that the flood work accounts only for fluvial flooding—that is, pluvial and flash floods are not considered in this analysis.

In general, risk assessments based on present-day exposure, hazard, and vulnerability estimates can have significant uncertainties. The uncertainties can be due to systematic and/or random errors that arise from multiple sources, such as flawed and/or missing estimates for the exposure, inaccurate simulations of hazard characteristics, the inherent uncertainty in the probability of events given the limit in sample size, and flawed vulnerability functions based on limited knowledge of a structure's performance in response to forces generated by a hazard event. In addition, it is difficult to determine what measures, if any, are taken to lower risk by reducing exposure and/or vulnerability. Risk assessments for future conditions are subject to the same sources of error, but the uncertainty for future conditions is even greater because of uncertain future changes in hazard, exposure, and vulnerability.

These results for Turkey illustrate two important factors related to the evolution of risk. First, an increase in population and GDP does not always lead to an increase in risk. Locating populations and economic activity in areas that are not subject to flood or other hazards will minimize risk. In cases where this is not possible—such as in response to earthquake risk in Turkey—more resilient building practices will help to minimize risk. Second, while changes in climate and meteorological hazards will likely occur in the future, these changes need to be considered in context with future changes in exposure. While meteorological hazards might increase in the future due to climate change, if exposure is controlled or reduced, the impacts can be moderated.

References

Allen, T. I., and D. J. Wald. 2007. "Topographic Slope as a Proxy for Global Seismic Site Conditions (VS30) and Amplification around the Globe." Open-File Report 2007-1357. U.S. Geological Survey. http://pubs.usgs.gov/of/2007/1357/index.html.

Daniell, J. E. 2014. "Development of Socio-economic Fragility Functions for Use in Worldwide Rapid Earthquake Loss Estimation Procedures." PhD diss. Karlsruhe Institute of Technology.

Daniell, J. E., F. Wenzel, and B. Khazai. 2012. "The Normalisation of Socio-economic Losses from Historic Worldwide Earthquakes from 1900 to 2012." Paper no. 2027. Proceedings of the 15th World Conference of Earthquake Engineering, Lisbon, Portugal.

Hempel, S., K. Frieler, L. Warszawski, J. Schewe, and F. Piontek. 2013. "A Trend-Preserving Bias Correction—The ISI-MIP Approach." *Earth System Dynamics* 4: 219–36. doi:10.5194/esd-4-219-2013.

Meinshausen, M., S. J. Smith, K. V. Calvin, J. S. Daniel, M. L. T. Kainuma, J.-F. Lamarque, K. Matsumoto, et al. 2011. "The RCP Greenhouse Gas Concentrations and Their Extension from 1765 to 2300." Climatic Change 109 (special issue): 213–41. doi:10.1007/s10584-011-0156-z.

Nakićenović N., R. J. Lempert, and A. C. Janetos. 2014. "A Framework for the Development of New Socioeconomic Scenarios for Climate Change Research: Introductory Essay." *Climatic Change* 122, no. 3 (special issue): 351–61. doi:10.1007/s10584-013-0982-2.

Van Beek, L. P. H., and M. F. P. Bierkens. 2009. "The Global Hydrological Model PCR-GLOBWB: Conceptualization, Parameterization and Verification." Department of Physical Geography, Faculty of Earth Sciences, Utrecht University, Utrecht, Netherlands. http://vanbeek.geo.uu.nl/suppinfo/vanbeekbierkens2009.pdf.

Van Beek, L. P. H., Y. Wada, and M. F. P. Bierkens. 2011. "Global Monthly Water Stress: 1. Water Balance and Water Availability." *Water Resources Research* 47: W07517. doi:10.1029/2010WR009791.

Ward P. J., B. Jongman, F. Sperna Weiland, A. Bouwman, R. Van Beek, M. F. P. Bierkens, W. Ligtvoet, and H. C. Winsemius. 2013. "Assessing Flood Risk at the Global Scale: Model Setup, Results, and Sensitivity." *Environmental Research Letters* 8: 044019. doi:10.1088/1748-9326/8/4/044019.

Weedon, G. P., S. Gomes, P. Viterbo, H. Oesterle, J. C. Adam, N. Bellouin, O. Boucher, and M. Best. 2010. "The WATCH Forcing Data 1958–2001: A Meteorological Forcing Dataset for Land Surface- and Hydrological-Models." WATCH Technical Report 22. EU-WATCH. http://www.eu-watch.org/publications/technical-reports.

Winsemius, H. C., L. P. H. Van Beek, B. Jongman, P. J. Ward, and A. Bouwman. 2013. "A Framework for Global River Flood Risk Assessments." *Hydrology and Earth System Sciences* 17: 1871–92. doi:10.5194/hess-17-1871-2013.

CASE STUDY H

Open Data and Dynamic Understandings of Risk

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The experience of the Open Data for Resilience Initiative (OpenDRI) project in Malawi provides an important example of how emerging approaches to risk information—open data, community mapping, and new tools for risk communication—can provide a more dynamic understanding of disaster risk, and a better understanding of the evolving nature of risk. Two years on, the project has demonstrated a number of important lessons in this regard:

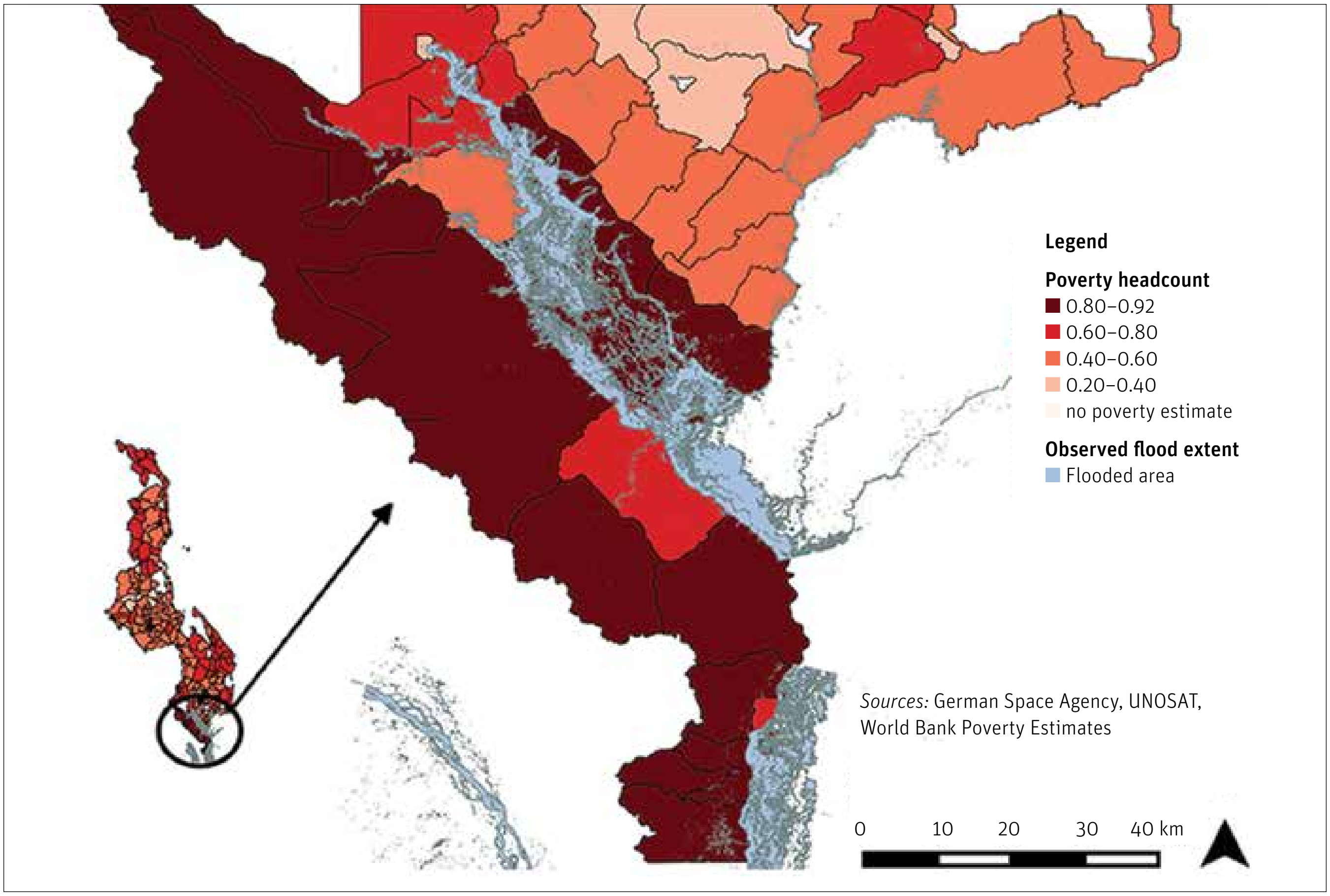
- Lack of access to information contributes to static understanding of risk. In many countries, risk data remain fragmented and inaccessible, even between government ministries. This can result in disaster risk assessments that incorporate outdated or inaccurate data. Open data helps to address this issue by making data available to all risk modelers, and allows countries to fully leverage the investment made in creating risk information.
- Community engagement can support efforts to understand risk. As shown in Malawi, but also in multiple similar projects conducted elsewhere, partnerships with local communities can produce up-to-date and accurate information about societal assets to inform risk assessment. When a local community is involved in creating and curating data, it provides a foundation for ongoing maintenance of risk information and supports an evolving understanding of hazard and risk.
- Tools that communicate risk in different ways can broaden the range of stakeholders involved in understanding risk. InaSafe and similar tools that help nonexperts make sense of complex risk information can engage new communities and actors in the challenge of disaster risk management.
- Time and sustained investment are needed to make meaningful changes to risk information systems. The partnership between OpenDRI and the Malawi Spatial Data Working Group has developed in valuable and unexpected ways since it began in 2012, and it will continue to evolve. Most technical assistance programs have short life spans that don't allow for such evolution, whereas ongoing partnerships can promote continued data generation as disaster is evolving into the future.

Case Study: OpenDRI Malawi

Malawi experiences severe annual flooding that affects tens of thousands of people and causes millions of dollars of damage, amounting to an estimated 0.7 percent of annual gross domestic product per year (GFDRR 2014). The 2015 flood season has been exceptionally severe, with over 600,000 people affected and 170,000 displaced in January and February alone (Hallegatte, Bangalore, and Nkoka 2015). The poor are particularly vulnerable to flooding and possess the least ability to recover from natural disasters (see figure H.1). Floods are not the only hazard that Malawi faces; the country is also exposed to drought, landslide, and seismic hazard.

In order to effectively build resilience to natural disasters and the impacts of climate change, policy makers and the public in Malawi need access to accurate and timely information on hazards, vulnerability, and exposure. In the past, however, these data have too often been inaccessible. The results of disaster risk assessments have typically been delivered in the form of PDF reports, with the valuable data collected or produced during the assessment locked away on someone's hard drive. In other cases, data have been fragmented across various government ministries, which were unable or unwilling to freely share them because of government mandates that data be sold in the name of cost recovery. These barriers to information access are common in many parts of the world, and they severely limit countries' ability both to understand and manage risk and to respond in the case of disasters.

Figure H.1. **Poverty map of Malawi (based on World Bank estimates) overlaid with data on flooding. The poorest parts of Malawi are among the most flood-prone.**



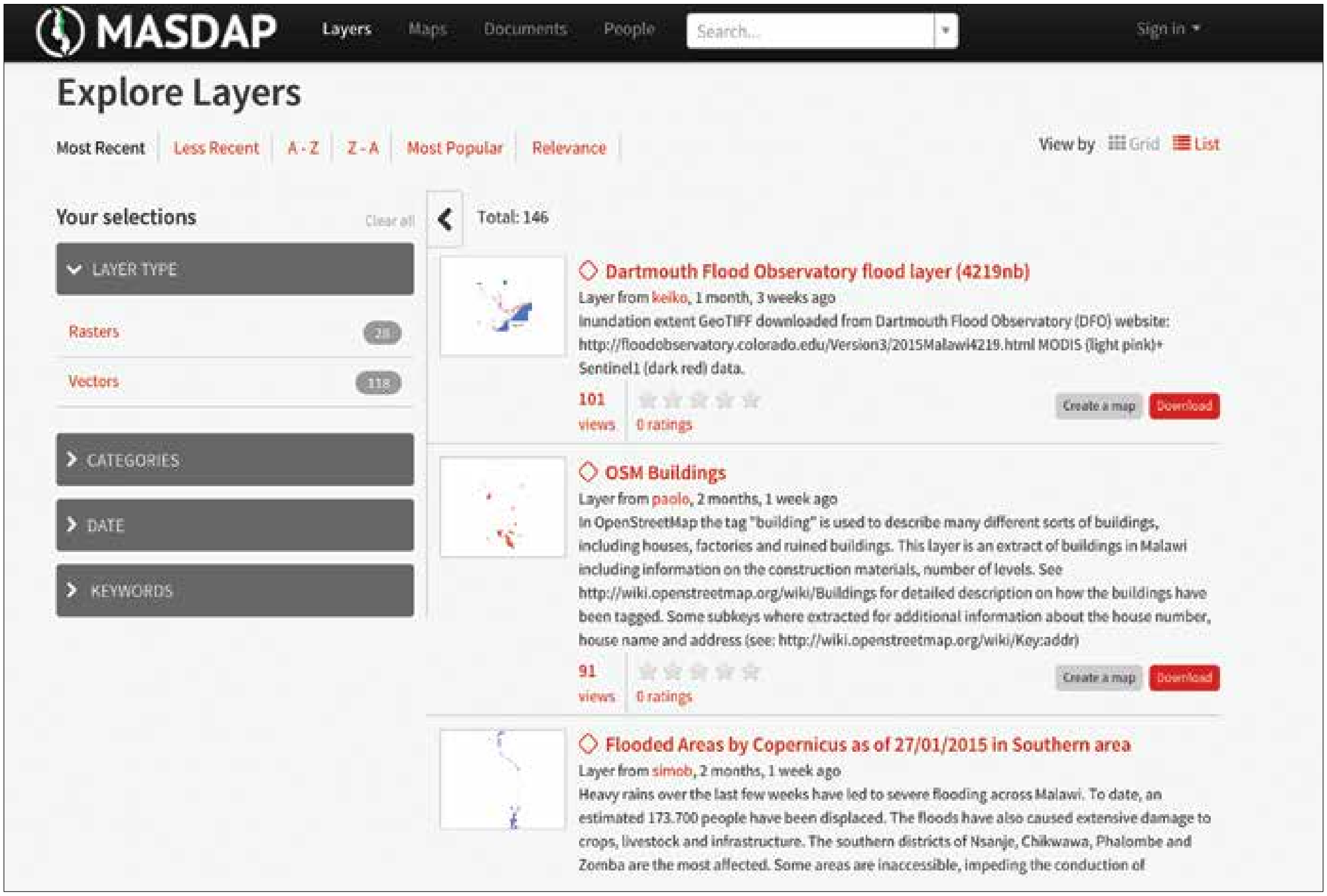
Source: Hallegatte, Bangalore, and Nkoka 2015.

The Malawi Spatial Data Portal (MASDAP): Improving access to information

In 2012 the World Bank's Open Data for Resilience Initiative launched a project to help support disaster risk management in Malawi by improving access to risk information. With the support of the World Bank, the government of Malawi was developing new flood risk maps for the Lower Shire River basin, one of the most at-risk catchments in the country. The team wanted to ensure that the results of the mapping work would be open and accessible to the public. This gave birth to the Malawi Spatial Data Working Group, a new partnership between the Department of Surveys, the National Statistics Office, the Department of Disaster Management and Affairs, and other key producers and users of data across government.

With the support of OpenDRI, the working group launched the Malawi Spatial Data Platform, or MASDAP (figure H.2), in November 2012. The initial offerings of the platform were limited to the results of the Shire River basin flood risk assessment as well as a few other data sets that participating government ministries were able to share at that time. However, thanks to continued work and negotiation by the Malawi Spatial Data Working Group, new data sets have been made available and added to the platform. Today, MASDAP contains over 140 individual data sets describing everything from Malawi's road network to land cover, elevation, and administrative units. In the words of World Bank Disaster Risk Management Specialist Francis Nkoka, "Instead of being dispersed and hard to access, disaster risk and climate-relevant data are

Figure H.2. **Data listing on the Malawi Spatial Data Portal (MASDAP), http://masdap.mw.**



now consolidated in one open and accessible platform, which is particularly useful for pre-event planning" (World Bank 2014).

Community mapping of the Lower Shire River Basin

One of the benefits of the MASDAP platform was that it allowed, for the first time, a comprehensive and accessible picture of the availability of spatial data in the country. Recent investments in flood modeling in the Shire River basin had created high-resolution and accurate flood maps of the region; but similarly detailed data describing the location and characteristics of roads, houses, and other aspects of the built environment did not exist. With this in mind, the Malawi Spatial Data Working Group, in partnership with the Humanitarian OpenStreetMap Team (HOT), launched a community-mapping project in target districts of the Lower Shire basin.

The project made use of the OpenStreetMap (OSM) platform. OSM, often called "the Wikipedia of maps," was founded in the United Kingdom in 2004. It has since grown to a global project with nearly 2 million registered members and local chapters in over 100 countries. After providing vital data to the international response following the 2010 Haiti earthquake, OSM has since been used in Indonesia, Nepal, and numerous other countries around the world to support disaster risk management efforts.

From July through September 2014, working with local partners from the Department of Surveys and Department of Disaster Management, HOT conducted a series of outreach and training events with university students and community groups in the

OpenStreetMap activities in Malawi.

Source: Humanitarian OSM Team. Licensed under Creative Commons Attribution 3.0 IGO, https://creativecommons.org/licenses/by/3.0/us/.

Chikwawa and Nsanje Districts. Over this period, 55 people were trained in the use of OpenStreetMap during three- to four-day sessions. Participants also engaged in hands-on data collection in key parts of the flood-prone districts, mapping numerous towns and villages. The group collected exposure data for 21,000 residential buildings and improved overall coverage of road infrastructure and other key features in the Shire River basin (figure H.3). All data collected through the project are available on the Malawi Spatial Data Portal. At the conclusion of this stage of the project, a team of six interns from the local university is continuing to support data collection and outreach with the goal of expanding the OSM community in Malawi. This mechanism for ongoing data collection and curation will help to ensure that exposure information in these districts is kept up-to-date. This, in turn, will enable future risk assessments to quantify risk based on current exposure rather than a snapshot from the past, and thus provide a more accurate view of risk. Current data are particularly important in areas where population growth, development, or new construction is occurring rapidly. Ongoing data collection can also be valuable for understanding growth trends through time.

Data to insight with InaSafe

Thanks to the efforts of the community mapping team, detailed information on the built infrastructure in the Lower Shire River basin is now available in OpenStreetMap and on the Malawi Spatial Data Portal. When combined with updated flood hazard layers created in 2012, these data allow for a more complete understanding of the potential impacts of floods in the region. In September 2014, in order to support flood preparedness and mitigation efforts, the OpenDRI team organized a training session for officials from Malawi's Department of Disaster Management Affairs and other ministries on the use of InaSafe software.

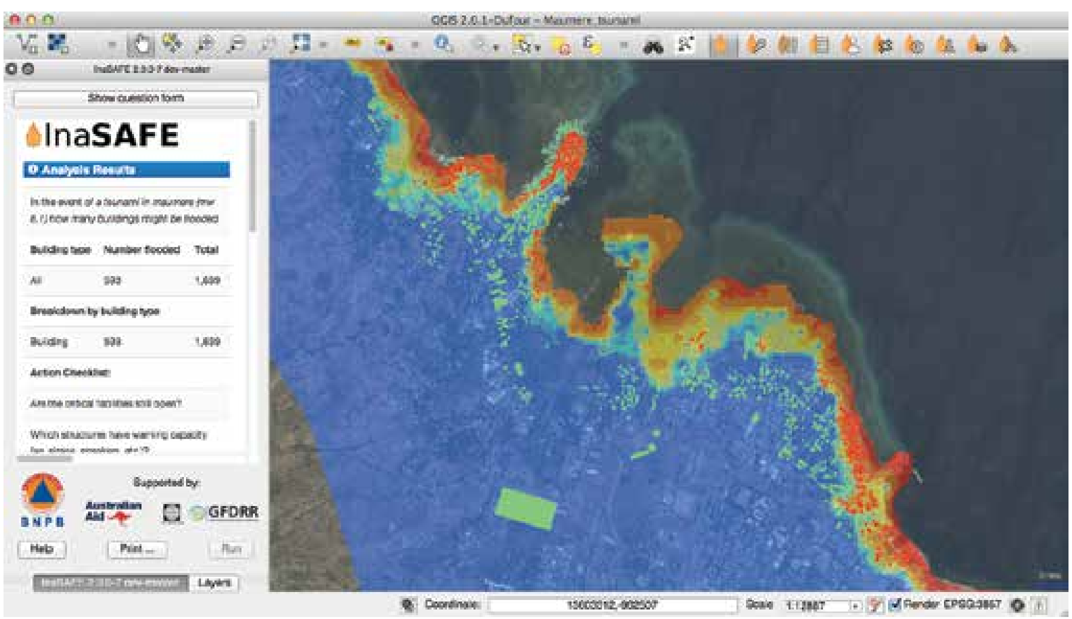
InaSafe (figure H.4) is a free and open source impact-analysis tool initially developed in Indonesia in partnership between the Indonesian government, Australian AID, and the World Bank. Designed for ease of use by disaster managers and policy makers, InaSafe allows users to combine data from a variety of sources to produce insights about various hazard scenarios. Following its initial development, it has been deployed in Sri Lanka, the Philippines, and elsewhere as part of disaster risk management efforts.

In Malawi, the tool is being used in support of flood impact projections that can both inform ex ante mitigation and preparedness work and support rapid ex post disaster needs assessments. These analyses are possible because of the increased information available

Figure H.3. **Nchalo District and other parts of the Lower Shire River basin, before and after volunteer mappers added detailed information about transportation infrastructure and other elements of the built environment to OpenStreetMap. These data are now openly available to be used for risk assessments and other purposes. The two images show the improvement in data coverage for the area as a result of the OpenDRI Malawi project.**

Source: OpenStreetMap. © OpenStreetMap contributors. Licensed under Open Database License, http://opendatacommons.org/licenses/odbl/1.0/.

Figure H.4. **The InaSafe Tool. More information can be found at http://inasafe.org.**



from community mapping exercises and the work of the Malawi Spatial Data Working Group. The working group and local OSM community are continuing to collect and create new information, and this will also be available for use with the InaSafe platform.

In 2015, the OpenDRI program has built on the foundation established during the first two years of work in Malawi. The project continues to focus on and support the Malawi Spatial Data Working Group. A technical committee, comprising a subset of this group, was formed in 2013 to meet the development and maintenance needs of the platform. During a recent meeting, the committee prioritized a number of user-interface customizations as well as further collaboration from the working group related to data curation. The community mapping work will also continue in the Shire River basin and other at-risk areas in the country; aided by student volunteers, the Survey Department will continue to work full time on OSM data collection and community building. Finally, plans are under way to expand upon the initial InaSafe trainings in Malawi and customize the software and training program for the country's particular requirements for contingency planning and post-disaster needs assessment. Together these activities will contribute to a more detailed and dynamic understanding of risk across new sectors of society in Malawi.

References

GFDRR (Global Facility for Disaster Reduction and Recovery). 2014. "Malawi Country Program Update." May. https://www.gfdrr.org/sites/gfdrr/files/region/MW.pdf.

Hallegatte, Stéphane, Mook Bangalore, and Francis Samson Nkoka. 2015. "Recent Floods in Malawi Hit the Poorest Areas: What This Implies." Voices: Perspectives on Development (World Bank blog). February 6. *http://blogs.worldbank.org/voices/recent-floods-malawi-hit-poorest-areas-what-implies*.

Humanitarian OpenStreetMap Team. 2014. "OSM Community Mapping for Flood Preparedness in Malawi." http://hot.openstreetmap.org/projects/osm_community_mapping_for_flood_preparedness_in_malawi.

World Bank. 2104. "In Malawi, Citizens Get Involved as Innovative Technologies Help Them Understand and Manage Disaster Risks." December 4. http://www.worldbank.org/en/news/feature/2014/12/04/in-malawi-citizens-get-involved-as-innovative-technologies-help-them-better-understand-and-manage-disaster-risks.

CASE STUDY I

Science Influencing Land-Use Policy: A Story from New Zealand

Wendy S. A. Saunders and James Beban (GNS Science)

In 2012 the Hutt City Council (part of the Wellington Region, and located at the northern end of Wellington Harbor), notified a plan change (known as Plan Change 29) that allowed for increased development within the southwestern portion of Petone, a suburb of Hutt City. The proposed plan-change area is subject to a number of natural hazards, including fault rupture, subsidence, sea-level rise, liquefaction, flooding, and tsunami. The previous district plan had very limited rules to address the risks from natural hazards, and no new rules were proposed as part of this plan change.

As a corporate citizen of Hutt City, GNS Science lodged a submission opposing the plan change. Much of the submission was informed by natural hazard information gathered from the "It's Our Fault" research project.[8] While the plan change still proceeded, it was amended as a result of the submission. The new provisions (objectives, policies, and rules) included in the final plan change strengthened the requirement that new development within the southwestern portion of Petone take into account the various natural hazards that may affect the area.

This paper describes the plan change process and the revisions made to the plan change when GNS Science brought relevant scientific and technical information to the council's attention. It also details the hazards to which the area in question is prone.

Summary of land-use planning in New Zealand

In New Zealand, no one agency is responsible for natural hazard management. Rather, a number of organizations, including the Ministry of Civil Defence Emergency Management (MCDEM), regional councils, territorial authorities, civil defense emergency management (CDEM) groups, and engineering lifeline groups hold these responsibilities (Saunders and Beban 2012). Cooperation between these agencies is essential to ensure a streamlined and holistic national approach to planning for disasters.

There are four key pieces of legislation that have a primary influence on natural hazard management in New Zealand: the Resource Management Act 1991 (RMA), Building Act 2004, Civil Defence Emergency Management Act 2002, and Local Government Act 2002. These four statutes all promote sustainability management or development, and are intended to be integrated in their purposes. The RMA is New Zealand's primary planning legislation. It seeks to promote the sustainable management of natural and physical resources. Toward that end, it calls for an effects-based approach (involving environmental assessments) rather than an activities-based approach; it devolves responsibilities through regional and territorial (i.e., city or district) authorities; and it supports public participation in decision making (May et al. 1996).

More specifically, the RMA requires (a) that planning take health and safety into account—i.e., not consider them as just a building or emergency management responsibility; and (b) that local authorities avoid or mitigate the effects, not the occurrence, of natural hazards. However, the RMA does not explicitly require that natural hazard *risk be planned for.*

Proposed development

Proposed Plan Change 29 sought to expand the existing zone known as Petone Commercial Activity–Area 2. This expansion included some rezoning of a portion of the General Business Activity Area to bring it within the Petone Commercial Activity Area–Area 2. The plan change area is bordered by two main arterial roads that link the main state highway to Wellington City, and by the Wellington Harbor to the south. Figure I.1 shows the area covered by the plan change.

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8 The goal of the It's Our Fault research program is to see Wellington positioned to become a more resilient city through a comprehensive study of the likelihood and effects of large Wellington earthquakes. See GNS Science, "It's Our Fault," http://www.gns.cri.nz/Home/IOF/It-s-Our-Fault.

Figure I.1. Area covered by Plan Change 29, Petone West.

Source: Hutt City Council 2012, 101.

Plan Change 29 proposed a single set of objectives, policies, and rules to encompass the area subject to the plan change. These new objectives, policies, and rules would replace the existing provisions for both the Petone Commercial Activity Area–Area 2 and the portion of the General Business Activity Area subject to the plan change.

As notified, Plan Change 29 proposed a number of changes, including the following (Hutt City Council 2012):

- *Building height.* Maximum building height of 30 m permitted throughout the area, with any building over 12 m requiring a wind assessment; maximum permitted building height of 15 m along the three main roads, with a 45° degree recession plane sloping inward from this 15 m height, up to the maximum permitted height of 30 m.
- *Design guidelines.* New and more specific design guidelines indicated for buildings along the three main roads.
- *Retail.* Retail developments permitted up to a maximum of 10,000 m2 of floor space, subject to compliance with the permitted activity conditions.
- *Residential.* Residential development permitted, subject to compliance with the permitted activity conditions.
- *Commercial.* Commercial development permitted everywhere, subject to compliance with the permitted activity conditions, along with some light industrial uses.
- *Wellington Fault.* Current requirements retained for addressing the extra risk of building within the Wellington Fault area. Building heights and density provisions within the fault area would be the same as elsewhere in the area.

Essentially, Plan Change 29 sought to introduce more types of activities and more intense development to the area by establishing a mixed-use area within the southwestern portion of Petone. The rules of the district plan prior to Plan Change 29 allowed for development that significantly increased the risk to people and property. Proposed Plan Change 29 was notified with no new or additional rules to address the risks associated with natural hazards.

Petone hazardscape

Petone West is susceptible to a range of hazards, including fault rupture, ground shaking, liquefaction, tsunami, flooding, landslides, sea-level rise, and tectonic subsidence. Each of these is discussed in further detail below.

Fault rupture

The Wellington region lies within the deforming boundary zone between the Pacific and Australian plates, and is located within one of the most seismically active areas of the country. The region is cut by a number of earthquake-producing active faults, both onshore and offshore. Since 1840, the region has been violently shaken by earthquakes three times, in 1848, 1855, and 1942 (Downes 1995; Robinson, Van Dissen, and Litchfield 2011; Stirling et al. 2012). The likelihood of a Wellington Fault earthquake (approximately magnitude 7.5) occurring within the next 100 years is approximately 10–15 percent (Rhoades et al. 2011).

The Wellington Fault is located along the western edge of the valley floor of Hutt City, as shown in figure I.2. In a single Wellington Fault event, Hutt City would likely experience subsidence of up to ~1.2 m at Petone West.

Ground shaking

The amount of ground shaking a location experiences is dependent on the ground materials. As a general rule, the weaker the materials are, the longer and stronger the ground shaking is. To assess soil types, five ground-shaking amplification classes have been formulated (Standards Australia/New Zealand 2004):

- Class A: strong rock
- Class B: weak rock
- Class C: shallow soil
- Class D: deep or soft soil
- Class E: very soft soil

These soil classes have implications for the foundations and subsequent performance of buildings. For example, ground classified as Class D can require far more extensive engineering—and hence be more costly to build on—than Class C ground.

The Petone Plan Change 29 area is within the Class D sites, overlain with a zone that may contain Class E sites. The presence of deep or soft soil, along with very soft soil, has implications for building foundation design, liquefaction potential, and nonstructural building damage.

Liquefaction

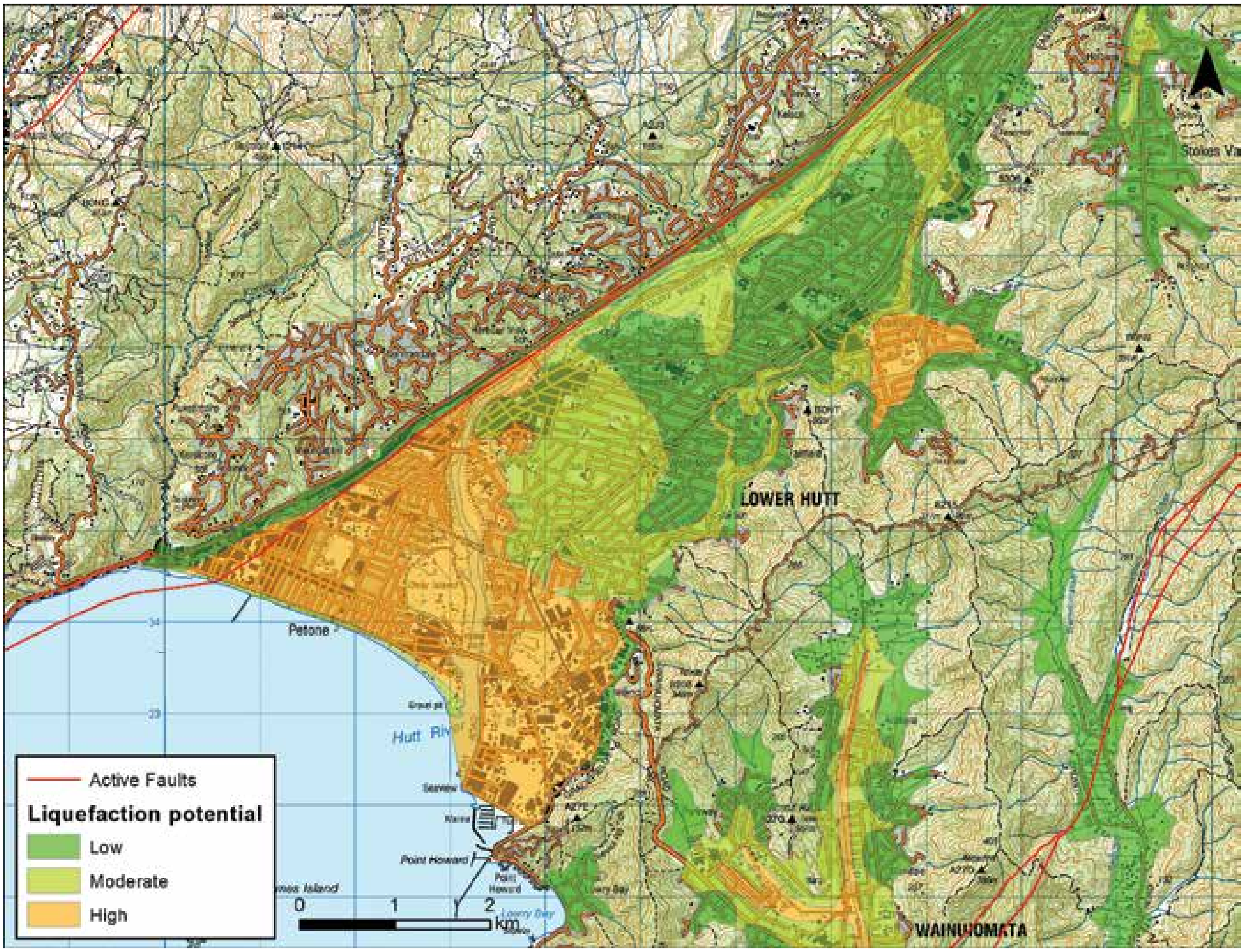
Figure I.2 presents the liquefaction potential for Lower Hutt. While there are no areas of very high susceptibility, the Petone West area is classified as having high susceptibility. In order for liquefaction to occur in the most susceptible soils, ground shaking would be required of peak ground acceleration of 0.1 g or more (Saunders and Berryman 2012). This threshold would certainly be exceeded if the Wellington Fault ruptures. The expected return time of 0.1–0.2 g shaking in Petone West is approximately 100 years (based on Stirling et al. 2012 and applying "deep or soft soil" site conditions).

Since the Canterbury earthquakes of 2010–2011, both the public and councils have better understanding of liquefaction and its consequences. They also better understand related zoning issues (e.g., the "red zoning," or retirement from use, of residential properties in Christchurch that are highly vulnerable to liquefaction) and options to mitigate the hazard (i.e., engineered remediation).

Tsunami

Wellington is susceptible to tsunami from both distant and regional sources. In 2013 a review of tsunami hazard was undertaken to summarize the current state of knowledge and to produce revised probabilistic hazard models. Petone West is located directly opposite the Wellington Harbor, within the "red" and "orange" tsunami evacuation zones (figure I.3), based

Figure I.2. **Liquefaction potential for Lower Hutt.**



Source: Adapted from Beetham et al. 2012.

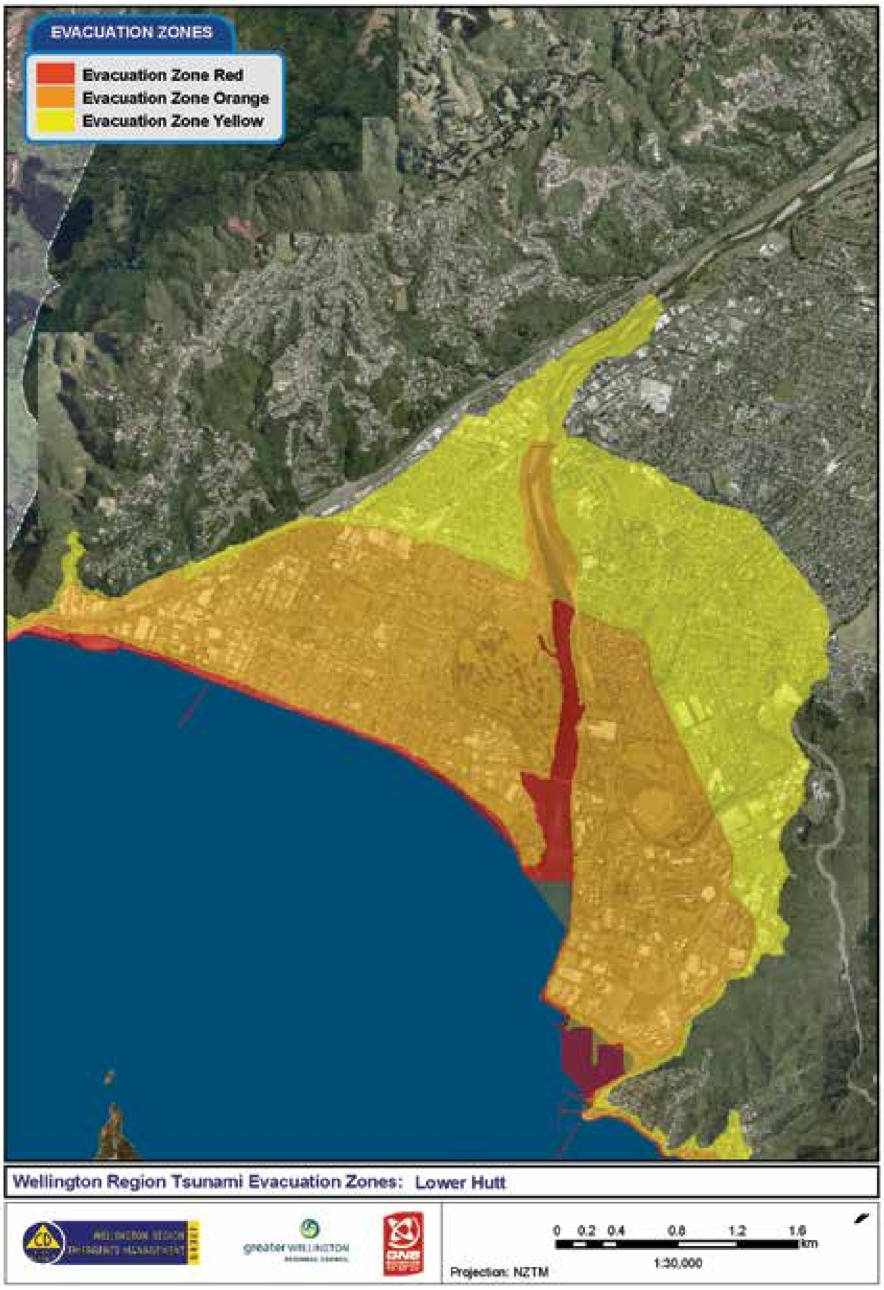
on distant and regional source tsunami modeling (Leonard et al. 2008). The red zone is intended as a shore-exclusion zone that can be designated off-limits in the event of any expected tsunami. It represents the highest level of risk and is the first place that should be evacuated in case of any sort of tsunami warning. People could expect activation of this zone several times during their lifetime. The orange zone is to be evacuated following most if not all distant and regional source official warnings—i.e., warnings that extend beyond the red zone, for tsunami from sources more than one hour of travel time away from the mapped location (MCDEM 2008).

For the red and orange zones, evacuation is limited to vertical structures because of the area's topography and infrastructure. For example, to evacuate on foot up the nearest hill, one would need to scale a two-meter-high fence to cross the electrified railway line, scale another two-meter-high fence to State Highway 2, hop over a concrete median barrier, then proceed up a very steep, scrub-clad hill, and wait for hours as the many waves swept in. Given the hurdles and the steepness of the hills, this option is not very realistic. As yet, there are no certified tsunami evacuation buildings located in Petone West.

Flooding

Flooding from the Hutt River is one of the biggest environmental and emergency management issues

Figure I.3. Tsunami evacuation zones for Lower Hutt.



Source: Leonard et al. 2008; Wellington Region Emergency Management Office 2013.

facing residents of the Hutt Valley. The Hutt Valley is the second-most densely populated and asset-rich floodplain in New Zealand.[9] The key focus of floodplain management planning is keeping floodwaters away from people and development (Wellington Regional Council 2001). This means continued reliance on physical protection (i.e., embankments) against flooding.

Figure I.4 shows that any breach of the flood protection system would affect parts of Petone West. Also relevant is the impact of a high tide and the need for water to drain across the road adjacent to Wellington Harbor (which could be impeded by an existing seawall).

The Hutt River Floodplain Management Plan includes both structural and nonstructural measures to reduce risks. Structural measures are physical works, such as embankments, rock linings, and vegetation buffers, while nonstructural measures include land-use planning regulations that keep people, possessions, and development out of or away from flood-prone areas. According to the Hutt River Floodplain Management Plan, "non-structural measures enable a community to be more resilient to flooding through flood awareness, preparation, and *sensible land use*" (Wellington Regional Council, 2001 13; emphasis added).

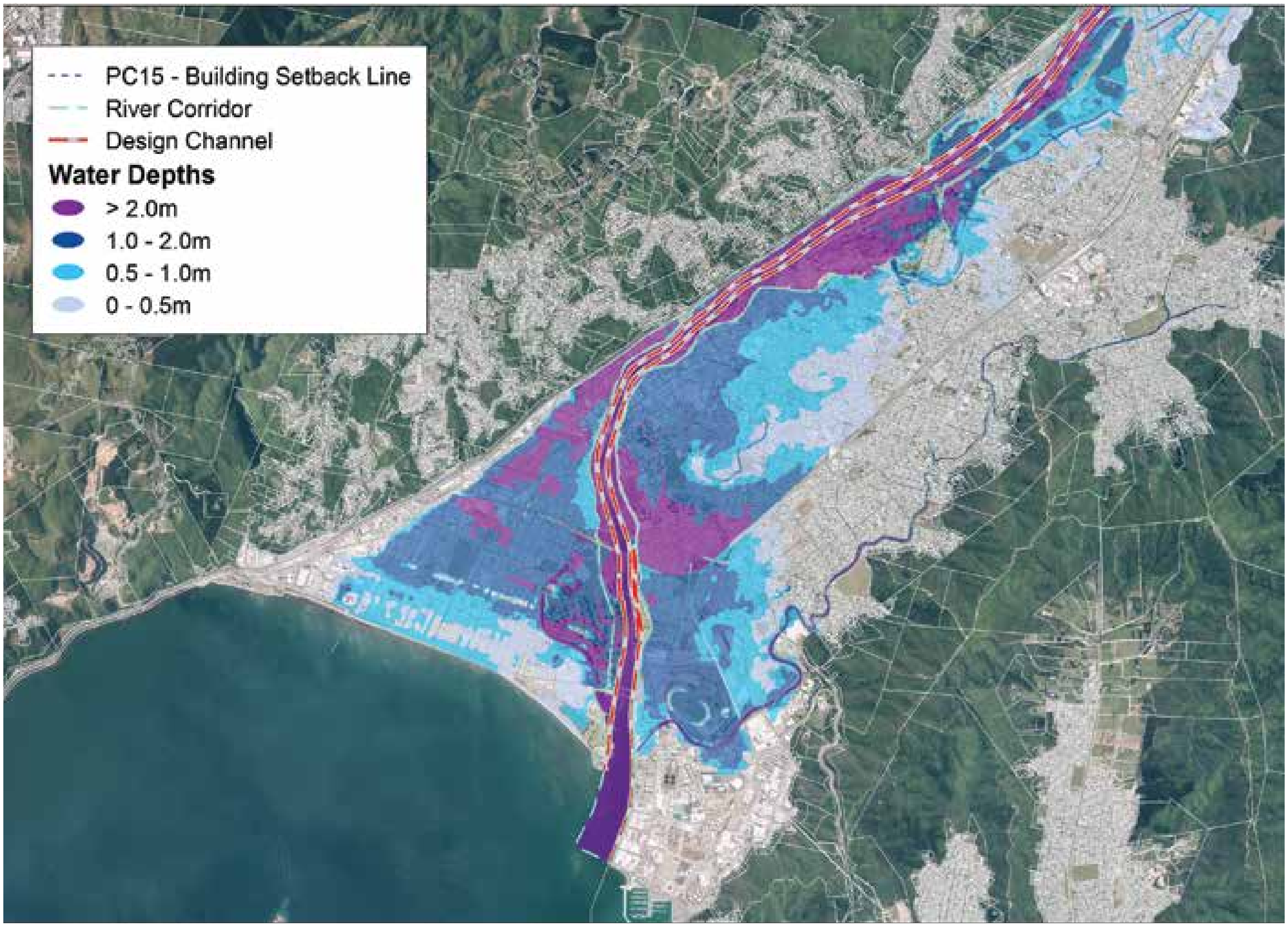
However, the Hutt River is not the only source of flooding for Petone. The nearby Korokoro Stream also has a history of flooding, with the last major event occurring in 1976. The consequences of that flood are shown in figure I.5: State Highway 2, the railway, and access to the overpass from Petone West were all affected by the floodwater, making evacuation options limited.

Landslides

While not a direct hazard for Petone West, landslides do have the potential to make access to Petone difficult. For example, after

9 The population is approximately 130,000.

Figure I.4. Flooding of the Hutt Valley with breaches for a 2,300 cumec flood extent (440-year event) under the upgraded flood protection system.



Source: Wellington Regional Council 2001, 8.

the 1855 Wairarapa earthquake, a large landslide occurred south of Petone on State Highway 2, between Hutt City and Wellington City. If a similar event happened today, it is likely that State Highway 2 and the railway (servicing the Hutt Valley and Wairarapa) could be blocked for many days or more (Brabhaharan 2010). This would have major implications for evacuation and would also affect those needing to travel to the Hutt Valley from Wellington.

Sea-level rise

One of the main outcomes of climate change for Petone is sea-level rise. A recent report (Bell and Hannah 2012) that assessed sea-level rise and coastal flooding from storm events in the Wellington region found that Wellington has the highest rate of sea-level rise in New Zealand. All low-lying areas around the coast are subject to storm-tide flooding, but this vulnerability will increase due to sea-level rise. Areas at risk include the mouth of the Hutt River and low-lying parts of Petone, including Petone West, which is the area subject to the Hutt City Council plan change.

Role of GNS Science

In response to the notified plan change, GNS Science decided to lodge a submission in opposition to the suggested changes. This submission was prepared with the input of several GNS staff members, including an engineering geologist, an earthquake geologist, a natural hazards planner, and a PhD student investigating vertical evacuation

Figure I.5. **Flooding from Korokoro Stream in 1976. The Petone Plan Change 29 area extends approximately from the Odlins Timber Yard corner between The Esplanade (located underwater on the far right) and the railway line.**

Source: Evening Post. ©Fletcher Trust Archives. Reproduced with permission; further permission required for reuse.

structures for tsunami.

The submission outlined the hazard environment of the plan change area and, where appropriate, identified measures to avoid or reduce the risk associated with these hazards. The hazards identified in the submission included fault rupture, earthquake-induced subsidence, tsunami hazard, liquefaction, and sea-level rise due to climate change. In addition to providing information on the specific hazards and the measures required to avoid or reduce the risk associated with them, the submission also commented on specific portions of the plan change.

Outcome of GNS Science response

Prior to the submission process, the plan change did not include any specific natural hazard–related objectives, policies, or additional restrictions. What was included focused on the Wellington Fault Special Study Area; no other hazards were specified. Based on the information provided by GNS Science, a new section has been inserted on natural hazards, which specifically includes ground rupture as well as subsidence, liquefaction, tsunami, and sea-level rise. Without GNS Science input, the result might have been different. Table I.1 summarizes the provisions before and after GNS Science's submission and shows the direct changes as a result of the submission process.

Ideally, these provisions should be incorporated into the entire district plan. Currently, the district plan addresses only the Wellington

Table I.1. Natural Hazard Provisions in Plan Change 29 before and after Submission Process

Before submission process: Proposed Plan Change 29	After submission process: Decision for plan change
Wellington Fault line: Retain current requirements to cope with the extra risk of building within the Wellington Fault area. Building heights and density provisions within the fault area would be the same as elsewhere in the area.	Addition of a natural hazard–specific objective: To avoid or mitigate to an acceptable level the vulnerability and risk of people and development to natural hazards. All new buildings require a case-by-case assessment of the natural hazard risks and consequences. There are specific references to the ground rupture, subsidence, liquefaction, and tsunami risks as well as the requirement for sea-level rise to be considered. In response to the risk from natural hazards, emergency facilities were made a noncomplying activity for the entire Petone Mixed Use Area. In response to the natural hazard risk, places of assembly, child-care facilities, education and training facilities, commercial activities (accommodating more than 300 people), community activities/facilities, housing for the elderly, and residential facilities were made a discretionary activity. Any development that includes these activities must consider the natural hazard risk and measures to avoid or reduce this risk.

Special Fault Study Area and only one hazard, flooding, even though other hazards (subsidence, liquefaction, tsunami, and sea-level rise) have the potential to affect areas outside of the Petone West plan change area.

GNS Science presented the community and council with the latest scientific understanding of the geological hazards in this area, and reminded the council of its legislative responsibilities for hazard management. The mayor and council staff indicated afterward that the presentation of this scientific information to the council planners, the community (via the pre-hearing meeting), and the commissioners played a key role in ensuring the objectives, policies, and rules pertaining to natural hazards were included in the plan change. This experience demonstrates that information provided by scientific and technical organizations like GNS Science can be used in appropriate forums to help educate planners and to inform policy debate regarding development and the mitigation of risks due to natural hazards. It is often assumed that councils and decision makers are aware of the natural hazards in their area. However, there may be only a basic understanding of what the natural hazards are, while the scale of the hazards and the potential risks they pose are often poorly understood.

While Plan Change 29 still went ahead in a highly hazardous area, GNS Science research was used with positive effect at a local scale. This was a successful instance of scientific information being used to educate decision makers and inform policy in order to reduce future risks from development in areas subject to natural hazards.

References

Beetham, R. D., J. Cousins, M. Craig, G. D. Dellow, and R. J. van Dissen. 2012. *Hutt Valley Trunk Wastewater Earthquake Vulnerability Study*. Lower Hutt, New Zealand: GNS Science.

Bell, R. G., and J. Hannah. 2012. *Sea-Level Variability and Trends: Wellington Region*. Hamilton, New Zealand: National Institute of Water and Atmospheric Research Ltd.

Brabhaharan, P. 2010. "Initiatives towards Integrated Resilience of Road Transportation Lifelines in the Wellington Region." Paper presented at the New Zealand Society of Earthquake Engineers, Wellington, March 26–28.

Downes, G. L. 1995. *Atlas of Isoseismal Maps of New Zealand Earthquakes*. Lower Hutt, New Zealand: Institute of Geological and Nuclear Sciences.

Hutt City Council. 2012. "District Plan Change 29." http://www.huttcity.govt.nz/district-plan-change-29.

Leonard, G. S., W. Power, B. Lukovic, W. Smith, D. Johnston, and G. Downes. 2008. *Tsunami Evacuation*

Zones for Wellington and Horizons Regions Defined by a GNS-Calculated Attenuation Rule. Lower Hutt, New Zealand: GNS Science.

May, P. J., R. J. Burby, N. J. Ericksen, J. W. Handmer, J. E. Dixon, S. Michaels, et al. 1996. *Environmental Management and Governance: Intergovernmental Approaches to Hazards and Sustainability*. London: Routledge.

MCDEM (Ministry of Civil Defence Emergency Management). 2008. *Tsunami Evacuation Zones: Director's Guideline for Civil Defence Emergency Management Groups [DGL08/08]*. Wellington, New Zealand: Ministry of Civil Defence and Emergency Management.

Rhoades, D. A., R. J. Van Dissen, R. M. Langridge, T. A. Little, D. Ninis, E. G. C. Smith, et al. 2011. "Re-evaluation of Conditional Probability of Rupture of the Wellington-Hutt Valley Segment of the Wellington Fault." *Bulletin of the New Zealand Society for Earthquake Engineering* 44 (2): 9.

Robinson, R., R. J. Van Dissen, and N. J. Litchfield. 2011. "Using Synthetic Seismicity to Evaluate Seismic Hazard in the Wellington Region, New Zealand." *Geophysical Journal International* 187 (1): 510–28.

Saunders, W. S. A., and J. G. Beban. 2012. "Putting R(isk) in the RMA: Technical Advisory Group Recommendations on the Resource Management Act 1991 and Implications for Natural Hazards Planning." GNS Science Miscellaneous Series 48, GNS Science, Lower Hutt, New Zealand.

Saunders, W. S. A., and K. R. Berryman. 2012. "*Just Add Water: When Should Liquefaction Be Considered in Land Use Planning?*" Miscellaneous Series 47, GNS Science, Lower Hutt, New Zealand.

Standards Australia/New Zealand. 2004. *NZS 1170.5 Sturctural Design Actions—Part 5: Earthquake Actions*. Wellington, New Zealand: Standards New Zealand.

Stirling, M. W., G. H. McVerry, M. C. Gerstenberger, N. J. Litchfield, R. J. Van Dissen, K. R. Berryman, et al. 2012. "National Seismic Hazard Model for New Zealand: 2010 Update." *Bulletin of the Seismological Society of America* 102 (4): 1514–42.

Wellington Region Emergency Management Office. 2013. "Wellington Region Tsunami Evacuation Zones: Lower Hutt." http://www.getprepared.org.nz/sites/default/files/uploads/lower-hutt-petone.pdf.

Wellington Regional Council. 2001. *Hutt River Floodplain Management Plan for the Hutt River and Its Environment*. Wellington, New Zealand: Wellington Regional Council.

GFDRR

Global Facility for Disaster Reduction and Recovery

www.gfdrr.org

The Global Facility for Disaster Reduction and Recovery (GFDRR) is a global partnership that helps developing countries better understand and reduce their vulnerabilities to natural hazards and adapt to climate change. Working with over 400 local, national, regional, and international partners, GFDRR provides grant financing, technical assistance, training and knowledge sharing activities to mainstream disaster and climate risk management in policies and strategies. Managed by the World Bank, GFDRR is supported by 34 countries and 9 international organizations.