Cities and Flooding

A Guide to Integrated Urban Flood Risk Management for the 21st Century

Abhas K Jha | Robin Bloch
Jessica Lamond

THE WORLD BANK

GFDRR
Global Facility for Disaster Reduction and Recovery

Cities and Flooding

Cities and Flooding

A Guide to Integrated Urban Flood Risk Management for the 21st Century

Abhas K Jha | Robin Bloch
Jessica Lamond

THE WORLD BANK
Washington, D.C.

GFDRR
Global Facility for Disaster Reduction and Recovery

Cover photo: Wilaiporn Hongjantuek walks through chest-high water in Amornchai on the outskirts of Bangkok, Thailand (2011). Source: Gideon Mendel

Back cover photos source: Gideon Mendel

The World Bank
1818 H Street NW
Washington DC 20433
Telephone: 202-473-1000
Internet: www.worldbank.org

1 2 3 4 15 14 13 12

ISBN (paper): 978-0-8213-8866-2
ISBN (electronic): 978-0-8213-9477-9
DOI: 10.1596/978-0-8213-8866-2

Library of Congress Cataloging-in-Publication data have been requested.

Contents

Acknowledgements

Cities and Flooding: A Guide to Integrated Flood Risk Management for the 21st Century and *A Summary for Policy Makers* were researched and written by a team led by Abhas K. Jha (Task Team Leader, The World Bank). Robin Bloch (GHK Consulting) was the Project Manager and Jessica Lamond (University of the West of England) the Technical Editor. Zuzana Svetlosakova (The World Bank) and Nikolaos Papachristodoulou (GHK Consulting) provided invaluable service and input as coordinators of the project.

We acknowledge the financial support of the Global Facility for Disaster Reduction and Recovery (GFDRR).

This document was prepared under the overall guidance of Zoubida Allaoua, John Roome and Saroj Kumar Jha.

Special acknowledgement is due to those organizations who were partners with the World Bank in this project: World Meteorological Organization (WMO) and Japan International Cooperation Agency (JICA).

The consultancy group was headed by GHK Consulting; Baca Architects, London; and the University of Wolverhampton's School of Technology. Contributors comprised Robert Barker, Alison Barrett, Namrata Bhattacharya, Alan Bird, John Davies, Emma Lewis, Peter Lingwood, Ana Lopez and David Proverbs.

The Guide's design concept was developed by Baca Architects. Chris Jones and Jamie Hearn from Artupdate, London, created the print version.

The large-format photographs, including the cover, are from 'Drowning World', a project by Gideon Mendel who since 2007 has photographed flood events in the UK, India, Haiti, Pakistan, Australia and Thailand. The work has featured in the Guardian, and in other publications.

We would also like to acknowledge contributions from the following institutions and organizations: Asian Disaster Preparedness Center (ADPC); UN-HABITAT; Central Public Health & Environmental Engineering Organisation (CPHEEO), Ministry of Urban Development, Government of India; Deltares; German Research Centre for Geosciences GFZ; Metropolitan Manila Development Authority (MMDA), Stadtentwässerungsbetriebe Köln, AöR (StEB-TB); and Queensland Reconstruction Authority.

We benefited greatly from our core peer reviewers and advisors: Franz Drees-Gross, Michael Jacobsen, Manuel Marino, Joe Manous, Carlos Costa, Frans van de Ven, Victor Vergara, Baba Hitoshi, Avinash Tyagi, Burrell E. Montz, Curtis B. Barrett, Jose Simas, Heinz Brandenburg, and Emily White.

For their sharing experiences, making suggestions, participation in regional stakeholder and expert workshops, contributing to case studies, and commenting on drafts, and providing support we are grateful for the inputs of the following individuals: Mathias Spalivero, Silva Magaia, R.D. Dinye, Madame Ayeva Koko, Ndaye Gora, Zounoubate N'Zombie, Pramita Harjati, Muh Aris Marfai, N.M.S.I. Arambepola, Ho Long Phi, Menake Wijesinghe, Fawad Saeed, Janjaap Brinkman, Fook Chuan, Trevor Dhu, Achmad Haryadi, Marco Hartman, Josefina Faulan, Dinesh Kumar Mishra, Stéphane Hallegatte, Aphisayadeth Insisiengmay, L.V. Kumar, Rajesh Chandra Shukla, Divine Odame Appiah, Robert Belk, Juzer Dhoondia, Heidi Kreibich, Philip Bubeck, Bill Kingdom, Fritz Policelli, Loic Chiquier, Marcus Wijnen, Marianne Fay, Nicola Ranger, Paul Huang, Rolf Olsen, Shahid Habib, Vijay Jagannathan, Winston Yu, Zachary Usher, John Frimpong Manso, Tony Asare, Segbefia Alexander Yao, Stephen Yao, Anthony Mompi, Richard Dugah, Martin Oteng-Ababio, Grace Abena Akese, Clifford Amoako, Solomon N-N Benni, Mohammed Alhassan, Kwasi Baffour Awuah, James K. Boama, Daniel Ayivie, Felix Agyei Amakye, Wise Ametefe, David Asamoah, Ranjini Mukherjee, Rajeev Malhotra, Rajesh Chandra Shukla, Anirban Kundu, Ranu Sinha, Amit Saha, Deepak Singh, Ahmed Kamal, Naseer Gillani, Hazrat Mir, Alamgir Khan, John Taylor, Oktariadi Adi, Nanang W.P. Safari, Febi Dwi Rahmadi, Teguh Wibowo, Jose Miguel Ruiz Verona, Desti Mega Putri, Matt Hayne, Jonathan Griffin, Aris Munardar, Gita Chandrika, Iwan Gunawan, Peter de Vries, Koen Elshol, Jurjen Wagemaker, Tanaka Kataya, Yulita Sari Soepardjo, M. Abdul, Anton Sunarwibowo, Olivia Stinson, M. Rudy, G. Dedi, M. Feuyadi, A. Andi, Elfina Rosita, Omar Saracho, Yusak Oppusunggu, Faisyar, Suryani Amin, Paul van Hofwegen, Rinsan Tobing, Achmad Haryadi, Shinghu Tamotsu, Ampayadi N, Bambang Sigit, M. Feryadiwinarso, Hetty Tambunan, Michael van de Watering, Dan Heldon, Christopher Yu, Ramon Santiago, Liliana Marulanda, Wilson A. Tabston, Gloria R., Arnold Fernandez, Aristioy Teddy Correa, Shelby A. Ruiz, Alvidon F. Asis, Noel Lansang, Reynaldo Versomilla, Joel Las, Yolando R. de Guzman, Morito Francesco, Gabrielle Iglesias, Khondoker Golam Tawhid, Prasad Modak, Young Kim, Arlan Rahman, Stefan G. Koeberle, Ousmane Diagana, Zie Ibrahima Coulibaly, Fasliddin Rakhimov, Makhtar Diop, Boris Enrique Utria, Yolande Yorke, Klaus Rohland, Kate Isles, Lasse Melgaard, Julia M. Fraser, Sombath Southivong, Khamlar Phonsavat, Alaa Hamood, Emmy Yokoyama, Faris Hadad-Zervos, Francis Ato Brown, Pilar Maisterra, Abdulhamid Azad, Suzy Kantor, Poonam Pillai, Anil Pokhrel, Penelope J. Brook, Ellen A. Goldstein, Swarna Kazi, Patricia Lopez, Tatiana Proskuryakova, Giovanna Prennushi, Raja Rehan Arshad, Haris Khan, Yan Zhang, Catherine G. Vidar, Mark C. Woodward, Asta Olesen, Nicholas J. Krafft, David Sislen, Jonathan Rothschild, Dzung Huy Nguyen, Dean A. Cira, Benita Sommerville, Josephine Masanque, A. David Craig, Piers E. Merrick, Chris Pratt, Marie E. Brown, Ana Campos Garcia, Geoffrey H. Bergen, Daniel M. Sellen, Eric Dickson, Francoise Clottes, Michael Corlett, Herve Assah, Syed Waqar Haider, Emmanuel Nkrumah, Camille Lampart Nuamah, Nelson Antonio Medina Rocha, Francisco Carranza, Charles Tellier, Helene Djoufelkit, Michael John Webster, Carlos Felipe Jaramillo, Giuseppe Zampaglione, Armando Guzman, Asif Faiz, and Rachid Benmessaoud.

We would also like to thank Liz Campbell, Ryan Hakim, Lawrence Dakurah, D.K. Ahadzie and Ruby Mangunsong for organizational and logistical support on regional workshops that took place in Accra, Ghana, Delhi, India, Jakarta, Indonesia, and Manila, the Philippines. Support was also provided by Mathis Primdal and Roy Brockman of GHK Consulting.

Carly Rose copy edited a late draft of the book. Jeffrey N. Lecksell at the World Bank's Map Design Unit developed a number of maps. The Office of the Publisher, The World Bank, provided printing services under the supervision of Patricia Katayama and with the support of Andrés Meneses and Denise Marie Bergeron. A portal and the project website: http://www.gfdrr.org/gfdrr/urbanfloods, on which the Guide and supporting materials can be accessed, was developed by Indy Gill, and constructed by the World Bank's Jaime Yepez and Ritesh Sanan, with assistance from Hemang Karelia.

About the authors

Mr. Abhas K. Jha is Lead Urban Specialist and Program Leader, Disaster Risk Management for the World Bank's East Asia and the Pacific Region. In this capacity he is responsible for managing the Bank's disaster risk management practice in the region. He has been with the World Bank since 2001, leading the Bank's urban, housing and disaster risk management work in Turkey, Mexico, Jamaica and Peru as well as serving as the Regional Coordinator, Disaster Risk Management for Europe and Central Asia. Abhas has also served as Advisor to the World Bank Executive Director for India, Bangladesh, Sri Lanka and Bhutan on issues related to urban development, infrastructure and climate finance. He earlier served for 12 years in the Indian Administrative Service (the national senior civil service of India) in the Government of India (in the Federal Ministry of Finance and earlier in the state of Bihar) and is also the lead author of the World Bank publication "Safer Homes, Stronger Communities: A Handbook for Reconstructing after Disasters". Abhas' core interests are urban resilience and cities as complex adaptive systems.

Dr. Robin Bloch is Principal Consultant and Head of the Planning, Land and Economic Development practice at GHK Consulting, London. He is an urban planner, educated first in South Africa and then in the United States. His main areas of expertise and research interest include urban, regional and metropolitan spatial and land use planning; urban environmental management, sustainability and resilience; and urban industry. Robin has over 20 years of international experience, principally in Sub-Saharan Africa and South Asia and East Asia, of policy, strategy and plan making, and project and programme formulation, implementation and evaluation. He is a Visiting Adjunct Professor at the School of Architecture and Planning, University of the Witwatersrand, Johannesburg, and an Associate Research Fellow at the Centre for Social Science Research at the University of Cape Town.

Dr. Jessica Lamond is an experienced researcher in Flood Risk Management with particular focus on the implications of flooding in the built environment. Her specialism includes flood recovery, financial and economic impacts on property stakeholders, the valuation of property at risk, the implications for insurance and the barriers to and drivers for adaptation to flooding. She is currently a senior research fellow at the University of the West of England, where she is currently involved in research supported by leading research funders and industry and consults for government bodies and the FRM profession. Jessica publishes widely in academic/research journals and is the principal editor of the book "Flood hazards: impacts and responses for the built environment" for Taylor publishing which brings together views from experts on structural and non-structural approaches to urban flood risk management.

Contributors

Robert Barker, Baca Architects

Alison Barrett, Independent Consultant

Namrata Bhattacharya, School of Technology, University of Wolverhampton

Alan Bird, Independent Consultant

Prof John Davies, Professor of Civil Engineering, Architecture and Building, Faculty of Engineering and Computing, Coventry University

Emma Lewis, GHK Consulting

Dr Peter Lingwood, CeConsult

Dr Ana Lopez, Grantham Research Institute and Centre for the Analysis of Time Series, London School of Economics and Political Science

Nikolaos Papachristodoulou, GHK Consulting

Prof David Proverbs, Professor and Head of the Department of Construction and Property, University of the West of England

How to use the Guide

Cities and Flooding: A Guide to Integrated Urban Flood Risk Management for the 21st Century provides comprehensive, forward-looking operational guidance on how to manage the risk of floods in a rapidly transforming urban environment and changeable climate. The Guide serves as a primer for decision and policy makers, technical specialists, central, regional and local government officials, and concerned stakeholders in the community sector, civil society and non-governmental organizations, and the private sector.

The Guide starts with *A Summary for Policy Makers* which outlines and describes the key areas which policy makers need to be knowledgeable about to create policy directions and an integrated strategic approach for urban flood risk management. The *Summary* concludes with 12 guiding policy principles for integrated flood risk management.

The core of the Guide consists of seven chapters, organized as follows:

Chapter 1. Understanding Flood Hazard

Chapter 2. Understanding Flood Impacts

Chapter 3. Integrated Flood Risk Management: Structural Measures

Chapter 4. Integrated Flood Risk Management: Non-Structural Measures

Chapter 5. Evaluating Alternative Flood Risk Management Options: Tools for Decision Makers

Chapter 6. Implementing Integrated Flood Risk Management

Chapter 7. Conclusion: Promoting Integrated Urban Flood Risk Management

Each chapter starts with a full contents list and a summary of the chapter for quick reference. It is then made up of sections which combine general narrative on key aspects of urban flood risk management, case study evidence in the form of lessons from the field on the methods and techniques of flood risk management, both positive and where relevant problematic, and "How To" sections on necessary and immediate operational tasks. Each chapter contains a full reference list. This is augmented by lists of further readings for operational tasks.

The last chapter captures briefly the essential considerations for ensuring that flood risk management is provided in an integrated way. It sets out benchmarks for assessing progress towards better urban flood risk management, which are presented in alignment with the 12 guiding policy principles and a five-step process, with reference to relevant case study examples.

The Guide is supported by a website: http://www.gfdrr.org/gfdrr/urbanfloods. The website aims to form a platform for practitioners for dialog around the Guide's themes and content as well as a vehicle for dissemination of the Guide. The website contains additional resources related to the content of the Guide.

A Summary for Policy Makers

A Summary for Policy Makers

Background

Urban flooding is a serious and growing development challenge. Against the backdrop of demographic growth, urbanization trends and climate changes, the causes of floods are shifting and their impacts are accelerating. This large and evolving challenge means that far more needs to be done by policy makers to better understand and more effectively manage existing and future risks.

This summary accompanies *Cities and Flooding: A Guide to Integrated Urban Flood Risk Management for the 21st Century* which provides forward-looking operational guidance on how to manage the risk of floods in a transforming urban environment and changeable climate. The Guide argues for a strategic approach to managing flood risk, in which appropriate measures are identified, assessed, selected and integrated in a process that both involves and informs the full range of stakeholders.

The Guide embodies the state-of-the art on integrated urban flood risk management. It is designed in a comprehensive and user-friendly way to serve as a primer for decision and policy makers, technical specialists, central, regional and local government officials, and concerned stakeholders in the community sector, civil society and non-governmental organizations, and the private sector.

It contains chapters which:

- Describe the causes, probabilities and impacts of floods
- Propose a strategic, innovative, integrated approach to managing flood risk accomplished by selecting and combining structural, hard-engineered measures and non-structural management measures
- Discuss the means by which these measures can be financed and implemented while engaging with and drawing on the capacities and resources of all involved stakeholders
- Specify the procedures by which progress with implementation can be monitored and evaluated.

Over fifty case studies on management measures and procedures from across the world illustrate the key policy messages. They demonstrate what has been implemented in a wide variety of urban contexts in order to meet the challenges of dealing with flood risk.

A series of "How To" sections covers the operational details of implementing a number of key flood risk management measures, and provides the reader with core technical information.

In conclusion, 12 guiding policy principles for integrated flood risk management are presented.

This overview summarizes the key areas that policy makers need to be knowledgeable about and to take action on as they create policy directions for urban flood risk management and develop the strategic frameworks to manage successfully the growing risk of urban flooding.

Urban flooding poses a serious challenge to development and the lives of people, particularly the residents of the rapidly expanding towns and cities in developing countries.

Ghulam Rasool Burro walks through the flooded centre of the town of Khairpur Nathan Shah, 2010, Pakistan. Source: Gideon Mendel

The growing challenge of urban flooding

Flooding is a global phenomenon which causes widespread devastation, economic damages and loss of human lives.

Over the past eighteen months, destructive floods occurred along the Indus River basin in Pakistan in August 2010; in Queensland, Australia, South Africa, Sri Lanka and the Philippines in late 2010 and early 2011; along with mudslides, in the Serrana region of Brazil in January 2011; following the earthquake-induced tsunami on the north-east coast of Japan in March 2011; along the Mississippi River in mid-2011; as a consequence of Hurricane Irene on the US East Coast in August 2011; in Pakistan's southern Sindh province in September 2011; and in large areas of Thailand, including Bangkok, in October and November 2011.

The occurrence of floods is the most frequent among all natural disasters. In the past twenty years in particular, the number of reported flood events has been increasing significantly. Figures 1 and 2 illustrate this trend. The numbers of people affected by floods and financial, economic and insured damages have all increased too. In 2010 alone, 178 million people were affected by floods. The total losses in exceptional years such as 1998 and 2010 exceeded $40 billion.

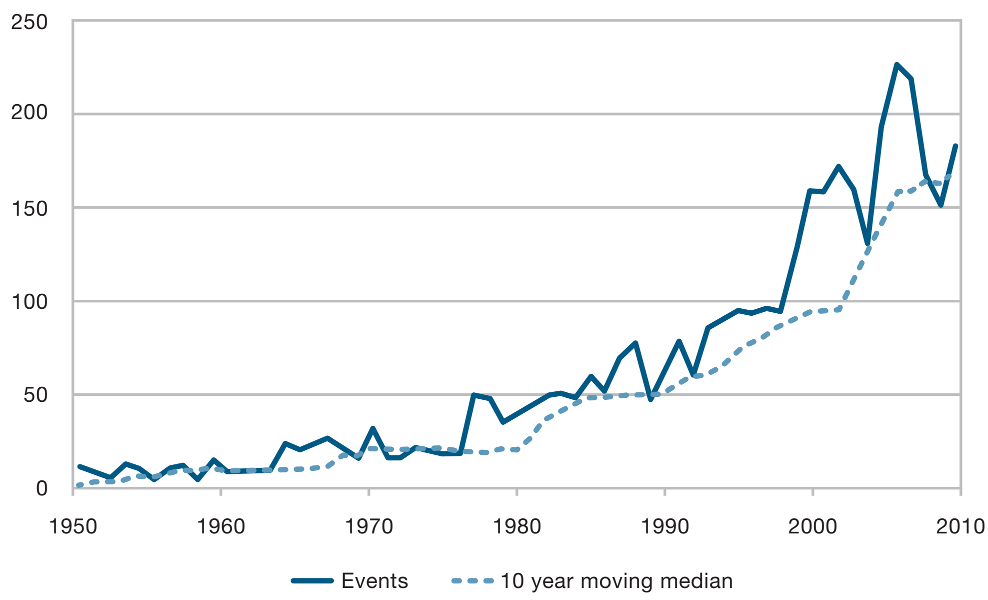

Figure 1: Number of reported flood events. Source: based on EM-DAT/CRED

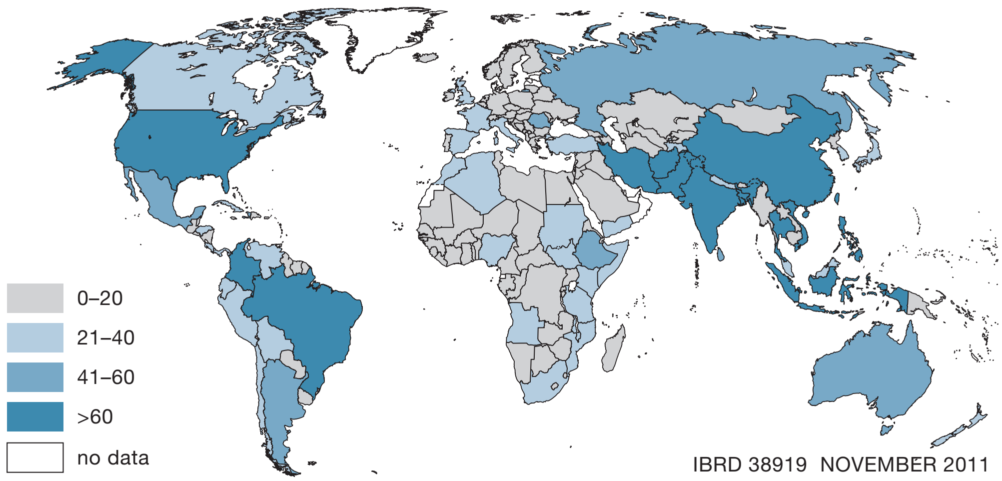

Figure 2: Flood Events, 1970-2011. Source: EM-DAT: The OFDA/CRED International Disaster Database www.emdat.be - Université Catholique de Louvain - Brussels - Belgium"

Immediate loss of life from flooding is increasing more slowly or even decreasing over time, reflecting the successful implementation of flood risk management measures. While this is encouraging, fatalities still remain high in developing countries where flood events have a disproportionate impact on the poor and socially disadvantaged, particularly women and children.

Urban areas at risk from flooding have been hit particularly hard by the observed increase of flooding impact across the world. The current and projected levels of flood impacts give urgency to the need to make flood risk management in urban settlements a high priority on the political and policy agenda. Understanding the causes and effects of flood impacts and designing, investing in and implementing measures which minimize them must become part of mainstream development thinking and be embedded into wider development goals.

Floods affect urban settlements of all types, from small villages and mid-sized market towns and service centers, for example along the Indus River, to the major cities, megacities and metropolitan areas like Sendai, Brisbane, New York, Karachi and Bangkok, all of which were struck by recent floods.

Countries define "urban" settlements in very different ways, which makes urban flooding hard to define in a consistent manner. Damage statistics are not usually classified by urban or rural location, making it difficult to apportion losses between urban and rural populations.

However, there are real functional differences between urban and rural flooding. While rural flooding may affect much larger areas of land and hit poorer sections of the population, urban floods are more costly and difficult to manage.

The impacts of urban floods are also distinctive given the traditionally higher concentration of population and assets in the urban environment. This makes damage more intense and more costly. Urban settlements also contain the major economic and social attributes and asset bases of any national population, so that urban flooding, by causing damage and disruption beyond the scope of the actual floodwaters, often carries more serious consequences for societies.

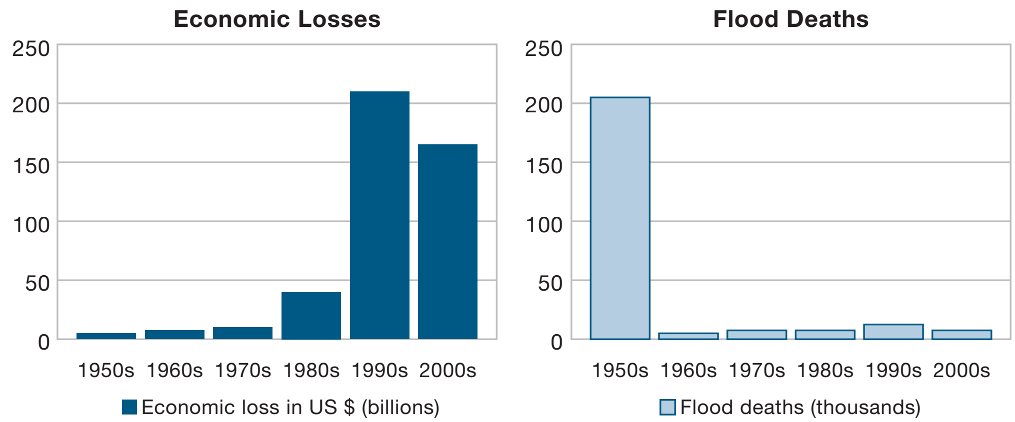

Figure 3: Reported economic losses and deaths. Source: based on EM-DAT/CRED

Direct impacts from major events represent the biggest risk to life and property. Figure 3 shows the growth in direct monetary impacts resulting from flood events. Indirect and often long-term effects, such as disease, reduced nutrition and education opportunities, and loss of livelihoods, can also erode community resilience and other development goals, as does the need to constantly cope with regular, more minor, flooding. Such indirect impacts can be hard to identify immediately and harder still to quantify and value. However, the poor and disadvantaged usually suffer the most from flood risk.

Urbanization, as the defining feature of the world's demographic growth, is implicated in and compounds flood risk. In 2008, for the first time in human history, half of the world's population lived in urban areas, with two-thirds of this in low-income and middle-income nations. This is estimated to rise to 60 percent in 2030, and 70 percent in 2050 to a total of 6.2 billion, or double the projected rural population for that time. As the urban population comes to represent the larger proportion of world population, urban floods will account for an increasing part of total flood impact.

Urban flooding is thus becoming more dangerous and more costly to manage because of the sheer size of the population exposed within urban settlements. This affects all settlement sizes: while in 2030 the forecast is for 75 agglomerations of over five million inhabitants, urban populations in all size classes are also expected to continue to grow, as Figures 4 and 5 demonstrate. By 2030 the majority of urban dwellers, in fact, will live in towns and cities with populations of less than one million where urban infrastructure and institutions are least able to cope. Management of urban flood risk is not an issue that is confined to the largest cities alone.

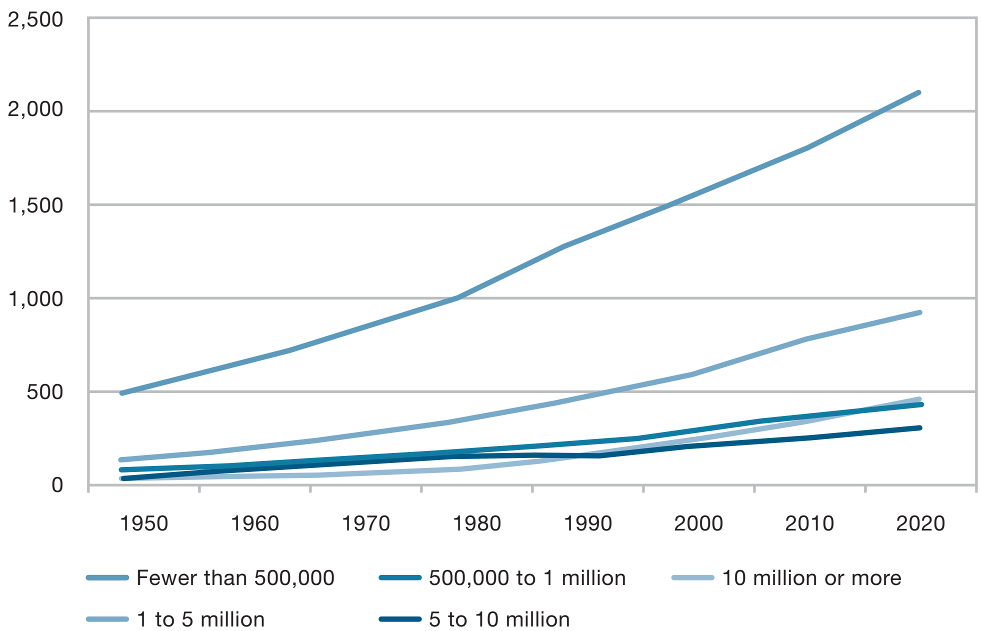

Figure 4: Growth in population by city scales. Source: based on Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: The 2008 Revision and World Urbanization Prospects: The 2009 Revision.

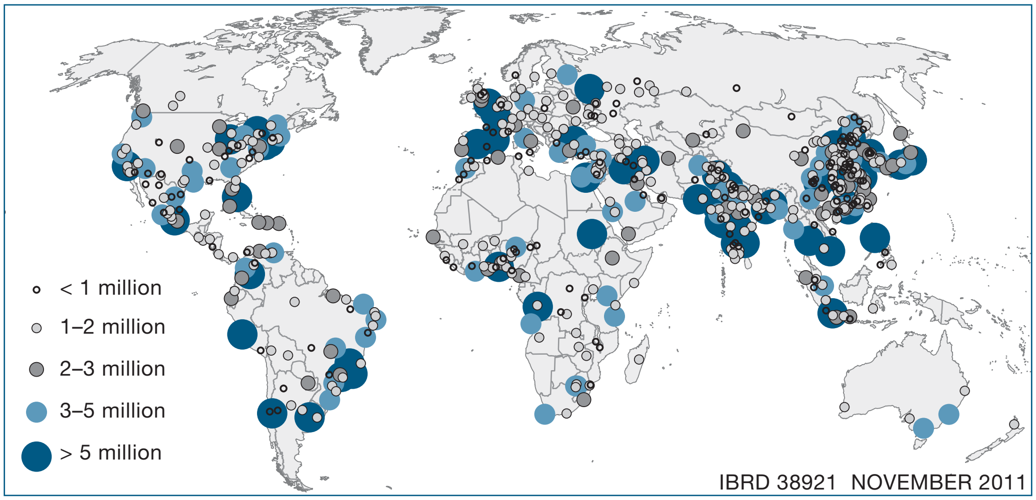

Figure 5: Urban agglomerations with more than 750,000 inhabitants, 2010.
Source: United Nations, Department of Economic and Social Affairs, Population Division; World Urbanization Prospects: The 2009 Revision; File 12: Population of Urban Agglomerations with 750,000 Inhabitants or More in 2009, by Country, 1950-2025 (thousands)

Poorly planned and managed urbanization also contributes to the growing flood hazard due to unsuitable land use change. As cities and towns swell and grow outwards to accommodate population increase, large-scale urban expansion often occurs in the form of unplanned development in floodplains, in coastal and inland areas alike, as well as in other flood-prone areas.

In the developing world, a very high proportion of urban population growth and spatial expansion takes place in the dense, lower-quality informal settlements that are often termed "slums." These are located in both city-center and peripheral, suburban or peri-urban locations and are frequently at highest risk. The concentration of the poor within these areas, which typically lack adequate housing, infrastructure and service provision, increases the risk of flooding and ensures that flood impacts are worst for the disadvantaged.

The increased impacts of urban flooding which policy makers must address are further affected by development outside the protection of existing flood defenses; an increase in paving and other impermeable surfaces; overcrowding, increased densities and congestion; limited, ageing or poorly maintained drainage, sanitation and solid waste infrastructures; over-extraction of groundwater leading to subsidence; and a lack of flood risk management activities.

Climate change is the other large-scale global trend perceived to have a significant impact on flood risk. The alterations in meteorological patterns which are associated with a warmer climate are potentially drivers of increased flooding, with its associated direct and indirect impacts. Observed and projected patterns of climate change can have an amplifying effect on existing flood risk, for example by:

- Augmenting the rate of sea level rise which is one of the factors causing increased flood damage in coastal areas
- Changing local rainfall patterns that could lead to more frequent and higher level of floods from rivers and more intense flash flooding
- Changing the frequency and duration of drought events that lead to groundwater extraction and land subsidence which compounds the impact of sea level rise
- Increasing frequency of storms leading to more frequent sea surges.

In the opinion of climate scientists, as reflected by the Intergovernmental Panel on Climate Change (IPCC), the observed increase in extreme weather is consistent with a warming climate. Although individual extreme weather events cannot be attributed to climate change, climate change can increase the chance of some of those events happening. Sea level rise is also an acknowledged and observed phenomenon. While climate change has the potential to greatly increase flood hazard and the risk from flooding, it does not appear to be the main driver of the increased impacts seen at present.

Over shorter time scales the natural variability of the climate system and other non-climatic risks are in fact expected to have a higher impact on flood risk than longer term climate trends. Accelerating urbanization and urban development could also increase significantly the risk of flooding independent of climate change. As an illustration, in Jakarta, Indonesia, land subsidence due to groundwater extraction and compaction currently has effects on the relative ground and seawater levels ten times greater than the anticipated impact of sea level rise.

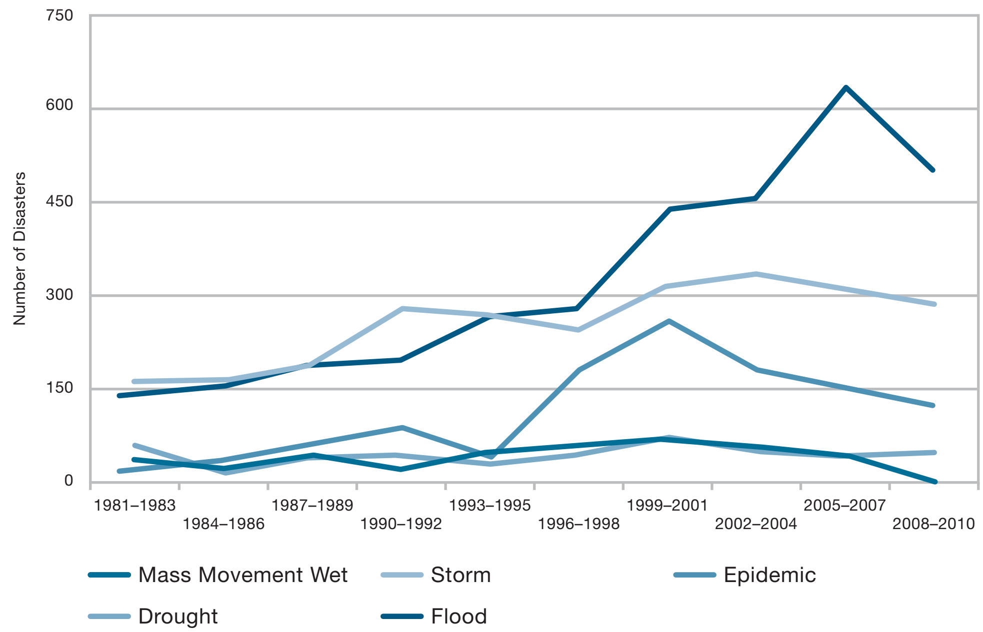

Figure 6: Trends in water-related disasters. Source: based on EM-DAT/CRED

On longer time scales, climate change might play a more significant role. Both short-term and long-term prospects need to be considered in managing flood risk: "The basic issue is finding ways to build into near-term investments and choices an appropriate consideration of long-term trends and worst-case scenarios."[1] Figure 6 illustrates trends in water-related disasters over a 30 year period.

In managing flood risk today, and in planning for the future, a balance must be struck between common sense approaches that minimize impacts through better urban management and the maintenance of existing flood mitigation infrastructure, and far-sighted approaches which anticipate and defend against future flood hazard by building new flood mitigation infrastructure or by radically reshaping the urban environment. The balance will be different for each city or town at risk. In reaching decisions on the appropriate prioritization of flood management effort, an understanding of both current and future flood risk is needed.

[1] Revkin A. "On Dams, Gutters, Floods and Climate Resilience." Dot Earth blog in The New York Times, August 30, 2011

A resident tries to remove mud after flooding in
Gonaïves, Haiti, 2008. Source: Gideon Mendel

Understanding the causes and risk of urban flooding

As a first step in urban flood risk management, policy makers need to understand the flood hazard that can affect the urban environment. Understanding hazard requires a better comprehension of the types and causes of flooding, their probabilities of occurrence, and their expression in terms of extent, duration, depth and velocity.

This understanding is essential in designing measures and solutions which can prevent or limit damage from specific types of flood. Equally important is to know where and how often flood events are likely to occur, what population and assets occupy the potentially affected areas, how vulnerable these people and their settlements are, and how these are planned and developed, and what they already do towards flood risk reduction. This is critical in grasping the necessity, urgency and priority for implementing flood risk management measures.

As flood risk evolves over time, policy makers also need to explore how decisions change in the light of changing climates. Information about the existing models used to account for climate change at different scales and an understanding of the uncertainties regarding those results need to be at the core of any decision-making process.

Urban areas can be flooded by rivers, coastal floods, pluvial and ground water floods, and artificial system failures. Urban floods typically stem from a complex combination of causes, resulting from a combination of meteorological and hydrological extremes, such as extreme precipitation and flows. However they also frequently occur as a result of human activities, including unplanned growth and development in floodplains, or from the breach of a dam or an embankment that has failed to protect planned developments.

It is important here to distinguish between the probability of occurrence of a weather event and the probability of occurrence of a flood event. Flooding is primarily driven by weather events which can be hard to predict. For this reason, flood hazard predictions are commonly available in terms of probabilities computed using historical data for the area of interest. The value of inference based on historic observations is naturally dependent on the availability and quality of data.

Understanding these probabilities is therefore critical to understanding risk. The language of probability can be confusing as people do not intuitively understand an annual one percent (or one in 100) chance of flooding. The use of the alternative concept of the estimated return period, such as “a 100-year flood” is also misunderstood as a flood that is certain to occur over the next 100 years – or is sometimes even assumed to be a flood that can only occur once in 100 years. Similarly, two events reported with the same return period can have different magnitudes, and consequently affect the same people in different ways. When the uncertainties are far-reaching or poorly understood, for instance due to inadequate data, the communication of flood risk in terms of flood probabilities and their use in flood management decisions can be misleading.

The use of maps for communicating hazard and associated risk is therefore a valuable aid to decision-making. Flood hazard maps are visual tools for communicating the hazard situation in an area. Hazard maps are important for planning development activities, for emergency planning, and for policy development. Flood risk maps incorporate flood hazard information within the context of data on exposed assets and population, and their vulnerability to the hazard. They can often be articulated in terms of expected damage, and can be used as supplementary decision-making tools.

Flood forecasting is another essential tool which provides people still exposed to risk with advance notice of flooding in an effort to save lives and property. However, without an analysis of the physical causes of recorded floods, and of the geophysical, biophysical and anthropogenic, or human-made, context that determines the potential for flood formation, predictions have the potential to contribute to the damages caused by floods by either under-estimating or over-estimating the hazard. Modelling today’s hazard has many challenges.

For the projection of future flood risk, there are even greater sources of uncertainty. The assumption usually made is that future flood patterns will be a continuation of the past because they are generated from the same cyclical processes of climate, terrain, geology, and other factors. Where this assumption holds true, a system is said to be stationary, which makes the future predictable from the past. If this assumption is not true, the future becomes much more uncertain. Figure 7 illustrates the use of hazard maps to depict current and future hazard situations. For urban flooding, two potential major sources of what is consequently termed non-stationarity (i.e. past patterns and trends are poor predictors of the future), are the rapid development of flood-prone areas as urbanization proceeds, and the changes in weather patterns associated with climate change.

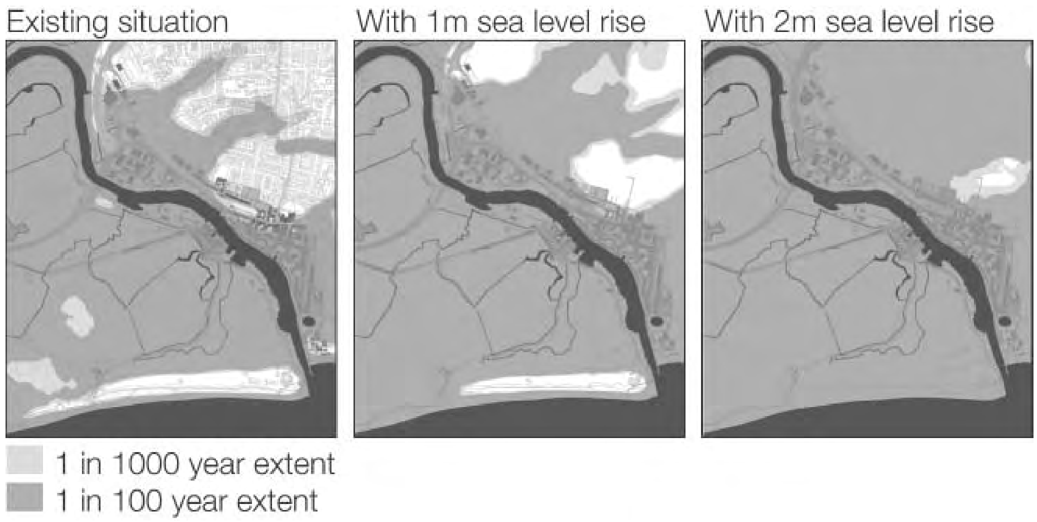

Figure 7: Flood hazard map. Source: Baca Architects

Urbanization is arguably an inevitable, unstoppable and positive trend which nevertheless has the potential to greatly increase flood risk. However, the projection of future urban population growth has associated uncertainties in the scale and spatial distribution of populations. Equally, the impact of future urban growth on flood risk is influenced by the policies and choices of urban dwellers as they may or may not occupy areas at risk of flooding, or adopt suitable urban planning and design.

There are also considerable uncertainties in climate projections. This owes to the difficulty of accurately predicting the future trajectory of socio-economic development, and as a consequence of incomplete knowledge of the climate system and the limitations of the computer models used to generate projections. The relative and absolute importance of different sources of uncertainty depends on the spatial scale, the lead time of the projection, and the variable under consideration.

The inevitable conclusion is that the accuracy or precision of long-term flood risk forecasts will be low, and that over-reliance on future probabilities is not appropriate. It is equally apparent that better planned and managed urban development can mitigate the expected growth in future flood risk.

The development of appropriate adaptations that will protect against an uncertain future risk is further complicated by a combination of the characteristics of the urban infrastructure to be protected and the long lead-in and lock-in periods of urban flood protection infrastructures and projects. This can result in large flood protection schemes facing new challenges even before they are completed as for example in Ho Chi Minh City, Vietnam, where the 2001 Master Plan to mitigate flooding via improved drainage had to contend with higher than expected increases in peak rainfall.

Defending against future floods will therefore require more robust approaches to flood management that can cope with larger uncertainty or be adaptive to a wider range of futures. This could lead to a greater reliance on more flexible, incremental approaches to flood risk management, the incorporation of greater flexibility into the design of engineered measures, or acceptance of potential over-specification for inflexible measures.

With a solid understanding of the causes and impacts of urban flooding, an appreciation of the likely future flood probability and of the uncertainties surrounding it, and knowledge of both the potentials and the limitations of various flood risk management approaches, policy makers can adopt an integrated approach to flood risk management.

People queue for food relief in the flooded city of Gonaives in Haiti two weeks after the entire city had been engulfed during Hurricanes Ike and Hanna, 2008, Haiti. Source: Gideon Mendel

An integrated approach to urban flood risk management

An integrated flood risk management approach is a combination of flood risk management measures which, taken as a whole, can successfully reduce urban flood risk. The Guide helps policy makers in developing such an integrated, strategic approach to reducing flood risk which fits their specific conditions and needs.

Flood management measures are typically described as either structural or non-structural. Structural measures aim to reduce flood risk by controlling the flow of water both outside and within urban settlements. They are complementary to non-structural measures that intend to keep people safe from flooding through better planning and management of urban development. A comprehensive integrated strategy should be linked to existing urban planning and management policy and practices.

Structural and non-structural measures do not preclude each other, and most successful strategies will combine both types. It is also important to recognize the level and characteristics of existing risk and likely future changes in risk to achieve the balance between the required long and short term investments in flood risk management. But as both urbanization and climate change accelerate, there may well be the need to move away from what is often today an over-reliance on hard-engineered defenses towards more adaptable and incremental non-structural solutions.

Structural measures range from hard-engineered structures such as flood defenses and drainage channels to more natural and sustainable complementary or alternative measures such as wetlands and natural buffers. They can be highly effective when used appropriately, as the well-documented successes of the Thames Barrier, the Dutch sea defenses and the Japanese river systems attest. Structural measures can, however, be overtopped by events outside their design capacity. Many structural measures also transfer flood risk by reducing flood risk in one location only to increase it in another. The redirection of water flows also frequently has environmental impact. In some circumstances this is acceptable and appropriate, while in others it may not be. In all cases a residual flood risk remains. Structural solutions can also have a high upfront cost, can sometimes induce complacency by their presence, and can result in increased impacts if they fail or are overtopped, as was tragically illustrated in the tsunami in Japan in 2011.

These considerations, and the fact that there will always remain a residual flood risk, leads to the need to incorporate non-structural measures into any strategy. There is always a role for non-structural measures which manage risk by building the capacity of people to cope with flooding in their environments. Non-structural measures such as early warning systems can be seen as a first step in protecting people in the absence of more expensive structural measures – but they will also be needed to manage the residual risk remaining after implementation of structural measures. Non-structural measures do not usually require huge investments upfront, but they often rely on a good understanding of flood hazard and on adequate forecasting systems – as an example, an emergency evacuation plan cannot function without some advance warning.

Non-structural measures can be categorized under four main purposes:

- Emergency planning and management including warning and evacuation as, for example, in local flood warning systems in the Philippines and in the Lai Nullah Basin, Pakistan.
- Increased preparedness via awareness campaigns as demonstrated in Mozambique and Afghanistan. Preparedness includes flood risk reducing urban management procedures such as keeping drains clear through better waste management.
- Flood avoidance via land use planning as seen in the German Flood Act and planning regulations in England and Wales. Land use planning contributes both to mitigation of and adaptation to urban floods.
- Speeding up recovery and using recovery to increase resilience by improving building design and construction – so-called "building back better." Planning the resilient reconstruction of a damaged village has been seen, for example, in the tsunami-damaged village of Xaafuun, Somalia. Appropriate risk financing such as flood insurance, where it is available, or using donor and government sources of funding assists in quick recovery.

The challenge with many non-structural measures lies in the need to engage the involvement and agreement of stakeholders and their institutions. This includes sometimes maintaining resources, awareness and preparedness over decades without a flood event, bearing in mind that the memory of disaster tends to weaken over time. This challenge is also made greater by the fact that most non-structural measures are designed to minimize but not prevent damage, and therefore most people would instinctively prefer a structural measure.

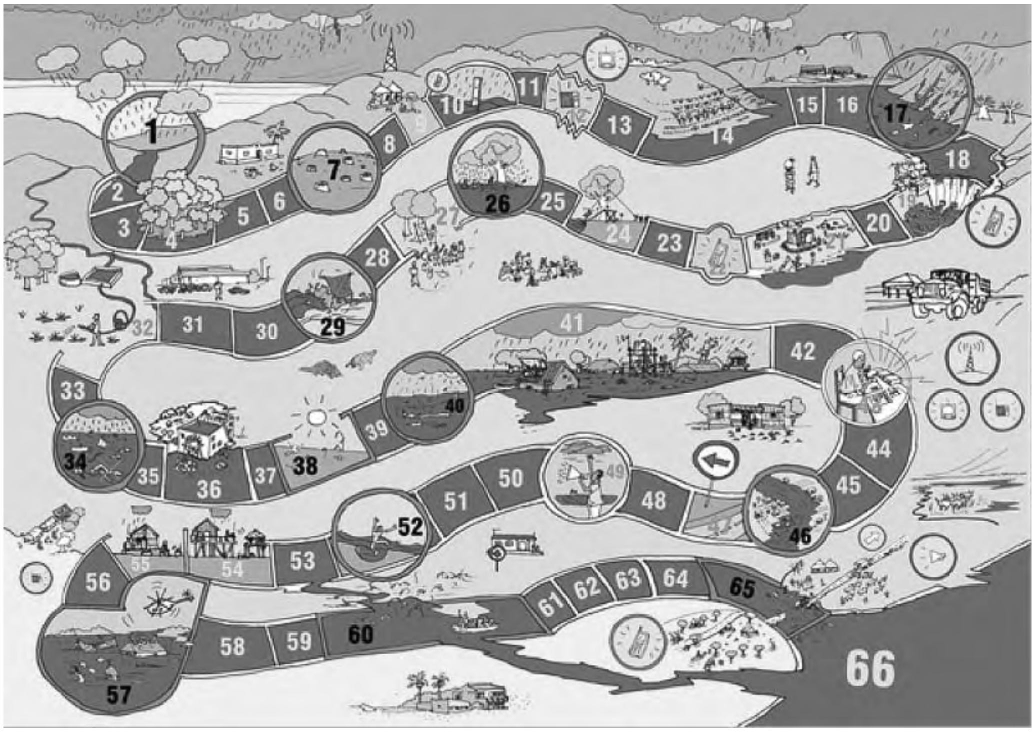

Figure 8: The River Game. Source: UN-HABITAT

Generating the necessary attitudinal and behavioral change may take time and investment in wide communication and consultation. A good practice example of community engagement via didactic tools is seen in Mozambique where the River Game developed under a Cities Alliance project by UN-HABITAT and local partners (Figure 8) is used to educate, communicate with and engage multiple stakeholders.

Flood management may hugely benefit by the involvement of stakeholders. Indeed, if the communication and consultation challenge is successfully overcome, the gains in flood resilience are significant.

It is also important to take account of temporal and spatial issues when determining strategy. Integrated urban flood risk management takes place at a range of scales, including at the river basin and water catchment as a whole. This is due to the fact that the source of flooding may be at some distance from the city or town. Often the best option may be to tackle flooding before it reaches the urban setting.

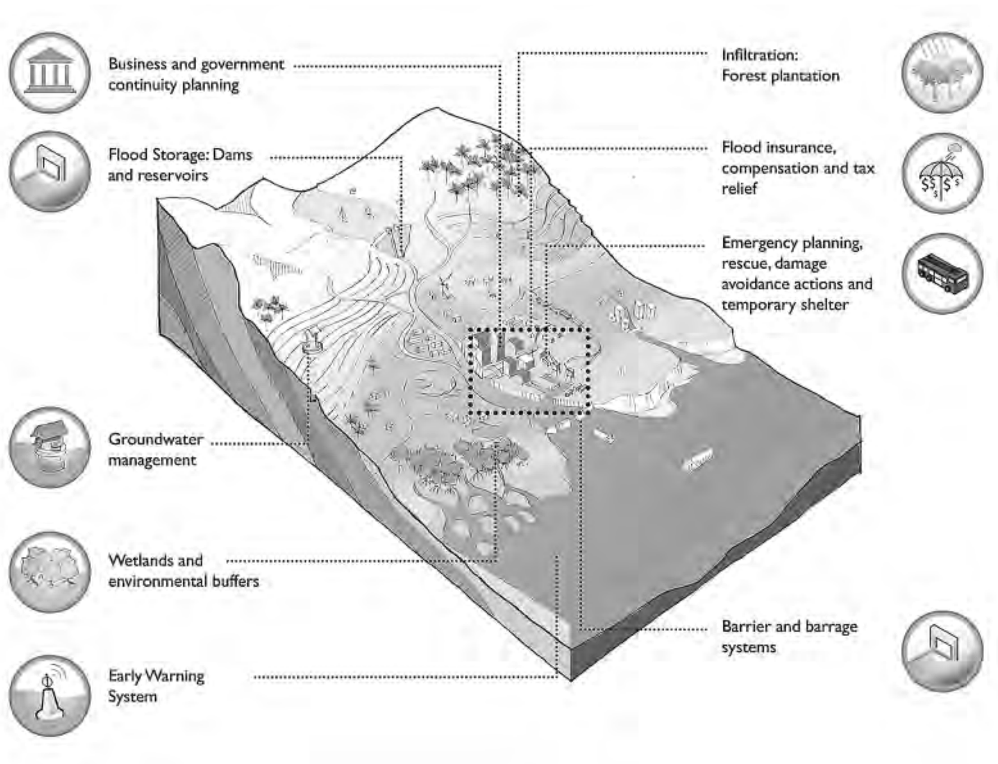

Figure 9: Overview of flood risk management options. Source: Baca Architects

There are multiple management techniques that can be identified in their appropriate catchment locations surrounding an urban environment, as illustrated in Figure 9. Structural measures such as flood defenses and conveyance systems can form a long-term response to flood risk. However, these require large investments which will not always be available. Non-structural measures such as flood warning systems and evacuation planning are necessary for the safeguarding of the population of cities and towns already at risk from flooding, whether protected by defenses or not. There are also urban design and management measures which can be implemented more quickly, such as better operations and maintenance of infrastructure; greening of urban areas; improved drainage and solid waste management; and better building design and retrofitted protection. These will enable occupation of flood risk areas while reducing the expected impacts from flooding.

Land use planning and the regulation of new development is a key aspect of integrated urban flood risk management. In developing countries in particular, the opportunity to better plan the formation of new urban areas is central to prevent the predicted increase in future flood impacts from being realized.

The need to integrate flood risk management into land use planning and management is therefore important in order to minimize risk and manage the impacts of flooding. In growing urban settlements in particular, flood risk may be seen to be of lesser importance than other social and economic concerns. It is hence likely that floodplain development will continue, due to pressure on land resources and other political and economic considerations. However, where new urban environments are better planned within areas at risk from flooding, flood-receptive design can be employed at a potentially lower cost and disruption during the build or reconstruction phase than to attempt to later retrofit. This allows the building in of resilient design – with potential payoff well into the future.

The potential for reduced costs and extended benefits from flood risk management measures also needs to be explored. For example, a highly effective utilization of the limited land available in densely populated cities and urban areas is the construction of multi-purpose retarding basins which store flood water for outflow control when necessary. At other times these basins are used for other purposes such as sport and leisure facilities or car parking. Rainwater harvesting can also be seen as an innovative measure to prevent urban flooding. It forms part of a sustainable drainage system and can simultaneously be used for non-drinking purposes, resulting in water conservation. Investment in better urban management, such as for solid waste, also reduces flood risk, can have health and environmental benefits, and can be used to create employment and relieve poverty.

Groundwater management can prevent land subsidence which mitigates flood risk in low-lying areas but also protects buildings and infrastructure from subsidence-induced failure, as for example has been attempted in Bangkok. Wetlands, bio-shields, environmental buffer zones and other "urban greening" measures that produce environmental and health benefits in urban areas can also reduce flood impacts. These greening measures will have many other benefits in addition to reducing flood risk in surrounding areas, including reducing the urban heat island effect and the level of CO_2 emissions, and thus creating a healthier urban environment. For example, buffer areas around the Primero River in the city of Cordoba, Argentina, improved the urban environment and removed residents at risk to safer locations.

Given the many urgent development goals and resource constraints faced by urban policy makers, it is not possible to be overly prescriptive in the application of flood risk management. The specific set of measures that might be suitable in a particular location should only be adopted after serious consideration – and consultation with stakeholders. Action to create an integrated approach will involve identifying technically feasible sets of measures designed to reduce flood risk.

Integrated urban flood risk management strategies are naturally designed to fit in with water-related planning issues and can be part of a wider agenda such as urban regeneration or climate change adaptation. Action to reduce flood risk should be carried out through a participatory process involving all those stakeholders that have an interest in flood management, including those people at risk or directly impacted by flooding. The measures selected will need to be negotiated by stakeholders, and to be adaptable to natural, social and economic conditions which can be expected to change over time.

Villagers work together to build flood defenses to keep the floodwaters out of their community, 2010, Pakistan. Source: Gideon Mendel

Implementing integrated urban flood risk management

A Guide to Integrated Urban Flood Risk Management argues for an integrated approach to urban flood risk management, which combines structural and non-structural measures. Such integrated urban flood risk management is holistic in scope, strategic in content and collaborative in nature.

An integrated approach can be difficult to achieve where municipal managements suffer from a lack of technical capacity, funding or resources. The interests of stakeholders also vary, leading to different incentives and motives for action. Very often, for instance, residents are unwilling to move from already-developed locations in floodplain areas, which are vulnerable and contravene the land use regulations drafted by decision makers and planners. This situation can involve poorer residents, living on riverbanks close to economic opportunities, or wealthier people who have houses on seafronts

Implementation requires wider participation and a change in traditional management methods to be successful. At political and institutional levels, actions to reduce flood risk need to employ tools and techniques to extrapolate current trends and drivers into the future, to assess alternative scenarios, and to build strategic, integrated approaches. Repeating past mistakes can have disastrous consequences for the present and the future.

It is a fundamental requirement to identify the information, experience and methods that different stakeholders, including practitioners and residents, can provide – and to design measures using such experience and knowledge. It is also important to be aware of the context within which urban flood risk management operates. It can fall between the dynamics of decision-making at national, regional, local/municipal and community levels.

Integrated flood risk management therefore requires greater coordination between city governments, national governments, ministries, public sector companies, including utilities, along with meteorological and planning institutions, civil society, non-government organizations, educational institutions and research centers, and the private sector. It is essential to understand the capacities and incentives of these actors, including how they choose or are able to use their own limited resources under high levels of uncertainty. Government decisions about the management of risk are balanced against competing, often more pressing, claims on scarce resources as well as other priorities in terms of land use and economic development.

Getting the balance right between structural and non-structural measures is also a challenge. Policy makers require a clear vision of the alternatives and methods and tools to assist them in making choices. Decisions regarding flood risk management are complex and require wide participation from technical specialists and non-specialists alike. Tools and techniques exist which allow policy makers and their technical specialists to decide between alternatives, and to assess their costs. There is clearly a role for tools which can predict the outcome of decisions, communicate risk and create linkages between stakeholders. Examples are risk and hazard maps or simulation and visualization techniques which can illustrate the impacts of decisions to multiple stakeholders, and cost-benefit analyses which can make the decision-making process more transparent and accountable.

The right metrics, realistic simulation games, good risk data and data visualization tools help. But underlying such tools there has to be a fundamental understanding, which is often lacking, of the physical processes involved in flooding and the expected outcome of the flood management measures which are undertaken.

While the implementation and outcomes of flood risk management measures can be defined in purely economic terms, the judgment made by policy makers, urban planners and technical specialists must also consider broader issues. They need to consider many aspects such as the impact of measures on environmental degradation, biodiversity, equity, social capital/capacity, and other potential trade-offs. It is important to recognize that the residual risk never reduces to zero, that the cost of reducing the risk may exceed the benefits of doing so, and that funds may not be available to invest in measures. In addition, policy making in the era of urbanization and climate change must deal with the large uncertainty associated with future predictions of flood patterns. Such uncertainty can lead to indecision.

Decision-making needs instead to be robust. Evaluation of the costs and benefits of each measure, or combination of measures, must be integral to a wider strategy which sets future targets for investment in measures and prioritizes spending on the most urgent and effective of these activities. Combining alternatives that perform well under different scenarios then becomes a preferred strategy rather than finding the optimal solution, as illustrated in Figure 10. This will lead to the preference for flexible and so-called no regret approaches that will include measures which will be cost effective regardless of changes in future flood risk.

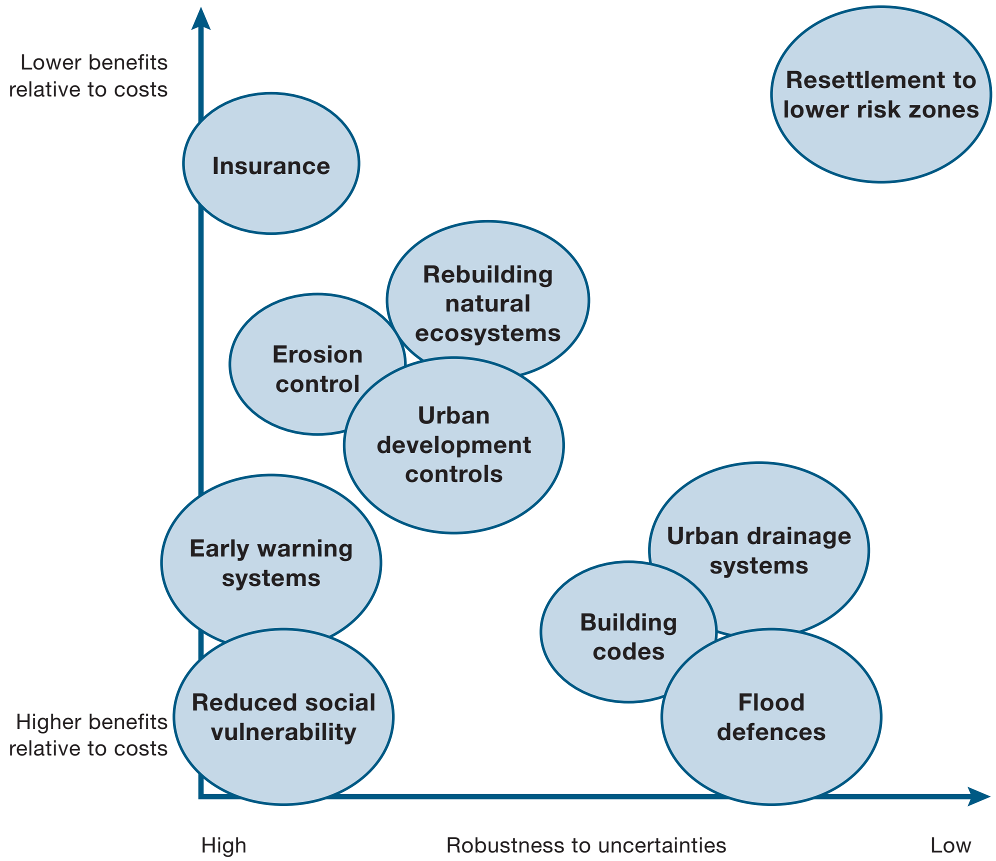

Figure 10: Relative costs and benefits of flood management options.
Source: Adapted from Ranger and Garbett-Shields 2011

Many non-structural measures tend to be inherently flexible, for example early warning systems or evacuation plans. Structural measures are seen as less flexible, but flexibility can sometimes be incorporated, such as in the installation of wider foundations for flood defenses so that they can be raised later without strengthening the base. The purchase of temporary flood defense barriers can also be seen as a flexible alternative as they can be deployed when and where necessary, as flood risks change. Such no regret measures yield benefits over and above their costs, independent of future changes in flood risk. Further examples here are forecasting and early warning systems which are not sensitive to future flood risk and are relatively low in cost to set up; improved solid waste management systems which have many benefits for environmental health regardless of flood risk; and environmental measures that have amenity value.

Identifying which institutional arrangements are most effective in the delivery of urban flood risk management measures is also fundamental to success. Countries – and cities – with well-performing institutions are better able to prevent disasters. Nevertheless, there is often lack of suitable institutional arrangements and lack of a suitable policy framework to encourage integrated and coordinated urban flood risk management. This mismatch between the governance of official disaster management mechanisms and what is actually needed for implementing integrated flood risk management is a major constraint to effect change. Where the role of institutions is not well established or clear, reforms are required so that institutions complement each other and complement existing systems to create efficiency in delivery of measures and faster uptake. Informal institutions and social networks also have a crucial role to play. Valuable lessons can be drawn from grassroots experiences of dealing with flooding at the household and community level.

Integrated urban flood risk management is a multi-disciplinary and multi-sectoral intervention that falls under the responsibility of diverse government and non-government bodies. Flood risk management measures need to be comprehensive, locally specific, integrated, and balanced across all involved sectors. Due to spatial proximity, local authorities are able to make well-informed decisions. Nevertheless, wider supportive political and organizational underpinnings are vital to ensure the success of integrated flood risk management.

Under the pressure of rapid urbanization, urban governance and decision-making often fall short of what is needed to adequately respond to the challenge of flooding. Enforcement of standards and regulations is often incomplete or even absent. Regulatory frameworks often demand unrealistic minimum standards while at the same time there is lack of adequate mechanisms for the enforcement of regulations. Funding is often limited too.

It is vital, then, to link urban flood risk management with poverty reduction and climate change adaptation initiatives, and with more specific issues of urban planning and management, such as housing provision, land tenure, urban infrastructure delivery and basic service provision. Robust solutions can contribute to flood risk reduction, while at the same time create opportunities to promote better and more sustainable and resilient urban development.

Figure 11 in the next page illustrates the process for Integrated Urban Flood Risk Management. It covers five steps from understanding flood hazard and identifying the most appropriate measures, to planning, implementing and finally evaluating the strategy and its measures.

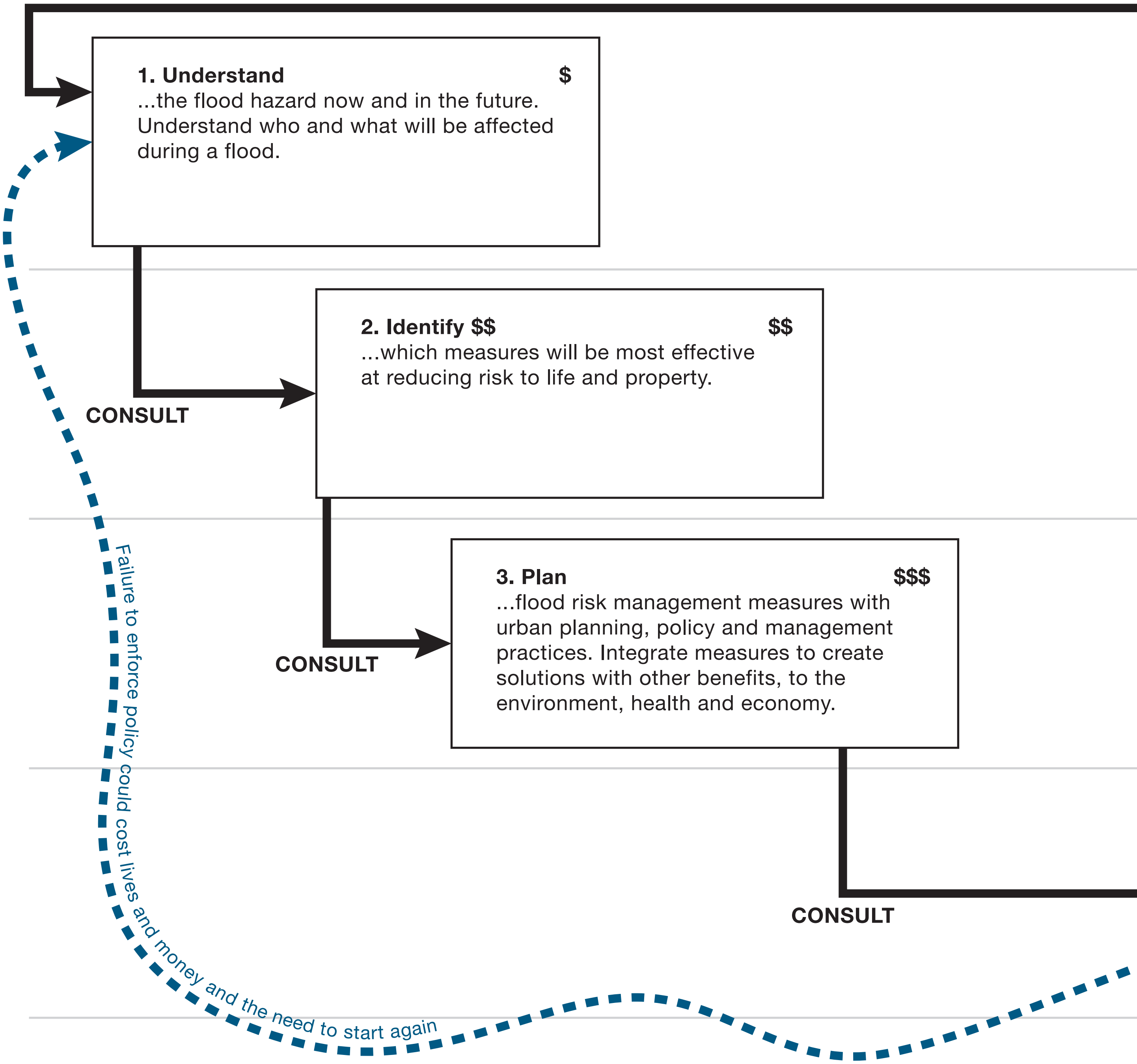

Figure 11: The five stages of integrated flood risk management.
Source: GHK Consulting and Baca Architects

IMPROVE: seek to reduce risk, raise awareness and improve implementation

Stage 1: Understanding the hazard is essential in designing measures and solutions which can prevent or limit damage from specific types of flood.

Stage 2: An integrated flood risk management approach is a combination of flood risk management measures which, taken as a whole, can successfully reduce urban flood risk.

Stage 3: Urban flood risk management requires the development of a comprehensive long-term integrated strategy which can be linked to existing urban planning and management policy and practices.

4. Finance & Implement **$$$$**
...measures to reduce risk.
Prioritize 'no regrets' measures and easy wins.

Stage 4: Integrated urban flood risk management is a multi-disciplinary and multi-sectoral intervention that falls under the responsibility of diverse government and non-government bodies.

CONSULT

5. Evaluate **$**
...how effectively the measures are working and what could be changed in the future.

Stage 5: Evaluation is important in improving the design and implementation of flood risk management measures, both structural and non-structural.

Twelve key principles for integrated urban flood risk management

1. Every flood risk scenario is different: there is no flood management blueprint.

Understanding the type, source and probability of flooding, the exposed assets and their vulnerability are all essential if the appropriate urban flood risk management measures are to be identified. The suitability of measures to context and conditions is crucial: a flood barrier in the wrong place can make flooding worse by stopping rainfall from draining into the river or by pushing water to more vulnerable areas downstream, and early warning systems can have limited impact on reducing the risk from flash flooding.

2. Designs for flood management must be able to cope with a changing and uncertain future.

The impact of urbanization on flood management is currently and will continue to be significant. But it will not be wholly predictable into the future. In addition, in the present day and into the longer term, even the best flood models and climate predictions result in a large measure of uncertainty. This is because the future climate is dependent on the actions of unpredictable humans on the climate – and because the climate is approaching scenarios never before seen. Flood risk managers need therefore to consider measures that are robust to uncertainty and to different flooding scenarios under conditions of climate change.

3. Rapid urbanization requires the integration of flood risk management into regular urban planning and governance.

Urban planning and management which integrates flood risk management is a key requirement, incorporating land use, shelter, infrastructure and services. The rapid expansion of urban built up areas also provides an opportunity to develop new settlements that incorporate integrated flood management at the outset. Adequate operation and maintenance of flood management assets is also an urban management issue.

4. An integrated strategy requires the use of both structural and non-structural measures and good metrics for "getting the balance right".

The two types of measure should not be thought of as distinct from each other. Rather, they are complementary. Each measure makes a contribution to flood risk reduction but the most effective strategies will usually combine several measures – which may be of both types. It is important to identify different ways to reduce risk in order to select those that best meet the desired objectives now – and in the future.

5. Heavily engineered structural measures can transfer risk upstream and downstream.

Well-designed structural measures can be highly effective when used appropriately. However, they characteristically reduce flood risk in one location while increasing it in another. Urban flood managers have to consider whether or not such measures are in the interests of the wider catchment area.

6. It is impossible to entirely eliminate the risk from flooding.

Hard-engineered measures are designed to defend to a pre-determined level. They may fail. Other non-structural measures are usually designed to minimize rather than prevent risk. There will always remain a residual risk which should be planned for. Measures should also be designed to fail gracefully rather than, if they do fail, causing more damage than would have occurred without the measure.

7. Many flood management measures have multiple co-benefits over and above their flood management role.

The linkages between flood management, urban design, planning and management, and climate change initiatives are beneficial. For example, the greening of urban spaces has amenity value, enhances biodiversity, protects against urban heat island and can provide fire breaks, urban food production and evacuation space. Improved waste management has health benefits as well as maintaining drainage system capacity and reducing flood risk.

8. It is important to consider the wider social and ecological consequences of flood management spending.

While costs and benefits can be defined in purely economic terms, decisions are rarely based on economics alone. Some social and ecological consequences such as loss of community cohesion and biodiversity are not readily measureable in economic terms. Qualitative judgments must therefore be made by city managers, communities at risk, urban planners and flood risk professionals on these broader issues.

9. Clarity of responsibility for constructing and running flood risk programs is critical.

Integrated urban flood risk management is often set within and can fall between the dynamics and differing incentives of decision-making at national, regional, municipal and community levels. Empowerment and mutual ownership of the flood problem by relevant bodies and individuals will lead to positive actions to reduce risk.

10. Implementing flood risk management measures requires multi-stakeholder cooperation.

Effective engagement with the people at risk at all stages is a key success factor. Engagement increases compliance, generates increased capacity and reduces conflict. This needs to be combined with strong, decisive leadership and commitment from national and local governments.

11. Continuous communication to raise awareness and reinforce preparedness is necessary.

Ongoing communication counters the tendency of people to forget about flood risk. Even a major disaster has a half-life of memory of less than two generations and other more immediate threats often seem more urgent. Less severe events can be forgotten in less than three years.

12. Plan to recover quickly after flooding and use the recovery to build capacity.

As flood events will continue to devastate communities despite the best flood risk management practices, it is important to plan for a speedy recovery. This includes planning for the right human and financial resources to be available. The best recovery plans use the opportunity of reconstruction to build safer and stronger communities which have the capacity to withstand flooding better in the future.

A woman surveys the flooded suburb of
Rocklea from the Ipswich Highway in Brisbane,
Australia (2011). Source: Gideon Mendel

Chapter 1

Understanding Flood Hazard

Chapter 1. Understanding Flood Hazard

1.1. Introduction

Chapter Summary

This chapter addresses some of the most fundamental questions asked by those who need to understand the flood risk faced by their cities and towns:

Where is the flooding coming from? How severe is it? How frequent will the flooding be? Is it going to be much worse in the future?

The key messages from this Chapter are:

- Understanding the type and source of flooding are both essential if the appropriate flood risk reduction measures are to be identified.
- The tools and models used to assess and forecast flood hazard are invaluable in planning and operationalizing flood risk reduction measures.
- Even the best flood models and climate predictions result in a large measure of uncertainty. Flood risk managers must therefore consider measures that are robust to uncertainty and to different flooding scenarios.

A flood is defined by the Oxford English Dictionary as “An overflowing or irruption of a great body of water over land in a built up area not usually submerged.” Floods are natural phenomena, but they become a cause for serious concern when they exceed the coping capacities of affected communities, damaging lives and property. Globally, floods are the most frequently occurring destructive natural events, affecting both rural and urban settlements. Urbanization has become the defining feature of the world’s demographic growth, with the populations of cities, towns and villages swelling, particularly in developing countries. As a result, floods are affecting – and devastating – more urban areas, where unplanned development in floodplains, ageing drainage infrastructures, increased paving and other impermeable surfaces, and a lack of flood risk reduction activities all contribute to the impacts experienced. These problems are compounded by the effects of a changing climate.

In terms of disaster management, it is necessary to understand flood hazards during flood emergencies, as well as before an event actually takes place, in order to allow for mitigation, preparation and damage reduction activities. The management of flood risk requires knowledge of the types and causes of flooding. This understanding is essential in designing measures and solutions which can prevent or limit damage from specific types of flood. Equally important is the knowledge of where and how often flood events are likely to occur. This is a critical step in understanding the necessity, urgency and priority for flood risk mitigation.

Understanding flood hazard requires knowledge of the different types of flooding, their probabilities of occurrence, how they can be modeled and mapped, what the required data are for producing hazard maps and the possible data sources for these. A detailed understanding of the flood hazard relevant to different localities is also crucial in implementing appropriate flood risk reduction measures such as development planning, forecasting, and early warning systems.

As flood risk evolves over time it also becomes relevant to explore how these decisions will need to change in the light of anticipated climate changes. Information about the existing models used to account for climate change at different scales and the uncertainties regarding those results are both important issues which need to be accommodated in any decision making process.

Sections 1.2 and 1.3 describe the different types and sources of flooding, and their frequency and probability. Ways of quantifying, assessing and forecasting the flood hazard are then highlighted in Section 1.4 and 1.5. Finally, in Section 1.6 the issue of dealing with changing flood hazard in the expectation of climate change is discussed. The chapter concludes with technical annexes, which signpost further technical resources which can assist decision makers and practitioners in accessing the expertise to develop appropriate flood models.

1.2. Types and causes of flooding

Floods usually result from a combination of meteorological and hydrological extremes, such as extreme precipitation and flows. However they can also occur as a result of human activities: flooding of property and land can be a result of unplanned growth and development in floodplains, or from the breach of a dam or the overtopping of an embankment that fails to protect planned developments. In many regions of the world, people moving from rural areas to cities, or within cities, often settle in areas that are highly exposed to flooding. A lack of flood defense mechanisms can make them highly vulnerable. Land use changes can also increase the risk of flooding: urban development that reduces the permeability of soils increases surface runoff. In many cases this overloads drainage systems that were not designed to cope with augmented flows.

Descriptions and categorizations of floods vary and are based on a combination of sources, causes and impacts. Based on such combinations, floods can be generally characterized into river (or fluvial) floods, pluvial (or overland) floods, coastal floods, groundwater floods or the failure of artificial water systems. Based on the speed of onset of flooding, floods are often described as flash floods, urban floods, semi-permanent floods, and slow rise floods.

All the above-mentioned floods can have severe impacts on urban areas – and thus be categorized as urban floods. It is important to understand both the cause and speed of onset of each type to understand their possible effects on urban areas and how to mitigate their impacts. Table 1.1 summarizes the type and causes of flooding and they are further described below.

Table 1.1: Types and causes of floods

Types of flooding	Causes		Onset time	Duration
	Naturally occurring	Human induced		
Urban flood	Fluvial Coastal Flash Pluvial Groundwater	Saturation of drainage and sewage capacity Lack of permeability due to increased concretization Faulty drainage system and lack of management	Varies depending on the cause	From few hours to days
Pluvial and overland flood	Convective thunderstorms, severe rainfall, breakage of ice jam, glacial lake burst, earthquakes resulting in landslides	Land used changes, urbanization. Increase in surface runoff	Varies	Varies depending upon prior conditions

Coastal (Tsunami, storm surge)	Earthquakes Submarine volcanic eruptions Subsidence, Coastal erosion	Development of coastal zones Destruction of coastal natural flora (e.g., mangrove)	Varies but usually fairly rapid	Usually a short time however sometimes takes a long time to recede
Groundwater	High water table level combined with heavy rainfall Embedded effect	Development in low-lying areas; interference with natural aquifers	Usually slow	Longer duration
Flash flood	Can be caused by river, pluvial or coastal systems; convective thunderstorms; GLOFs	Catastrophic failure of water retaining structures Inadequate drainage infrastructure	Rapid	Usually short often just a few hours
Semi-permanent flooding	Sea level rise, land subsidence	Drainage overload, failure of systems, inappropriate urban development, Poor groundwater management	Usually slow	Long duration or permanent

1.2.1. Urban flooding

Urban floods are a growing issue of concern for both developed and developing nations. They cause damage to buildings, utility works, housing, household assets, income losses in industries and trade, loss of employment to daily earners or temporary workers, and interruption to transport systems. The damage caused by urban floods is on the rise. It is therefore important to understand the causes of and impacts different types of flooding have on urban areas.

Urban floods typically stem from a complex combination of causes. The urban environment is subject to the same natural forces as the natural environment and the presence of urban settlements exacerbates the problem. Urban areas can be flooded by rivers, coastal floods, pluvial and groundwater floods and artificial system failures, all of which are discussed in detail below. In cities and towns, areas of open soil that can be used for water storage are very limited.

All precipitation and other flows have to be carried away as surface water or through drainage systems, which are usually artificial and constrained by the competing demands on urban land. High intensity rainfall can cause flooding when drainage systems do not have the necessary capacity to cope with flows. Sometimes the water enters the sewage system in one place and resurfaces in others. This type of flood occurs fairly often in Europe, for instance the floods that affected parts of England in the summer of 2007.

In other places, such as Mexico City, constant urban expansion has reduced the permeability of the soil in groundwater recharge areas. This factor, combined with significant land subsidence due to over-exploitation of groundwater during the last century, has increased the risk of flooding. It is now common that floods in low-lying areas consist partially of sewage fluids.

Urban floods are also caused by the effects of deficient or improper land use planning. Many urban areas are facing the challenge of increased urbanization with rising populations and high demands for land. While there are existing laws and regulations to control the construction of new infrastructure and the variety of building types, they are often not enforced properly owing to economic or political factors, or capacity or resource constraints. This leads to obstruction in the natural flow path of water, which causes floods.

Decision makers and city managers may also be influenced by such issues before revealing the actual level of risk applying to an area to the public, which sometimes has much bigger negative impacts on the flood risk situation of the area. Unless there is awareness amongst residents and proper cooperation between decision makers, risk management authorities and the public in the process of flood risk management, it will be very difficult to control the deterioration of the global urban flood risk situation.

1.2.2. River or fluvial floods

River or fluvial floods occur when the surface water runoff exceeds the capacity of natural or artificial channels to accommodate the flow. The excess water overflows the banks of the watercourse and spills out into adjacent, low-lying floodplain areas.

Typically, a river such as the Mississippi in the United States or the Nile in North Africa floods some portion of its floodplains. It may inundate a larger area of its floodplains less frequently, for instance once in twenty years, and reaches a significant depth only once in one hundred years on average. The flow in the watercourse and the elevation it reaches depend on natural factors such as the amount and timing of rainfall, as well as human factors such as the presence of confining embankments (also known as levees or dikes).

River floods can be slow, for example due to sustained rainfall, or fast, for instance as a result of rapid snowmelt. Floods can be caused by heavy rains from monsoons, hurricanes or tropical depressions. They can also be related to drainage obstructions due to landslides, ice or debris that can cause floods upstream from the obstruction. Case Study 1.1 examines how severe flooding in China is caused by the Yangtze River.

Case Study 1.1: Floods in Southern China

In Southern China tropical air masses and cyclones of tropical origin accompanied by heavy precipitation influence the regional climate. In 1931 torrential rain caused the greatest flood since the beginning of hydrological observations in the Yangtze River, affecting 60 million people. In 1998 another large flood killed more than 4,000 people and caused economic losses estimated at US$25 billion.

The Yangtze River Basin is now host to more than 400 million people, and includes large urban areas like the cities of Wuhan, Changsha and Nanchang. Forty percent of China's gross domestic product is generated in the area. The increased frequency of flooding in the region has been attributed primarily to the reclamation of floodplains for agriculture, forcing flood waters into smaller areas and increasing the flood peak, and to increased erosion in the watershed leading to silting up of the central Yangtze lakes and floodplain areas that could otherwise retain flood waters and slowly release flow peaks.

In response to the 1998 flood event, the Chinese government decided to take action to reduce flood risk in the region. Instead of implementing conventional hard engineering measures to control floods in the Yangtze River, the Government adopted a new approach that includes restoration of 14,000 km2 of natural wetlands by 2030.

Floodplain restoration is a flexible, no regret approach that will be cost- effective regardless of changes in future flood risk.

Source: Pittock and Xu 2011.

1.2.3. Pluvial or overland floods

Pluvial floods also known as overland floods are caused by rainfall or snowmelt that is not absorbed into the land and flows over land and through urban areas before it reaches drainage systems or watercourses. This kind of flooding often occurs in urban areas as the lack of permeability of the land surface means that rainfall cannot be absorbed rapidly enough, flooding results. Pluvial floods are often caused by localized summer storms or by weather conditions related to unusually large low pressure areas. Characteristically, the rain overwhelms the drainage systems, where they exist, and flows over land towards lower-lying areas. These types of floods can affect a large area for a prolonged period of time: the 2007 floods in the Hull area in the UK were the result of prolonged rainfall onto previously saturated terrain which overwhelmed the drainage system and caused overland flooding in areas of the city outside the fluvial floodplain. Pluvial floods may also occur regularly in some urban areas, particularly in tropical climates, draining away quickly but happening very frequently, even daily, during the rainy season.

1.2.4. Coastal floods

Coastal floods arise from incursion by the ocean or by sea water. They differ from cyclic high tides in that they result from an unexpected relative increase in sea level caused by storms or a tsunami (sometimes referred to as a tidal wave) caused by seismic activities.

In the case of a storm or hurricane, a combination of strong winds that causes the surface water to pile up and the suction effects of low pressure inside the storm, creates a dome of water. If this approaches a coastal area, the dome may be forced towards the land; the increasing sea floor level typically found in inshore waters causes the body of water to rise, creating a wave that inundates the coastal zones. The storm surge usually causes the sea level to rise for a relatively short period of time of four to eight hours, but in some areas it might take much longer to recede to pre-storm levels.

Coastal floods caused by tsunamis are less frequent than storm surges, but can also cause huge losses in low-lying coastal areas. The 2004 Indian Ocean Tsunami was caused by one of the strongest earthquakes ever recorded and affected the coasts around the ocean rim, killing hundreds of thousands of people in fourteen countries.

1.2.5. Groundwater floods

Water levels under the ground rise during the winter or rainy season and fall again during the summer or dry season. Groundwater flooding occurs when the water table level of the underlying aquifer in a particular zone rises until it reaches the surface level. This tends to occur after long periods of sustained high rainfall, when rising water levels may cause flooding in normally dry land, as well as reactivate flows in bourns, which are streams that only flow for part of the year. This can become a problem, especially during the rainy season when these non-perennial streams join the perennial watercourses. This can result in an overwhelming quantity of water within an urban area. Groundwater flooding is more likely to occur in low-lying areas underlain by permeable rocks; where such an area has been developed, the effect of groundwater flooding can be very costly.

Groundwater flooding can also occur when an aquifer previously used for water supply ceases to be used; if less water is being pumped out from beneath a developed area the water table will rise in response. An example of this occurred in Buenos Aires, when pollution of groundwater led to a cessation of pumping. Drinking water was imported instead. The resulting water table rise caused flooded basements and sewage surcharge, which is a greater volume of combined water and sewage than the system is designed to convey (Foster 2002).

Since groundwater usually responds slowly compared to rivers, groundwater flooding might take weeks or months to dissipate. It is also more difficult to prevent than surface flooding, though in some areas water pumps can be installed to lower the water table. Flooding can also therefore occur in the event of the failure of pumping systems and may underlie the phenomenon of semi-permanent flooding, discussed below in 1.2.8.

In many cases groundwater and surface flooding are difficult to distinguish. Increased infiltration and a rise in the water table may result in more water flowing into rivers which in turn are more likely to overtop their banks. A rise in the water table during periods of higher than normal rainfall may also mean that land drainage networks, such as storm sewers, cannot function properly if groundwater is able to flow into them underground. Surface water cannot then escape and this causes flooding.

1.2.6. Failure of artificial systems

As mentioned above, human-made systems which contain water have the potential to fail, and the resulting escape of water can cause flooding. Examples of this include burst water mains or drainage pipes, as well as failures of pumping systems, dams or breaches in flood defenses. This type of flooding is not only confined to locations usually considered at risk of flooding, although low-lying areas and areas behind engineered defenses are at greater risk. Often the onset will be rapid, as failure of a system will lead to an escape of water at high pressure and velocity: dam failure, for example, may be devastating as the volume and speed of water is typically large. Failure of embankments, levees or dikes also has the potential to cause devastating floods, which may persist for a long time where the water has few escape routes. Between April and October of 1993 a large flood affected the US Midwest along the Mississippi and Missouri rivers and their tributaries. Many levees had been constructed along these rivers to protect residential areas and agricultural land, but many of these failed, contributing to widespread flooding. Fifty lives were lost and the economic damages were estimated to be US$15 billion (Larson 1993).

1.2.7. Flash floods

The US National Oceanic and Atmospheric Administration (NOAA) defines a flash flood as one whose peak appears within six hours from the onset of a torrential rainfall. Flash floods can be caused by local convective thunderstorms, or by the sudden release from an upstream impoundment created behind a dam, landslide, glacier or ice-jam. Factors that contribute to this type of flooding are, in addition to rainfall intensity and duration, surface conditions and the topography and slope of the receiving basin. For instance, in areas with steep slopes, heavy rain collected on the slopes can end up in a river bed that originally held very little or no water at first. The water level increases rapidly in the river and finally floods the area.

Urban areas are notably susceptible to flash floods because a high percentage of their surfaces are composed of impervious streets, roofs, and car parking areas where runoff occurs very rapidly

Flash floods can be particularly dangerous because they occur suddenly and are difficult, if not impossible, to forecast. They typically affect a more localized area compared to other floods, but can still cause serious damage as the water may be travelling at high speed and carrying large amounts of debris, including rocks, trees and cars.

In November 2009, flash flooding affected the city of Jeddah in Saudi Arabia. In four hours, more than 90 mm of rain fell, nearly twice the yearly average and the heaviest rainfall recorded in Saudi Arabia in a decade. More than a hundred lives were taken and business losses were estimated at US$270 million.

Another type of flash flooding is known as a Glacial Lake Outburst Flood (GLOF). Glaciers are very susceptible to rises in temperature, which can cause accelerating melting of glacial ice leading to the formation of lakes. If the material damming or capping the lake is eroded, or otherwise fails, the burst causes floods downstream in the valleys. The damage caused by these floods depends on factors such as the depth of the lake, the nature of the outburst, the geomorphology of the river valleys and the characteristics of the elements exposed to the flash flood. This type of flood is a particular hazard in Nepal and Hindu-Kush Himalaya region where for instance, 24 GLOF events have been documented. One of them, caused by the outburst of the Dig Tsho Glacial Lake in 1985, resulted in major financial losses and damage to infrastructure, including a nearly completed hydroelectric power plant located 11km from the breach, caused damage for tens of kilometers downstream, and resulted in the loss of five lives (ICIMOD 2011; Matambo 2011).

1.2.8. Semi-permanent flooding

In some cases urban settlements are built on land which is flooded regularly and for long periods of time. Often these areas may lie below sea level or where the water table is close to the surface. This is usually the case where settlements are informal, unplanned and built on less expensive land due to rapid urban expansion and the poverty of the inhabitants. A typical scene of flooding is illustrated in Photo 1.1.

Photo 1.1: Stagnant water seven months after the 2010 floods in Baguida, Lome. Source: K. Ayeva

Semi-permanent flooding may also occur where settlements are in the vicinity of failed human-made structures awaiting repair. In New Orleans, for instance, following the failure of levees damaged by Hurricane Katrina, some residents remained in homes that were standing in water for over six weeks (Kates et al. 2006). Sea level rise and land subsidence have the potential to create many more such areas in the future.

1.3. The probability of flooding

A sound understanding of the likelihood of occurrence of a flood hazard is a fundamental step in dealing with flood risk. Risk from flooding can be conceptualized into four stages as in Figure 1.1 below:

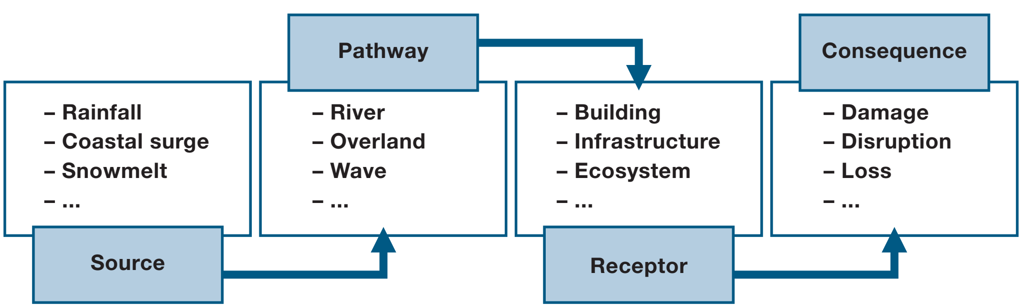

Figure 1.1: The Source, Pathway, Receptor Model

This model breaks down the process of flooding into the identification of a source of the flood water, the pathway which is taken by it, and the receptor of the flooding, which is the human settlement, building, field or other structure or environment that is exposed to the consequences. Flood hazard encompasses the first two of these steps, the source of flood water and the pathway by which it has the potential to damage any receptors in its path. To fully evaluate risk, the degree of exposure and the nature of exposed receptors and their potential to sustain or resist damage also need to be considered. This section deals only with the hazard, focusing on its nature, source and pathway, together with the probability of an event.

Probability in itself can be a difficult concept to translate from the purely scientific generation of hydro-meteorological models into a description of hazard that lay people can comprehend and decision makers can use to evaluate their real options. This section explains different methods of calculating the probability of occurrence of flooding and clarifies some of the concepts of hazard and their communication.

It is important to distinguish between the probability of occurrence of a weather event and the probability of occurrence of a flood event. Flooding is primarily driven by weather events which are hard to predict due to what is termed their chaotic nature. In other words, despite the great advances in weather forecasting, it cannot be determined with certainty when and where rain will fall or storms will form. This means that it is impossible to know exactly when and where a flood will occur in the future, nor how high (either in water level or discharge) the next flood will be. Hazard predictions are commonly given in terms of probabilities, computed using historical data for the area of interest.

This section now describes the use of frequency analysis and hydrological modeling in the estimation of flood probability, through to providing and communicating flood hazard forecasts.

1.3.1. The probability of occurrence of floods

Flood forecasts for a natural drainage area or a city are usually obtained by analyzing the past occurrence of flooding events, determining their recurrence intervals, and then using this information to extrapolate to future probabilities. This common approach is described below in simplified form for fluvial flooding.

The probability of occurrence for pluvial, groundwater, flash, and semi-permanent floods is much more difficult to estimate, even if historical data is available. This is due to the fact that the causes of these types of floods are, as seen above, a combination of a meteorological event such as heavy rainfall and other factors such as insufficient drainage capacity, mismanagement of key infrastructure and other human factors.

In the case of coastal floods caused by seismic activities, predicting their probability is as difficult as predicting the occurrence of an earthquake. For coastal floods caused by storms or hurricanes, their probability of occurrence can, in principle, be computed using historical data or numerical simulations of key variables such as wind speed, sea level, river flow and rainfall.

1.3.1.1. Recurrence interval

The recurrence interval or return period is defined as the average time between events of a given magnitude assuming that different events are random. The recurrence interval or return period of floods of different heights varies from catchment to catchment, depending on various factors such as the climate of the region, the width of the floodplain and the size of the channel. In a dry climate the recurrence interval of a three meter height flood might be much longer than in a region that gets regular heavy rainfall. Therefore the recurrence interval is specific to a particular river catchment.

Since only the annual maximum discharge is considered, the amount of data available to perform the return period calculation can be very limited in some cases. In Europe and Asia, partial records extending over centuries may be found, as for instance in the case of sea floods in the Netherlands. In other places, data may be scarce and records are rarely longer than for 50 years. This poses an important limitation to the calculation of recurrence intervals which must be taken into account when evaluating and communicating uncertainties in flood probability estimations.

Once the recurrence intervals are determined based on the historical record, some assumption about the flood frequency distribution has to be made in order to extrapolate or interpolate to events that have not been recorded historically. To achieve this, an assumption about the distribution of flood frequency has to be made. In this way the recurrence interval for any discharge (and not just those present in the observational record) can be inferred.

1.3.1.2. Flood probability

The recurrence interval, as discussed above, refers to the past occurrence of floods, whilst flood probability refers to the future likelihood of events. The two concepts are related because the recurrence interval of past events is usually used to estimate the probability of occurrence of a future event:

For any discharge, or alternatively, any recurrence period, the probability of occurrence is the inverse of the return period $p=1/T$

Using the relationship between return period T and flood probability p, it is clear that a flood discharge that has a 100-year recurrence interval has a one percent chance of occurring (or being exceeded) in a given year. The term 'one hundred year flood' has often been used in relation to floods with a 100-year recurrence interval (Defra 2010; Dinicola 1996). This can be misunderstood, as a 100-year flood does not have a 100 percent chance of occurring within a 100 year period. The probability of a 100-year flood not occurring in any of the next 100 years is 0.99100=0.366. Therefore the probability of one of these floods occurring is 0.636, closer to two-thirds.

1.3.1.3. Discharge, stage and inundation

In the case of fluvial floods, measures which are commonly used to describe the severity of a flood are discharge, stage, and crest (or peak). Discharge (or flow) is the volume of water that passes through a given channel cross-section per unit time (usually measured in cubic meters per second). Stage is the level of the surface of the water (usually expressed as height above a reference level, often the sea level). As discharge increases, stage increases, but this relationship is not linear and is specific to each river and catchment. The crest or peak is the highest stage reached during a flood event. Stage as used in this context is different from "flood stage," a term sometimes used to describe when over bank flows are of sufficient magnitude to cause considerable inundation of land, roads or significantly threaten life and property.

The relationship between discharge and stage at a particular location is empirical and usually represented graphically by a rating curve which is obtained using observed data for both parameters. These curves are at best approximations because the relationship between discharge and stage is non-linear; interpolation of discharges that have been not been observed cannot, therefore, be accurately inferred. There may also be significant scatter in the data, and it also should be noted that rating curves can change over time, due to both natural and human-induced changes in the geomorphology of the watercourse.

Once stage is known, the next step is to determine the corresponding inundation area. This is not straightforward: a flood that raises the water level by two meters in a steep canyon might not have a significant impact, while on a broad floodplain the water could cover a great area. The potential for damage caused by a flood, therefore, depends not only on the discharge and stage, but also on the local topography. To establish the inundation area corresponding to a given stage, a topographic map is necessary, allowing the flood probability for any given discharge to be illustrated by means of an inundation map for the corresponding stage.

Often, even for fluvial flooding, the combined effects of river flow with one or more additional factors such as tide, surge, rainfall and possibly waves might be needed to determine the overall river water level, and the resulting likelihood of out-of-bank flow and flooding.

In coastal engineering, the combined effects of sea level and waves determine the overall loads on coastal structures, and consequent likelihood of damage or severe overtopping and flooding. In urban drainage of coastal towns, the combined effects of sea level and high intensity rainfall are of interest in determining the probability of tide-locking of drains. In cases where the probability of flooding depends on two or more variables, these probabilities need to be jointly estimated.

1.3.2. Uncertainties in flood probability estimations

The approach described above to compute probability of flooding is based on a series of assumptions that are questionable in most practical cases. These assumptions are as follows (Klemeš 1993, 2000):

- A long and high quality observational record is available
- There is no serial correlation between flood events
- The physical system is stationary (i.e., not subject to changes) and, as a result, the observational record is a representative sample of all possible flood events
- The frequency distributions built from the historical time series represent instantaneous probability distributions at any point in time.

It is important for decision makers to understand that these assumptions exist.

The impact they may have on the robustness of flood predictions if the scale of uncertainty would lead to changes in the most effective flood mitigation measures is also of significance. The impacts of two of the above assumptions, quality of data and of the so-called stationarity of the system, are now examined in more detail.

1.3.2.1. Quality of historic record

The value of inference based on historic observations is naturally dependent on the availability and quality of data. If they are to provide useful statistics, hydrological data must be accurate, representative (representing the range of possible values occurring over time), homogeneous (measuring the same quantities over time) and of sufficient length. Data rarely meet these specifications: the magnitude of a particular return period event on a river may change following the observation of a significant flood event, or an improvement in the quality of the data available. For example, if measured flows change by a small amount, due to improvements in measurement techniques, the recurrence interval for a particular value of the discharge, or the magnitude of the event for a particular return period, can change significantly. Similarly, the recurrence interval will be sensitive to the incorporation of any new data (Dinicola 1996).

The use of historical events should take into account the causes of the flood. Estimates generated from one type of event cannot warn of the possibility of other possibly rarer flood type. For example in Eastern Canada most annual maximum discharges are generated by snowmelt, but there is the possibility of a hurricane striking and causing a much larger flood than conceivable via the snowmelt mechanism alone (Klemeš 1989). It is also important to recognize that the extrapolation from historical records, (in many cases less than 50 years duration) to the 1,000 or 10,000 year event will be beset with problems. The prediction of such high impact but low probability events is critical for the design of facilities such as toxic waste dumpsites or nuclear power plants. Making judgments of this nature using a best fit probability distribution may lead to absurdities, as the conditions under which a flood of the corresponding magnitude could occur are physically impossible. Moreover, the same probability distribution can be a best fit for historical records coming from two different climatic regions: one dominated by snowmelt flows and the other by convective storms. There is no good reason to assume that a 1,000 year flood, for instance, will be of similar magnitude in both cases, even though that will be the mathematical prediction. Without an analysis of the physical causes of recorded floods, and of the whole geophysical, biophysical and anthropogenic context that determines the potential for flood formation, predictions based solely on the fitting of a probability distribution, may under-estimate or over-estimate the flood hazard (Klemeš 1989, 1993, 2000).

1.3.2.2. Assumption of stationarity

The greatest source of uncertainty in the estimation of future urban flood probabilities is the assumption of stationarity: that the occurrence and recurrence intervals of floods in the observed past are assumed to represent occurrence in the future, thus permitting extrapolation. This assumption presupposes that the system is stationary, and that the observed record provides an exhaustive sampling of all possible events. That is clearly invalid if, for instance, drainage basins are changed by human activities and other events, or if rainfall patterns are affected by local or global climate variations (Klemeš 1989, 1993, 2000).

Two potential major sources of non-stationarity with regard to urban flooding are the rapid development of floodplains as urbanization proceeds, and the changes in weather patterns associated with climate change. There are other changes which can change flood probabilities such as the effects of mitigation measures. An example is the completion of the Howard Hanson Dam on the Green River in Washington State in the US in the 1960s which reduced the magnitude of the 1 in 100 year flood some 30 kilometers downstream at Auburn, Washington, by nearly a half (Dinicola 1996). Major flood events can also change the physical conditions for future flooding, as they may alter the flow or cross-section of rivers.

In summary, these limitations suggest that flood probabilities for short-term projections of events of similar magnitude to those previously observed are more robust in catchments with long historical records. Extrapolation beyond and outside the historical record should be approached with great caution, particularly where a changing climate may make a significant difference to the pattern and frequency of future events. In such cases, the use of flood probabilities to estimate flood hazard should be carried out with a full understanding of the uncertainties involved. The optimal approach to flood management incorporates adaptations that are robust (meaning insensitive) to these uncertainties as a way forward.

1.4. Flood hazard assessment

The concept of hazard is defined as the potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation (UNISDR 2004).

Hazard events have a probability of occurrence within a specified period within a given area and have a given intensity. Studies related to analysis of physical aspects and phenomena through the collection of historical or near real time records are called hazard assessment. For a better understanding of the nature of flooding, three main aspects are taken into consideration: the probability of occurrence, the magnitude and intensity of occurrence and the expected time of next future occurrence (ADPC 2002). Hazard assessment and hazard maps, as distinct from risk maps, are now considered. Risk maps are discussed in Chapter 2 in Section 2.4 after discussion of the receptors affected by and the consequences of flooding.

Flood hazard maps are important tools for understanding the hazard situation in an area. Hazard maps are important for planning development activities in an area and can be used as supplementary decision making tools. They should therefore be easy to interpret: the aim should be the generation of simple hazard maps which can be read and understood by both technical and non-technical individuals. There is, therefore, a need to generate maps based on user-specific requirements, whether for individual or institutional purposes. Flood hazard maps are characterized by type of flooding, depth, velocity and extent of water flow, and direction of flooding. They can be prepared based on specified flood frequencies or return periods, for example, 1:10 years, 1:25 years, 1:100 years, or to more extreme events such as the 1:1000 year return period for different scales.

1.4.1. Probability of flood into hazard estimation

Flood hazard is determined by the conjunction of climatic and non-climatic factors that can potentially cause a flood: the magnitude of a fluvial flood will depend on physical factors such as intensity, volume and timing of precipitation. The antecedent conditions of the river and its drainage basin (such as the presence of snow and ice, soil type and whether this is saturated or unsaturated) will also have an impact on the development of the event, as will human-made factors such as the existence of dykes, dams and reservoirs, or the loss of permeability caused by urban expansion into floodplains.

Flood hazard is usually estimated in terms of a rainfall event or 'design flood' such as the 100 year flood discussed above. The estimation of flood probability or hazard combines statistics, climatology, meteorology, hydrology, hydraulic engineering, and geography. The standard approach described in Section 1.3.1 assumes that the flow data is sufficient to compute the design flood using statistical methods. In places where these data are not available because there are no gauges, or are of poor quality, other approaches are used. Data from a neighboring watercourse may be interpolated to the site of interest, or, if precipitation data are available, a design rainfall event can be computed, and a rainfall-runoff model used to estimate river flow. This is then fed into a hydraulic model that computes the depth and extent of the resulting flood. Finally, this information is combined with topographic, infrastructure, population and other geographic data in order to compute the flood hazard. Table 1.2 below illustrates the range of model types used; the 'generation' denotes the level of sophistication inherent in the model, progressing from 'first generation' models including a number of simplified assumptions, through to the more advanced generations with fewer simplifying assumptions.

Table 1.2 Types of flood models

Type of models	Useful in areas	Advantages	Disadvantages
First Generation with 2DH grid	Good for estimation of duration of flood, volume propagation, Useful in compact channels	Low to medium cost, simple calculation, low runtime (minutes to hours)	Does not give good results for vast areas or vast floodplains
Second generation 1D/2D and 2D and Finite element models	Good for broad scale modeling, urban inundation ,useful for compound channels	Medium to high cost, accuracy and run time (hours to days), , can get outputs like percolation and seepage other than depth, velocity and volume	Broad scale application requires coarse grid otherwise the computational time becomes immense, high data demand

Third generation models	Good for showing breaching in 3D and flood propagation in 2D, useful for local predictions	High cost, accuracy, computation time (days) , flow velocity and flood boundaries accurately simulated	High run time, high demand for data, high cost
Erosion models Vellinga (1986)	Predicts final erosion profile based on wave height and storm surge water level	Can be used in coasts of different morphology	Does not include wave period
Komar et al (1999, 2001)	Predicts maximum erosion during an extreme event	Simplistic model	Does not take into account the storm duration
Sheach Model	Analytical more versatile	Estimation of cross shore transport rate in different shore zones	Demands high level of data, huge dataset
TIMOR3 and SWAN	Process based model, useful for short term	Detailed morpho-dynamic result	Not efficient to calculate initial response

Source: Floodsite Report T03-07-01 2008

1.4.1.1. Communication of flood hazard in the context of integrated flood risk management

The UN International Strategy for Disaster Reduction (UNISDR) states that public awareness is a primary element of risk reduction, and defines a set of basic principles that should underline public awareness campaigns: they should be designed and implemented with a clear understanding of local perspectives and requirements; they should target all sections of society including decision makers, educators, professionals, members of the public and individuals living in exposed areas; messages should be designed in a way that can reach the different target audiences; and special disaster awareness campaigns and events should be used to sustain any efforts (UNISDR 2004).

Traditionally, flood risk management has consisted predominantly of structural measures, such as the construction of retention basins and dykes. The planning and implementation of these types of measures has been, for the most part, the responsibility of governments. The increasingly prominent role of non-structural measures such as early warning systems requires a much greater involvement of the public, including clear communication of flood risks and a dialogue about mitigation options as key elements of any integrated flood risk management plan (Merz 2010). Both types of measure are discussed at length in the following two chapters.

In practice, numerous projects have demonstrated the benefit of involving affected people in flood risk management: in Switzerland, for example, an approach that involves local stakeholders has been developed for municipalities. By means of workshops moderated by risk experts, the knowledge and experiences of local stakeholders (members of authorities and organizations involved in disaster mitigation and disaster management, and people who have been affected by floods) are systematically collected and structured. These are then used to derive representative damage scenarios, to assign probabilities to the scenarios, to establish a risk profile of the community and to discuss response actions. This approach guarantees that local characteristics are taken into account in the management plan, but also triggers a dialogue that improves the understanding and acceptance of the derived safety measures (Merz 2010).

The need for the communication of the large uncertainties present in any flood risk estimate to the wider non-hydrological community presents a challenge. As mentioned previously, the actual meaning in probability terms of the "one-hundred year event" is frequently misunderstood. Instead of a flood with a probability of occurrence of one percent in any given year, it is sometimes assumed to be a flood that can only occur once every 100 years, or one that recurs regularly on a 100 year cycle.

Another source of confusion when communicating flood risks is the fact that two events reported as having the same return period due to re-assessment after the occurrence of the first event can have different magnitudes and consequently affect the same people in different ways. When the uncertainties are very large or poorly understood, owing to a lack of data or process understanding, the communication of risk in terms of flood probabilities and their use in flood management decisions can be misleading. In these cases, focusing the communication exercise on the consequences of flooding might be more appropriate.

1.4.2. Data requirements for flood hazard assessment

Both qualitative and quantitative flood data can be used for either modeling or analysis. Quantitative data can be exemplified by hydro-meteorological data, while qualitative data can include descriptions of the type of areas affected, depth, and velocity. Data can be collected from the local municipality; governmental environment ministries and environmental agencies; weather and meteorological offices (local or regional); reports from the media and document archives; and through Participatory Rural Appraisal (PRA) tools. Hydrological data can be obtained from monitoring stations and gauging stations (where available), as well as satellite imageries (in real time or post-flood scenario) which can be obtained from national or international organizations involved in collection and storing of satellite images (for example the National Aeronautics and Space Administration (NASA), European Space Agency (ESA), and Indian Institute of Remote Sensing (IIRS). Photographs for post-flood analysis can be obtained either from the media or from local authorities.

An example of collaborative data collection is demonstrated by the Manila Typhoon Ondoy flood map. The Manila Observatory developed an interactive map showing the maximum flood depths noted in various locations in the city of Manila, the Philippines. The most important component of this project is that everyone living in the flood-affected areas was requested to collect the flood data and submit it online. The collected data has been used to validate flood simulations and identify future floods in Manila (Manila Observatory 2010). The growing awareness on the damaging impacts of disaster has resulted in a similar platform set up by the National Institute of Geological Studies that allows reporting across the entire country. While these platforms allow citizen's feedback, a weakness of these methods is that the collected data warrant further validation. As with all types of flood hazard mapping, it is important for any data to be updated regularly, since any changes will have impact on the final output.

Major international institutions involved in collection and archiving of disaster data include: the Global Emergency Events Database (EM-DAT) supported by the Centre for Research on Epidemiology of Disaster (CRED); the World Health Organization (WHO); the Nat-Cat SERVICE provided by Munich Re; Relief Web supported by the UN Office for the Coordination of Humanitarian Affairs (UNOCHA); and the Global Disaster Information Network (GDIN). Most of the historical data from the international organizations are freely available, with the exception of real time hydro-meteorological data.

The method of data capture and its quality determines the final products of hazard assessment. Guidelines are provided by the Federal Emergency Management

Agency (FEMA 2003) regarding practical aspects of ground surveys and control points; measurement of hydraulic structures; photogrammetric mapping using aerial photographs and satellite imageries; use of LIDAR (LIght Detection And Ranging) technology; and quality of spatial data sets, which are used as base maps for the production of final risk maps. There are similar guidelines for data capture standards.

The most important element of any hydraulic mapping is the production of a Digital Terrain Model (DTM) which demands accurate elevation data. Techniques like photogrammetry, LIDAR and SAR (Synthetic Aperture Radar) are used along with traditional topographic maps and surveying methods using DGPS (also known in this context as 'ground truthing'). They all have their limitations: data validation in larger areas, feasibility and cost effectiveness can become major issues. Remote sensing based methods are popularly used for generation of high resolution DTMs, but it should be kept in mind that errors resulting from data capture and data accumulation may still affect the accuracy of the final flood hazard maps.

Floodplain topography is another important aspect of flood hazard assessment. Traditionally, topographic and bathymetric data were obtained from land surveying and bathymetric surveying, including technology such as Real Time Kinematic GPS (RTK-GPS) for coastal topographic measurement and underwater surveying. LIDAR technology is becoming increasingly popular for characterization of changing coastal topography worldwide. Techniques like SHOALS (Scanning Hydro-Graphic Operational Airborne LIDAR Survey) are useful in measuring both topography and bathymetry at the same time, thereby reducing the uncertainties in data due to time difference in data capture (Lillycrop et al. 1996). The most common technology for updating bathymetric data is called Multi Beam Eco-Sounder Surveying (MBES).

Areas with limited or no data face particular challenges. Both remote sensing and use of GIS techniques are especially useful solutions. These techniques can also be used in areas where physical accessibility is a problem. Satellite imagery, aerial photographs, and LIDAR technology can generate data in real time and both historical and hazard maps can be generated from them. Un-gauged catchments can be assessed using regional datasets such as flood frequency curves or regional regression equations (WMO 1999).

The cost of data acquisition is always an issue of concern: purchasing expensive data and technologies like LIDAR and SAR must be set against the benefits of obtaining more accurate results for hazard analysis.

Case Study 1.2 discusses the use of data sources and GIS techniques for hazard assessment in Senegal.

Case Study 1.2: Spatial analysis of natural hazards and climate variability risks in the peri-urban areas of Dakar

A pilot study was carried out in 2009 by the World Bank to identify natural risk hazards in the peri-urban areas of Dakar, Senegal. The Dakar Metropolitan Area covers less than one percent of Senegal's national territory, but houses about 50 percent of the country's urban population. Dakar is a low-lying, peninsula-like area with a long coastal line. Flooding, coastal erosion, and sea level rise are causing major disruption in the city. Significant flood events have been reported in this past decade in 2008, 2007, 2003, 2002, and 2000.

Much of the population growth in Dakar takes place in unplanned peri-urban areas, which are particularly vulnerable to natural hazards. Administrative and governance arrangements in the Dakar Metropolitan Area are unclear, further complicating city management. Systematic attention to hazard risk management in peri-urban areas and the strengthening of institutional capacities are necessary to manage hazard risk. One of the objectives of the pilot study was to propose a new methodology for quick assessment of natural hazard risk, utilizing new tools for spatial analysis based on Geographic Information Systems (GIS) data.

Hazard maps were combined with population maps, land price data and land cover information to measure the exposure of different variables with regards to potential flood, coastal erosion and coastal inundation. Spatial analysis also generated statistical results and maps to identify potential hotspot areas, as well as built-up and non-built-up areas exposed to hazard risks.

The study concluded that this approach and methodology can be adapted to other local contexts and needs and can be further developed to:

- Consider a broader range of natural hazards
- Analyze the economic impacts of hazards in more detail
- Consider different relationships between building density and population density depending on whether the area is planned or unplanned
- Add information (via layering) such as major infrastructure (roads, electricity networks, drainage and sanitation systems).

Lastly, this methodology allows for better understanding of flood hazard risk, in particular in peri-urban areas, and enables a better integration of flood risk management with land use planning.

Sources: Wang et al. 2009; GLIDE Disaster Data.

1.4.3. How to prepare a flood hazard map (Riverine)

Production of hazard maps is the first step towards flood risk assessment. Their purpose is to better understand and communicate flood extent and flood characteristics such as water depths and velocity. Multiple stakeholders such as city managers, urban planners, emergency responders and the community at risk can use hazard maps in planning long term flood risk mitigation measures and the appropriate actions to be taken in an emergency.

Method

For accurate estimation of flood hazard, selection of appropriate data, type of model, schematization, proper parameterization, calibration and validation of results are all important steps. A step by step process for achieving this is outlined below. This incorporates the factors to be considered at each stage.

1. **Data collection and integration for generation of digital terrain and surface models**
2. **Calculation of return period of flooding**
3. **Modeling flood scenarios using 1D, 2D or 1D2D hydraulic models (flood modeling software required)**
4. **Model result validation**
5. **Flood maps prepared and distributed to different user groups**
6. **Monitoring and regular updating of maps**

1. Data collection and integration for generation of digital terrain and surface models

Data that can be used for generating Digital Terrain Model (DTM) and Digital

Surface Model (DSM) includes laser scan terrain data; geographical survey data; ortho-photos; satellite images; human-made objects and terrain in digitized format; river cross section data; discharge data; and bathymetric data.

Digitization of the available data is the preliminary stage in the generation of digital surface models. Interpolation methods are then used based on the specific needs of the surface. Error correction follows, to ensure that the modelled surface matches reality as closely as possible.

The Digital Terrain and Digital Surface Models must accurately represent the terrain on which the model will base its results if reliable flood hazard modeling is to be obtained. A combination of laser-derived terrain data and geographical survey data (digitised contours) using GIS software will provide the best results, but laser-derived terrain data are expensive to obtain. The quality of output can be influenced by type of data, expertise, knowledge and understanding of the user, all of which will further have an effect on the end product.

2. Calculation of return period of flooding

The annual maximum flood series is the maximum volume flow rate passing a particular location (typically a gauging station) during a storm event. This can be measured in ft3/sec, m3/sec, or acre feet/hr) and is calculated using the following formula:

$$Tr = (N + 1)/ M$$

(where Tr = Return Period of flooding; N= Peak annual discharge;
and M = Rank, according to order of highest flow).

Where a number of tributaries exist within the catchment of interest, methods of gauging flows on each watercourse may be necessary. (For a detailed discussion of recurrence intervals and flood probability see Section 1.3.1.)

Output from the return period calculations will enable users to understand the 'exceedance probability' of given flood events. If actual annual maximum discharge data is unavailable then approximation will be needed. But it must be recognized that this may lead to uncertainties within the model and thus in the end product.

3. Modeling flood scenarios using 1D, 2D or 1D2D hydraulic models (flood modeling software required)

As shown in section 1.4.1 and in Table 1.2, various flood models are now available, with varying degrees of simplification and applicability; each has its own advantages and disadvantages, particularly in terms of the costs of the software and computer model runtime involved. Whichever one is chosen, schematization with the available input data, as above, is needed together with the boundary conditions for scenario generation according to the user's requirements. Calibration of the model should then be performed followed by validation in order to get results closer to the reality (for example, by comparison with known flood extents in historic events in the locality).

Model outputs are obtained in the form of water depth, water velocity and extent of flooding for different return periods depending upon the model chosen. Depending on the nature of the flooding under consideration, the flood model adopted should ideally be the closest to the technological 'cutting edge' that available resources permit. Where the number of actual observations is limited, a process known as 'parameterization' of the inputs is needed in order to get the output as close as possible to the natural event. The details of this critical exercise vary according to the model used. Output can also be affected by the internal formula used by the model in performing the modelling process.

4. Model result validation

Validation of results by means of surveying, also known as 'ground truthing' of the model, is extremely important to ascertain the quality of the model output. Additional validation, using actual event data, provides another way of testing how appropriately the hazard model has performed.

Both the above checking processes are required in order to improve the precision of the model outputs and thereby the usefulness of the final map product.

5. Flood maps prepared and distributed to different user groups

Model outputs can be exported in a variety of GIS formats (raster or vector) which can then be used to generate maps, thereby translating the model results into a user-friendly format. Hazard maps in different formats are helpful for different kind of users (in terms of scales, size, the amount of information, and the level of generalization). The appropriate software will permit outputs to be tailor-made in order to adhere to specific user requirements.

Most of the models and software used for flood hazard assessment are quite expensive to buy and are not freely available to the public. Due to their high price they are an impractical consideration for many developing nations. Therefore there is a need for high quality open source software which will be able to serve these highly sophisticated models to the extent that they can provide a general idea of the areas under threat.

Some of the open source software freely available for analysis and visualization purposes is as follows:

- Flow map designed by Utrecht University in the Netherlands is specifically designed to display flow data and works under Windows platform.
- GRASS is the most popular and well known open source software application which has raster and vector processing systems with data management and spatial modeling system. It works with Windows, Macintosh, Linux, Sun-Solaris, HO-Ux platforms.
- gvSIG is another GIS software application written in Java and works in Windows, Macintosh and Linux platforms.
- Ilwis is a multi-functionality GIS and Remote sensing software which has the capacity of model building. Regular updates are available for this software.
- Quantum GIS is a GIS software which works with Windows, Macintosh, Linux and Unix
- SPRING is a GIS and Remote sensing image processing software with an object oriented model facility. It has the capacity of working with Windows, Linux, Unix and Macintosh.
- uDig GIS is yet another open source desktop application which allows viewing of local shape files and also remote editing spatial database geometries.
- KOSMO is a popular desktop application which provides a nice graphic user interface with applications of spatial database editing and analysis functions.

Interactive visualization tools:

- Showing sea level rise: http://globalfloodmap.org/South_Africa
- Global Archive map of extreme flood events (1985-2002): http://floodobservatory.colorado.edu/Archives/GlobalArchiveMap.html

A major step taken by Deltares, a leading research institute based in the Netherlands, is to release specific modules of the Delft 3D model (FLOW, Morphology and Waves) as open source to bring experts all over the world together to share their knowledge and expertise. It is a robust, stable, flexible and easy to use model which is internationally recognized. For more information please see the following link: http://oss.deltares.nl/web/opendelft3d/home

However it is observable that uncertainty exists in every stage of hazard assessment. Uncertainty exists in every stage of data accumulation, model selection, input parameters, operational and manual handling of the model till the final output is obtained. Each element contributes to the uncertainty in accuracy of the final output. Therfore it is necessary to consider the impact that uncertainty has on the output of a model and is essential to reduce it as much as possible.

6. Monitoring and regular updating of maps

Typically, for public access purposes, general maps with limited information are produced using GIS software, showing only the flood extent and perhaps protection measures where these exist. For use by local authorities for decision making more detailed information will be required, such as municipality level maps with real estate data. For professional bodies, maps with still more detailed supplementary data can be generated, going down to individual household plot level if required.

Flood hazard maps must be updated regularly with both field information (for example, major building developments or road construction that significantly alter the terrain) as well as other relevant data, such as any changes in the peak recorded flows from gauging stations following extreme events. Monitoring of the hazard map's performance in use is also required (for example, where data from actual events following map production are found to exceed the modelled predictions).

Known uncertainties in the model need to be incorporated into the decision making processes of the local authorities; revisions to the maps following any amendments to input data will also be required. A process to ensure that the superseded copies are taken out of use is further needed, such that future decisions are made on the basis of the updated information.

Figure 1.1: Flood hazard map:
Source: The Defra funded LifE Project by Baca.

1.4.4. How to prepare a flood hazard map in the coastal zone

Hazard maps for the coastal region are different from the hazard map preparation for non-coastal areas. These maps are particularly suitable for coastal areas where flooding is mainly caused by storm surges. With the changing nature of climate and sea level rise this type of mapping is very important for any coastal urban area. The coastal topography and the depth of water in the shallow water zone area are two most important aspects which make the modeling of coastal flooding possible.

These maps are important for city managers who can have a better understanding of the possible hazardous areas and take appropriate actions. The process described below is a guide for preparing coastal hazard maps. However there are other important aspects like differences in meteorological conditions and unique physical processes which differ in different parts of the world which are not specifically addressed here. A user should keep in mind that some procedures may be applicable to specific settings. With this kind of coastal hazard map, the severity of an event can be anticipated to some extent, which is extremely helpful for planning purposes.

Method

The following section will outline the techniques and methods useful to evaluate flood risk in a coastal environment. The different variables responsible for causing flood risk need to be evaluated properly for producing hazard maps. The major technical aspects in estimation of flood hazard for storm surges in coastal areas are similar to any other kind of hazard estimation following data collection, model schematization, model parameterization and output visualization. However there are certain factors that should be taken into account for each stage of hazard assessment and finally production of maps. The factors that are considered for each step of this process are listed below.

1. **Data collection to characterize coastal domain and generation of digital terrain model**
2. **Characterization of Morphology and bathymetry of coastal fringe**
3. **Data generation for water levels of different probability of occurrence**
4. **Modelling event in coastal zone (numeric and analytical models)**

1. **Data collection and integration to characterize coastal domain and generation of digital terrain model**

The first step of producing a hazard map is collection of appropriate data. Database generation is either performed using historical information or prepared from scratch by collecting required information through surveying. The type of data to be collected is morphology of coastal fringe, cross section of the water bodies and bathymetry data. The instruments for collection of data can be either ground survey of control points using DGPS, measurement of hydraulic structures, and topographic mapping using photogrammetry, SAR and LIDAR. Ground truth methods are however very expensive and time consuming and difficult to obtain in inaccessible terrains. Therefore remote sensing methods are recommended. The scanned data obtained through remote sensing and the surveyed data are processed and combined to generate grids for generation of digital terrain models. The process of interpolation is used to create the surface for their generation. Error correction is necessary to gain accuracy. Accurate topographic information in both vertical and horizontal dimensions is also necessary. The models also depend on the data quality, with data capture standards highly essential for the quality of output. Generated DTM is essential for delineation of floodplains. To incorporate other factors existing within the coastal region land use data are sometimes used for understanding the total damage effect.

2. **Characterization of Morphology and bathymetry of coastal fringe**

The two different domains of data that are required for characterization of the morphology of the coastal fringe are the sub-aerial part and the sub-aqueous part. The sub-aerial part consists of topographic data, and the subaqueous part consists of bathymetric data. They are important for understanding the level of existing barriers and the intensity of storm surges to the hinterland. Changes in beach slope can also bring changes in level of overtopping. Since the coastal morphology is dynamic and variable in nature, consideration has to be made to reduce the level of uncertainty as much as possible. It is also recommended that coastal morphology should be updated at frequent intervals to obtain the pre-storm morphology as accurately as possible. Topo-bathymetric data gathering can be done using Kinematic GPS, land surveying for the sub-aerial part and bathymetric survey for the subaqueous part through LIDAR survey. LIDAR survey is gaining more importance worldwide although it is expensive and requires expertise and high end technology. It should be kept in mind that both the surveys have to be done at the same time and using the same datum. The end product is affected by the changes in morphology: for instance modification of wave and surge propagation can affect flood intensity. Variations in result may be observed due to changes in beach crest and dune.

The sub-aqueous part of data collection and generation of a database is important to describe the process of coastal changes for characterization of bathymetry of the area. It is generally not very easy to keep updating the bathymetry because of its highly dynamic nature. It is neither cost effective nor time efficient. Scanning of bathymetry is better in clear water where accuracy can go up to a level of +- 15cm (Lillycrop et al., 1996). In turbid water it is much less, and is often not acceptable for modeling. The range of surveyable depth based on the turbidity of water lies between 50 m to 10 m. Bathymetric data for the nearshore region is important for underwater morphology to model the nature of wave propagation near the shoreline.

3. Data generation for water levels of different probability of occurrence

The method employed in calculating the water levels for different probability of occurrence are based on the nature of available data. It can be done through direct calculation from the existing database which is known as the response approach or by attributing contribution of each variable component (astronomical, meteorological, and wave induced) to calculate the joint probability which is known as the event approach. The response approach uses existing time series of water level data. The problem with such historical data is that they generally do not reflect the wave-induced contribution. The case of the response approach includes one or more than one combination of water level and wave conditions. For instance, the joint probability (combined wave tide effect) is calculated using the following formula:

$$P_{c.k}(H_{I,}C_I) = P_{H.I}\,(H_I)\times P_{c.j}\,(C_j)\;(K-1,\,i\times j)$$

Where wave height is PH.I (HI), tidal elevation is PC.j (Cj), event is k=1

It is important not only to define the level of water but also to include the duration of the event, i.e., the time dimension. The result may vary based on the type of approach used. The response approach is recommended when the different variables are not directly correlated. When simultaneous wave conditions and water levels exist, adding individual contribution to the total calculation (i.e, the event approach) is more effective and accurate.

4. Modelling event in coastal zone (numeric and analytical models)

Several models are available for modelling flooding in a coastal region. The run up estimation is performed based on characteristics of zones i.e., offshore, near-shore, shoreline response and flood inundation zones. Based on the nature of coastal structures, the wave impact is affected and by using an appropriate formula wave, the run up can be estimated. Coefficients that are accounted for wave run up estimation are beach slope, beach roughness, beach permeability and percolation and wave obliquity. The wave overtopping discharge is then calculated based on the mean discharge of water per linear meter of width of beach moving towards land. Fema (2003) proposes the use of discharge rate formula for calculation of sloping surfaces. This is then converted to the volume of water entering the hinterland to understand the actual amount of water that will be overtopping the barriers. Barrier configurations are incorporated in the model using the morphological data. Scenarios based on zonal wave generation, surges, tides, and wave-wave interaction are generated through models. There are different numerical and analytical types of models that are used for flood modelling in a coastal area. Numerical models are considered to be more versatile than the analytical models. One of the most common models used by modellers was introduced by Vellinga (1986). Other models like those introduced by Komar et al (1999, 2001), Sheach Model and TIMOR3 and SWAN are also used frequently. More sophisticated models like Delft 3D are also used to complement other models especially for beach erosion and breach scenarios. Scenario-based (overtopping, overflowing, breaching) flood parameter maps are generated and parameter maps are obtained as an output from the models. Outputs vary based on the type of model used, accuracy of data, model calculation and parameter used for modelling.

5. Calibration and validation of model:

Model calibration is performed during the output generation phase and calibrated results are validated with existing data to confirm the accuracy of results. Transport coefficient values are sometimes applied as calibration parameter in some of the models to estimate the level of uncertainty in the calculated variables. Models sometimes recommend default values for calibration based on calibrations in numerous applications. The result is a model output with reduced level of uncertainty.

6. Generation of flood hazard maps

Publication of the resultant parameter maps from the model output are done using GIS applications. It is important that uncertainty is represented on the generated maps so that users are aware of the zone of uncertainty. Zone of uncertainty should be taken into account for policy making purposes as this still remains a major source of conflict.

7. Monitoring and update

As mentioned earlier, flood hazard maps should be updated with field information and other relevant data. Remote sensing methods are useful for dynamic areas like coastal zones to keep the database updated. Monitoring is required so that uncertainties in the model can be incorporated in the decision making processes for applicable mitigation processes.

Common Problems with producing Maps

Lack of data, appropriate modelling software and skilled personnel are common problems encountered. Where data is not available, hazard maps can be produced from participatory processes, historic event records (such as newspapers from the time, where these exist, or flood depths marked on historic buildings and structures, photographs from previous events) and digitised.

Time and Cost to Produce Maps

The effort and resources necessary to produce flood maps will be dependent on the available data, and the type of map required. As expected there will be a trade-off between financial cost and other resources and the precision, currency and functionality of maps. Where high resolution data is available to purchase, maps of flood extent can be produced almost instantly. Once all the required data is available, modelling to mapping can take a matter of weeks for a well-defined area. Consultants can be employed for a one-off mapping exercise removing the need to develop expertise and buy modelling software.

However, in general the biggest investment in cost and/or time will be in obtaining the data required and validating the model outputs. Experience shows that digitizing data is laborious and time consuming and that, particularly in urban flood mapping, seemingly small inaccuracies in mapping can result in large inaccuracies on the ground. Often urban environments are the areas where air survey techniques perform badly due to complex ground coverage and therefore ground based surveys or extensive historic records are needed. If large areas with complex river formations are modelled there are often boundary issues where models of individual flows may merge.

For a robust up-to-date mapping and zoning system which can support both emergency planning and land use regulation, long-term investment in skills and capacity to maintain and update models and maps is required. This investment can form part of a wider land use planning or emergency management capacity.

1.4.5. Further Reading

FLOODsite. 2008. "Review of Flood Hazard Mapping." Integrated Flood Risk Analysis and Methodologies. No: T03-07-01, Wallingford, UK.

Neelz, S. and Pender, G. 2010. "Benchmarking of 2D hydraulic modeling packages." Bristol, Environment Agency.

WMO. 1999. "Comprehensive Risk Assessment for Natural Hazards." WMO/TD No. 955. Geneva, WMO.

1.5. Short term and real time flood forecasting

Short term and real time flood forecasting has a different role from flood hazard assessment. Hazard assessment is primarily aimed at making plans to reduce flood hazard and control exposure. Flood forecasting is an essential tool for providing people still exposed to risk with advance notice of flooding, in an effort to save life and property. Over recent decades in the UK, for instance, there have been great advances in flood forecasting and warning systems, in terms of improvements in technique, accuracy, forecast lead time and service delivery. Rather than estimating the probability and intensity of future events, short term forecasting of flood events stems from the translation of current weather and catchment conditions into predictions of where and when the flood waters will arrive.

The models and tools required for hazard assessment and flood forecasting purposes overlap somewhat. Some of these have been covered in Section 1.4.2. More are examined in Section 1.5.3 below, where the approaches in different countries are discussed. Different flood forecasting service models exist based on the needs of end users: a system may be developed for the public or strictly dedicated to the authorities. There is no single consistent approach worldwide but the basic principles of a good warning system are shared by all. These comprise:

- Better detection in times of need well before the actual event occurs
- Interpretation of the detected phenomena and forecasting this to the areas likely to be affected
- Dissemination of the warning message to the relevant authorities and public via the media and other communication systems.

The fourth and final aspect is to encourage the appropriate response by the recipients by preparing for the upcoming event. This can be improved through flood response planning by people at risk and their support groups.

1.5.1. Uncertainty in flood forecasting

Models, by definition, are approximations of reality. As described earlier, all models suffer from a certain level of approximation or uncertainty in spite of powerful computing systems, data storage and high level technologies. Decision makers have to consider the effects of uncertainties in their decision-making process. Errors in forecasting of an event, for example stage or time of arrival, may lead to under-preparation (at the cost of otherwise avoidable damage) or over-preparation (resulting in unnecessary anxiety). The balance between failure to warn adequately in advance and the corrosive effects of too many false alarms must be carefully managed.

The reliability of flood forecasting models relies on the quantification of uncertainty. All natural hazards are uncertain. The various sources that give rise to uncertainty in forecasting and early warning can be classified (Maskey. 2004) as:

- Model Uncertainty
- Parameter Uncertainty
- Input Uncertainty
- Natural and Operational Uncertainty.

It is necessary to gain a better understanding of the options available to deal with the uncertainties within the system arising from these different sources. For example:

- Model uncertainty can be reduced by a combination of different approaches for different models and the generation of best optimized result
- Input uncertainty can be minimized through improvement in spatial-temporal density of data, enhancing processing speed, stochastic (random element) simulation, and detailed knowledge of error structure
- Natural or operational uncertainty must be highlighted by reporting on the quality and reliability of data.

These methods can reduce uncertainty but can never eliminate it.

In order to produce a forecast, the initial conditions are typically determined by means of observations from rain gauges; these may, however, be unevenly spaced throughout the catchment, leading to uncertainty as to the total volume of rainfall. Where hydrologically important areas (such as steep slopes) are unrepresented, the model may utilize an interpolation method (introducing another element of uncertainty) in order to estimate run-off volume and peak flows. More sophisticated modeling can address these issues, but this in turn may demand high processing speeds and lengthy run-times.

To offset some of this uncertainty, operational flood forecasting systems are moving towards Hydrological Ensemble Prediction Systems (HEPS), which are now the ‘state of the art’ in forecasting science (Schaake et al. 2006; Theilen et al. 2008). This method formed part of initiatives such as HEPEX (Hydrological Ensemble Prediction EXperiment) which investigated how best to produce, communicate and use hydrologic ensemble forecasts for short, medium and long-term predictions. Despite its demonstrated advantages the use of this system is still limited: it has been installed on an experimental basis in France, Germany, Czech Republic and Hungary.

To deal with the uncertainty in spatio-temporal distribution and prediction of rainfall for extreme events, especially through radar derived data, a promising approach has been to combine stochastic simulation and detailed knowledge of radar error structure (Germann et al. 2006a, 2006b, 2009; Rossa et al. 2010). Radar ensembles have the potential benefits of increasing the time for warning especially for flash floods (Zappa et al. 2008). Advanced techniques, such as disdrometer networks (equipment capable of measuring the drop size, distribution and velocity of different kinds of precipitation) and LIDARs are being used to capture small scale rainfall phenomenon, whilst satellite remote sensing is more appropriate for regional and global level applications. A combination of all these methods and blending information is considered to be the most promising way forward.

Case Study 1.3 highlights a web-based flood forecasting initiative in India.

Case Study 1.3: Flood forecasting in India: a web-based system (WISDOM)

The Central Water Commission (CWC) in India developed a website to facilitate the process of making information about hydrological and hydro-meteorological data (i.e., meta-data) available to the public. The WISDOM website provides a flood warning service to non-registered users. Registered users can access and request the available data in their preferred format by selecting from the following options:

- List-based selection of the data made by either state/district/tahsil or by basin/major river/local river, and by Data Storage Centers (DSC) of any agency for both surface water and groundwater.
- Map-based selection can be made either by state boundary, surface water basin or by groundwater basin.

After the selection of the preferred parameters, an electronic Data Request File (DRF) is e-mailed to all the concerned DSCs. Once payment is made, the DSC of the respective agency will send the data to the user through e-mail, soft copy, or hard copy in the requested format.

Web-based systems such as WISDOM are an effective way to disseminate widely scientific information, such as hydrological and hydro-meteorological data, to a range of users and to facilitate better flood forecasting and research on the issue.

Source: CWC: http://www.cwc.nic.in/

1.5.2. Constraints in developing better forecasting systems

Commonly faced problems in the development of short term and real time forecasting are lack of surface measurement stations for rainfall and other land surface parameters and lack of aggregation between upstream and downstream data sharing in real time. Where upstream countries lack the necessary financial resources for real time monitoring, or treaties do not exist, the non-cohesiveness of the system limits the flood forecasting lead times. As a lower riparian country, Bangladesh suffers from such delays due to challenges related to real time data and information sharing for flood forecasting across national boundaries.

A notable exception is the Mekong River Commission (MRC) in Southeast Asia, which, as seen in Case Study 1.4 below, has a well-integrated system of data collection, monitoring and dissemination on a regular basis to its member countries. Satellite remote sensing technologies are being used to derive surface parameters in real time, thus enhancing the chances of increasing the forecast lead time.

Although data are available to all from the Global Data Processing and Forecasting System (GDPFS), discussed below, resources and technical capacity to use the data may still be lacking. Where access to technology is limited, there exists a continuing conflict between cost and reliability and a need for prioritization and leadership both by the government and the responsible local authorities. In these cases it is important to integrate the locally available resources in sustainable capacity. To progress, the aim should be to move towards an adapted system which can be maintainable and accessible by both technical and non-technical persons for the long term. Data sharing and regular communication throughout the catchment is just as important for establishment of a better forecasting and warning system as the latest technology.

Case Study 1.4: Mekong River Commission: Mekong Flood Forecast

The Mekong River Commission (MRC) was formed in 1995 by an agreement between the governments of Cambodia, Lao PDR, Thailand and Vietnam. The four countries agreed on joint management of their shared water resources and development of the economic potential of the river. The MRC has made available data about water levels along the main stream of Mekong River. Users have access to a range of data and information of 22 hydrological stations, such as observed and forecast water levels on the mainstream Mekong River. Data are available online on a weekly basis.

The MRC Mekong Flood Forecast is in general more accurate for downstream locations, as there is limited access to upstream monitoring stations contributing to the forecast. The accuracy of forecasts is highest for short-term prediction (1-3 days) as the daily input parameters are certain, but it decreases as forecasts look further ahead in time. Data and information from the stations is supplied as a service to the governments of the MRC member states so that it may be used as a tool within existing national disaster forecast and warning systems.

MRC's program significantly enhanced capacities in flood risk management among member states, especially through mechanisms such as the flood forecasting system, and has promoted trans-boundary cooperation and coordination. Over the past years, cooperation in flood forecasting and exchange of data and information between the riparian countries through MRC has made significant progress and there is now much more awareness about the importance of joint flood risk management.

Source: The Mekong River Commission:
http://www.mrcmekong.org; MRC 2010.

1.5.3. Flood forecasting systems

National Meteorological and Hydrometeorological Services (NMHS) are responsible for monitoring, detecting, forecasting and developing hazard warning for water related hazards in 187 member nations, supported by the WMO. The Global Observing System (GOS), also supported by the WMO, coordinates regular and systematic observation of climatic and water phenomena from around the globe. The Global Telecommunication Systems (GTS) is the supporting network for exchange of information. Through this, the WMO has developed the Global Data Processing and Forecasting System which provides alerts and bulletins to local NMHS member states.

This system is not universal and therefore in many cases, especially in African, Asian and Caribbean regions, there is a lack of fully-fledged flood monitoring and warning systems. In tropical areas, such as the Indian Ocean Commission (COI) region, the flood monitoring system is typically closely linked with the cyclone warning system. Many of the existing flood warning systems are part of stand-alone national warning systems without international coverage. Some of the rivers that are covered under international systems are the Rhine, Danube, Elbe, and Mosel in Europe; the Mekong River, Indus-Ganges-Brahmaputra-Meghna Basin in Asia; and the Zambezi in South Africa.

The International Flood Network (IFNeT), which was formed in order to facilitate international cooperation in flood management, provides flood warning information using satellite data through the Global Flood Alert System (GFAS). The National Oceanographic and Atmospheric Administration (NOAA) in the US provide seasonal forecasts based on the information from the major river basins using satellite data.

Most developed countries use reasonably sophisticated flood forecasting system as compared to developing countries. Near real time forecasting is possible using remotely sensed satellite data, for example NOAA-AVHRR images. Institutions like NASA and the US National Snow and Ice Data Centre (NSIDC) make data available to the public within 16 to 72 hours of acquisition. Some countries also use the WMO's GTS to acquire real time data. NASA and JAXA, the Japanese Space Agency, have collaborated on the provision of tropical rainfall data, as seen below in Case Study 1.5.

Some examples of operational flood forecasting systems, and their inception dates, are FEWS (flood early warning system) in Sudan (1990), FEWS Pakistan (1998), EFAS (1999-2003) covering many parts of Europe), NFFS and SFFS in the UK (2002) and the Community Hydrological Prediction System in the US (2009). The Bureau of Meteorology (BOM) in Australia (2010) has a system currently in the developmental stage. In Asia, the Asian Disaster Preparedness Centre (APDC) and Mekong River Commission are the major flood forecasting authorities.

There are two approaches to flood forecasting: deterministic or probabilistic. As an illustration of these methods, in England and Wales, the Environment Agency employs a mixture of deterministic and probabilistic flood forecasting method, whereby warnings are issued in areas where flooding is expected. In catchments that have very short lead times, it is difficult to respond well before an event actually occurs. A paradigm shift towards probabilistic flood forecasting, in which the likelihood of an event taking place is incorporated into the forecast, is currently in the experimental stages, with a view to providing better information to stakeholders and therefore increasing the time available for decision making.

Case Study 1.5: The Tropical Rainfall Measuring Mission (TRMM)

The Tropical Rainfall Measuring Mission (TRMM) is a partnership between NASA and JAXA, the Japanese Space Agency. It was developed to monitor and study tropical rainfall. TRMM observations have improved modelling of tropical rainfall processes and have led to better forecasting of inland flooding during hurricanes. The TRMM provides imagery and animations of hurricanes and shows precipitation coverage and rainfall estimates in land falling regions.

Precipitation data from the TRMM are made available within a few hours after being received by satellites and can be used to create rainfall maps to calculate precipitation rates in other weather systems or to perform Multi-satellite Precipitation Analysis (TMPA) analysis. Such scientific information allows for better understanding of the interactions between land masses, the sea and air, which impact global weather and climate.

All TRMM data are made publicly available by the NASA Goddard Earth Sciences Data and Information Services Center Distributed Active Archive Center (GES DISC DAAC). The online archive and other information about TRMM products can be found on: http://disc.sci.gsfc.nasa.gov/ and ftp://pps.gsfc.nasa.gov/pub/trmmdata/

Sources: NASA TRMM: http://trmm.gsfc.nasa.gov/

1.5.4. Considerations in designing a flood forecasting system

A flood forecasting system is essential for any urban area prone to flooding. It helps in forecasting the flow rate and water levels. It is an important component of flood warning – and the higher the accuracy of flood forecasting system, the easier it becomes for decision makers to decide whether they should issue a warning to the public. This also helps in extending the lead time that people get in moving to a safer location prior to the occurrence of a disaster. The components for designing an integrated system are outlined below in Table 1.3.

Table 1.3: Components for Designing of an integrated flood forecasting or warning system:

Actions	Considerations/ operations	Outputs/ Benefits
Data assimilation / acquisition	Remotely sensed meteorological and hydrological data (from gauging stations) Historical Data collection; Uncertainty reduction from data	Database generation. Collection of data from several sources and putting it together in one single hub makes it easier to work and share the resources

Data Communication	Standard data exchange digital formats; communication through reliable sources like line of site radio, satellite, cellular radio	Conversion and dissemination of data in a standard universal format This is helpful in using the data in a coordinated manner (coordination between national, regional and local organizations for data sharing)
Forecast (Other parameters included: environmental factors, historical flood data, economic and demographic factors)	Meteorological and hydrological forecasting using ensemble techniques (multiple forecast scenarios generated by several model runs) Debris flow models, Flash Flood Guidance, NWS river forecasting System	Scenario generation based on different parameters This is helpful in highlighting the effects of different factors or parameters used in the actions stage and their potential impacts on changing future conditions. Effective when performed in an integrated manner
Decision support	Advanced planning and action are the main considerations Inclusion of uncertainty in forecast in a non-technical manner	Different products based on the end user's requirements (e.g. tables, hydrographs, inundation maps) Important in decision making process as this gives a clear picture of priorities and areas of immediate attention
Dissemination	Inventory of user groups: user specific information Rapid action	Rapid dissemination of information to population at risk with sufficient lead time and in understandable format
Coordination / Response	End to end flood response program Vigilant authorities Understanding the importance of forecast and warnings	Better linked communication system to reach the population Important for fast and effective response

1.5.5. Further Reading

EXCIMAP (2007) Handbook on good practices for flood mapping in Europe, European exchange circle on flood mapping. http://ec.europa.eu/environment/water/flood_risk/flood_atlas/pdf/handbook_goodpractice.pdf.

1.6. Accounting for climate change and sea level rise

Climate change is likely to have implications for today's urban flood risk management decisions, but is one of many drivers that must be considered (e.g. urbanization, aging infrastructure, and population growth). Many decisions made today regarding flood risk management will have ramifications well into the future. Failure to adequately treat climate change in decision making today could lead to future unnecessary costs, wasted investments and risks to life. Decision makers therefore require long term projections of risk, as well as detailed hazard maps of current flood risk. The idea that climate change will cause huge changes in risk and therefore render current flood risk management practice obsolete in the future is widespread and justified in some cases. This makes it highly problematic for governments and individuals to make confident decisions and to critically assess their investments in risk management. Long-term infrastructure is an area where planning decisions are likely to be sensitive to assumptions about future climate conditions. This can lead to indecision, delay in investment and higher damages from flood events in the short term. It is, therefore, crucially important to explore the implications of climate change for future flood hazard and to look for ways to build those implications into decision making processes.

There exists a broad consensus that flood risk is already changing at a significant rate, and that the rate of change might intensify in the next coming decades (Pall et al. 2011). As discussed in Section 1.2, a variety of climatic and non-climatic variables influence flood processes. Some of the climatic variables that flood magnitudes depend upon are precipitation intensity, timing, duration, phase (rain or snow) and spatial distribution. In the case of floods caused by sudden snowmelt, temperature and wind speed are also key factors. In this section we focus on the climatic drivers of floods and briefly discuss their observed and projected changes.

1.6.1. Potential impacts of climate change on cities

Around half of the world's population now lives in urban areas and this figure is projected to reach 60 percent by 2030. Urban population and infrastructure is increasingly at risk to some of the possible negative impacts of climate change.

There is potential for increased flood risk from:

- Increased precipitation

- Drought leading to land subsidence
- Rising sea levels
- Rapid snowmelt

Urban centers located predominantly in low-lying coastal areas are particularly vulnerable to sea level rise, storm surge and heat waves, all of which are likely to worsen due to climate change. In 2005, 13 out of the 20 most populated cities in the world were port cities (Nicholls. 2007a).

Deltas are also widely recognized to be highly vulnerable to the impacts of climate change, particularly sea level rise and changes in runoff. Most deltas are undergoing natural subsidence that exacerbates the effects of sea level rise. This is compounded with some human actions, such as water extraction and diversion, as well as declining sediment input as a consequence of entrapment in dams. It is estimated that nearly 300 million people inhabit a sample of 40 deltas globally. The average population density is 500 people per square kilometer, with the largest population in the Ganges-Brahmaputra Delta and the highest density in the Nile Delta. Due to these high population densities, many people are exposed to the impacts of river floods, storm surges and erosion. Modeling studies indicate that much of the population of these 40 deltas will continue to be at risk primarily through coastal erosion and land loss, but also through accelerated rates of sea level rise (Nicholls. 2007b).

Estimation of impacts of sea level rise, increasing temperatures and changing rainfall patterns on cities, and the development of robust adaptation pathways, is complicated by a combination of the characteristics of the infrastructure to be protected and the uncertainty of local and regional climate projections. Adaptation measures have to take into account the fixed or long term life span of urban infrastructure already in place, and the long lead times for the planning of replacements, as seen in Case Study 1.6 below.

Case Study 1.6: Climate-proofing road infrastructure in Kosrae, Federated States of Micronesia

The primary purpose of this project implemented by the Government of the Federated States of Micronesia in the Pacific was to provide road access to the remote village of Walung in the southwest of the Kosrae Island. Construction of the 16 km long road started in 2004. The road is 7 to 10 m above sea level, with the lowest point at about 4 m. The weather and climate-related risks that affect the design of the road infrastructure are related to determining its hydraulic design features.

By 2005, 3.2 km of road were built with drainage works designed for an hourly rainfall of 178 mm with a recurrence interval of 25 years. Because of the lack of local hourly rainfall data, this value was actually derived using hourly rainfall data for Washington DC. At present however, the hourly rainfall condition is up to 190 mm – and by 2050 the hourly rainfall is expected to increase to 254 mm. In 2005, although 3.2 km were already built, it was decided that the design of the road be modified so the drainage works could accommodate the higher hourly rainfall of 254 mm.

This delayed the completion of the road. Moreover, due to the need to climate-proof, the costs of retroactively fitting the necessary adaptation were much greater than those envisaged in the original budget. However, accumulated costs, including maintenance and repairs, for the climate proofed design will be lower than if the road was constructed in the original design after only about 15 years.

This case demonstrates the importance of integrating climate change scenarios into current and future planning decisions. The location and nature of all necessary newly planned infrastructures should draw on projections of climate change. The key issue here is how to incorporate deep uncertainty into infrastructure design with long lead-in and lock-in periods and avoid damages that could impose unnecessary costs.

Source: ADB 2005.

Although individual extreme weather events cannot be attributed to climate change, recent studies have shown that anthropogenic climate change can increase the chance of some of those events happening (Pall 2011; Min 2011; Stott 2004). A recent IPCC special report on managing the risks of extreme weather events and disasters concludes the frequency of heavy precipitation, daily temperature extremes, intensity of tropical cyclones, droughts, and sea level will be increased (IPCC 2011).

Analysis of specific extreme events can serve to illustrate their possible impacts were they to become more frequent or intense in the future. One well-known such example is that of Hurricane Katrina which made landfall in coastal Louisiana in August 2005. One result of the hurricane was the loss of 388 square kilometers of coastal wetlands, levees and islands that flank New Orleans in the Mississippi River delta plain. As these areas collectively act as the first natural defense against storm surge, this attribute was also lost. Over 1,800 people died and the economic losses totaled more than US$100 billion. Roughly 300,000 homes, and over 1,000 historical and cultural sites, were destroyed along the coasts of Louisiana and Mississippi, whilst the loss of oil production and refinery capacity helped to raise global oil prices in the short term (Nicholls 2007).

1.6.2. Climate change and variability: observed and projected changes.

1.6.2.1. Observed changes

At continental, regional, and ocean basin scales, some significant changes in the climate system have already been observed:

The warming rate as demonstrated by global mean surface temperature over the last 50 years (0.13ºC ± 0.03 ºC per decade) is almost double that over the 100 years from 1906-2005 (0.07 ºC ± 0.02 ºC per decade). Moreover, the 10 warmest years on record have all occurred since 1998 (Trenberth 2007). At the end of the melt season in September 2010, the ice extent in the Arctic Sea was the third smallest on the satellite record after 2007 and 2009. Global mean sea level is rising faster than at any other time in the past 3,000 years, at approximately 3.4 millimeters per year in the period from 1993 to 2008 (WMO 2009).

Precipitation over land generally increased during the 20th Century at higher latitudes, especially from 300N to 850N, but it has decreased in the past 30 to 40 years in the more southerly latitudes between 100S and 300N. There was an increase of precipitation in this zone from around 1900 until the 1950s, but this declined after about 1970. Global averaged precipitation does not show any significant trend in the period 1951-2005, with significant discrepancies between different data sets, and large decadal variability.

Observed changes in weather extremes are all consistent with a warming climate. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (Solomon et al. 2007) stated that increases in heavy precipitation over the mid-latitudes have been observed since 1950. This includes places where mean precipitation amounts are not increasing. Since 1970, large increases in the number and proportion of strong hurricanes globally have also been recorded, even though the total number of cyclone and cyclone days decreased slightly. The extent of regions affected by drought has also increased due to a marginal decrease of precipitation over land, with a simultaneous increase in evaporation due to higher temperatures.

Increases in precipitation intensity and other observed climate changes during the last few decades, such as sea level rise, suggest that robust future projections for flood management systems cannot be based on the traditional assumption that past hydrological experience provides a comprehensive guide to future conditions (Bates el al. 2008). In the IPCC Summary for Policy Makers (IPPC 2007), the conclusion drawn is that it is likely that the frequency of heavy precipitation events has increased over most areas during the late 20th Century, and that it is more likely than not that there has been a human contribution to this trend (Solomon et al. 2007). It is expected that global warming will affect both atmospheric and ocean circulation in such a way that many aspects of the global water cycle will change.

1.6.2.2. Projected changes

The IPCC has identified a range of possible futures for the planet, depending on the levels of greenhouse gas emissions that may be expected. These are defined in the Special Report on Emissions Scenarios (SRES) (IPCC 2000). There are four groups of scenarios, termed 'families', which range from A1, covering the highest emissions envisaged, through A2 and B1, to the lowest emissions grouping, B2. Within each of the family groups, there are multiple scenarios depending upon the levels of individual variables chosen: for example, the A1 family encompasses scenarios 'A1T' and 'A1F1', amongst others.

The range of global mean temperatures projected by several of these scenarios suggests marginally higher temperatures even if emissions were held at their 2000 values. This continued rise further suggests that even if emissions were drastically reduced now, at least in the short term the world will become warmer (IPPC 2007) by about 0.5 degrees. The projection of temperature rise for the worst case scenario sees a potential six degree warming by 2100.

Projections of global mean temperature change and rainfall for the highest and the lowest emissions scenario overlap until the 2020s. For the 2020s, changes in global mean precipitation are masked by its natural variability in the short term. The picture is different for longer term projections, when the emissions path does matter (Solomon et al. 2007). Changes in global mean precipitation become distinguishable from its natural variability, and some robust patterns emerge, such as an increase in the tropical precipitation maxima, a decrease in the subtropics and increases at high latitudes. However, due to larger uncertainties in the simulation of precipitation, the confidence in precipitation response to greenhouse gas increases is much lower than the confidence in simulated temperature response (Stone 2008).

Clearly, regional changes can be larger or smaller than global averages and, in general, the smaller the scale the less consistent the picture when viewed across the ensemble of global climate model (GCM) projections, particularly for some climate variables. The Regional Climate Projections chapter of the IPCC's AR4 report (Christensen et al. 2007), presents projections at continental scales, and then goes down to sub-continental scales in the form of so-called Giorgi regions: for example, Africa is subdivided into Western, Eastern, Southern and Sahara regions. One key feature of these regions is that they are typically greater than a thousand kilometers square and therefore much larger than the spatial scales relevant for most impact studies.

The greatest amount of warming is expected, and has been observed, over the land masses. In particular, it is expected that significant warming will occur at higher latitudes. In spite of the fact that these are regions with the largest uncertainties in their projections, and by the 2020s some GCMs project very small (or even slightly negative) temperature changes; by the 2080s all GCMs project warming of one or more degrees with respect to the 1997-2006 decade (Stone 2008).

Precipitation changes are less consistent than temperature changes, partly because precipitation is much more variable than temperature, and partly because it does not respond as directly to increases in concentrations of greenhouse gases' as temperature does.

The changes in annual means projected for the 2020s indicate that the largest potential changes – and simultaneously the largest uncertainties – occur in areas where precipitation is low, such as deserts and Polar Regions. By the 2080s projections show even greater variability, but some patterns emerge, such as the fact that precipitation in the Polar Regions is projected to increase. This is related to the fact that models project a retreat of sea and lake ice, allowing surface waters to evaporate directly (Stone 2008).

At the regional level, then, the seasonality of changes has to be considered, since clearly changes in annual averages do not uniquely determine the way in which the frequency or intensity of extreme weather events might change in the future. In Europe for example, where the annual mean temperature is likely to increase, it is likely that the greatest warming will occur in winter in Northern Europe and in summer in the Mediterranean area (Christensen et al. 2007).

Levels of confidence in projections of changes in frequency and intensity of extreme events (in particular regional statements concerning heat waves, heavy precipitation and drought) can be estimated using different sources of information, including observational data and model simulations. Extreme rainfall events, for example, are expected to be unrelated to changes in average rainfall. Average rainfall amount depends on the vertical temperature gradient of the atmosphere which, in turn, depends on how quickly the top of the atmosphere can radiate energy into space; this is expected to change only slightly with changes in carbon dioxide concentrations. On the other hand, extreme precipitation depends on how much water the air can hold, which increases exponentially with temperature. Thus it is reasonable to expect that in a warmer climate, short extreme rainfall events could become more intense and frequent, even in areas that become drier on average. Some studies have found that in regions that are relatively wet already, extreme precipitation will increase, while areas that are already dry are projected to become even drier, due to longer dry spells.

Projections of extreme events in the tropics are uncertain, due in part to the difficulty in projecting the distribution of tropical cyclones using current climate models with too coarse a spatial resolution, but also due to the large uncertainties in observational cyclone datasets for the 20th Century. For instance, some studies suggest that the frequency of strong tropical cyclones has increased globally in recent decades in association with increases in sea surface temperatures. These results are consistent with the hypothesis that, as the oceans warm, there is more energy available to be converted to tropical cyclone wind. However, the reliability of estimating trends from observational data sets has been questioned based on the argument that improved satellite coverage, new analysis methods, and operational changes in the tropical cyclone warning centers have contributed to discontinuities in the data sets and more frequent identification of extreme tropical cyclones after 1990 (Fussel 2009).

Global mean sea level has been rising; there is high confidence that the rate of rise has increased between the mid-19th and the mid-20th centuries. However, even though the average rate was 1.7 ± 0.5 millimeters per year for the 20th Century, the data shows large decadal and inter-decadal variability and the spatial distribution of changes is highly non-uniform. For instance, over the period 1993 to 2003, while the average rate of increase was 3.1 ± 0.7 millimeters per year, rates in some regions were larger while in some other regions sea levels fell (Solomon et al. 2007). Factors that contribute to long term sea level change are thermal expansion of the oceans, mass loss from glaciers and ice caps and mass loss from the Greenland and Antarctic ice sheets.

The present understanding of some important effects driving sea level rise is too limited. Consequently the IPCC AR4 (Solomon et al. 2007) does not assess the likelihood, nor provide a best estimate or upper bound, for sea-level rise. Model based projections of global mean sea-level rise between the late 20th century (1980-1999) and the end of this century (2090-99) fall within a range of 0.18 to 0.59 meters, based on the spread of GCM results and different SRES scenarios. These projections do not, however, include the uncertainties noted above (Bates et al. 2008). Sea level rise during the 21st Century is expected to have large geographical variations due to, for instance, possible changes in ocean circulation patterns. Even though it is expected that significant impacts in river deltas and low-lying islands might occur, the range of the plausible impacts are, therefore, yet to be specified.

1.6.2.3. Uncertainties in projections

There are different sources of uncertainties in climate change projections. These are partially due to the fact that the future socio-economic development is inherently unknown, but also as a consequence of the incomplete knowledge of the climate system, and the limitations of the computer models used to generate the projections (Stainforth 2007). The relative and absolute importance of different sources of uncertainties depends on the spatial scale, the lead-time of the projection, and the variable of interest. At shorter time scales, in many cases the natural variability of the climate system and other non-climatic risks would have a higher impact than climate change. For example, during the next few years, changes in urbanization and urban development in unsuitable areas could increase significantly the risk of flooding independently of climate change. On longer time scales, it is expected that climate change might play a more significant role. In this context, any strategy adopted to manage climatic hazards has to take into account the fact that projections of climate change include high levels of uncertainty and, even more importantly, acknowledge that in many cases, particularly at local scales, current tools to generate projections cannot tell us anything about future changes (Oreskes et al. 2010; Risby et al. 2011). The Kolkata Case Study below is a useful one, as it shows how to identify the underlying causes of flooding using hydrological, hydraulic and urban storm models.

Case Study 1.7: A megacity in a changing climate

The Kolkata Metropolitan Area (KMA) in India has a population of around 14.7 million and ranks amongst the 30 largest cities in the world. The city experiences regular floods during monsoons. According to the OECD report on "Ranking of the World's Cities Most Exposed to Coastal Flooding Today and in the Future", in the 2070s Kolkata will rank first in terms of population exposed to coastal flooding amongst port cities with high exposure and vulnerability to climate extremes. Potential threats to Kolkata include:

– Natural factors associated with its flat topography and low water relief of the area
– Unplanned and unregulated urbanization
– Lack of adequate drainage and sewerage infrastructure that have not been upgraded during the growth of the city
– Obstruction due to uncontrolled construction in the natural flow of the storm water, reclamation of and construction in natural drainage areas such as marshlands
– Climate change aspects, such as an increase in the intensity of rainfall, sea level rise and increase in storm surges which may increase the intensity and duration of flood events.

To identify the underlying causes of flooding in the KMA, hydrological, hydraulic and urban storm models were used. These incorporated historical rainfall data from 1976 to 2001 and assumed climate change effects, as follows:

– To estimate the water flow in the Hooghly River, water flow was modeled using the rainfall and temperature data obtained from the India Meteorological Department for the whole catchment area during the past 35 years. This modeling generated daily flow series at various locations along the river
– A hydraulic model was used to generate flood waves moving through the

river channel. Output from the model provided water surface profiles all along the river, coupled with change in flow depth during the flood period

– By incorporating the existing urban characteristics, an urban storm model was used to simulate the flooding that will result once river flooding is combined with the local rainfall and drainage capability of the KMA area.

By assessing all three sources of flooding and incorporating climate change in the analysis, technical specialists can present a better representation of risk in the targeted area, and decision makers can avoid choosing inadequate measures.

Sources: World Bank 2011; Nicholls et al. 2007a.

1.6.3. Incorporating climate change scenarios in probability analysis and flood risk management

A comprehensive modeling approach to assess changes in flood hazard due to climate change requires the combined simulation of all the domains: atmosphere and ocean, catchment river network, floodplains and indirectly affected areas. Considerable uncertainty is introduced on each of the modeling steps involved, including uncertainties about the greenhouse gas emission scenario, in the representation of physical processes in the global climate model, in the characterization of natural variability, in the method of downscaling to catchment scales, and in hydrological models' structure and parameters.

The uncertainty associated to a complete model chain, therefore, grows in each step and becomes very large, particularly at the scale relevant for decision-making. Some authors refer to this effect as an 'explosion of uncertainty' caused by the accumulation of uncertainties, through the various levels of the analysis carried out to inform adaptation decisions (Dessai 2009). Moreover, in many cases different results are obtained using different model set ups, indicating that results are highly conditional on the assumptions made for the modeling exercise (Merz 2010).

It is interesting to notice that the uncertainties present in the estimation of the impacts of climate change at local scales (i.e., a river flow in a particular catchment), have common characteristics with the uncertainties in the estimation of flood probabilities based on historical records. In both cases the estimates strongly depend on modeling assumptions and gaps in the understanding of relevant processes. Accurately predicting changes in flood hazard is, therefore, highly uncertain: climate change and other dynamic processes such as land use changes only increase the uncertainty with which flood risk management has to cope.

Flood hazard not only changes due to the natural and human induced variability of the climatic factors involved, but also due to the dynamics of societal factors. The contribution of the different drivers is largely unknown. In the short term, rapid economic, social, demographic, technological and political changes seem more important and immediate than climate change. Consequently, the effects of climate change on flood hazard should be considered in the context of other global changes that affect the vulnerability of flood-prone settlements Very importantly, flood risk management should be a constantly revised and updated process (Merz 2010).

Finally, flood risk is dynamic and the large uncertainties associated with the estimates of future risk make its management under climate change a process of decision-making under deep uncertainty. It is necessary to take a robust approach. Some risk management options that increase the robustness of urban flood risk management investments and decisions to climate change are so-called 'no-regrets' measures that reduce the risk independently of the climate change scenario being realized (for example, measures that reduce current vulnerabilities to weather and climate, or other non-climatic drivers); options that incorporate flexibility into long-lived decisions; or options that have significant co-benefits with other areas, like ecosystems-based flood control (Ranger 2010). Figure 1.2 summarizes the key processes towards robust decision making in an era of climate change, while Case Study 1.8 focuses on the flexible and no regret measures that Mexico City is implementing under its climate change adaptation program.